International Journal of Engineering, Science, and Environmental Research (IJESER)

Federal Polytechnic Wannune

Volume-1, Issue-2, pp-140-146

ISSN: 3121-8180

Literature Review

Peer-Reviewed/Open Access/ www.ijeser.com

Digital and Computational Innovations in Physical Sciences: A Tool for Sustainable Development in Nigeria

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Abstract

Nigeria's sustainable development faces critical challenges arising from climate variability, energy insecurity, and environmental degradation, necessitating robust applications of the physical sciences. Conventional analytical methods have been limited in addressing the nonlinear and data-intensive nature of environmental and energy systems, particularly within tropical contexts. Digital and computational innovations, including artificial intelligence, machine learning, and computational optimization, have emerged as effective tools for enhancing predictive accuracy, system optimization, and evidence-based decision-making. This study examines the application of digital and computational innovations in advancing physical sciences research in Nigeria, with focus on climate modeling, rainfall prediction, and renewable energy system optimization using a systematic literature review. Machine learning and adaptive neuro-fuzzy models demonstrate improved rainfall prediction accuracy, enhancing disaster preparedness and climate planning. Computational optimization applied to hybrid renewable energy system integrates solar, wind and storage solutions. It is cost efficient, reliable, and reduces carbon emissions, thereby supporting sustainable energy transitions. The study finds that digital and computational innovations are crucial for societal impact in supporting climate resilience, energy security, and long-term socio-economic growth, also strengthening the contribution of physical sciences to Nigeria's sustainable development agenda.

Keywords: Artificial Intelligence; Computational science; Digital innovation; Machine Learning; Physical sciences; Sustainable development.

Introduction

Sustainable development in Nigeria increasingly relies on evidence-based solutions from the physical sciences—physics, chemistry, and earth sciences—to address pressing socio-economic and environmental challenges such as energy security, climate resilience, resource management, and industrial innovation (Adeyemi & Akinyele, 2020; Ogunleye & Bello, 2018). These disciplines provide the theoretical and practical frameworks needed for scalable, scientifically sound solutions, though their full potential is often limited by traditional experimental methods, scarce real-time data, and resource-intensive laboratory procedures (Chukwu & Okeke, 2019).Recent advances in digital and computational technologies, including artificial intelligence (AI), machine learning, cloud computing, and big data analytics, are transforming physical sciences research. These tools enable more precise experiments, predictive modeling, and data-driven decision-making, improving accuracy while reducing research costs and time (Makinde, Sulyman, & Ibrahim, 2024; Ojika et al., 2023).Despite this potential, adoption in Nigeria remains limited due to inadequate infrastructure, a lack of skilled personnel, and restricted access to high-quality datasets. Additionally, applying these tools often requires interdisciplinary collaboration, which is still underdeveloped in many research settings.This study aims to:

Examine the contributions of physical sciences to Nigeria's sustainable development.

1. Assess how digital and computational innovations enhance physics-based applications.
2. Synthesize evidence of sustainability outcomes from physics-driven interventions in Nigeria.
3. Identify barriers to the integration of digital technologies in physical sciences research.
4. Analyse strategies for maximising the potential of digital innovations through policy, collaboration, and human capital development.

By situating physical sciences at the core, this paper emphasizes that digital tools are enablers, not replacements, augmenting traditional scientific principles to accelerate discovery and support sustainable development in Nigeria.

Literature Review

Physical Sciences and Sustainable Development in Nigeria

The physical sciences are central to Nigeria's sustainable development, underpinning critical sectors such as energy, climate monitoring, environmental management, industry, and infrastructure (Bello et al., 2025; Dada et al., 2024). This discipline contributes directly to several Sustainable Development Goals, including SDG 7 (Clean Energy)**,** SDG 9 (Industry & Innovation)**,** SDG 12 (Responsible Consumption)**,** and SDG 13 (Climate Action)**,** supporting sustainable energy, innovation, and environmental responsibility.Advanced computational and AI-driven models improve rainfall prediction, disaster preparedness, and resource management, addressing challenges posed by Nigeria's complex tropical climate (Ojo & Ogunjo, 2022; NiMet, 2019). AI and machine learning bridge data gaps and enhance predictive capacity, though adoption is limited by infrastructure, expertise, and data constraints (Olasehinde et al., 2025).

Digital and Computational Tools as Enablers

Digital technologies—AI, machine learning, cloud computing, and data analytics—enhance physics-based research and education in Nigeria, overcoming infrastructure and resource limitations (Ekwu et al., 2025; Ojika et al., 2023). In energy research, computational simulations optimize renewable systems, reduce reliance on costly prototypes, and improve reliability and economic feasibility (Adeyemi & Akinyele, 2020; Olodu et al., 2025).In climate science, AI-assisted models outperform traditional methods in predicting rainfall and extreme weather events, supporting disaster management and climate resilience (Ojo & Ogunjo, 2022; Okonkwo et al., 2024). In education, virtual and augmented laboratories, cloud platforms, and AI-driven tools expand access to physics experiments, interactive learning, and remote collaboration (Ojika et al., 2023; Prayogi & Verawati, 2024).Digital innovations also support environmental policy and resource allocation by integrating physics-based models with data analytics to forecast trends and optimize resources (Ekeh et al., 2025). These tools amplify the impact of physical sciences but depend on strong scientific principles, infrastructure, and skilled personnel.

Linking Physical Sciences to Sustainability Outcomes

According to the Nigeria Society of Physical Science, physical sciences remain central to advancing innovation, economic transformation and sustainable development in Nigeria. (Oladiran & Babatunde 2026). Sustainable development outcomes depend on applying physics-based knowledge to real-world systems. In Nigeria, energy efficiency, environmental monitoring, and industrial innovation rely on core physical principles, complemented by computational tools and guided by national climate and environmental policies (Federal Ministry of Environment, 2020). Renewable energy optimization reduces emissions and enhances reliability, environmental sensors improve pollution management, and thermodynamic analyses guide efficient industrial processes (Bello et al., 2025; Olodu et al., 2025; Ojo & Salami, 2021). While digital tools enhance modeling, scalability, and predictive capacity, the sustainability of outcomes remains grounded in physical sciences. Successful integration of physics research with digital technologies, policy, and industry is essential to translate scientific knowledge into tangible, long-term sustainable development benefits. A conceptual framework highlights this relationship: physical sciences form the foundation, digital tools act as enablers, and the interaction produces measurable outcomes, moderated by infrastructure, data availability, and institutional support (see Figure 1).

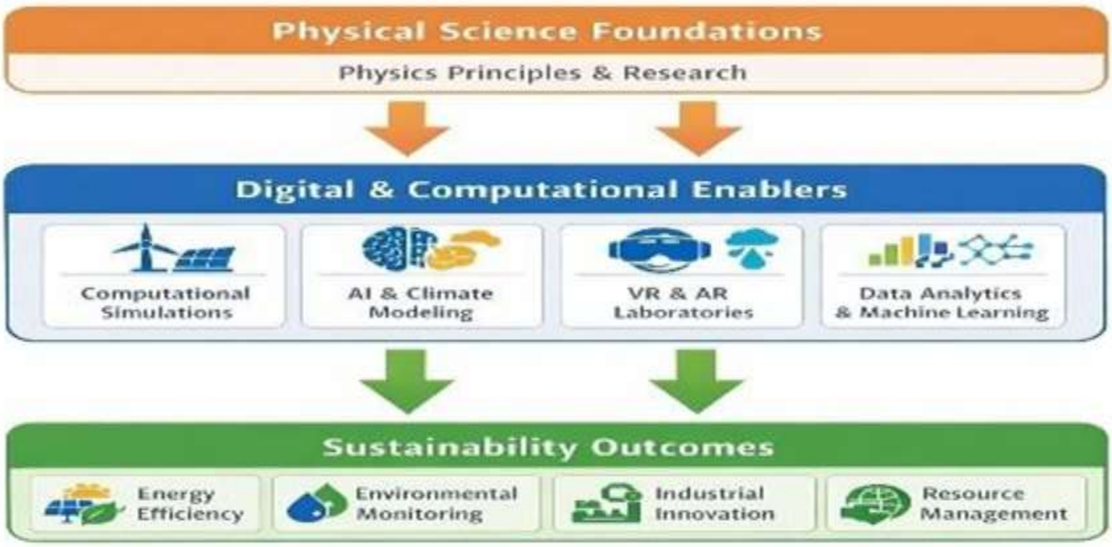

Figure 1: Framework illustrating how physical sciences, amplified by digital tools, drive sustainable development outcomes, with barriers and enabling factors shaping the effectiveness of interventions.

Methodology

This study employed a systematic literature review (SLR), analyzing 18 peer-reviewed articles, government reports, and academic papers published between 2018 and 2025 (Agbeyangi et al., 2024; Makinde et al., 2024; Rosário et al., 2025).
Sources were selected based on their relevance to:

- Physics-based solutions for sustainable development,
- Applications of digital and computational tools in the physical sciences, and
- Measurable sustainability outcomes in Nigeria and Africa.

A structured data extraction process captured key information, including:

- Physics application areas (energy systems, climate modeling, materials science, laboratory education),
- Type of digital or computational tools (AI, machine learning, cloud computing, virtual/augmented reality, data analytics),
- Observed sustainability impacts, and
- Barriers and enablers affecting implementation.

This methodology ensured systematic alignment with the study's objectives and relevant Sustainable Development Goals (SDGs). It provided a comprehensive understanding of how physics-based approaches, digital tools, and contextual factors converge to influence sustainability outcomes, forming the foundation for the conceptual framework and subsequent analysis.

Results and Discussion

The findings of this study address the five research aims. First, the contributions of physical sciences to Nigeria's sustainable development are evident across energy, climate, education, and industry. Second, the application of digital and computational innovations, including AI, machine learning, and big data analytics, enhances traditional physics-based research methods, improving predictive modeling, efficiency, and scalability. Third, evidence from renewable energy, climate forecasting, education, and industrial optimization demonstrates measurable sustainability outcomes, including increased energy efficiency, improved climate resilience, reduced material waste, and expanded human capital. Fourth, the study identifies key barriers to adopting these digital tools, notably inadequate infrastructure, limited skilled personnel, and restricted access to high-quality datasets. Finally, strategies for maximizing digital innovations—such as promoting interdisciplinary collaboration, investing in human capital, and strengthening policy support—are integrated throughout the discussion.

Renewable Energy Optimization: Physics underpins the design and optimization of solar, wind, and hydropower systems, influencing efficiency through material properties, thermodynamics, and fluid dynamics. Computational modeling and machine learning improve predictions of energy yields, maintenance needs, and environmental impacts, supporting national sustainability goals such as reducing emissions and enhancing energy security. These interventions illustrate the measurable benefits of physics-driven approaches while highlighting areas where digital tools can address skill and infrastructure gaps.

Climate and Environmental Applications: Physics-based climate models, combined with AI and big data analytics, improve forecasts of rainfall, temperature, and extreme events. These predictions inform agriculture, urban planning, and disaster management, enhancing water resource management and climate resilience. Digital tools amplify the accuracy and scalability of climate interventions, demonstrating both the contributions of physical sciences and the value of computational enhancements.

Education and Laboratory Innovation: Virtual labs, augmented reality, and interactive simulations enable hands-on physics learning in resource-constrained settings, reducing material waste and energy use. AI-powered adaptive platforms personalize learning, improve problem-solving skills, and expand access to quality education. These approaches foster human capital for sustainable development and address infrastructural and resource barriers, providing a pathway for strategy implementation.

Industrial and Material Science Applications: Physics principles in materials, thermodynamics, and fluid dynamics, supported by computational simulations, optimize industrial processes, reduce waste, and improve energy efficiency. These innovations align with SDG 9 and SDG 12, enabling cleaner, safer, and more efficient production while building technical expertise for long-term industrial growth. The integration of digital tools highlights the potential to overcome operational challenges and improve outcomes.

Synthesis of Findings

The study shows that physics, amplified by digital tools, is central to sustainable development in Nigeria. Renewable energy, climate modeling, education, and industry all benefit from computational and AI-enabled solutions. However, overcoming infrastructural, skills, and access barriers is essential. A coordinated approach integrating technology, human capacity, and policy support is critical to achieving measurable sustainability outcomes.As illustrated in Figure 2, physics principles amplified by digital tools and AI drive sustainable development across energy, climate, education, and industrial sectors, while barriers such as infrastructure, skills, and access require targeted interventions.

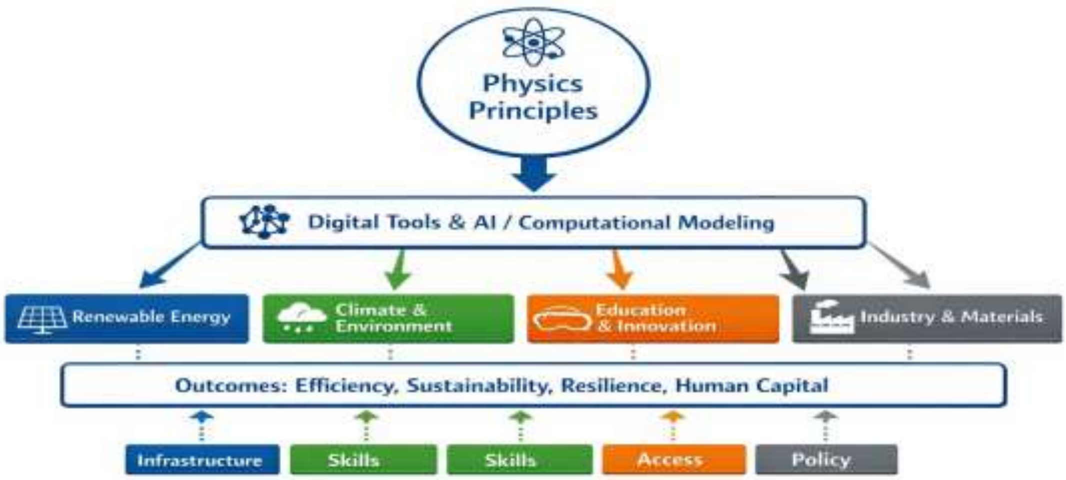

Figure 2: Integration of physics principles and digital tools for sustainable development across energy, climate, education, and industrial sectors, highlighting barriers and outcomes aligned with SDGs.

Conclusion and Recommendations

Physical sciences remain fundamental to achieving sustainable development in Nigeria, providing the principles and analytical frameworks necessary for informed decision-making. Digital and computational innovations serve as “enablers”, enhancing experimental efficiency, predictive accuracy, and the capacity for data-driven solutions across energy, environmental, educational, and industrial sectors.

Recommended strategies:

- **Invest in research infrastructure:** Build advanced labs and cloud computing platforms.
- **Expand capacity-building:** Train researchers and educators in computational physics, data analytics, and AI.
- **Ensure equitable access:** Make software, simulations, and digital tools widely available.
- **Integrate into policy:** Align national strategies with physics-based evidence.
- **Foster public-private partnerships:** Promote collaborations to advance tech-enabled physics applications.

By implementing these strategies, Nigeria can position the physical sciences as a "cornerstone of evidence-based, technology-enhanced sustainable development", yielding measurable socio-economic and environmental benefits while strengthening the nation's capacity to address current and future challenges.

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How to cite this work: Usani, J. O., Offiong, J. E., Omole, O. A., & Uyi, A. (2026). Digital and computational innovations in physical sciences: A tool for sustainable development in Nigeria. *International Journal of Engineering, Science, and Environmental Research, 1*(2), 140–146.