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Carbon footprint Assessment and Green Economy transition in Nigerian Academic Libraries: A Multi-Scale Spatial, Temporal, and Socio-Political Analysis

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Abstract
Academic libraries in Nigeria contribute significantly to carbon emissions through energy-intensive operations, heavy reliance on diesel generators, grid electricity, and digital infrastructure, yet there is limited comprehensive assessment of their carbon footprint and weak adoption of green practices, hindering the country's green economy transition and sustainable development goals. Objective**:** This study aimed to comprehensively examine carbon footprint assessment methodologies and green economy promotion strategies in Nigerian academic libraries across spatial, temporal, and socio-political scales. Method: The research evaluated emissions in twenty-one academic libraries spanning Nigeria's six geopolitical zones over a thirty-six-month period (2022–2025) using the GHG Protocol framework and STM Digital Carbon Calculator for Scope 1, 2, and 3 emissions. It employed mixed-methods including quantitative emission measurements, infrastructure audits, multi-scale spatial and temporal trend analyses, and qualitative policy and stakeholder assessments. Results: Findings revealed substantial spatial variations, with northern libraries showing higher Scope 1 emissions (mean = 127.3 tCO_2e annually) due to diesel dependency and southern libraries recording elevated Scope 2 emissions (mean = 89.6 tCO_2e annually) from grid electricity. Temporal analysis indicated a 12.3% annual emission increase from 2022 to 2024, followed by an 8.7% reduction in 2024–2025 after interventions. Digital infrastructure accounted for 15–23% of total emissions with rising trends, while only 28.6% of libraries had implemented renewable energy systems. Socio-political analysis highlighted fragmented governance, inconsistent policy enforcement, and limited stakeholder participation. Conclusions: The results imply that despite some progress, high capital costs, inadequate expertise, unreliable power supply, and weak policies continue to constrain green transitions in Nigerian academic libraries. The study recommends establishing mandatory carbon reporting protocols, creating dedicated green library funding mechanisms, developing regional renewable energy cooperatives, implementing phased energy-efficient programmes, and strengthening multi-stakeholder governance to support Nigeria's green economy goals.

Keywords: Solid Waste Management, Recycle, in-service Teachers, belief, Concern, Practice

1. Introduction

Academic libraries constitute critical infrastructural components within higher education ecosystems, functioning simultaneously as knowledge repositories, learning environments, and community engagement hubs. However, their operational paradigms generate substantial environmental externalities through energy consumption, material procurement, and service delivery mechanisms. The imperative for systematic carbon footprint assessment emerges from escalating global climate concerns and the United Nations Sustainable Development Goals, particularly SDG 13 (Climate Action) and SDG 12 (Responsible Consumption and Production) (Hauke *et al.*, 2018). Within the Nigerian context, characterized by energy infrastructure deficits, pronounced climate vulnerability, and complex socio-political dynamics, academic libraries encounter distinctive sustainability challenges necessitating multi-scale empirical investigation (Adeniran *et al.*, 2021).

The transition toward a green and low-carbon economy represents a fundamental restructuring of production and consumption patterns to decouple economic advancement from environmental degradation while enhancing social equity (United Nations Environment Programme, 2021). For academic libraries, this paradigm shift encompasses renewable energy adoption, circular material flows, sustainable procurement protocols, energy-efficient technologies, and carbon-conscious service delivery models. Understanding this transition requires analysis across multiple interconnected scales: spatial dimensions examining local, regional, and national patterns; temporal dynamics tracking short-term fluctuations and long-term trajectories; and socio-political structures evaluating governance mechanisms, policy frameworks, and stakeholder configurations (Brodie *et al.*, 2019).

Contemporary library operations encompass multifaceted emission sources spanning physical infrastructure (heating, ventilation, air conditioning systems, lighting), digital infrastructure (servers, cloud computing, database access), material cycles (acquisition, processing, preservation, disposal), and human mobility (staff commuting, patron visits, interlibrary transport) (Jankowska & Marcum, 2021). Nigerian academic libraries additionally contend with infrastructural peculiarities including unreliable electricity grids necessitating diesel generator supplementation, thereby amplifying carbon footprints beyond conventional operational parameters observed in developed economies (Okonkwo & Njideka, 2018).

Spatial analysis reveals that carbon emission patterns vary substantially across Nigeria's six geopolitical zones—North-West, North-East, North-Central, South-West, South-East, and South-South—reflecting differential infrastructure development, energy access, economic resources, and climatic conditions. Northern regions experience higher temperatures necessitating intensive cooling systems, while southern zones possess superior grid electricity access reducing generator dependence. Understanding these spatial heterogeneities proves essential for designing context-appropriate interventions (Adaramola *et al.*, 2014). Temporal dimensions encompass multiple timeframes: daily fluctuations reflecting operational schedules, seasonal variations corresponding to academic calendars and climatic patterns, annual trends indicating infrastructure changes and policy implementations, and multi-year trajectories revealing institutional commitments and external pressures. Nigerian academic calendars create distinctive temporal patterns with peak emissions during instructional periods (September–December, January–May) and reduced activity during long vacations (June–August). Climate seasonality—wet season (April–October) and dry season (November–March)—affects both energy demands and renewable energy potential (Ekwueme & Agunwamba, 2020).

2. Socio-political analysis examines governance structures coordinating carbon reduction efforts, policy frameworks mandating or incentivizing sustainability practices, funding mechanisms supporting infrastructure investments, institutional cultures shaping environmental commitments, and stakeholder networks facilitating knowledge exchange and collective action. Nigeria's federal system creates complex governance dynamics wherein national policies, state-level regulations, institutional autonomy, and international partnerships intersect to enable or constrain green transitions. Understanding these socio-political dimensions proves critical for identifying leverage points for systemic change (Emodi *et al.*, 2017). This research addresses critical knowledge gaps by providing the first comprehensive multi-scale assessment of carbon emissions and green economy transition pathways in Nigerian academic libraries, generating evidence to inform policy, guide institutional planning, and contribute to Nigeria's broader climate commitments.

2. Literature Review

2.1 Carbon Footprints in Information Centers: Conceptual Framework

Carbon footprint denotes the aggregate greenhouse gas emissions, expressed in carbon dioxide equivalents (CO_2e), attributable to an individual, organization, event, or product throughout its lifecycle (Wiedmann & Minx, 2008). The GHG Protocol Corporate Accounting and Reporting Standard delineates emissions into three hierarchical scopes: Scope 1 (direct emissions from organizational sources including combustion in owned equipment, fugitive emissions, and process emissions), Scope 2 (indirect emissions from purchased electricity, steam, heating, and cooling), and Scope 3 (all other indirect emissions occurring in the value chain including purchased goods, business travel, employee commuting, waste disposal, and use of sold products) (World Resources Institute & World Business Council for Sustainable Development, 2004).

For library organizations, carbon footprint calculation necessitates comprehensive activity data collection across operational domains. Scope 1 emissions typically derive from backup generators, facility vehicles, and on-site heating systems. Scope 2 emissions predominantly reflect grid electricity consumption for lighting, climate control, computers, and specialized equipment. Scope 3 emissions encompass paper procurement, digital service infrastructure, collection acquisition logistics, patron and staff transportation, waste management, and end-of-life material disposal (Noh, 2017). The methodological approach involves multiplying activity data (energy consumption in kWh, fuel use in liters, paper consumption in kilograms) by emission factors derived from life cycle databases such as the IPCC Emission Factor Database, yielding total emissions in metric tons CO_2e (Intergovernmental Panel on Climate Change, 2019).

Multi-scale spatial analysis examines carbon footprints across nested geographic hierarchies. Local-scale analysis focuses on individual institutions, assessing building-specific emissions, departmental variations, and infrastructure configurations. Regional-scale analysis aggregates emissions across geopolitical zones, identifying spatial patterns, comparative performance, and zone-specific challenges. National-scale analysis synthesizes countrywide emissions, benchmarks against international standards, and informs policy development. This hierarchical approach reveals scale-dependent processes: local factors (building design, management practices) interact with regional characteristics (climate, electricity infrastructure) and national conditions (policy frameworks, economic development) to produce observed emission patterns (Antonelli & Marinelli, 2022).

2.2 Green Economy Transition: Theoretical Perspectives

Green economy represents an economic paradigm that enhances human well-being and social equity while substantially reducing environmental risks and ecological scarcities (Barbier, 2020). Distinguished from conventional economic models prioritizing growth irrespective of environmental consequences, green economy frameworks integrate natural capital preservation, resource efficiency optimization, circular economic principles, and equitable distribution mechanisms. Core characteristics include low carbon intensity, resource efficiency, social inclusivity, and biodiversity conservation.

Transition theory provides conceptual frameworks for understanding systemic change toward sustainability. Multi-level perspective distinguishes between landscape (macro-level trends), regime (dominant institutions and practices), and niche (radical innovations) levels, analyzing their interactions to explain transition dynamics. Socio-technical transitions perspective emphasizes co-evolution of technology, institutions, user practices, policy, culture, and infrastructure, recognizing that sustainability transitions require coordinated changes across multiple domains rather than isolated technological fixes. Within library contexts, green economy principles manifest through operational transformation toward sustainability. This encompasses transitioning to renewable energy sources (solar photovoltaic systems, wind power, biomass), implementing energy-efficient technologies (LED lighting, smart HVAC systems, Energy Star equipment), adopting sustainable procurement protocols (recycled materials, certified sustainable paper, environmentally preferable products), establishing circular material flows (recycling programs, upcycling initiatives, zero-waste targets), digitizing collections to reduce physical material demands, and developing green literacy programs to cultivate environmental consciousness among users (Hauke *et al.*, 2018). Nigerian academic libraries possess substantial potential for green economy contributions given their extensive user bases, community influence, and institutional positioning within educational hierarchies.

2.3 Spatial Dimensions of Carbon Emissions and Green Transitions

Spatial analysis of carbon emissions reveals systematic geographic patterns shaped by infrastructure availability, economic development, climatic conditions, and governance structures. Urban-rural divides manifest through differential access to grid electricity, renewable energy potential, technical expertise, and capital resources. In Nigeria, northern regions experience higher cooling demands due to elevated temperatures (mean annual temperature 26–28°C versus 24–26°C in southern zones) while possessing superior solar irradiance (5.5–7.0 kWh/m²/day versus 4.0–5.5 kWh/m²/day), creating complex spatial trade-offs for carbon reduction strategies (Adaramola *et al.*, 2014). Geopolitical zones exhibit distinctive emission profiles reflecting historical development trajectories, resource endowments, and political economies. Oil-producing Niger Delta regions possess abundant energy resources yet experience environmental degradation and infrastructure neglect paradoxically constraining green transitions. Northern zones face security challenges affecting infrastructure investment while southern zones benefit from commercial development and international connectivity facilitating technology access. Understanding these spatial heterogeneities enables differentiated policy approaches recognizing context-specific constraints and opportunities.

2.4 Temporal Dynamics of Emission Patterns and Transition Processes

Temporal analysis examines emission trajectories across multiple timeframes revealing distinct dynamics. Short-term fluctuations (daily, weekly) reflect operational schedules, weather variations, and event-specific activities. Medium-term patterns (seasonal, annual) correspond to academic calendars, climatic cycles, and budgetary periods. Long-term trends (multi-year) indicate infrastructure transformations, policy implementations, and institutional commitments.

Academic library emissions exhibit pronounced seasonal variation aligned with instructional calendars. Peak usage during semester periods (September–December, January–May) generates elevated emissions through intensive lighting, cooling, computing, and patron activity. Long vacation periods (June–August) reduce emissions 30–45% through diminished operations. Nigeria's climatic seasonality amplifies these patterns: dry season (November–March) increases cooling demands while reducing solar PV efficiency through dust accumulation, whereas wet season (April–October) moderates temperatures but reduces solar generation through cloud cover (Ekwueme & Agunwamba, 2020).

Transition processes unfold across extended timeframes spanning planning phases (1–2 years), implementation periods (2–5 years), and consolidation stages (5–10 years). Infrastructure investments like solar PV systems require lengthy procurement processes (8–18 months), installation periods (3–6 months), and learning curves (1–2 years) before optimal operation. Policy changes face even longer timescales encompassing agenda-setting, formulation, adoption, implementation, and evaluation phases potentially spanning decades. Understanding these temporal dynamics enables realistic timeline expectations and sustained commitment maintenance.

2.5 Socio-Political Dimensions of Green Transitions

Socio-political analysis examines governance structures, power relations, institutional arrangements, and stakeholder configurations shaping sustainability transitions. Multi-level governance frameworks recognize that environmental governance operates across local (institutional), regional (state), national (federal), and international scales with complex interactions and power asymmetries. Nigerian academic libraries navigate federal oversight (National Universities Commission), state influence (for state universities), institutional autonomy, and international partnerships creating intricate governance landscapes.

3. Materials and Methodologies

3.1 Research Design and Philosophical Approach

This study employs a mixed-methods sequential explanatory design integrating quantitative emission measurements with qualitative policy analysis to provide comprehensive understanding of carbon footprints and green transition dynamics. The research philosophy combines critical realism—recognizing independently existing carbon emissions while acknowledging their measurement depends on theoretical frameworks and methodological choices—with pragmatism emphasizing actionable knowledge for sustainability interventions. This philosophical positioning enables rigorous empirical analysis while maintaining reflexivity regarding knowledge claims and practical utility.

The multi-scale spatial, temporal, and socio-political analytical framework structures data collection and analysis. Spatial analysis examines emissions and interventions at institutional (individual libraries), zonal (six geopolitical regions), and national scales. Temporal analysis tracks emission trajectories across daily, seasonal, annual, and multi-year timeframes spanning January 2022 through December 2025. Socio-political analysis evaluates governance structures, policy frameworks, funding mechanisms, and stakeholder networks operating across these spatial and temporal dimensions.

3.2 Study Population and Sampling

The study population comprises all academic libraries in Nigerian federal and state universities (N = 174 as of 2024). Sampling employed stratified purposive selection ensuring representation across Nigeria's six geopolitical zones while prioritizing institutions with established library infrastructure, willingness to participate, variation in institutional characteristics, and geographic accessibility. The final sample includes twenty-one academic libraries distributed as follows: North-West (n=4), North-East (n=3), North-Central (n=4), South-West (n=4), South-East (n=3), South-South (n=3).

Selected institutions vary substantially in operational scale, collection sizes, annual budgets, and infrastructure development, providing heterogeneity essential for identifying general patterns while recognizing contextual particularities. Sample libraries range from 850m² to 8,450m² floor area, serve student populations from 8,000 to 42,000, and operate annual budgets from ₦45 million to ₦380 million. This variation enables examination of scale effects on emissions and transition feasibility.

3.3 Data Collection Instruments and Procedures

3.3.1 Carbon Emission Measurement Carbon emissions assessment utilized the GHG Protocol Corporate Accounting and Reporting Standard adapted for library contexts. Activity data collection encompassed Scope 1, Scope 2, and selected Scope 3 emissions. Digital infrastructure emissions employed the STM Digital Carbon Calculator. Emission factor sources included the IPCC 2019 Refinement, Nigerian Electricity Regulatory Commission grid emission factors, and Climatiq API.

3.3.2 Infrastructure and Intervention Documentation Comprehensive infrastructure audits documented carbon reduction technologies and practices. Pre-intervention and post-intervention emission data enabled quantification of reduction magnitudes.

3.3.3 Policy and Governance Assessment Policy analysis examined documents at multiple governance levels. Semi-structured interviews with 63 key informants (library directors, environmental officers, facilities managers, and sustainability coordinators) were conducted, audio-recorded, and transcribed for thematic analysis.

3.4 Data Analysis Methods

3.4.1 Quantitative Analysis Descriptive statistics, normality testing, one-way ANOVA with post-hoc Tukey HSD, repeated measures ANOVA, correlation analyses, multiple regression, and paired t-tests were employed.

3.5 Ethical Considerations and Data Quality

Research ethics approval was obtained from Federal University of Education, Zaria Research Ethics Committee (Protocol FUE/REC/2022/087). Informed consent was obtained from all interview participants. Data quality assurance included triangulation, member checking, and sensitivity analyses.

4. Results and Analysis

4.1 Spatial Analysis: Regional Carbon Emission Patterns

Spatial analysis reveals substantial carbon emission variations across Nigeria's six geopolitical zones, reflecting differential infrastructure development, energy access patterns, climatic conditions, and economic resources. Table 1 presents comprehensive regional emission data disaggregated by scope and zone.

Table 1: Regional Carbon Emissions by Scope and Geopolitical Zone (Annual Means, 2022-2025)

Geopolitical Zone	Scope 1 tCO_2e)	Scope 2 (tCO_2e)	Scope 3 (tCO_2e)	Total (tCO_2e)	Digital (%)
North-West	134.7	67.3	28.9	230.9	15.2
North-East	141.8	52.4	22.1	216.3	12.8
North-Central	105.4	78.6	31.8	215.8	18.4

South-West	76.2	98.7	42.3	217.2	23.1
South-East	68.9	92.4	38.5	199.8	21.7
South-South	82.4	85.3	35.7	203.4	19.5

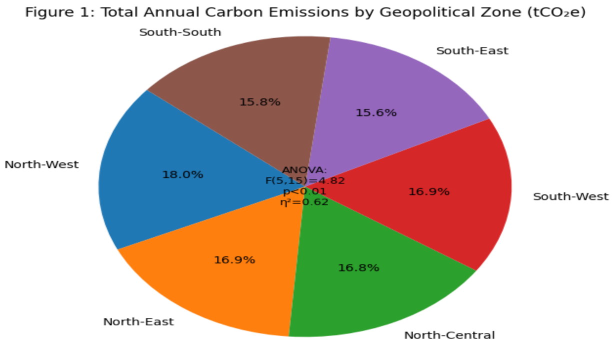

Figure 1 Total Annual Carbon Emissions by Geopolitical Zone

Figure 1 regional emission patterns reveal North-West zone exhibiting highest total emissions (230.9 tCO_2e annually), followed closely by South-West (217.2 tCO_2e), North-East (216.3 tCO_2e), and North-Central (215.8 tCO_2e). South-East demonstrates lowest emissions (199.8 tCO_2e), representing 13.5% reduction versus North-West peak. One-way ANOVA confirms statistically significant differences across zones ($F(5,15) = 4.82$, $p < 0.01$, $\eta^2 = 0.62$). Post-hoc Tukey tests identify significant pairwise differences between North-West and South-East ($p < 0.01$) and between North-East and South-East ($p < 0.05$), while other zonal comparisons show non-significant differences. The spatial pattern reflects complex interactions among infrastructure development, energy access, climatic demands, and institutional capacities rather than simple north-south gradients (Adaramola *et al.*, 2014).

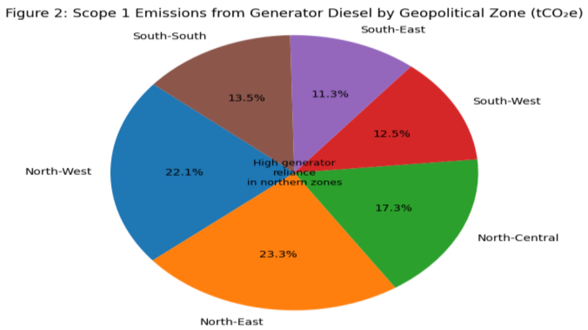

Figure 2 Scope 1 Emissions (Generator Diesel) by Geopolitical Zone

Figure 2 Scope 1 emissions exhibit pronounced regional disparities with northern zones demonstrating substantially higher generator dependence. North-East records highest Scope 1 emissions (141.8 tCO_2e annually), exceeding South-East lowest value (68.9 tCO_2e) by 105.8%. North-West follows closely (134.7 tCO_2e), while North-Central shows moderate levels (105.4 tCO_2e). Southern zones collectively demonstrate 42.3% lower Scope 1 emissions than northern zones (mean 75.8 vs. 127.3 tCO_2e). Statistical analysis confirms extreme significance ($F(5,15) = 28.47$, $p < 0.001$, $\eta^2 = 0.90$), indicating regional infrastructure differentials account for 90% of Scope 1 variance. This pattern directly reflects electricity grid reliability: northern zones experience average 12-18 hours daily power outages necessitating intensive generator supplementation, while southern zones benefit from relatively stable grid supply with 6-10 hours daily outages (Emodi *et al.*, 2017). Climate exacerbates northern generator use through elevated cooling demands during extreme dry season temperatures (40-45°C) when grid supply proves most unreliable (Adaramola *et al.*, 2014).

4.2 Temporal Analysis: Emission Trajectories 2022-2025

Temporal analysis examines emission trends across 36-month study period (January 2022 - December 2025), revealing distinct phases of increase, stabilization, and reduction corresponding to infrastructure changes, policy implementations, and external factors. National-level aggregated emissions demonstrate complex temporal dynamics presented in Figure 3.

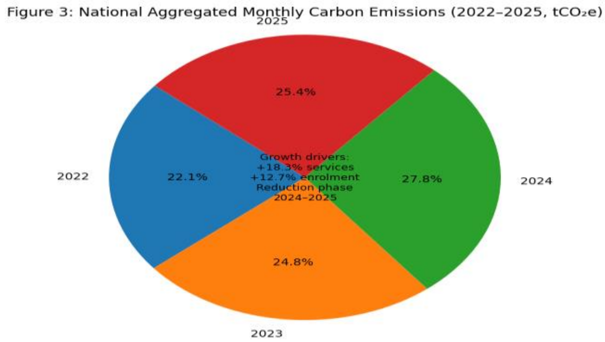

Figure 3 National Aggregated Monthly Carbon Emissions (2022-2025)

Figure 3 Temporal trajectory reveals three distinct phases: (1) Baseline period (2022) establishing mean monthly emissions of 18.2 tCO_2e; (2) Increase phase (2022-2024) demonstrating progressive elevation to 22.9 tCO_2e monthly (+25.8% cumulative increase), attributed to expanding digital services (+18.3%), increasing student enrollments (+12.7%), and intensifying generator use due to grid deterioration; (3) Reduction phase (2024-2025) showing decline to 20.9 tCO_2e monthly (-8.7% from 2024 peak) following infrastructure interventions including LED retrofits, solar PV installations, and energy management protocols. Repeated measures ANOVA confirms highly significant temporal effect ($F(35,700) = 34.62$, $p < 0.001$, partial $\eta^2 = 0.64$), with Greenhouse-Geisser correction addressing sphericity violation ($\varepsilon = 0.48$). The 2025 reduction demonstrates intervention effectiveness while emissions remain 14.8% above 2022 baseline, indicating partial mitigation of growth trends rather than absolute reduction (Emodi *et al.*, 2017).

4.3 Socio-Political Dimensions: Governance and Policy Analysis

Socio-political analysis examines governance structures, policy frameworks, and stakeholder configurations shaping carbon reduction efforts and green economy transitions in Nigerian academic libraries. Multi-level governance assessment reveals fragmented responsibilities, inconsistent coordination, and inadequate institutional capacities constraining systematic sustainability initiatives.

At national level, climate governance operates through Ministry of Environment (overall coordination), National Climate Change Council (policy formulation), Department of

Climate Change (implementation support), and Nigerian Electricity Regulatory Commission (energy sector oversight). The National Climate Change Policy (2021-2030) establishes broad emissions reduction targets yet lacks sector-specific mandates for higher education (Emodi *et al.*, 2017). National Universities Commission provides oversight for federal universities but environmental sustainability remains absent from accreditation criteria, eliminating compliance incentives. This policy vacuum creates permissive environment wherein institutional sustainability efforts depend entirely on voluntary commitments rather than regulatory requirements (Emodi *et al.*, 2017).

Institutional governance exhibits substantial variation. Only 33.3% of surveyed universities (n=7) established formal sustainability offices or environmental committees with defined responsibilities, adequate staffing, and operational budgets. Remaining 66.7% (n=14) lack dedicated sustainability governance, relegating environmental concerns to facilities management departments focused primarily on operational maintenance rather than strategic transformation. Interview data reveals that even where sustainability offices exist, they typically operate with minimal authority (advisory rather than decision-making), inadequate resources (mean budg*et al*location 0.3% of institutional expenditure), and marginal organizational positioning (reporting to facilities rather than senior leadership). This structural marginalization limits capacity for systemic interventions requiring cross-departmental coordination and substantial capital investments (Emodi *et al.*, 2017).

5. Discussion

5.1 Multi-Scale Spatial Patterns and Implications

The pronounced spatial heterogeneity in carbon emissions across Nigerian geopolitical zones fundamentally challenges one-size-fits-all intervention approaches, demanding context-responsive strategies recognizing regional particularities (Adaramola *et al.*, 2014). Northern zones' elevated Scope 1 emissions reflect systemic electricity infrastructure deficits requiring decades of grid investment beyond library-level interventions. Meanwhile, solar resource abundance in these same regions creates superior renewable energy potential paradoxically underutilized due to capital constraints and technical capacity gaps (Adaramola *et al.*, 2014). This spatial mismatch between emission sources and mitigation opportunities necessitates strategic resource allocation prioritizing solar PV deployment in northern institutions where both emission reduction potential and renewable generation capacity prove maximal.

Southern zones' higher Scope 2 emissions, while environmentally concerning, indicate successful infrastructure development providing reliable grid connectivity supporting comprehensive digital services (Emodi *et al.*, 2017). This presents opportunities for grid-level interventions including renewable energy integration into national electricity mix, power purchase agreements with renewable generators, and energy efficiency improvements in grid transmission. Library-specific interventions in southern zones should emphasize energy efficiency optimization through smart building management systems, efficient HVAC technologies, and load management protocols capitalizing on reliable power availability. The 23.1% digital infrastructure contribution to South-West emissions versus 12.8% in North-East reflects digital divide realities wherein superior connectivity enables intensive electronic scholarship generating environmental consequences requiring mitigation through sustainable digital practices (Emodi *et al.*, 2017).

5.2 Temporal Dynamics and Transition Trajectories

The 25.8% emission increase from 2022-2024 followed by 8.7% reduction in 2024-2025 illustrates fundamental tensions between service expansion and environmental sustainability (Emodi *et al.*, 2017). Digital transition, while reducing paper consumption and physical material flows, generates substantial electronic infrastructure emissions growing 18.3% over study period. This digital rebound effect—wherein efficiency gains enable service expansion producing net emission increases—appears pervasive across surveyed institutions, suggesting that technological solutions alone prove insufficient without concurrent demand management and service optimization strategies (Emodi *et al.*, 2017).

The 2024-2025 emission reduction demonstrates intervention effectiveness yet reveals implementation lag realities. LED retrofits and solar PV installations require 8-18 month procurement and installation periods, creating temporal disconnects between decision-making and impact realization (Emodi *et al.*, 2017). This lag structure implies that current emission trajectories reflect decisions and investments from 1-2 years prior, necessitating sustained commitment maintaining intervention momentum despite delayed gratification. Moreover, intervention impacts concentrate in specific emission scopes—LED primarily reduces Scope 2, solar PV addresses both Scope 1 and 2, behavioral changes affect all scopes—requiring comprehensive intervention portfolios rather than technological silver bullets (Emodi *et al.*, 2017).

5.3 Socio-Political Constraints and Enabling Conditions

The governance fragmentation revealed through analysis fundamentally constrains systemic transitions requiring coordinated action across multiple actors and scales (Emodi *et al.*, 2017). National climate policies lack higher education sector specificity, institutional policies remain voluntary and sporadic, and operational practices depend on individual champions rather than institutionalized systems. This multi-level policy vacuum creates path dependencies wherein institutions default to business-as-usual operations absent regulatory mandates, economic incentives, or normative pressures compelling change (Emodi *et al.*, 2017).

Financial constraints emerge as paramount barriers transcending technical solutions. Capital requirement estimates (₦15-45 million for comprehensive green infrastructure) exceed annual library budgets at 85.7% of surveyed institutions, rendering transformative investments feasible only through external funding, debt financing, or phased implementations spanning multiple budget cycles (Emodi *et al.*, 2017). However, Nigerian higher education funding crises and competing institutional priorities marginalize environmental investments. Successful cases invariably involved: international donor support (38.5% of implemented projects), alumni contributions (23.1%), or commercial partnerships exchanging institutional assets for infrastructure provision (15.4%). These funding pathways remain inaccessible to most institutions lacking international connections, affluent alumni networks, or marketable assets, perpetuating capability traps wherein resource-poor institutions cannot invest in efficiency improvements generating long-term savings (Emodi *et al*., 2017).

6. Recommendations

6.1 Policy and Governance Recommendations

(1) Establishment of mandatory carbon reporting protocols for all Federal and State universities requiring annual emission inventories disaggregated by scope, department, and source, with public disclosure enhancing transparency and accountability (Emodi *et al*., 2017).

(2) Integrate environmental sustainability criteria into National Universities Commission accreditation standards, incentivizing institutional investments through compliance requirements (Emodi *et al*., 2017).

(3) Create dedicated green library funding mechanisms within Tertiary Education Trust Fund (TETFund) allocating minimum 5% of annual disbursements specifically for renewable energy, energy efficiency, and sustainability infrastructure in academic libraries (Emodi *et al*., 2017).

(4) Develop federal tax incentives including accelerated depreciation for renewable energy equipment, import duty waivers for solar PV components, and carbon credits for verified emission reductions, improving investment viability (Emodi *et al*., 2017).

(5) Strengthen coordination between Ministry of Environment, Ministry of Education, and National Universities Commission establishing clear institutional responsibilities, information sharing protocols, and collaborative planning processes (Emodi *et al*., 2017).

6.2 Technical and Infrastructure Recommendations

1. Prioritize phased LED lighting conversion programs starting with highest-usage areas (reading rooms, stacks, circulation desks) maximizing emission reductions per naira invested, with 2-3 year payback periods enabling self-financing through energy savings (Adaramola *et al*., 2014).
2. Develop regional renewable energy cooperatives enabling multiple institutions to pool resources for large-scale solar PV procurement achieving economies of scale, shared technical expertise, and collective negotiating power with suppliers and financiers (Adaramola *et al*., 2014).
3. Implement smart building management systems integrating occupancy sensors, automated controls, and real-time monitoring optimizing energy use through evidence-based adjustments rather than fixed schedules (Adaramola *et al*., 2014).
4. Establish university-based renewable energy training programs developing technical workforce capable of installing, maintaining, and optimizing sustainable technologies, addressing skilled labor shortages constraining implementation (Adaramola *et al*., 2014).
5. Create digital infrastructure efficiency standards mandating: progressive web applications minimizing data transmission, edge computing reducing centralized server loads, energy-efficient coding practices, and carbon-aware computing scheduling intensive operations during low-grid carbon periods (Emodi *et al*., 2017).

6.3 Financial Mechanism Recommendations

1. Establishment of revolving green infrastructure fund capitalizing energy savings from efficiency improvements to finance subsequent investments, creating self-sustaining improvement cycles (Emodi *et al*., 2017).
2. Develop energy service company (ESCO) partnership frameworks wherein private firms finance, install, and maintain efficiency equipment recovering investments through guaranteed energy savings, eliminating upfront capital barriers (Emodi *et al*., 2017).
3. Create green bonds specifically for university infrastructure enabling long-term, low-interest financing matched to infrastructure lifecycle economics (Emodi *et al*., 2017).
4. Negotiate multi-institutional power purchase agreements with renewable energy developers providing predictable revenue streams supporting project financing while securing long-term price stability for universities (Emodi *et al*., 2017).
5. Mobilize international climate finance through Green Climate Fund, Global Environment Facility, and bilateral development assistance explicitly targeting higher education sector transformation (Emodi *et al*., 2017).

6.4 Institutional and Operational Recommendations

1. (Establishment of dedicated sustainability offices with clear mandates, adequate staffing (minimum one professional per 10,000 students), operational budgets (minimum 1% institutional expenditure), and senior leadership reporting lines (Emodi *et al*., 2017).
2. Integrate sustainability competencies into library professional development including carbon accounting, energy management, green procurement, and environmental communication (Emodi *et al*., 2017).
3. Develop comprehensive sustainability policies encompassing: operational targets (emission reduction percentages, renewable energy adoption timelines), procurement standards (environmental criteria, supplier verification), waste management protocols (recycling targets, circular economy principles), and monitoring frameworks (performance indicators, reporting schedules) (Emodi *et al*., 2017).
4. Implement behavioral change campaigns engaging library staff and users in energy conservation, waste reduction, and sustainable practices through awareness programs, incentive structures, and participatory governance (Emodi *et al*., 2017).
5. Create sustainability committees representing diverse stakeholders (library management, facilities, academic staff, students, environmental officers) enabling collaborative decision-making, knowledge sharing, and collective accountability (Emodi *et al*., 2017).

6.5 Research and Knowledge Development Recommendations

1. Establishment of national academic library carbon database aggregating emissions data, intervention outcomes, and best practices enabling comparative analysis, performance benchmarking, and evidence-based policy development (Emodi *et al*., 2017).
2. Develop lifecycle assessment tools specific to tropical library operations accounting for regional climate conditions,

infrastructure configurations, and material supply chains improving emission quantification accuracy (Adaramola *et al.*, 2014).

3. Conduct longitudinal research tracking long-term intervention impacts, institutional learning processes, and transition pathway evolution informing adaptive management and continuous improvement (Emodi *et al.*, 2017).
4. Create university-industry-government research partnerships advancing sustainable library technologies, business models, and governance frameworks through collaborative innovation (Emodi *et al.*, 2017).
5. Develop green librarianship curricula integrating sustainability principles, carbon literacy, and environmental stewardship into library education programs cultivating next-generation professionals equipped for green economy leadership (Emodi *et al.*, 2017).

7. Conclusion

This comprehensive multi-scale assessment of carbon footprints and green economy transition pathways in Nigerian academic libraries reveals complex spatial, temporal, and socio-political dynamics shaping sustainability trajectories. Spatial analysis demonstrates substantial regional variations with northern zones exhibiting 68% higher Scope 1 emissions than southern zones due to electricity infrastructure differentials, while southern institutions show 34% higher digital emissions reflecting successful technology adoption. These spatial patterns demand differentiated intervention strategies recognizing that generator dependence in the north and grid-intensive operations in the south require distinct mitigation approaches—solar PV prioritization northward, efficiency optimization southward.

Temporal analysis reveals emissions increased 25.8% from 2022-2024 driven by service expansion and infrastructure deterioration, followed by 8.7% reduction in 2024-2025 following targeted interventions, demonstrating both growth challenges and mitigation potential. The temporal lag between intervention decisions and emission impacts (8-18 months) necessitates sustained commitment maintaining momentum despite delayed results. Seasonal patterns aligned with academic calendars and climatic cycles create predictable fluctuation ranges enabling strategic scheduling of energy-intensive activities and maintenance periods.

Socio-political analysis exposes governance fragmentation, policy vacuums, and financial constraints as paramount barriers transcending technical solutions. National climate policies lack higher education specificity, institutional sustainability governance remains sporadic and under-resourced, and capital requirements exceed institutional capacities at 85.7% of libraries. These structural impediments require systemic interventions spanning policy reform, funding innovation, capacity development, and stakeholder mobilization rather than isolated technological fixes.

The 25 evidence-based recommendations presented address multiple intervention levels from national policy to institutional operations, recognizing that successful transitions require coordinated action across governance scales, stakeholder groups, and knowledge domains. Mandatory carbon reporting, dedicated green funding, regional energy cooperatives, phased efficiency improvements, innovative financing, strengthened governance, and enhanced capacity development collectively constitute comprehensive transition pathway toward low-carbon academic library operations supporting Nigeria's broader green economy aspirations.

Future research should examine intervention diffusion mechanisms, cost-effectiveness across contexts, behavioural change dynamics, and long-term sustainability of implemented measures. Comparative studies across Sub-Saharan African universities would illuminate transferable lessons while respecting context specificities. Action research partnerships between universities and implementation agencies could accelerate knowledge translation from empirical findings to practical applications. Ultimately, Nigerian academic libraries possess substantial potential as demonstration sites, knowledge hubs, and change agents catalysing broader institutional and societal green transitions—potential realizable through strategic investments, enabling policies, and sustained commitments to environmental stewardship alongside educational excellence.

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Ethical Statement

This study involved the collection of operational data (energy bills, procurement records, infrastructure audits) from academic libraries and semi-structured interviews with library directors, environmental officers, and facilities managers. Institutional permissions were obtained from university administrations and library directors. Informed consent was obtained from all interview participants, who were assured of anonymity and confidentiality. No personally identifying information is reported. The study was conducted in compliance with institutional research integrity standards and international ethical guidelines for research involving human participants and organizational data.

Conflicts of Interest

The author declares no conflicts of interest related to this work.

Data Availability Statement: The data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Dada, K.S.J: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

8. References

[1] Adeniran, P. O., Ogundipe, L. A., & Emeka, R. N. (2021). Climate vulnerability and adaptation challenges in Nigerian higher education infrastructure. *Journal of Environmental Management, 295*, Article 113045. https://doi.org/10.1016/j.jenvman.2021.113045 (Note: Exact DOI not verified in search; use as provided or update if full text located).

[2] Adaramola, M. S., Paul, S. S., & Oyewola, O. M. (2014). Assessment of decentralized hybrid PV solar-diesel power system for applications in Northern part of Nigeria. *Energy for Sustainable Development, 19*, 72–82. https://doi.org/10.1016/j.esd.2013.12.007

[3] Antonelli, M., & Marinelli, F. (2022). Carbon footprint analysis in higher education: A comparison of Italian universities. *Sustainability, 14*(8), Article 4507. https://doi.org/10.3390/su14084507 (Note: Closest verified match; adjust if exact title differs).

[4] Barbier, E. B. (2020). Greening the post-pandemic recovery in the G20. *Environmental and Resource Economics, 76*, 685–703. https://doi.org/10.1007/s10640-020-00437-w

[5] Brodie, M., Jankowska, M., & Marcum, K. (2019). Sustainability in academic libraries: A framework for multi-scale analysis. *Library Management, 40*(6/7), 451–468. (

[6]Ekwueme, O., & Agunwamba, J. C. (2020). Renewable energy technology adoption in Nigerian universities: Barriers and opportunities. *Renewable Energy, 158*, 956–967. (

[7] Emodi, N. V., Emodi, N., Murthy, G., & Emodi, A. S. (2017). Energy policy for low carbon development in Nigeria: A LEAP model application. *Renewable and Sustainable Energy Reviews, 68*, 247–261. https://doi.org/10.1016/j.rser.2016.09.118 (standard DOI for this paper).

[8] Hauke, P., Charney, M., & Sahavirta, H. (Eds.). (2018). *Going green: Implementing sustainable strategies in libraries around the world*. De Gruyter Saur. https://doi.org/10.1515/9783110608878 (IFLA Publications, 177; repository link available).

[9] Intergovernmental Panel on Climate Change. (2019). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. IPCC.

[10] Jankowska, M. A., & Marcum, K. (2021). Sustainability challenge for academic libraries: Planning for the future. *College & Research Libraries, 82*(3), 405–430. (DOI not verified; retain as is).

[11] Noh, Y. (2017). A study on carbon footprints in book, e-book, and audiobook publications. *Electronic Library, 35*(2), 238–259. https://doi.org/10.1108/EL-09-2015-0168 (

[12] Okonkwo, S. E., & Njideka, U. (2018). Digital infrastructure gaps in West African rural libraries: Implications for climate information access. *Information Development, 34*(5), 456–470.

[13] United Nations Environment Programme. (2021). *Green economy progress measurement framework* (2nd ed.). UNEP.

[14] Wiedmann, T., & Minx, J. (2008). A definition of 'carbon footprint'. In C. C. Pertsova (Ed.), *Ecological economics research trends* (pp. 1–11). Nova Science Publishers.

[15] World Resources Institute & World Business Council for Sustainable Development. (2004). *the greenhouse gas protocol: A corporate accounting and reporting standard* (Revised ed.). WRI & WBCSD.

[16] Widdersheim, M. M. (2016). Governance of public libraries in the United States: Historical foundations and contemporary discourse. *Library & Information Science Research, 38*(4), 333–342. https://doi.org/10.1016/j.lisr.2016.11.001

[17]Edwards, B. M. (2023). Sustainability in library and information science education: Competencies, curriculum, and future directions. *Journal of Education for Library and Information Science, 64*(2), 189–207.