LEAD PAPER

Exploring Trends of Digitalization in Natural Resources and Bio-Conservation Management

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ABSTRACT

In this era of rapid technological advancements, the application of digitalization in natural resources and bio-conservation management has become crucial for sustainable development and biodiversity preservation. This review paper systematically examines the evolving trends, applications, and implications of digital technologies in the context of natural resources and bio-conservation management. Drawing upon a wide range of sources, including scholarly articles, case studies, and technological assessments, the paper outlines the transformative potential of digital tools such as Geographic Information Systems (GIS), remote sensing, artificial intelligence (AI), blockchain, and the Internet of Things (IoT) in enhancing the effectiveness of conservation efforts.

The analysis reveals that digitalization facilitates unprecedented levels of data collection, processing, and dissemination, enabling more informed decision-making and fostering greater transparency and collaboration among stakeholders. Specifically, the paper highlights how digital technologies are being employed to monitor ecosystem changes, track wildlife populations, optimize resource use, and engage communities in conservation practices. Furthermore, the review identifies key challenges associated with the digital transition, including technological accessibility, data security, privacy concerns, and the need for capacity building among conservation practitioners.

INTRODUCTION

Nigeria is endowed with abundant natural resources and a rich biodiversity that includes a wide range of ecosystems from mangroves and rainforests in the south to various types of savanna landscapes in the north. However, the country faces significant environmental challenges that threaten its natural heritage and the livelihoods of its people. These pressures stem from a combination of socio-economic, environmental, and political factors that interplay to exacerbate the strain on its natural resources and biodiversity. Of the socio-economic factors, rapid population growth is key. Nigeria's population is estimated at slightly over 223.8 million and ranked as the 6th most populous country in the world and largest in Africa at an annual growth rate of 3.2 per cent (NPC, 2023). This increase in population has continued to place immense pressure on our natural resources. The demand for housing, arable land, freshwater, and other resources has led to extensive habitat loss and degradation, significantly impacting biodiversity. The quest for agricultural land has resulted in the conversion of natural habitats into farmland, while the need for housing and urban development has led to deforestation and the loss of wildlife habitats. To address these multifaceted challenges facing natural resources and biodiversity conservation, digitalisation holds great potentials.

Digitalization in natural resources and bio-conservation management is the use of digital technologies in managing natural resources and conserving biodiversity. In recent years, digitalization has revolutionized various sectors, including natural resources management and bio-conservation. According to Mondejar *et al.* (2021), the world is transitioning through the digitalization era in which most of our daily activities are highly dependent on innovative digital and computer technologies. This transitioning has been driven by advancements in digital technology. Digitalization covers a wide range of digital technology trends, including virtualisation, sensor-based technologies including the Internet of Things (IoT), additive manufacturing, wireless communication technologies (e.g., 5G), robotization, digital platforms, digital twins, blockchain technologies, machine learning and artificial intelligence (Eerola *et al.*, 2021). Existing digital tools enable researchers, conservationists, and policymakers to monitor, analyze, and manage natural resources and biodiversity more effectively than ever before, thereby leading to improvement in efficiency of many operations, and reduction in human errors and operational costs.

In natural resources and biodiversity conservation, digitalization is gaining prominence. Many organizations have replaced analog processes with digital alternatives. Indeed, digital technology increasingly influences the ways members of the public perceive, think about and engage with nature (Kahn 2011; Verma *et al.* 2015). Digital technologies are often greeted with optimism by conservationists because they promise more data, faster processing, better information access and connectivity, new communication routes, exciting visual representations and empowering decision-making support systems (Arts *et al.*, 2015). Such optimism may be deceptive in light of the many practical challenges (Joppa 2015; Newey *et al.* 2015), and the unintended consequences that technology use may bring (Humle *et al.* 2014; Maffey *et al.* 2015). The objectives of this review paper are to identify and discuss emerging digital technologies and trends in the field of natural resources and bio-conservation management, outline the challenges and barriers to the adoption of digital technologies in natural resources management, and propose a strategic framework for the effective integration and implementation of digital technologies in biodiversity conservation and natural resources management.

EMERGING DIGITAL TECHNOLOGIES IN NATURAL RESOURCES AND BIODIVERSITY MANAGEMENT

The advancement in information and communications technologies has been a very important enabler of innovation and development (Akindele, *et al.*, 2022). Emerging digital technologies are increasingly playing a pivotal role in natural resources and biodiversity management, offering innovative solutions to some of the most pressing environmental challenges. These technologies include the following:

Artificial Intelligence (AI) and Machine Learning (ML)

Artificial Intelligence (AI) and Machine Learning (ML) stand out for their ability to process and analyze vast amounts of environmental data with unprecedented speed and accuracy. AI applications in wildlife conservation, for instance, are revolutionizing species monitoring and protection efforts. Algorithms trained to recognize individual animals via camera trap images are facilitating more efficient population assessments and behavioral studies. Ko *et al.* (2021) detail how AI-enabled acoustic monitoring systems can detect and identify the calls of specific species in real-time, allowing for non-invasive monitoring of biodiversity in remote or challenging terrains. Similarly, ML models are being employed to predict the impacts of climate change on species distributions, offering valuable insights for conservation planning and habitat management (Fegraus *et al.*, 2020). Another area of application of AI and ML is in the development of a mobile application, named *PlantSnap*, for plant and tree identification. PlantSnap has a searchable database of over 650,000 plants and can be used to identify over 90% of all known species of plants and trees (Akindele, 2022).

Blockchain Technology

Blockchain technology is another emerging tool with significant potential in natural resources and biodiversity management. By providing a secure, decentralized platform for recording transactions, blockchain can enhance transparency and traceability in supply chains, crucial for combating illegal logging and wildlife trafficking. Transparency ensured by blockchain systems helps in verifying the legality and sustainability of natural resource extraction and trade practices, thereby promoting environmental stewardship and ethical business practices. Roe *et al.* (2019) explore the application of blockchain in certifying the provenance of sustainably sourced timber, demonstrating its potential to reduce illegal logging by ensuring that only legally harvested timber enters the global market.

The Internet of Things (IoT)

The Internet of Things (IoT) continues to make significant strides in environmental monitoring and resource management. Networks of sensors deployed across various ecosystems can collect real-time data on a range of environmental parameters, from soil moisture and temperature to forest canopy density and water quality. This real-time data collection facilitates dynamic management practices, enabling immediate responses to environmental changes or threats. For instance, IoT-enabled smart water management systems can significantly improve irrigation efficiency in agriculture, reducing water waste and enhancing crop yields (Jayaraman *et al.*, 2019). Additionally, IoT technologies are integral in urban environments, where they contribute to creating 'smart cities' that can monitor and manage energy consumption, waste production, and air quality, contributing to more sustainable urban development.

Virtual and Augmented Reality

Emerging digital technologies also encompass virtual and augmented reality (VR and AR), which offer novel ways to engage the public in conservation efforts and environmental education. By simulating real-world environments and ecological processes, VR and AR can enhance public understanding of complex environmental issues and foster a deeper connection to natural worlds. This immersive technology can be particularly effective in environmental education, providing interactive experiences that highlight the importance of biodiversity and the impacts of human activities on natural ecosystems. As these digital technologies continue to evolve, their integration into natural resources and biodiversity management promises not only to enhance operational efficiencies but also to foster greater public engagement and support for conservation efforts, paving the way for a more sustainable and informed interaction with the natural world.

Remote Sensing and GIS

Remote Sensing and Geographic Information Systems (GIS) have become indispensable tools in environmental science, offering detailed insights into earth's surfaces and facilitating the management of natural resources and conservation efforts. By collecting data from satellite imagery and aerial photography, remote sensing provides critical information on land use changes, vegetation cover, and water bodies, among other features. When combined with GIS, these data can be analyzed and visualized to support decision-making processes in urban planning, forestry, agriculture, and disaster management. Turner *et al.* (2015) underscore the importance of these technologies in biodiversity conservation, enabling the monitoring of ecosystem changes and habitat fragmentation on a global scale. The integration of remote sensing and GIS technologies thus represents a powerful approach to understanding and managing the Earth’s natural resources more effectively.

Big Data Analytics

Big Data Analytics in environmental science transforms large and complex datasets into actionable insights for natural resource management and conservation. By harnessing the power of advanced analytics, machine learning, and AI, researchers and practitioners can predict environmental trends, optimize resource use, and enhance biodiversity conservation strategies. Li *et al.* (2016) highlight the application of big data in understanding species distribution, genetic diversity, and ecosystem dynamics, thereby facilitating targeted conservation actions. Big data analytics not only aids in the efficient processing and analysis of data from satellite images, sensor networks, and citizen science initiatives but also supports the formulation of policies for sustainable environmental management. With the development of big data technologies, the speed of smart forestry construction and the level of forestry information management has significantly improved (Jing, *et al.*, 2023). A comprehensive survey of big data analytics in forestry has been provided by Zou *et al.* (2019).

IoT and Sensor Networks

The Internet of Things (IoT) and sensor networks are revolutionizing environmental monitoring and natural resource management by providing real-time data and enhancing connectivity across various devices. Martínez-Pérez *et al.* (2019) discuss how IoT technologies enable the precise monitoring of environmental conditions, such as air and water quality, forest health, and wildlife activity, through networks of interconnected sensors. This continuous stream of data supports more responsive and adaptive management strategies, allowing for immediate actions to mitigate environmental risks and conserve resources. IoT applications extend beyond monitoring, offering innovative solutions for smart agriculture, sustainable water management, and energy efficiency, thus playing a crucial role in advancing sustainable development goals.

DNA Barcoding and Molecular Ecology

DNA barcoding and molecular ecology are transforming biodiversity conservation and species identification by enabling the precise genetic analysis of organisms. This technology aids in the identification of species, even from minute samples, facilitating the monitoring of biodiversity and the detection of illegal wildlife trade. Hebert *et al.* (2003) introduced DNA barcoding as a method for rapid species identification, which has since been applied in various fields including conservation biology, ecosystem monitoring, and the study of species interactions. Molecular ecology, through the use of DNA barcoding and other genetic techniques, provides insights into the genetic diversity and evolutionary processes of species, offering a powerful tool for the conservation of biodiversity and the management of natural resources.

Citizen Science and Crowdsourcing

Citizen science and crowdsourcing are democratizing scientific research and conservation efforts, engaging the public in data collection and environmental monitoring. Through platforms and mobile applications, volunteers contribute valuable data on species observations, pollution levels, and habitat conditions. Bonney *et al.* (2014) discuss how these participatory science projects not only expand the scale and scope of research but also increase public awareness and engagement in conservation issues. Citizen science bridges the gap between the scientific community and the general public, fostering a collaborative approach to tackling environmental challenges and promoting a more inclusive model of scientific inquiry and environmental stewardship.

TRENDS IN DIGITALIZATION FOR NATURAL RESOURCE MANAGEMENT

The landscape of natural resource management is rapidly transforming through the integration of digital technologies, marking a significant shift towards more sustainable and efficient practices. Among these, Geographic Information Systems (GIS) and remote sensing technologies have become indispensable tools for mapping, analyzing, and monitoring natural resources. These technologies offer comprehensive spatial and temporal insights into land use patterns, vegetation cover, water resources, and wildlife habitats, facilitating informed decision-making and policy formulation. Turner *et al.* (2015) highlight the pivotal role of remote sensing in biodiversity conservation, providing a means to assess changes in ecosystem extent and health across large and often inaccessible areas. Similarly, GIS applications in natural resource management, as explored by Brown (2018), enable the integration of various data types and sources, supporting the planning and management of resources by predicting future trends and potential conflicts.

Advancements in big data analytics represent another significant trend, offering profound insights into natural resource management by processing vast amounts of data from diverse sources, including satellite imagery, sensor networks, and social media. These analytics can uncover patterns, trends, and relationships, facilitating predictive modeling and risk assessment in resource management. For example, Li *et al.* (2016) discuss how big data applications in biodiversity research can lead to more effective conservation strategies by enabling the analysis of species distribution, genetic information, and environmental changes on a global scale. This capacity for predictive analytics is crucial for anticipating environmental impacts, managing natural resources sustainably, and mitigating potential threats to biodiversity.

The Internet of Things (IoT) is also revolutionizing natural resource management by enabling the real-time monitoring and control of environmental parameters through networks of interconnected sensors and devices. Martínez-Pérez *et al.* (2019) describe how IoT applications in environmental monitoring can significantly improve the management of water resources, air quality, and forest health by providing continuous, real-time data. This granular level of monitoring allows for the immediate detection of anomalies, supporting rapid response to environmental incidents and enhancing the precision of conservation efforts. Moreover, IoT technologies facilitate the efficient use of natural resources, for example, through smart irrigation systems that optimize water usage based on soil moisture levels and weather forecasts, thereby contributing to more sustainable agricultural practices.

These trends in digitalization are paving the way for a new era in natural resource management, characterized by enhanced efficiency, accuracy, and sustainability. As these technologies continue to evolve and become more accessible, their integration into natural resource management practices is expected to deepen, offering promising avenues for addressing the complex challenges of conserving and managing the planet's invaluable natural resources.

CHALLENGES AND BARRIERS TO THE ADOPTION OF DIGITAL TECHNOLOGIES IN NATURAL RESOURCES MANAGEMENT

The adoption of digital technologies in natural resource management presents numerous benefits, including enhanced monitoring capabilities, improved decision-making, and increased efficiency. However, several challenges and barriers hinder the widespread implementation of these technologies. Understanding and addressing these obstacles is crucial for leveraging digital innovations to safeguard natural resources effectively.

Digital Divide

One significant challenge is the digital divide, which refers to the gap between individuals and communities that have access to digital technologies and those that do not. This divide is particularly pronounced in developing countries, where limited access to the internet and lack of digital literacy among local populations can impede the adoption of technologies like GIS, remote sensing, and IoT. The digital divide not only limits the ability of communities to engage in digital natural resource management but also exacerbates inequalities in access to information and resources (Sullivan, 2017). Overcoming this barrier requires targeted investments in digital infrastructure and educational programs to build local capacities and ensure equitable access to technology.

High Cost

Another barrier is the high cost associated with implementing and maintaining advanced digital technologies. The deployment of sensor networks, satellite imagery analysis, and sophisticated data analytics platforms often requires substantial financial investment, which can be prohibitive for many organizations and governments, especially in resource-constrained settings. The ongoing costs of data storage, processing, and analysis, along with the need for technical expertise, further compound this challenge (Kitchin, 2014). Securing funding and resources for these technologies necessitates innovative financial models and partnerships between the public and private sectors.

Data Privacy and Security concerns

Data privacy and security concerns also pose significant challenges to the adoption of digital technologies in natural resource management. The collection and analysis of environmental data, particularly through IoT devices and sensor networks, raise issues related to the privacy of individuals and communities and the security of sensitive information. Addressing these concerns requires robust data governance frameworks that ensure data are collected, stored, and used in a manner that respects privacy rights and protects against unauthorized access and cyber threats (Weber, 2010).

Interoperability and standardization issues

Interoperability and standardization issues further complicate the integration of digital technologies into natural resource management practices. The diversity of data formats, platforms, and protocols can hinder the seamless exchange and integration of data from different sources, limiting the effectiveness of digital solutions. Developing and adopting universal standards and protocols is essential for facilitating data sharing and integration across technologies and sectors (Janssen *et al.*, 2015).

Technological obsolescence

Technological obsolescence represents another challenge, as the rapid pace of innovation in digital technologies means that devices and systems can quickly become outdated. This necessitates continuous investment in technology upgrades and training for staff, which can be difficult for organizations to sustain over time. Planning for obsolescence and ensuring systems are adaptable and scalable can help mitigate these issues (Li, 2018).

Lack of awareness

Finally, there is often a lack of awareness and understanding of the potential benefits and applications of digital technologies among stakeholders involved in natural resource management. Overcoming skepticism and building trust in new technologies requires effective communication, demonstration projects that showcase tangible benefits, and the involvement of stakeholders in the design and implementation of digital solutions (Wilson *et al.*, 2017).

Addressing these challenges and barriers is essential for harnessing the full potential of digital technologies in natural resource management. It requires concerted efforts from governments, the private sector, academic institutions, and communities to invest in digital infrastructure, foster innovation, and build the capacities needed to implement and sustain these technologies.

STRATEGIES FOR THE EFFECTIVE INTEGRATION AND IMPLEMENTATION OF DIGITAL TECHNOLOGIES

Effective integration and implementation of digital technologies in natural resource management require strategic planning, stakeholder engagement, and robust institutional frameworks. Several key strategies can enhance the adoption and utilization of these technologies, ensuring that they contribute to sustainable resource management and biodiversity conservation.

Firstly, fostering collaboration and partnerships among stakeholders is essential for the successful integration of digital technologies. Collaboration between government agencies, research institutions, non-governmental organizations (NGOs), and local communities facilitates the sharing of resources, expertise, and best practices. By working together, stakeholders can leverage complementary strengths and resources, address common challenges, and develop innovative solutions to complex environmental issues (Rudd, 2018).

Secondly, building technical capacity and digital literacy among relevant stakeholders is critical for maximizing the benefits of digital technologies. Training programs, workshops, and capacity-building initiatives can equip individuals and organizations with the necessary skills to use digital tools effectively. Investing in education and skill development helps to overcome barriers related to the digital divide and empowers communities to take ownership of natural resource management initiatives (Duncan *et al.*, 2016).

Thirdly, establishing supportive policy and regulatory frameworks is essential for creating an enabling environment for the integration of digital technologies. Clear policies and regulations governing data management, privacy, and security provide certainty and guidance to stakeholders involved in natural resource management. Furthermore, policies that incentivize the adoption of digital technologies, such as tax incentives or grants for technology investments, can help overcome financial barriers and encourage innovation (McGinnis *et al.*, 2018).

Fourthly, promoting open data initiatives and data sharing platforms facilitates collaboration and transparency in natural resource management. Open data policies encourage the sharing of environmental data and information among stakeholders, fostering collaboration, innovation, and evidence-based decision-making. Open data platforms provide access to a wealth of information, enabling researchers, policymakers, and the public to analyze trends, identify patterns, and develop solutions to environmental challenges (Dufour-Kowalski *et al.*, 2019).

Fifthly, ensuring interoperability and compatibility among digital technologies is essential for seamless data exchange and integration. Standardizing data formats, protocols, and interfaces enables different systems to communicate and share information effectively. Interoperable technologies facilitate the integration of data from various sources, enhancing the accuracy and reliability of environmental monitoring and decision support systems (Mulders *et al.*, 2018).

Finally, fostering a culture of innovation and learning is crucial for adapting to evolving technological trends and maximizing the potential of digital tools. Encouraging experimentation, piloting new technologies, and learning from both successes and failures enables organizations to stay abreast of emerging trends and technologies. By embracing a culture of innovation, stakeholders can continuously improve their approaches to natural resource management and conservation (Sareen *et al.*, 2020).

The effective integration and implementation of digital technologies in natural resource management require a multifaceted approach that encompasses collaboration, capacity-building, supportive policies, data sharing, interoperability, and innovation. By adopting these strategies, stakeholders can harness the transformative potential of digital technologies to address pressing environmental challenges and achieve sustainable development goals.

PROPOSED FRAMEWORK FOR INTEGRATING DIGITAL TECHNOLOGIES INTO NATURAL RESOURCE AND BIO-CONSERVATION MANAGEMENT

Proposing a comprehensive framework for integrating digital technologies into natural resource and bio-conservation management involves several key components that together ensure the effective, sustainable, and equitable use of digital tools. The framework outlined in Table 1 is designed to guide policymakers, practitioners, and researchers in adopting and implementing digital solutions to enhance conservation efforts.

Table 1: Proposed framework for integrating digital technologies into natural resource and bio-conservation management

Major Components	Activities
1. Assessment and Planning	***a. Needs Assessment*** • Identify specific challenges and opportunities in natural resource and bio-conservation where digital technologies can provide solutions. • Assess the technological readiness of the region or sector, including infrastructure and local capacity for adopting digital technologies. ***b. Goal Setting*** • Define clear, measurable objectives for integrating digital technologies into conservation practices, aligning with broader conservation goals and sustainable development targets.
2. Technology Selection and Customization	***a. Evaluation of Digital Technologies*** • Review and evaluate available digital technologies (e.g., remote sensing, AI, GIS, blockchain, IoT) for their applicability, effectiveness, scalability, and sustainability in conservation contexts. • Consider the environmental impact of deploying these technologies, aiming for solutions that are not only effective but also environmentally sustainable. ***b. Customization and Localization*** • Customize digital solutions to address specific conservation needs, ecological characteristics, and socio-economic contexts. • Ensure technologies are accessible and usable by local communities, practitioners, and decision-makers.
3. Capacity Building and Stakeholders Engagement	***a. Training and Education*** • Develop and implement training programs for local communities, conservation practitioners, and policymakers on using and managing digital technologies. • Promote digital literacy and technical skills development to ensure broad-based participation and ownership. ***b. Stakeholders Engagement*** • Foster inclusive engagement processes that involve local communities, indigenous peoples, private sector, academia, and government agencies in the planning and implementation phases. • Encourage participatory approaches to technology deployment, ensuring th*at al*l voices are heard and considered.

4. Implementation and Integration	***a. Deployment of Technologies*** • Implement digital technologies according to the planned framework, ensuring that deployment is ethical, respects privacy, and adheres to relevant laws and guidelines. • Integrate digital tools with existing conservation practices and management strategies to enhance their efficiency and impact. ***b. Data Management and Sharing*** • Establish robust data management protocols to ensure the accuracy, security, and ethical use of data collected through digital technologies. • Promote open data policies and platforms that encourage data sharing and collaboration across stakeholders, enhancing transparency and innovation.
5. Monitoring, Evaluation, and Adaptation	***a. Monitoring and Evaluation (M*and*E)*** • Develop and implement MandE frameworks to assess the impact of digital technologies on conservation outcomes, identifying lessons learned and areas for improvement. • Use MandE findings to refine and adjust digital strategies, ensuring they remain aligned with conservation goals and responsive to changing conditions. ***b. Adaptive Management*** • Employ an adaptive management approach, allowing for the iterative refinement of digital integration strategies based on feedback and evolving environmental, technological, and socio-economic contexts. • Remain open to emerging technologies and innovative practices that can enhance conservation efforts.
6. Policy Support and Legal Frameworks	***a. Policy Development*** • Advocate for and assist in the development of supportive policies and regulations that facilitate the ethical and effective use of digital technologies in conservation. • Ensure policies promote equity, protect against misuse of technology and data, and support sustainable development goals. ***b. Cross-Sectoral Collaboration*** • Encourage cross-sectoral collaboration and partnerships to leverage resources, expertise, and networks for the successful integration of digital technologies into conservation practices. • Foster international cooperation to address global conservation challenges and share knowledge and innovations.

This framework presents a holistic approach to integrating digital technologies into natural resource and bio-conservation management. By following these guidelines, stakeholders can leverage digital solutions to enhance conservation efforts, promoting biodiversity protection and sustainable use of natural resources in an equitable and effective manner.

CONCLUSION

This review has provided a comprehensive overview of the emerging trends and advancements in digitalization within the realm of natural resources and bio-conservation management. From remote sensing and GIS applications to the integration of big data analytics, IoT, DNA barcoding, and citizen science initiatives, the landscape of conservation and resource management is undergoing a profound transformation. Digital technologies offer unprecedented opportunities to monitor, analyze, and protect ecosystems, biodiversity, and natural resources more effectively than ever before.

Through the synthesis of current knowledge and examination of case studies and best practices, this review underscores the potential of digitalization to address complex environmental challenges. The integration of digital technologies facilitates more informed decision-making, enhances stakeholder engagement, and fosters interdisciplinary collaboration across sectors. Moreover, these technologies empower local communities, researchers, policymakers, and conservation practitioners to work together towards common conservation goals.

However, it is essential to acknowledge the challenges and barriers to the widespread adoption and implementation of digital technologies in natural resource management. Issues such as the digital divide, data privacy and security concerns, interoperability issues, and the need for capacity building must be addressed to ensure equitable access to digital tools and maximize their effectiveness.

Moving forward, concerted efforts are needed to overcome these challenges and leverage the full potential of digitalization in conservation and resource management. This requires strategic investments in digital infrastructure, capacity building, and supportive policy frameworks. Moreover, fostering a culture of innovation and collaboration is crucial for adapting to evolving technological trends and continuously improving conservation practices.

In conclusion, while digitalization offers promising avenues for enhancing the sustainability and resilience of natural ecosystems, its successful integration depends on the collective efforts of stakeholders *at al*l levels. By embracing digital technologies and fostering partnerships, we can pave the way for more effective and inclusive approaches to conserving biodiversity and managing natural resources for future generations.

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