AJLLSE GLOBAL RESEARCH NETWORK

AMERICAN Journal of Language, Literacy and Learning in STEM Education
Volume 4, Issue 09, 2026 ISSN (E): 2993-2769

Promoting Green Chemistry in Tertiary Institutions in Nigeria

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Abstract. *Green chemistry has emerged as an important approach to achieving environmental sustainability through the prevention of pollution, reduction of hazardous substances, efficient use of resources and development of safer chemical products and processes. Tertiary institutions in Nigeria have an important role to play in promoting green chemistry because they serve as centres for chemistry education, scientific research, technological innovation and human-capacity development. However, inadequate laboratory facilities, limited awareness, insufficient funding, weak institutional policies, inappropriate chemical-waste management and inadequate integration of green chemistry into the curriculum may constrain its effective implementation. This paper discusses strategies for promoting green chemistry in Nigerian tertiary institutions. The strategies include integrating green chemistry into chemistry curricula; transforming conventional laboratories into green laboratories; strengthening staff training and research collaboration; providing institutional policies, funding and incentives; establishing dedicated green chemistry research centres; promoting practical and project-based learning; strengthening chemical-waste management and green procurement; developing partnerships with industries and research organisations; using digital technology, virtual laboratories and artificial intelligence to support green chemistry education; and establishing green chemistry clubs and student sustainability programmes. The paper argues that effective implementation requires collaboration among tertiary institution management, academic staff, students, government agencies, industries and professional organisations. It concludes that promoting green chemistry can improve the quality of chemistry education while contributing to environmental protection, resource conservation, innovation and sustainable development in Nigeria.*

Keywords: *Green chemistry, tertiary institutions, chemistry education, environmental sustainability.*

1. Introduction

Green chemistry represents a preventive approach to chemistry that seeks to design chemical products and processes in ways that reduce or eliminate the use and generation of hazardous substances. Anastas and Warner define green chemistry as the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Unlike conventional approaches that frequently depend on treating pollution after it has been produced, green chemistry seeks to prevent pollution at the molecular and process-design stages [1]. The importance of green chemistry has increased because of growing concerns about environmental pollution, climate change, depletion of natural resources, hazardous chemical exposure and increasing quantities of industrial and laboratory waste. The American Chemical Society (ACS) identifies waste prevention, safer chemical synthesis, energy efficiency, renewable feedstocks and the design of safer chemicals among the major principles through which chemistry can contribute to environmental sustainability. Consequently, green chemistry is increasingly relevant to chemistry education and research.

Tertiary institutions occupy a strategic position in the promotion of green chemistry in Nigeria. Universities, polytechnics and colleges of education produce the scientists, teachers, laboratory

technologists, researchers and industrial professionals who will determine how chemicals are designed, used and managed in the future [2]. Chemistry laboratories in these institutions also provide important environments for experimentation and research. Integrating green chemistry into these settings can therefore influence both current practices and the future behaviour of chemistry graduates.

Despite its importance, the implementation of green chemistry in Nigerian tertiary institutions faces several challenges. These include inadequate specialised laboratory facilities, limited financial resources, insufficient staff training, weak chemical-waste management systems and inadequate incorporation of green chemistry principles into teaching and research. Research on green chemistry laboratory development in Nigeria has highlighted the need for appropriate infrastructure and capacity building to support sustainable chemistry education and research [3]. Similarly, research involving Nigerian pre-service chemistry teachers has reported deficiencies in knowledge of green chemistry principles, demonstrating the need for stronger integration of sustainability concepts into chemistry education [4]. Promoting green chemistry therefore requires a comprehensive institutional approach. It should not be restricted to adding a few topics to chemistry courses but should involve curriculum reform, laboratory transformation, research development, staff capacity building, appropriate policies and student participation. The following strategies provide practical approaches through which Nigerian tertiary institutions can strengthen the adoption of green chemistry.

2. Methodology

2.1 Concept of Tertiary Education

Tertiary institutions constitute the highest level of formal education in Nigeria and provide advanced education and training after secondary or post-basic education. They are important institutions for human-capital development, research, innovation, professional preparation and national development. The Nigerian tertiary education system comprises universities, polytechnics, monotechnics, colleges of education and other approved specialised institutions. Tertiary education refers to education provided after post-basic education and includes universities, inter-university centres, polytechnics, monotechnics, colleges of education and innovation enterprise institutions. This definition emphasises the structural composition of Nigeria's tertiary education system. From a legal perspective, tertiary institutions encompass institutions established to provide education at the tertiary level, including universities, polytechnics, colleges of technology, colleges of education and other approved professional and specialised institutions. This definition emphasises the legal and institutional status of tertiary education providers. World Bank views tertiary education sector in Nigeria comprises post-secondary institutions such as universities, polytechnics, monotechnics and colleges of education. The sector contributes to skills development, human-capital formation and economic development. Orok et al. on the university perspective, tertiary institutions can be understood as higher-education environments in which students receive advanced academic and professional training while participating in research and other institutional activities. Tertiary education, also called post-secondary education, is any level of education pursued beyond high school, including undergraduate and graduate credentials.

Campbell and Rozsnyai further assert that tertiary education represents a formal, non-mandatory educational phase that succeeds secondary education. They conclude that tertiary educational institutions are distinctly differentiated from educational structures at primary and secondary levels. Ogunode defined Tertiary education as the level of education that students pursue after completing secondary school. It takes place in institutions such as universities, polytechnics, colleges of education, and other specialized institutions that provide advanced knowledge and professional training. At this stage, education moves beyond basic learning and focuses on developing deeper understanding, specialized skills, and critical thinking that prepare individuals for professional careers and leadership roles in society. Tertiary education plays a very important role in personal and national development. For individuals, it provides opportunities to acquire knowledge, develop talents, and build competencies that can improve their quality of life. Students in tertiary institutions are exposed to new ideas, research activities, innovation, and diverse cultures, which help them grow

intellectually and socially. It also helps them become more confident, independent, and capable of solving real-life problems.

2.2 Concept of Green Chemistry

Green chemistry is a relatively modern approach to chemistry that focuses on preventing pollution and reducing hazards at the molecular and process-design level. The following are five useful definitions from authoritative sources and scholars. Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. This definition is regarded as one of the foundational definitions of the field. Green chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances, covering the life cycle of chemical products from design and manufacture through use and disposal (United States Environmental Protection Agency EPA**)**. Green chemistry and sustainable chemistry involve a different way of designing and carrying out chemistry, with emphasis on reducing waste, conserving energy, replacing hazardous substances, and considering the entire life cycle of chemical products (American Chemical Society, ACS, n.d).

Green chemistry can be viewed as the design, development, and implementation of chemical products and processes that minimize the use and generation of hazardous chemicals, thereby reducing negative impacts on human health and the environment (American Chemical Society Green Chemistry Institute, n.d**)**. Green chemistry is the development of chemical products and processes that minimize hazardous substances, reduce waste, and reduce dependence on diminishing resources, while considering human health and environmental impacts throughout the product life cycle (ACS Sustainable Chemistry & Engineering literature, n.d**)**. From these definitions, green chemistry can be described as the scientific approach to designing chemical substances, products and processes in ways that prevent pollution, minimize waste and toxicity, conserve energy and resources, and protect human health and the environment**.**

Importance of Green Chemistry

Reduction of Environmental Pollution

Green chemistry prevents pollution at its source rather than relying mainly on treating pollution after it has been generated. It encourages chemical processes that produce little or no hazardous waste.

Protection of Human Health

It promotes the design and use of chemicals with lower toxicity, thereby reducing risks to workers, consumers and communities exposed to hazardous chemical substances.

Reduction of Chemical Waste

Green chemistry emphasizes **waste prevention and atom economy**, ensuring that as much of the starting material as possible becomes part of the desired product. This reduces the amount of material that must be discarded or treated.

Conservation of Energy and Natural Resources

Green chemistry encourages energy-efficient chemical processes and the use of renewable feedstocks. Conducting reactions under less energy-intensive conditions can reduce both environmental impacts and resource consumption.

Promotion of Sustainable Industrial Development

Green chemistry helps industries develop safer and more resource-efficient products and processes. By reducing waste, hazardous materials, energy consumption and dependence on non-renewable resources, it contributes to long-term economic and environmental sustainability.

3. Result and Discussion on Strategies to Promote Green Chemistry in Tertiary Institutions in Nigeria

Green chemistry provides a preventive approach to chemistry by encouraging the design of chemical products and processes that reduce or eliminate hazardous substances, waste and environmental harm.

In Nigerian tertiary institutions, promoting green chemistry is important because universities, polytechnics and colleges of education are not only centres for scientific training but also major sites of chemical experimentation, laboratory research and innovation. The following four strategies can help strengthen green chemistry education and practice [5].

Integrate Green Chemistry into the Chemistry Curriculum

One major strategy is to systematically integrate green chemistry principles into existing undergraduate and postgraduate chemistry courses [6]. Rather than treating green chemistry as an isolated topic, lecturers can incorporate the 12 principles of green chemistry into organic chemistry, inorganic chemistry, analytical chemistry, physical chemistry, industrial chemistry and laboratory courses. Students should be taught concepts such as waste prevention, atom economy, safer solvents, renewable feedstocks, energy efficiency and safer chemical synthesis. This approach is supported by the American Chemical Society's Green Chemistry Institute, which has emphasized that green and sustainable chemistry should be systematically incorporated into undergraduate chemistry education. A major curriculum roadmap identified core competencies that can prepare graduates to apply systems thinking and sustainability principles to chemical problems [7]. For Nigerian tertiary institutions, curriculum integration could involve revising course outlines, introducing green chemistry case studies and incorporating green chemistry questions into examinations and laboratory assessments. Recent work by Day et al. also recommends connecting chemical concepts with sustainability problems and using student decision-making and engineering practices as part of green chemistry education.

Transform Chemistry Laboratories into Green Laboratories

Tertiary institutions should adopt green laboratory practices by reducing the quantities of chemicals used, replacing highly hazardous chemicals with safer alternatives, minimizing chemical waste and improving waste segregation and disposal. Laboratory experiments can also be redesigned to use microscale procedures, renewable materials and less toxic solvents where scientifically appropriate. This is particularly relevant to Nigerian institutions because inadequate chemical-waste management can create environmental and occupational risks [8]. Green laboratory practice changes the emphasis from simply treating waste after it has been produced to preventing waste at the source. The ACS Green Chemistry Institute identifies waste prevention, hazard reduction and safer chemical processes as central elements of green chemistry practice. Institutions can therefore establish laboratory guidelines requiring departments to assess the toxicity, quantity and environmental implications of chemicals before purchasing and using them. Students should also be trained to calculate waste generation, evaluate solvent selection and consider safer alternatives when designing experiments.

Strengthen Staff Training, Research and Industry Collaboration

Another important strategy is to provide continuous professional development for chemistry lecturers, laboratory technologists and researchers. Workshops, seminars, conferences and short courses can expose academic staff to current green chemistry methodologies, green analytical chemistry, safer solvents, renewable feedstocks, life-cycle thinking and green metrics. Evidence from green chemistry education research indicates that lack of knowledge, teaching resources and technical expertise can constitute barriers to integrating green chemistry into undergraduate education. The ACS Green Chemistry Institute's roadmap therefore emphasizes educator preparation, educational-resource development and sustained institutional efforts to mainstream green chemistry [9]. Nigerian tertiary institutions should also establish partnerships with industries, research institutes and professional bodies to support green chemistry research. Such partnerships could provide laboratory equipment, research grants, industrial problems for student projects and opportunities for students to develop environmentally safer chemical products. Collaboration can make green chemistry education more practical and connect university research to Nigeria's environmental and industrial challenges.

Provide Institutional Policies, Funding and Incentives for Green Chemistry

Green chemistry will be difficult to sustain if it remains dependent on the enthusiasm of individual lecturers. Tertiary institutions should therefore establish institutional policies that make

environmental sustainability and green chemistry part of departmental and institutional planning. Management can provide dedicated funding for green laboratory equipment, safer chemicals, waste-management systems and green chemistry research. Institutions can also introduce awards for lecturers and students who develop environmentally friendly chemical processes, organize annual green chemistry competitions, support student research projects and recognize departments that demonstrate effective waste reduction. Green chemistry should also be included in institutional environmental-management policies and laboratory safety regulations. The importance of institutional support is reinforced by the experience of the ACS Green Chemistry Institute, which has pursued a coordinated, long-term approach involving curriculum development, educator support, educational resources and partnerships [10], [11]. The ACS also reports that green chemistry can be integrated into existing chemistry programmes rather than necessarily requiring a completely separate course. This provides a useful model for Nigerian institutions, where curriculum space and financial resources may be limited.

Establish Dedicated Green Chemistry Research Centres and Laboratories

Nigerian tertiary institutions should establish dedicated green chemistry laboratories, research centres and innovation hubs where students and researchers can develop environmentally safer chemical processes and products [12]. Such facilities should be equipped for research involving renewable feedstocks, biomass conversion, green solvents, catalysis, waste valorisation, renewable energy materials and environmentally friendly analytical methods. This strategy is particularly relevant to Nigeria because a case study at the University of Uyo identified inadequate specialised laboratory infrastructure as a major constraint to green and sustainable chemistry research in Nigerian tertiary institutions. The authors proposed dedicated green chemistry laboratories for teaching, research, innovation and capacity building [13], [14]. Institutions can therefore establish green chemistry laboratories through internally generated funds, government grants, TETFund support, international research grants and industry partnerships. Such centres could also serve several neighbouring institutions rather than each university having to develop every specialised facility independently.

Promote Green Chemistry through Practical, Experiential and Project-Based Learning

Another strategy is to move beyond theoretical teaching and expose students to hands-on green chemistry projects**.** Students can be required to redesign conventional experiments to reduce chemical waste, substitute hazardous substances with safer alternatives, improve atom economy, reduce energy consumption or use locally available renewable materials [15]. Research on green and sustainable chemistry education recommends using chemistry-based sustainability problems as decision-making activities in which students apply scientific and engineering practices to real-world challenges [16], [17], [18]. Similarly, experiential approaches have been shown to connect sustainability concepts with practical chemistry education [19]. In Nigeria, students could undertake projects involving agricultural waste, biomass, water purification, biodegradable materials, renewable energy materials and locally available natural products. This would make green chemistry more relevant to Nigerian environmental and economic challenges while developing students' research and innovation skills.

Develop Strong Chemical Waste-Management and Green Procurement Systems

Tertiary institutions should establish comprehensive systems for chemical waste reduction, segregation, storage, recycling, recovery and safe disposal. Departments should also adopt green procurement policies by considering toxicity, biodegradability, quantity, packaging and environmental impact when purchasing chemicals and laboratory materials [20], [21]. This is important because knowledge of chemical waste management does not automatically translate into good practice. A Nigerian study found that chemistry students demonstrated good knowledge but relatively poor practices concerning chemical waste management, indicating a need to build a stronger institutional culture of sustainability and environmental protection. Universities can introduce chemical inventories to prevent unnecessary purchases, encourage microscale experiments, recover solvents where feasible, and establish clearly labelled waste streams. Laboratory personnel

and students should also receive regular training on waste classification and disposal. Such measures can simultaneously reduce environmental risks and lower expenditure on chemicals [22].

Establish Green Chemistry Partnerships, Competitions and Innovation Programmes

Tertiary institutions should establish partnerships among universities, polytechnics, research institutes, industries, government agencies and professional chemical organisations to promote green chemistry innovation. These partnerships can provide research funding, technical expertise, laboratory facilities, internships, mentorship and opportunities to commercialise environmentally friendly chemical technologies. The University of Uyo green chemistry laboratory initiative demonstrates the value of knowledge exchange, partnerships and collaboration in developing sustainable chemistry infrastructure and capacity in Nigeria [23], [24]. Institutions can also organise annual Green Chemistry Innovation Competitions, where students compete to develop solutions to Nigerian problems such as plastic pollution, oil contamination, water treatment, agricultural waste, energy efficiency and hazardous laboratory waste. Winning projects could receive research grants, incubation opportunities and industry mentorship. This would encourage students to view chemistry not simply as an academic discipline but as a tool for solving environmental and socioeconomic problems [25].

Use Digital Technology, Virtual Laboratories and AI to Support Green Chemistry Education

Tertiary institutions in Nigeria should make greater use of virtual laboratories, computer simulations, digital learning platforms and artificial intelligence (AI) to teach and practise green chemistry. Digital tools can allow students to model chemical reactions, compare alternative reaction pathways, assess toxicity and explore ways of reducing energy consumption and chemical waste before conducting physical experiments. This approach can reduce the quantity of chemicals required for some instructional activities while giving students opportunities to investigate safer alternatives. Research on green chemistry education has identified technology-enhanced learning as one of the useful pedagogical approaches for promoting green chemistry in Nigerian universities. Akinsipo and Anselm specifically identified AI and advanced material science as emerging opportunities for strengthening green chemistry education and research in Nigerian universities. Nigerian universities can therefore develop virtual green chemistry experiments, simulation-based assignments and AI-supported research activities. Institutions should, however, ensure that digital learning complements rather than completely replaces essential practical laboratory experiences [26].

Establish Green Chemistry Clubs and Student Sustainability Programmes

Universities, polytechnics and colleges of education should establish Green Chemistry Clubs, sustainability societies and student innovation programmes. These platforms can give students opportunities to organise seminars, laboratory demonstrations, environmental campaigns, recycling projects, green chemistry competitions and community outreach programmes. Student-led activities can help transform green chemistry from a classroom concept into a practical culture within the institution. For example, the Faculty of Education at the University of Lagos has developed green chemistry-related courses and identified student clubs, seminars, workshops, sustainability challenges and student research as mechanisms for expanding green chemistry education. This strategy is particularly important because Nigerian research has found gaps in students' knowledge and actual environmental behaviour. Moju, for example, reported low knowledge of green chemistry principles among Nigerian pre-service chemistry teachers and recommended curriculum restructuring to incorporate sustainable-development concepts. Student clubs can complement formal curriculum reforms by providing continuous opportunities for students to practise and promote sustainable chemistry.

4. Conclusion and Recommendations

Green chemistry is an important pathway through which Nigerian tertiary institutions can contribute to environmental protection, sustainable development and scientific innovation. Its promotion requires a transition from conventional approaches that focus primarily on managing chemical waste

after production to preventive approaches that reduce hazards and waste at the design and experimental stages.

This paper has identified ten major strategies for promoting green chemistry in Nigerian tertiary institutions. These include curriculum integration, development of green laboratories, staff training and research collaboration, institutional policies and funding, dedicated green chemistry research centres, practical and project-based learning, improved chemical-waste management and green procurement, partnerships with industry and research organisations, digital and AI-supported learning, and the establishment of student green chemistry clubs. Based on the findings, the paper recommends the following: Green chemistry should be incorporated into chemistry curricula. The National Universities Commission (NUC), National Board for Technical Education (NBTE) and other relevant regulatory bodies should encourage tertiary institutions to incorporate green chemistry principles into undergraduate and postgraduate chemistry programmes. Tertiary institutions should establish green laboratories. Universities, polytechnics and colleges of education should gradually convert conventional laboratories into green laboratories through the use of microscale experiments, safer chemicals, efficient equipment and appropriate waste-management systems. Regular staff training should be provided. Chemistry lecturers, laboratory technologists and researchers should receive regular training, workshops and professional development programmes on green chemistry principles, green solvents, safer synthesis, waste minimisation and sustainable laboratory practices. Dedicated funding should be provided for green chemistry research. Government agencies, TETFund, tertiary institutions and private-sector organisations should provide grants for research into renewable feedstocks, waste valorisation, biodegradable materials, safer chemical processes and other green technologies. Chemical-waste management should be strengthened. Institutions should develop clear policies for chemical inventory, waste segregation, storage, recycling, recovery and environmentally responsible disposal. Students and laboratory personnel should receive appropriate training in chemical-waste management. Industry–university collaboration should be encouraged. Tertiary institutions should establish partnerships with chemical industries, research institutes and environmental organisations to provide students and researchers with practical opportunities to develop green chemical technologies. Student green chemistry clubs should be established. Institutions should encourage students to organise green chemistry seminars, innovation competitions, recycling programmes, environmental campaigns and community-based sustainability projects. Digital technologies should be utilised. Universities should employ simulations, virtual laboratories and appropriate artificial intelligence tools to support green chemistry teaching, research and experimental design while maintaining essential hands-on laboratory training. Green procurement policies should be introduced. Institutions should consider toxicity, environmental impact, quantity, packaging and sustainability when purchasing chemicals and laboratory equipment rather than relying exclusively on price and availability. Green chemistry should become part of institutional sustainability policy. Management should include green chemistry within institutional environmental and sustainability plans and establish measurable targets for reducing chemical waste, hazardous substances, energy consumption and resource use.

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