

Integrating geoethics and digital innovation for transformative geoscience education in Africa: pathways to sustainability and environmental justice

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Abstract

Africa is endowed with critical minerals essential for technological advancement and therefore needs skilled geoscientists to address multiple challenges related to resource management, natural hazards, water management, environmental justice, climate change, and training systems. Unfortunately, Geoscience education in Africa is faced with inadequate infrastructure, limited access to modern analytical tools, and unstandardized curricula that are not in line with global standards. These structural gaps are obstacles to the development of a new generation of geoscientists capable of responding to these concerns. This review paper employed a systematic narrative approach, synthesizing peer-reviewed literature, policy documents, and regional reports published between 2000 and 2025, using keywords like 'geoscience education Africa' and 'AI geoethics', applying inclusion criteria for Africa-focused/analogous studies ($n = \sim 312$ retrieved, 120 screened by abstract/full-text, 87 retained post-quality appraisal via relevance/impact scoring; solo review with reflexivity for validity). Sources were retrieved from major databases (Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar) and supplemented with African regional journals, government white papers, and NGO reports to ensure contextual relevance.

Findings highlight three key areas: (i) existing gaps in the quality of geoscience education, inclusivity, and embracing technological advancement; (ii) new emerging opportunities in ICT technologies, virtual fieldwork, and AI-assisted learning models that are already being deployed worldwide and could be adapted for African contexts; and (iii) the potential to integrate geoethics digitally enhanced curricula to produce geoscientists that are ethically conscious and embrace technology. The study concludes that integrating geoethics and digital innovation is necessary for developing ethically grounded and technologically competent geoscientists capable of addressing Africa's socio-environmental challenges. The implications of this review underscore the need for policy reform, institutional investment, and cross-sector partnerships to build resilient and sustainable geoscience education ecosystems across Africa.

Keywords: Geoethics, Geoscience education, Digital innovation, Sustainability, Environmental justice, Africa.



1. Introduction

Africa's wealth of natural resources, coupled with natural hazards such as climate change, desertification, and water scarcity, underscores the need for a standardized Geoscience education for sustainable development. Africa's future is intimately tied to the sustainable management of its natural resources and the resilience of its societies to environmental change. Geoscience provides the knowledge base for understanding the distribution and use of critical minerals, energy resources, soils, and water, while also equipping societies to mitigate natural hazards such as floods, droughts, and landslides (Metzger, 2024; Lar, 2025).

Effective geoscience education will not only produce a highly skilled cadre of geoscientists that enable the exploration and responsible use of minerals, water, and energy resources but also equip societies to mitigate natural disasters, adapt to environmental change, and support critical infrastructure (AUC/OECD, 2021; UNESCO, 2024; Lar, 2025; Quarshie et al., 2025). Geoscience education is strategically important for driving both economic growth and resilience for a continent such as Africa where, its communities are intricately linked to the land for survival (Various

Authors, 2018; UNEP, 2019). Yet, despite the critical role of geosciences education in Africa, it is faced with pressing challenges such as its fragmented higher education systems with outdated curricula that often fail to integrate interdisciplinary approaches or address emerging local community issues such as artisanal mining and its attendant adverse environmental consequences (Jessel et al., 2018; Odoh et al., 2024; Lar, 2025). Many Universities lack modern laboratories, digital libraries, and adequate teaching aids, while fieldwork opportunities are constraint by insufficient funding and logistics (Jessel et al., 2018). The migration of qualified geoscientists in search of better research opportunities exacerbates the scarcity of skilled human resources and researchers (Imoniri, 2025). Furthermore, high-quality geoscience education needs to be accessible to both urban and rural communities to bridge social and gender disparities (Jessel et al., 2018; Sapah et al., 2024). Collectively, these constitute impediments to Africa's ability to be able to equip a new generation of geoscientists capable of contributing to Africa's sustainable development (WEF, 2020; Sey and Mudongo, 2021).

1.1. Why geoethics and Artificial Intelligence (AI) in geoscience education matter in the African context

Recent studies on artificial intelligence capacity in Africa show a mixed reality (West and Allen, 2018; Williamson and Eynon, 2020; Quarshie et al., 2025). On one hand, there are persistent structural challenges, such as unreliable electricity supply, weak broadband infrastructure, inadequate teacher training, and uneven levels of digital literacy (UNESCO, 2024; Quarshie et al., 2025). On the other hand, scholars also emphasize the powerful, transformative potential of AI, particularly when it is implemented within ethical, inclusive, and well-regulated frameworks (West and Allen, 2018; Plantinga et al., 2024; Segooa et al., 2025). Without ethical governance, AI deployment risks reinforcing inequalities, reproducing extractive data practices, and marginalizing local knowledge systems (Peppoloni and Di Capua, 2021, 2022, 2023, 2024; Di Capua and Peppoloni, 2025).

In geoscience specifically, digital tools are increasingly used for mineral exploration modeling, groundwater prediction, climate risk mapping, and geohazard assessment (MacDonald et al., 2021; Shaikh and Biajdar, 2024; Oláh, 2025). However, the integration of these tools into African higher education remains uneven. At the same time, Africa faces acute socio-environmental challenges, artisanal mining conflicts, environmental injustice, land degradation, and climate vulnerability, that demand ethically grounded geoscientific practice (Hilson, 2016; Hilson and Maconachie, 2020). Geoethics provides a normative framework for responsible decision-making in resource governance, community engagement, and environmental stewardship

(Peppoloni and Di Capua, 2021, 2022, 2023, 2024; Di Capua and Peppoloni, 2025). Integrating geoethics with AI and digital innovation is therefore not optional but necessary to ensure that technological transformation aligns with sustainability and social justice objectives (Aden, 2020; AAU, 2023; Okebukola, 2025). Despite growing scholarship on AI capacity and geoethics globally, limited work has examined their combined implications for geoscience education in Africa. This gap justifies the present review.

1.1.1. Defining geoethics

Geoethics is an emerging field that puts emphasis on the ethical, social, and cultural dimensions of geoscience knowledge and practice (Di Capua et al., 2017; Peppoloni and Di Capua, 2017, 2020). It seeks to address the responsibilities of geoscientists to the environment and society, highlighting values such as sustainability, inclusivity, equity, and respect for local communities. Fundamentally, geoethics serves as a foundational guide for decisions about how geoscience is taught, researched, and practised, ensuring that professional activities promote actions that benefit society and uphold environmental responsibility (Peppoloni and Di Capua, 2020; Di Capua and Peppoloni, 2025).

1.1.2. Relevance to Africa's context

In Africa, where humans interact closely with the environment through agriculture, artisanal mining/smelting, groundwater-dependent etc. and their attendant environmental and socio-economic consequences, geoethics is of critical importance (Various Authors, 2018; UNEP, 2019). Activities such as artisanal and small-scale mining, widespread land degradation, competition over mineral and water resources, and increasing vulnerability to climate change often place significant pressure on both ecosystems and livelihoods (Hilson, 2016; Hilson and Maconachie, 2020). These challenges underscore the need for geoscientists to not only demonstrate technical proficiency but also uphold strong ethical principles to guide responsible, equitable, and sustainable decision-making (Peppoloni et al., 2017). For example, the exploitation of mineral resources in the Democratic Republic of Congo and Nigeria and its devastating consequences not only about environmental impacts but also about human rights, community displacement, and governance raises serious concerns (African Union, 2009; World Bank, 2016). The inclusion of geoethics in geoscience education ensures that graduates are equipped to effectively

navigate such complex intersections of the Earth system, society, and sustainable development (Peppoloni et al., 2019).

1.1.3. Integrating geoethics into education

Despite its importance, geoethics is yet to find its rightful place in African geoscience curricula. The current geoscience curricula emphasize technical competencies to the expense of values such as responsibility, equity, and justice. Modernizing geoscience curricula by integrating geoethics ensures that it is incorporated in teaching modules, field training, and research supervision (Peppoloni et al., 2019; Di Capua et al., 2017; Peppoloni and Di Capua, 2022). Ethical responsibility becomes a core component of fieldwork, given that African geoscientists often work in vulnerable ecosystems and under-developed communities.

Case-based learning, for instance, can expose students to real-world problems such as balancing mineral exploitation with environmental protection or ensuring fair community engagement in resource exploitations (Sey and Mudongo, 2021).

1.1.4. Linking geoethics with professionalism and policy

Adopting geoethics deepens the professional identity of geoscientists, highlighting their responsibility not just as technical specialists but as guardians of Earth's systems. It aligns with international codes of conduct, such as those promoted by the International Association for Promoting Geoethics (IAPG, <https://www.geoethics.org>, accessed 21 April 2026), while encouraging adaptation to local cultural contexts (Peppoloni and Di Capua, 2017, 2020). Integrating geoethics into geoscience education will require the enactment of a regional policy across Africa that promotes the principles of transparency, accountability, and environmental justice in resource governance. In this vein, geoethics becomes both an educational and a societal tool, that bridges geoscience academic training with broader sustainable development goals (Peppoloni and Di Capua, 2017, 2020; Ayeh and Bleicher, 2021; Paska, 2021).

1.2. Digital innovation in geoscience education

1.2.1. The potential of digital tools

Digital technologies are transforming higher education worldwide, and geoscience is no exception (Imoniri, 2025). Across Africa, where limited infrastructure and

resources restrict conventional teaching methods, digital tools offer new opportunities to enhance learning, expand access, and strengthen research capacity (UNESCO, 2025). Innovations such as AI, virtual and augmented reality (VR/AR), online learning platforms, and open-access geoscience repositories are reshaping how students learn, conduct virtual fieldwork, and interpret complex datasets (Evelpidou et al., 2021; Kitambo et al., 2022; Jatileni et al., 2024; Ajani and Ramaila, 2025; Imoniri, 2025; Maphalala and Ajani, 2025; Mudi et al., 2025).

By opening doors to high-quality learning experiences, these technologies help integrate African students into the broader international scientific community (Metzger, 2024).

1.2.2. Artificial Intelligence (AI) and Machine Learning (ML)

AI has the potential to revolutionize geoscience teaching and practice. In education, AI-powered platforms can deliver personalized learning experiences, adaptive assessments, and automated feedback (West and Allen, 2018; WEF, 2020; Quarshie et al., 2025; UNESCO, 2025). In most geoscience research nowadays, AI is already being used for mineral exploration survey, climate modeling, and groundwater prediction, exposing students to new emerging techniques (Zhao et al., 2024). Of utmost importance, AI can also assist in processing large datasets generated overtime by satellite imagery, or geophysical and geochemical surveys, skills that are required to rethink on strategies of revamping Africa's mining, energy, and environmental sectors (Boateng, 2024; Plantinga et al., 2024; Maphalala and Ajani, 2025; Segoa et al., 2025).

1.2.3. Virtual and Augmented Reality (VR/AR)

A major obstacle in African geoscience education is limited access to fieldwork due to financial, logistical, or security challenges (Asunka, 2008; Echezona and Ugwuanyi, 2010). VR/AR technologies can simulate field environments, enabling students to interact with geological structures, stratigraphy, and mineral deposits in immersive 3D environments. Through Virtual field trips, learners in remote or under-resourced institutions can gain exposure to diverse geological terrains without leaving the classroom (Evelpidou et al., 2021; Jatileni et al., 2024; Imoniri, 2025; Maphalala and Ajani, 2025). These tools are designed to complement rather than replace physical fieldwork, ensuring students gain both practical experience and simulated practical skills (Botha et al., 2020; Ajani and Ramaila, 2025; Mudi et al., 2025).

1.2.4. Online learning platforms and open resources

The COVID-19 pandemic accelerated the shift toward online education in Africa, exposing both opportunities and persistent inequalities. Online platforms such as Coursera, edX, and FutureLearn, regional initiatives like the African Virtual University, provide access to high-quality courses and specialized training (Asunka, 2008; Echezona and Ugwuanyi, 2010). In addition, open-access resources, including geological map repositories, remote-sensing datasets, and software platforms like QGIS, have reduced reliance on expensive proprietary systems (Odoh et al., 2024; Occhipinti, 2025; UNESCO, 2025). Incorporating these resources into geoscience curricula equips students with internationally relevant skills and promotes collaboration across institutions and national boundaries (Asunka, 2008; Echezona and Ugwuanyi, 2010).

1.2.5. Challenges and Risks of Digital Innovation

Despite its potential, digital innovation faces critical challenges in Africa. Limited internet connectivity, high data costs, unreliable electricity, and low level of digital literacy among Staff and students hinder widespread adoption of digital tools (Nyaaba et al., 2024). Furthermore, dependence on imported technologies can lead to solutions that fail to address local geological realities or educational priorities. Without adequate training, many teachers lack sufficient training to effectively integrate digital platforms into their teaching (Odoh et al., 2024; Occhipinti, 2025). These challenges highlight the need to pair digital innovation with robust capacity building, institutional investment, and locally tailored adaptation (Williamsom and Eynon, 2020; Boateng, 2024; UNESCO, 2024; Quarshie et al., 2025).

These tools can expand open access to high-quality learning, simulate field experiences, enhance research collaboration, and align African geoscience education with global best practices. Importantly, the convergence of geoethics and digital innovation can ensure that responsible and socially beneficial outcomes are imbibe with technological advancement (Peppoloni and Di Capua, 2021, 2022, 2023, 2024; Di Capua and Peppoloni, 2025; Peppoloni et al., 2025) (Figure 1).

Against this backdrop, this paper aims to critically review the role of geoethics and digital tools in reshaping geoscience education in Africa. Specifically, it seeks:

- 1) To analyze the persistent challenges in African geoscience education.
- 2) To highlight emerging opportunities from geoethics and digital innovation.
- 3) To propose a framework for integrating these opportunities into practice.
- 4) To illustrate the potential through selected African examples and offer recommendations for the way forward.

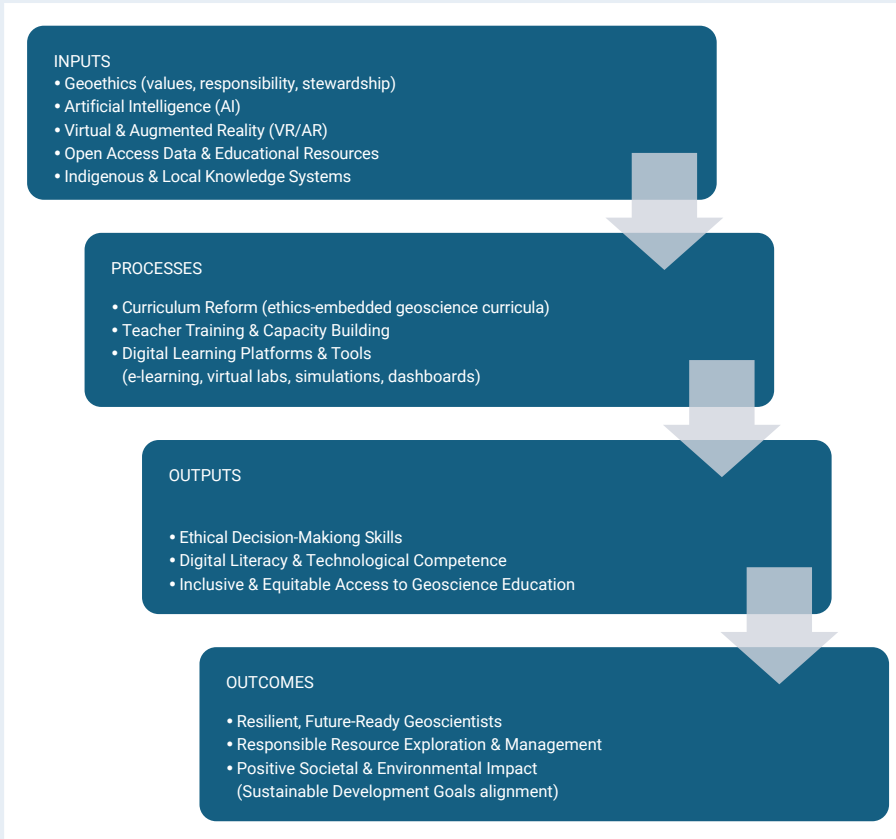


Figure 1. Conceptual flow diagram framework that links geoethics and digital innovation. This figure presents a layered conceptual framework that links geoethics and digital innovation to transformative education and long-term sustainable development. At the input level, foundational elements include geoethical principles (responsibility, stewardship, equity), emerging digital technologies such as AI and VR/AR, open-access data and educational resources, and Indigenous and local knowledge systems. These inputs collectively provide the ethical, technological, and contextual base for innovation in geoscience education. The process layer represents institutional and pedagogical mechanisms through which these inputs are operationalized. Key processes include curriculum reform that embeds ethical reasoning within geoscience training, continuous teacher training and capacity building, and the deployment of digital learning platforms such as e-learning systems, virtual laboratories, simulations, and interactive dashboards. The shift from inputs to action relies on strong institutional support, effective teaching approaches, and appropriate use of technology to turn available resources into practical outcomes. This layer emphasizes the transformation of traditional teaching approaches into inclusive, technology-enabled, and ethics-driven educational practices. The output layer highlights the immediate educational gains resulting from these processes, notably enhanced ethical decision-making skills, improved digital literacy and technological competence, and expanded inclusive access to geoscience education across diverse socio-economic and geographic contexts. Finally, the outcome layer illustrates the broader societal and professional impacts, including the development of resilient and future-ready geoscientists, responsible and ethical management of Earth resources, and positive societal and environmental impacts aligned with the Sustainable Development Goals (SDGs). Overall, the framework demonstrates a linear yet interconnected progression from ethical and digital inputs to education-driven sustainability outcomes.

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In doing so, this article aims to contribute a forward-looking perspective on how Africa can harness ethical considerations and technological innovation to train the next generation of geoscientists for sustainable development. The Figure 1 conceptually illustrates how integrating geoethics with digital innovation can drive transformative approaches in geoscience education while supporting sustainable development outcomes.

2. Methodology

A systematic narrative review approach was conducted to examine the intersection of geoethics and digital innovation in geoscience education across Africa. The approach followed four key steps: defining scope, identifying sources, screening records, and thematic analysis.

2.1. Review design and scope: a systematic narrative approach

This study adopts a systematic narrative review approach, blending the structured rigor of systematic reviews with the flexibility and depth of narrative synthesis (Baumeister and Leary, 1997; Green et al., 2006; Snyder, 2019). This combined method is especially well-suited to interdisciplinary topics, such as the intersection of geoethics, digital innovation, and geoscience education, where evidence comes from a wide range of sources, including empirical studies, conceptual frameworks, and policy documents.

Rather than limiting the analysis to narrowly defined questions or purely quantitative outcomes, this approach allows the study to draw meaningfully from diverse types of evidence while still maintaining transparency and methodological discipline. In essence, it strikes a balance: it is more structured and transparent than a traditional narrative review, yet more adaptable and interpretive than a strictly quantitative systematic review.

In practical terms, the “systematic” aspect of the review is reflected in the use of clearly defined databases and keyword combinations, well-articulated inclusion and exclusion criteria, and a stepwise screening process involving both title/abstract and full-text evaluation. It also includes a structured coding and thematic synthesis process, ensuring that the findings are grounded in carefully analyzed evidence rather than relying solely on interpretation (Baumeister and Leary, 1997; Green et al., 2006; Snyder, 2019).

At the same time, the “narrative” dimension is evident in how the study brings together insights from different types of literature. It synthesizes findings across varied sources, integrates conceptual, empirical, and policy perspectives, and develops an interpretive framework that connects geoethics with digital innovation in geoscience education. This allows for a richer, more context-sensitive understanding of the subject.

The scope of the review is organized around three main domains: (a) the current state of geoscience education in Africa, including curricula, institutional capacity, and access; (b) the role of geoethics in promoting responsible practice and teaching; and (c) the use of digital technologies – such as AI, VR/AR, online learning platforms, and open-access data – in transforming geoscience education. The review covers the period from 2000 to 2025, capturing both foundational studies and more recent developments in digital and ethical innovation.

Overall, this integrated approach provides a comprehensive yet carefully grounded understanding of how geoscience education in Africa is evolving, while ensuring that the review process remains transparent, systematic, and reproducible.

To make the review more transparent and give a clear picture of the evidence used, the key features of the selected studies are summarized in Table 1. The table groups the sources by their type, main themes, and geographic focus. This organization

Category	Sub-category	Number of Sources (n)	Percentage (%)
Source Type	Peer-reviewed journal articles	25	28.74
	Conference proceedings	5	5.75
	Policy documents	3	3.45
	Reports/NGO publications	3	3.45
	Preprints	2	2.30
	Book chapters	3	3.45
Thematic Focus	Geoscience education	10	11.48
	Digital innovation	7	8.05
	Geoethics and sustainability	9	10.34
	Integrated studies	4	4.60
Geographic Focus	Africa-specific	10	11.49
	Global (applied)	6	6.90
Total		87	100.00
Temporal Distribution	2000-2010	15	17.2
	2011-2020	31	35.6
	2021-2025	41	47.2
Total		87	100.0

Table 1. Summary of characteristics of reviewed literature (n = 87).

highlights the interdisciplinary nature of the review, bringing together peer-reviewed research alongside policy and practice-based materials to provide a well-rounded understanding of geoscience education, geoethics, and digital innovation in Africa.

2.2. Sources of data

Relevant articles were retrieved from major databases such as Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, supplemented by African regional journals, institutional repositories, and policy documents from UNESCO, the African Union, and NGOs. While peer-reviewed articles were prioritized, government white papers, educational policy briefs, and NGO reports were included to capture Africa-specific realities often absent from academic literature.

2.3. Search strategy and inclusion criteria

Some of the keyword combinations used in the search to identify relevant sources were *“geoscience education in Africa”*, *“geoethics”*, *“digital learning tools”*, *“AI in higher education”*, *“VR/AR in science teaching”*, and *“sustainable geoscience capacity Africa”*. A total of 312 records were retrieved across databases and institutional repositories. After abstract and full-text screening, 87 records were retained for analysis. Inclusion criteria required relevance to geoscience education, geoethics, or digital innovation in African or comparable contexts. Exclusion criteria applied to studies outside education or lacking methodological rigor. Thematic analysis followed Braun and Clarke’s (2006) framework, with categories validated through cross-checking and triangulation to ensure reliability.

2.4. Analytical approach and thematic coding

A systematic thematic analysis was used to identify key patterns in the selected literature on geoscience education, geoethics, and digital innovation in Africa (Green et al., 2006; Snyder, 2019). The process involved reading the studies, extracting relevant information, and grouping similar ideas into broader themes (Braun and Clarke, 2006).

First, all articles were carefully reviewed, and important passages were extracted. These were then assigned simple codes based on their main ideas. Related codes were grouped into broader categories, which eventually formed three main themes:

structural and institutional challenges, digital transformation and opportunities, and geoethical and sustainability issues (Green et al., 2006).

Finally, these themes were brought together to build a clear, integrated understanding of how geoethics and digital innovation can shape geoscience education.

To ensure reliability, the process was carefully documented, reviewed multiple times for consistency, and supported by evidence from different types of sources (Braun and Clarke, 2006).

This study uses a structured coding and thematic synthesis approach to ensure that its findings are firmly based on carefully and systematically analyzed evidence, rather than relying solely on interpretation or narrative description.

3. Results: geoscience education in Africa – progress, challenges, and the way forward

Geoscience education in Africa has increased immensely in the past two decades, especially through the establishment of geology, mining, and environmental science departments in higher Institutions with the support of regional initiatives such as the African Mining Vision (AMV) and UNESCO's Earth Science Education for Africa (ESEfA) to mention but a few (African Union, 2009; World Bank, 2016; Gill et al., 2019). Regional and International collaborations, donor-funded programs, and umbrella professional bodies like the Geological Society of Africa (GSAf – <https://gsafr.org/>, accessed 21 April 2026) facilitated training, retraining, research, and knowledge sharing among African geoscientists (UNESCO, 2024, 2025). The incorporation now of open-access digital platforms have complemented traditional teaching approaches. However, the system falls far of meeting its intended impact. Major challenges facing Geoscience Education in Africa are well encapsulated in the Table 2. While universities such as Ibadan, Johannesburg, and Nairobi rank top in training and research, many other institutions in West, East, and Central Africa are faced with fragmented and underdeveloped curricula, insufficient laboratories, and limited funding (African Union, 2009; AAU, 2023; Okebukola, 2025; African Union – Agenda 2063: https://au.int/Agenda2063/popular_version, accessed 21 April 2026). North and Southern Africa, particularly South Africa, have comparatively well-funded universities with advanced and well-structured geoscience programs, stronger infrastructures, and industry links, but most regions lack the resources to align academic training with modern scientific advances and industry needs, which undermines the development of a critical mass of skilled geoscientists (Semken et al., 2018; AAU, 2023; Okebukola, 2025; UNESCO, 2025). Geoscience education requires significant investment in laboratories, field equipment, and

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computational tools. Thus, chronic underfunding leaves many institutions unable to maintain basic facilities (Imoniri, 2025; Lar, 2025; Quarshie et al., 2025).

Geoethical challenge	Examples	Digital/AI-enabled solutions
Resource exploitation without community consent	Mining conflicts in DRC, Nigeria	AI-driven community engagement simulations
Limited access to quality field training	High costs, unsafe terrains	VR/AR field trips, virtual core logging
Corruption and lack of transparency	Licensing, data hoarding	Blockchain + open-access platforms
Exclusion of Indigenous knowledge	Ignored in curricula	Digital storytelling, GIS-based geoh heritage mapping

Table 2. Key geoethical challenges in African geoscience education and digital solutions.

3.1. Curriculum and pedagogy

Geoscience curricula in Africa remain largely outdated and are insufficiently aligned with current industry needs and emerging technological advancement (Metzger, 2024; Lar, 2025; Occhipinti, 2025; Okebukola, 2025; Semken et al., 2025). It is largely based on the classical geology (mineralogy, petrology, and stratigraphy) rather than being refashioned to integrate modern disciplines such as environmental geoscience, climate change, medical geology, and sustainability science.

Some top-ranking Universities have modernized their curricula, but many still rely on archaic and underdeveloped geoscience curricula which calls for the harmonization of geoscience curricula across the continent to ensure that all students receive a standardized and high-quality education that is relevant to Africa's unique geological context (Odoh et al., 2024; African Union – Agenda 2063: https://au.int/Agenda2063/popular_version, accessed 21 April 2026).

Majority of geoscience teaching methods are predominantly lecture-based, face-to-face and theoretical, with less attention to fieldwork or practical training due to inadequate funding, logistics, and security concerns (Aden, 2020; Sey and Mudongo, 2021; AAU, 2023; Odoh et al., 2024; Plantinga et al., 2024; Lar, 2025; Occhipinti, 2025; Okebukola, 2025). Most universities lack modern state of the art laboratory facilities and analytical equipment, and digital learning tools (Table 3), leaving students underexposed to contemporary analytical methods. Universities also face a shortage of qualified academics, worsened by brain drain, which further

limit their capacity for innovation and mentorship (Aden, 2020; AAU, 2023; Lar, 2025; Okebukola, 2025). In addition, gender imbalance stemming from weak inclusion policies do not allow for diversity in the discipline. Overall, curricula are fragmented, and underdeveloped curricula, failing to reflect recent advances in earth systems science, and interdisciplinary approaches (Odoh et al., 2024; Lar, 2025). Also, the traditional teaching methods are being maintained, and resource deficits continue to undermine the effectiveness and relevance of geoscience education in addressing Africa's pressing developmental priorities and environmental challenges.

3.2. Funding and institutional capacity

The migration of highly qualified geoscientists to greener pastures abroad, largely driven by limited research opportunities, inadequate funding, and poor working conditions, leaving departments understaffed and overburdened (Imoniri, 2025; Lar, 2025). These challenges are compounded by the limited opportunities for staff development and mentorship, by non-adherence to gender policies which make women significantly underrepresented in the geoscience discipline.

3.3. Digital and technological gaps

There has been in the recent past a tremendous global advancement in virtual learning, GIS (Geographic Information Systems), and AI-driven geoscience tools, but many African universities are limited in aligning with these trends due to unreliable internet, lack of unstable power supply, and expensive operational software (AAU, 2023; UNESCO, 2024; Okebukola, 2025). The COVID-19 pandemic has exposed these digital inadequacies in Africa especially in most urban and rural communities. However, Africa is growing a mobile-based digital culture that will offer opportunities for innovative and an affordable e-learning models (Imoniri, 2025; UNESCO, 2025; African Union – Agenda 2063: https://au.int/Agenda2063/popular_version, accessed 21 April 2026).

3.4. Industry and societal linkages

In Africa, the collaboration among between academia, industry, and communities is often weak or limited (Asunka, 2008; Echezona and Ugwuanyi, 2010; Quarshie et al., 2025). This has resulted in limited exposure to real-world challenges that affect

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geoscience education (Table 2) and reduced employability. Despite environmental injustices caused by indiscriminate mining and anthropogenic activities in Africa, the current geoscience curricula in most African Universities rarely incorporates geoethics, sustainability concepts, or Indigenous knowledge systems (Peppoloni and Di Capua, 2022, 2023, 2024).

3.5. Access and inclusion

Lack of equal access to socioeconomic opportunities, gender biases, and our localities limit access to geoscience education, driving many talented individuals away from rural and marginalized communities (AAU, 2023; Lar, 2025; Okebukola, 2025). This does not give room for diversification or for retaining the sector’s potential talent pool.

3.6. Regional contrasts and global standing

With relatively stronger opportunities, highly competent staff strength and robust research facilities, North and Southern Africa seem to lead in geoscience education, exemplified by the top ranking of South African Universities in the world university rankings (e.g., QS World University Rankings, Times Higher Education). West, East, and

Challenge area	Specific issues	Implications
Infrastructure & Resources	Poor labs, limited field equipment, outdated software, inadequate libraries	Weak practical skills, limited exposure to modern techniques
Curricula	Outdated, fragmented, lacking integration of sustainability and digital skills	Graduates are underprepared for contemporary challenges
Funding & Investment	Chronic underfunding, limited research grants, scarce field training support	Poor teaching quality, limited innovation
Brain Drain & Faculty Shortages	Migration of skilled staff, limited mentoring capacity	Weak institutional capacity, reliance on external expertise
Digital Divide	Unstable internet, power shortages, expensive digital tools	Limited adoption of e-learning, AI, VR/AR
Industry & Societal Links	Weak collaboration with industry, communities, and policymakers	Low employability, poor societal relevance
Access & Inclusion	Gender disparities, socioeconomic and geographic inequities	Reduced diversity, underutilization of the talent pool

Table 3. Major challenges facing geoscience education in Africa.

Central African universities lag behind due to inadequate funding and underdeveloped curricula (AAU, 2023; Nyaaba et al., 2024; Lar, 2025; Okebukola, 2025). Compared to world standards, Africa universities lag in infrastructure, human capacity, and digital adoption, notwithstanding their vast geological diversity and youthful population that would have offered a strong foundation for rekindling.

The Figure 2 depicts Africa's comparatively low level of digital readiness in higher education, especially relative to Europe, Asia, and the Americas.

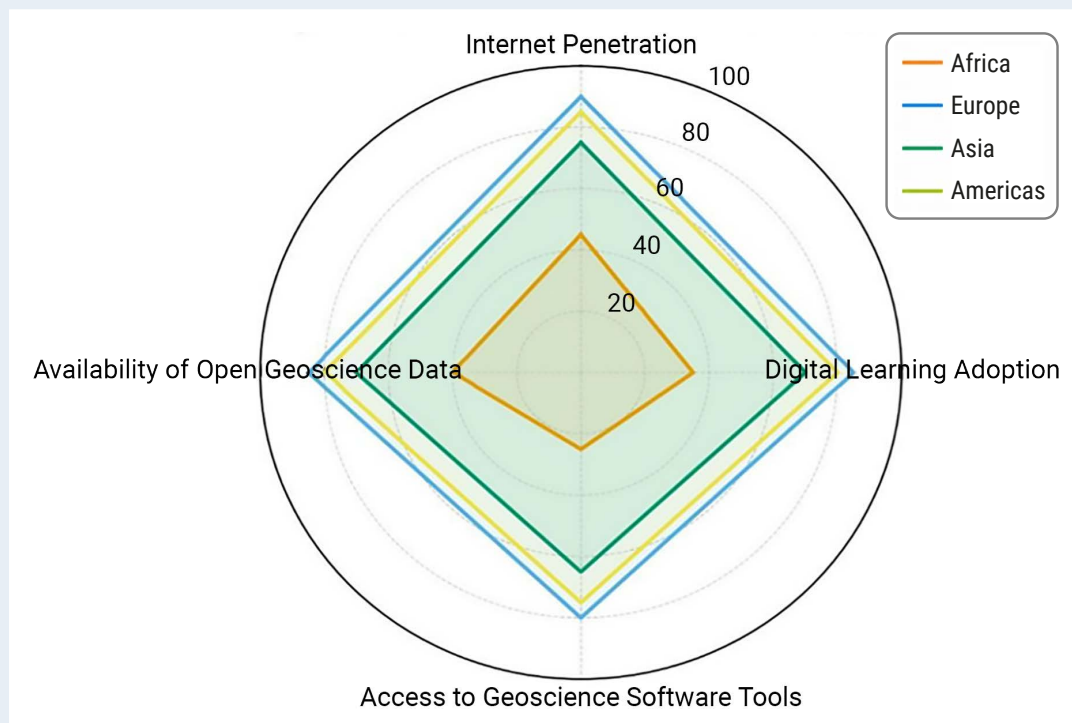


Figure 2. Africa versus global digital readiness in higher education (comparative chart). Specifically for higher education in Africa, the chart shows that a) Internet penetration is substantially lower, limiting reliable access to online learning, research databases, and digital collaboration; b) digital learning adoption (e-learning platforms, virtual classrooms, blended learning) remains modest, reflecting infrastructural and capacity constraints; c) Access to geoscience software tools (e.g., GIS, modeling, remote sensing, data analysis platforms) is limited, affecting practical training and research competitiveness; d) The availability of open geoscience data is relatively low, constraining data-driven teaching, research, and innovation. Overall, the diagram highlights a persistent digital divide in African higher education. It underscores structural challenges – connectivity, affordability, infrastructure, and skills – that hinder the effective integration of digital technologies in teaching and research. In the context of geoscience education, this highlights the need for targeted digital investment, open-access initiatives, capacity building, and context-sensitive innovation to enable Africa to fully participate in global knowledge production and sustainable development.

4. Discussion: integrating geoethics and digital innovation – emerging models and best practices

4.1. The case for integration

While geoethics and digital innovation in geoscience education are concerned with values and tools respectively, their integration offers a powerful framework for transforming African geoscience education (Semken et al., 2018; Peppoloni et al., 2019; Occhipinti, 2025). Digital technologies expand access and enhance learning, while geoethics ensures that their application is done in a socially responsible, environmentally sustainable, and culturally sensitive manner (Peppoloni and Di Capua, 2017, 2020, 2022). Together, they enable geoscience graduates not only to master technical skills and make ethical decisions in resource management, environmental protection, and community engagement.

4.2. Emerging models in African contexts

Already, some African universities and regional centers of excellence (University of Ibadan, Nigeria; University of Witwatersrand, South Africa; Jomo Kenyatta University of Agriculture and Technology, Kenya, etc.) have begun to experiment with approaches that combine ethics and digital innovation:

- a) Virtual Fieldwork with Ethical Scenarios: pilot projects in South Africa and Kenya have combined VR-based field trips with case studies on mining conflicts and environmental justice, allowing students to practice ethical reasoning in virtual geological settings (Peppoloni et al., 2019; Evelpidou et al., 2021; Ajani and Ramaila, 2025; Maphalala and Ajani, 2025).
- b) AI-Enhanced Curriculum Design: in Nigeria and Ghana, research initiatives are exploring AI-based platforms for tailoring learning paths while incorporating modules on responsible governance of resources (Asunka, 2008; Echezona and Ugwuanyi, 2010; Botha et al., 2020; Plantinga et al., 2024).
- c) Community-Based Online Platforms: initiatives such as the *Africa Groundwater Atlas* integrate open-access data with discussions on water equity and rights, demonstrating how digital tools can reflect both technical competence and ethical consideration (UNGA, 2010; BGS, 2019; MacDonald et al., 2021).

These emerging models demonstrate that integration is possible when trainers intentionally agree to align ethics with technology.

4.3. International best practices with African applicability

Examples exist worldwide that can encourage African adaptations:

- a) The International Association for Promoting Geoethics (IAPG) has developed teaching resources that integrate ethical concerns with digital tools (<https://www.youtube.com/user/iapgeoethics/videos>, accessed 21 April 2026), which could represent templates for adaptation (Peppoloni and Di Capua, 2017, 2020, 2022).
- b) The UNESCO Open Educational Resources (OER) platform provides a global repository of digital learning content (<https://www.unesco.org/en/open-educational-resources>, accessed 21 April 2026), which can be adapted to African socio-ecological contexts (UNESCO, 2024, 2025).
- c) Gamified simulations used in North America and Europe to teach geohazard response could conveniently be adapted in African contexts vulnerable to floods, landslides, and earthquakes (Semken et al., 2018).

These best practices underscore the need to customize such practices within the African context rather than wholesale adoption.

4.4. Principles for successful integration

From the emerging experiences, quite a few guiding principles can be extracted:

- 1) In contextual relevance, digital tools must reflect African geologies, resources, and socio-cultural contexts.
- 2) For inclusivity, both technology and ethics training should deliberately address gender and rural-urban gaps.
- 3) For capacity building, academic staff development is critical for the effective integration of geoethics within digitally modernized curricula.
- 4) Partnerships such as collaborations with international institutions, industry, and professional societies can fast-track integration.
- 5) For sustainability, programs should prioritize open-access and low-cost technologies to guarantee long-term adoption.

By adhering to these principles, African geoscience education can move beyond under-developed innovation toward a coherent model that is grounded in both advanced technology and ethics.

4.5. Opportunities: convergence of geoethics and digital innovation

4.5.1. Geoethics as a framework for responsibility

Geoethics emphasizes values such as responsibility to society, environmental stewardship, transparency, and inclusivity (Di Capua and Peppoloni, 2025). Incorporating geoethics into curricula, will ensure that African institutions produce geoscientists who are not only technically competent but also act responsibly toward both society and nature (Di Capua and Peppoloni, 2025).

4.5.2. Harnessing AI

AI provides powerful tools for data analysis, predictive modeling of hazards and groundwater availability (BGS, 2019; MacDonald et al., 2021; Kitambo et al., 2022). Resources exploration and decision support in geoscience (Boateng, 2024; Maphalala and Ajani, 2025). Thus, integrating AI into geoscience education will allow students to tackle large datasets with greater efficiency and develop data literacy skills in solving real-world problems mentioned earlier.

4.5.3. VR/AR

Fieldwork is the backbone of geoscience, but it often requires frequent student exposure and is frequently constrained by logistical and financial constraints. Immersive VR/AR fieldwork simulations will enable students to experience geology remotely, even when resources are constrained (Evelpidou et al., 2021; Nyaaba et al., 2024). Students can explore geological formations, practice sampling techniques, or visualize 3D subsurface models, thereby bridging the gap between theory and practice (Botha et al., 2020; Ajani and Ramaila, 2025; Mudi, 2025).

4.5.4. Online and hybrid platforms

Digital platforms create opportunities for cross-border collaboration, remote teaching, and direct access to knowledge. Pan-African e-learning platforms can democratize access to knowledge and reduce costs of geoscience training (Aden, 2020; Sey and Mudongo, 2021; Metzger, 2024; Odoh et al., 2024), bringing world-class resources to under-resourced institutions and enabling continuous professional development for practitioners.

4.5.5. Collaborative Networks and Open Science

Cross-border partnerships between African institutions, international collaborators, and industry can enhance open science and ethical practice in Africa (Aden, 2020; Sey and Mudongo, 2021; Metzger, 2024; Di Capua and Peppoloni, 2025). A unified curriculum with open data repositories, and regional research will strengthen capacity and competence. Integrating geoethics into these networks ensures that such collaborations are achievable in equitable and just manner (Peppoloni et al., 2019; Di Capua and Peppoloni, 2025).

4.5.6. Integrating geoethics and digital innovation: a framework for Africa

The approach of integrating of geoethics and digital innovation will transform geoscience education in Africa under the following four pillars (Figure 3):

- 1) Curriculum Review, where the programs are updated to incorporate geoethical principles, sustainability science, and digital competencies (Odoh et al., 2024; UNESCO, 2025; African Union – Agenda 2063: https://au.int/Agenda2063/popular_version, accessed 21 April 2026).
- 2) Capacity Building, where students and staff are trained/retrained in AI, VR/AR, and online teaching, and encouraged in ethical enlightenment (Nyaaba et al., 2024; Segooa et al., 2025; UNESCO, 2025).
- 3) Infrastructure and Partnerships to facilitate the establishment of shared digital laboratories, cloud-based platforms, and regional centers of excellence to curb resource deficits. (Boateng, 2024; Metzger, 2024; UNESCO, 2024, 2025).
- 4) Involvement and sensitization of communities to understanding the link between geoscience education and local challenges, thereby ensuring accountability and inclusivity (Ayeh and Bleicher, 2021; Di Capua and Peppoloni, 2025).

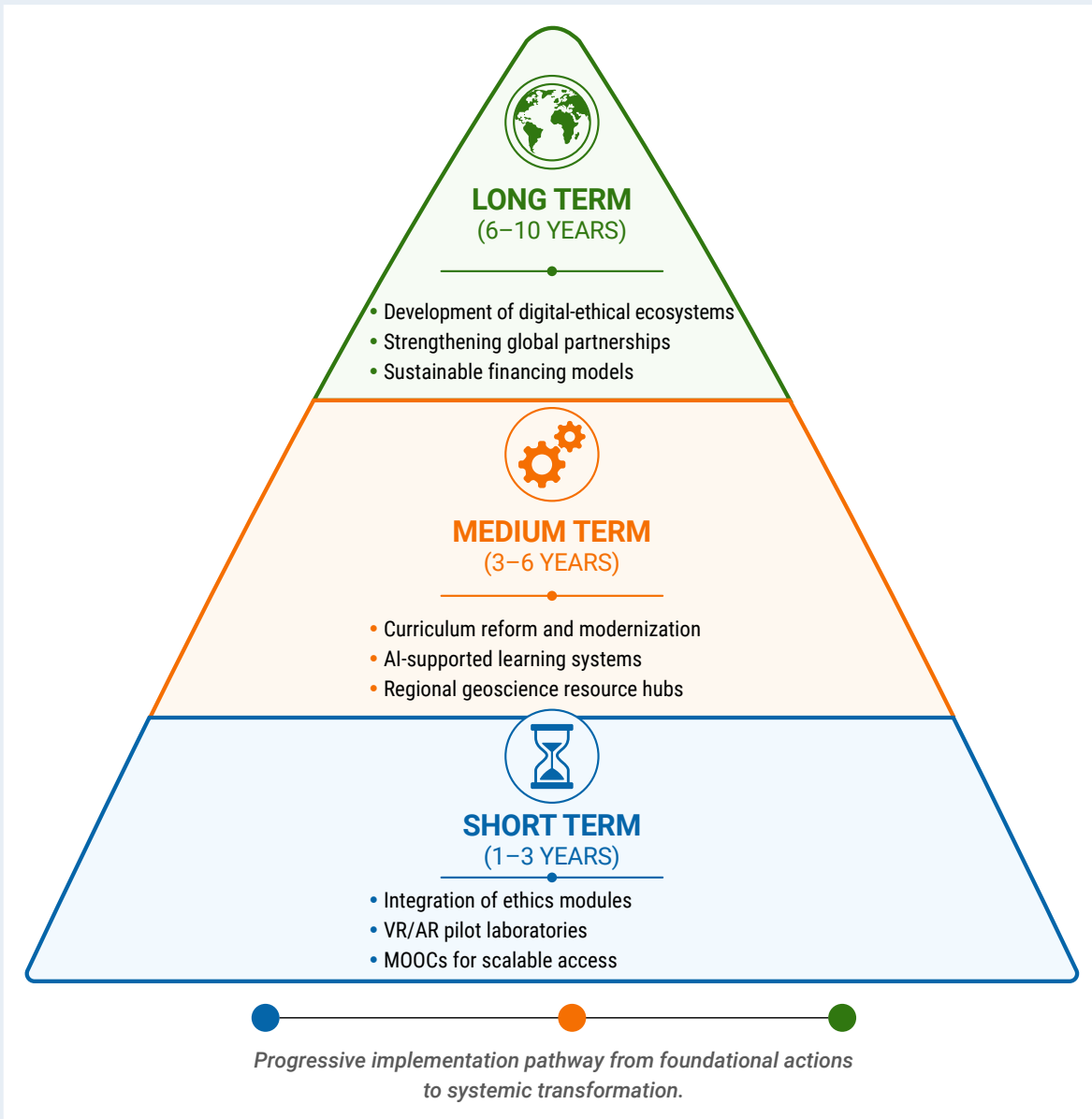


Figure 3. Roadmap for integrating geoethics and digital innovation in African universities: a) Base (Short term, 1-3 years): Foundational capacity (ethics modules, VR/AR pilots, MOOCs); b) Middle (Medium term, 3-6 years): System integration and scaling (curriculum reform, AI learning, regional hubs); c) Apex (Long term, 6-10 years): Mature digital-ethical geoscience ecosystem with global partnerships and sustainable financing.

5. Implications for policy, practice, and future research

5.1. Policy implications

The integration of geoethics and digital innovation in African geoscience education requires deliberate policy support at both national and regional levels (AAU, 2023; Lar, 2025; Okebukola, 2025). Ministries of education and science must recognize geoscience as a strategic discipline for sustainable development and allocate resources accordingly (UNESCO, 2024, 2025). Policies should:

- Encourage the revision of curricula to integrate geoethics as a core component alongside technical skills.
- Promote investment in digital infrastructure, including affordable internet access, cloud-based learning platforms, and renewable energy to power educational technology in rural areas (UNESCO, 2024, 2025).
- Strengthen the enforcement and implementation of quality assurance mechanisms to ensure that digital tools and ethical frameworks are consistently applied across institutions of higher learning.
- Regional bodies such as the African Union and the Association of African Universities as they already do, can coordinate the establishment of continental benchmarks and support partnerships (African Union, 2009; African Union – Agenda 2063: https://au.int/Agenda2063/popular_version, accessed 21 April 2026).

5.2. Practical implications for institutions and educators

Universities and training centers should see the integration of ethics and digital tools as an opportunity to enhance both teaching and professional development (AAU, 2023; Lar, 2025; Okebukola, 2025). These could be achieved by:

- Curriculum redesign to integrate case-based learning that incorporates digital simulations with ethical problems drawn from African contexts (Semken et al., 2018; AAU, 2023; Lar, 2025; Okebukola, 2025).
- Staff capacity building through training workshops on AI applications, VR/AR pedagogy, and geoethics in practice (World Bank, 2021).
- Establishing centers of excellence that function as hubs for innovation, sharing best practices, and fostering collaboration with industry.
- Strengthening industry-academia partnerships, ensuring students are trained with the ethical alertness and digital competencies required to tackle challenges in professional contexts such as mining, water management, and climate adaptation.

5.3. Implications for future research

Research is needed to sustain innovation and adapt practices to Africa's diverse contexts. There are three priority areas:

- 1) Impact assessment of digital tools to evaluate how AI, VR/AR, and online platforms affect learning outcomes, inclusivity, and employability in geosciences.
- 2) Localized geoethics frameworks, to develop context-specific ethical models that incorporate African cultural values, traditional knowledge systems, and governance structures.
- 3) Scalable integration models by designing and testing models of unified ethics-technology curricula that can be replicated across universities and other institutions of higher learning with varying levels of resources.

Future research should be interdisciplinary, linking geosciences, education, information technology, and the social sciences. In doing so, it can provide evidence-based guide to policymakers, educators, and practitioners seeking to revolutionize geoscience education in Africa (African Union, 2009; African Union – Agenda 2063: https://au.int/Agenda2063/popular_version, accessed 21 April 2026).

6. Illustrative examples

6.1. AI in water resource management

Pilot projects have been applied in East Africa to demonstrate the use of AI-driven modeling to predict groundwater availability under climate stress (BGS, 2019; MacDonald et al., 2021; Kitambo et al., 2022). Incorporating such applications in university curricula not only enhances students' technical skills but also show the potential for climate resilience (Jatileni et al., 2024; Oláh, 2025).

6.2. VR Fieldwork Simulations

Universities in South Africa and Nigeria have experimented with virtual geological field trips, allowing students to access and learn in complex terrains digitally (Botha et al., 2020; Ajani and Ramaila, 2025; Mudi, 2025). These experiences supplement, rather than replace, traditional fieldwork, and provide access to students who are constrained financially (Nyaaba et al., 2024; Odoh et al., 2024).

6.3. Regional online networks

The African Virtual University and similar platforms display the potential of online collaboration in science education at a regional level (AAU, 2023; Okebukola, 2025). Expanding such networks with a geoscience and geoethics focus could foster collective teaching modules, reduce costs, and strengthen regional e-learning collaboration in geoscience education (Peppoloni et al., 2019; Aden, 2020; Sey and Mudongo, 2021; Metzger, 2024).

7. Conclusion and recommendations

Geoscience education is central to Africa's sustainable development, underpinning efforts to harness mineral resources, manage water, mitigate natural hazards, and adapt to climate change. Presently, Africa is besieged with persistent challenges, ranging from outdated curricula and inadequate infrastructure to brain drain and regional differences. Against this backdrop, the integration of geoethics and digital innovation offers a unique opportunity to rejuvenate geoscience education for the 21st century (Metzger, 2024; Peppoloni and Di Capua, 2021, 2022, 2023, 2024; Di Capua and Peppoloni, 2025). By incorporating the values of responsibility, sustainability, and justice into the curricula and harnessing transformative digital tools (AI, VR/AR, and online platforms), African geoscience can become more accessible, innovative, globally competitive, and locally/globally relevant (Peppoloni et al., 2019; Peppoloni and Di Capua, 2020; AAU, 2023; Boateng, 2024; Nyaaba et al., 2024; Okebukola, 2025; Segooa et al., 2025).

This article has highlighted both progress and limitations in African geoscience education, examined the relevance of geoethics, and assessed the potential and limits of digital technologies in revolutionizing African geoscience education. Emerging models from across Africa, alongside international best practices, demonstrate that integrating ethics with innovation is not only possible but also necessary for training a new generation of geoscientists who are not only technically skilled but also ethically grounded and globally competitive, capable of addressing the continent's pressing challenges while contributing to global scientific progress (AUC/OECD, 2021). Such integration, however, must be context-specific, inclusive, and supported by deliberate policy, institutional reform, and investment in faculty capacity. By doing so, universities, governments, industry, and international partners must collaborate to create modernized curricula, digital platforms, and governance structures that are both innovative and socially just.

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To realize this vision, the following recommendations are proposed:

- 1) Integrate geoethics into geoscience education as a mandatory core component of the curriculum, rather than offering it as an elective.
- 2) Invest in advanced digital infrastructure, including AI laboratories, immersive VR/AR fieldwork modules, and robust online learning platforms.
- 3) Strengthen institutional capacity by developing human resources with expertise in both digital technologies and geoethical education.
- 4) Foster regional collaboration through open science platforms, jointly developed curricula, and shared research and teaching infrastructure.
- 5) Engage local communities and policymakers to ensure that geoscience education supports the development and implementation of laws addressing sustainability and environmental justice.

In embracing these pathways, Africa can train a generation of geoscientists equipped not only with technical expertise but also with the ethical awareness and digital competence necessary to ensure sustainable development and environmental justice across the continent.

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