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# Advancing Green Chemistry for Sustainable Industrial Pollution Control and Waste Management in Owerri, Nigeria

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**Abstract** **Original Research Article**

Green chemistry offers a transformational solution to industrial pollution and waste management issues in Owerri, Nigeria, a rapidly industrialising metropolis. This qualitative research investigates the feasibility of employing green chemistry principles to reduce environmental deterioration caused by industrial activity in Owerri, with an emphasis on wastewater treatment, solid waste management, and air pollution control. The study identifies important pollution sources, assesses the viability of green chemistry solutions, and investigates adoption hurdles and potential using semi-structured interviews with industrial stakeholders, environmental regulators, and academic experts. The findings show that bio-based solvents, photocatalysis, and waste-to-resource technologies are possible in Owerri, but they face barriers like as regulatory gaps, budgetary limits, and limited awareness. Policy changes, stakeholder engagement, and capacity-building efforts are proposed to incorporate green chemistry into Owerri's industrial processes, in line with Sustainable Development Goals (SDGs) 9 and 12. This study adds to the body of knowledge by presenting a Nigerian-specific framework for long-term industrial growth.

**Keywords:** Green chemistry, industrial pollution, waste management, Owerri, sustainability, Nigeria.



## 1. INTRODUCTION

Owerri, the capital of Imo State in southeastern Nigeria, has developed as a major industrial hub in recent decades, owing to increasing urbanisation and economic growth (Okoro, Uzoukwu, & Ademe, 2016). The city is home to a varied range of small and medium-sized businesses, including food processing sectors (such as cassava and palm oil processing), textile manufacturing, and chemical production, all of which contribute to the region's economic growth (Okonkwo et al., 2010). These sectors employ thousands of people and contribute to local markets, with Owerri's industrial production accounting for almost 15% of Imo State's GDP (NBS, 2023). However, this industrial boom has come at a high environmental cost, with increased pollution of the air, water, and soil, endangering human health and ecosystems (Eneh, 2010). For example, untreated industrial effluents from textile dyeing and food processing have contaminated key water bodies such as the Otamiri and Nworie rivers, with biochemical oxygen demand (BOD) levels exceeding the World Health Organization's acceptable limit of 50 mg/L (Onyekuru, Nwankwoala, & Uzor, 2017). Similarly, industrial trash, such as plastics and organic wastes, contributes to Owerri's estimated 1,200 tonnes of municipal garbage each day, much of which is inappropriately disposed of in open dumps (Amasuomo and Baird, 2016).

Traditional pollution management technologies, such as end-of-pipe treatments (e.g., chemical precipitation and incineration), are commonly employed in Nigeria, but they are frequently expensive, energy-intensive, and unsustainable. These techniques prioritise waste treatment above prevention, resulting in repeated environmental and economic consequences (Veleva & Cue, 2019). For instance, the application of chemical treatment of wastewater in Owerri textile industry requires the application of harmful chemicals leading to increase of secondary pollutants that further loads vulnerable waste management infrastructure (Okonkwo et al., 2010). Open burning of industrial waste in Owerri contributes to emissions of volatile organic compounds (VOCs) and particulate pollution (PM2.5) which is above WHO standard of 25 µg/m³ (Ezeonyejiaku, Okoye, & Obiakor, 2022). These

problems highlight the absolute necessity for new and long-lasting industry pollution control and waste management solutions in Owerri.

The proactive response to these challenges is in the form of green chemistry, which can be described as the creation of chemical products and processes that reduce or dispense with the use and productions of hazardous substances (Anastas & Warner, 1998). The fellowship was led to the foundation of green chemistry formulated by Anastas and Warner based on 12 principles with the focus on waste minimisation, energy efficiency and using safer, renewable resources (American Chemical Society [ACS], 2020). Such principles consist of waste prevention, maximum atom economy, safer solvents and the design of products degrade, all within the context of global sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs), notably SDG 9 (Industry,

The 17 goals are (Innovation, and Infrastructure) and 12 (Responsible Consumption and Production) (Anastas & Zimmerman, 2018). Across the world, green chemistry has turned industries into low-impact industries: examples include the incorporation of bio-based solvents that have reduced toxicity in waste water in the textile industries in India by 60% (Hessel et al., 2022), and waste-to-energy technologies have avoided 40% of landfilling in South Africa (Amoo, Fagbenle, 2013). Those achievements demonstrate that green chemistry can address Nigerian environmental problems in Owerri, but it remains unknown how to implement it in that country (Ibe, Verla, Achukee, & Ekeke, 2025). The application of green chemistry is quite essential in view of the distinct industrial and environmental environment of Owerri.

Most of the industry in the city is small-and medium-sized and has poor resources and outdated technologies that aggravate pollution (Okoro, et al., 2016). As an illustration, food processing companies in Owerri produce large amounts of organic waste, but one establishment alone might yield an estimated 5 tonnes of cassava peels per week, most of which the authors estimate to be either buried or incinerated (Amasuomo and Baird, 2016). In the same way, the production of textiles uses synthetic dyes and solvents that cause pollution of heavy metals in local water bodies (Onyekuru, et al., 2017). Enforcement of the regulatory frameworks applies through the National Environmental Standards and Regulations Enforcement Agency (NESREA) which has impractical policies that lack proper monitoring and enforcement with low compliance with the policies by small-scale companies (Okonkwo et al., 2010). They are reinforced by poor knowledge of sustainable industrial practices by industrial stakeholders, financial and technological impediments to deployment of advanced pollution control technologies (Veleva & Cue, 2019).

This project will deal with these issues by examining how green chemistry has the potential to minimize industrial pollution and improve the problem of waste management in Owerri. The research adopts a qualitative research methodology in studying the views of stakeholders, including managers of the industry, the regulators of the environment and academic experts in pollution control to determine significant pollution sources, the feasibility of green chemistry solutions and barriers and opportunities to their adoption. These applications of green chemistry like bio-based solvents, photocatalysis, waste-to-resource technologies, are assessed in terms of their suitability in the Owerri environment. Eidsvag et al. (2021) describe that TiO2 nanoparticles in photocatalysis can be used to kill organic pollutants in textile effluent using the solar light abundant in Nigeria. On the same note, the anaerobic digestion process may convert organic waste to biofuels to reduce the dependency on landfills (Shah, 2023).

The study is guided with the following objectives.

1. To ascertain what constitutes the major causes of industrial pollution and waste in Owerri.
2. In order to determine the feasibility of green chemistry to solve the problem of pollution and waste management.
3. Explore the problems and opportunities to introduce green chemistry into Owerri.
4. Introduce a local framework of integrating green chemistry in the industrial processes in Owerri.

The significance of the research is related to the growing area of the study that is regularly faced with the conflict between economic development and environmental sustainability. The study does this by providing qualitative information on the potential of green chemistry, and thereby filling a gap between global sustainability theories and local application in Nigeria, giving specific recommendations to policymakers, businesses, and universities. The work contributes to the sparse collections of green chemistry in Nigeria and especially in Owerri where localised studies are rare (Ibe, et al., 2025). Moreover, it aligns with the National Policy on Environment of Nigeria, which focuses on the sustainable growth of industries and promotes the global initiatives to develop a circular economy (UNEP, 2024). This case aims at leading the way to a sustainable industrial future as it will address the pollution issues in Owerri through the application of green chemistry, thereby ameliorating the health condition of the population, preserving ecosystems, and stimulating economic robustness in Imo State.

## 2. LITERATURE REVIEW

The literature review is synthesis of existing literature on green chemistry, industrial pollution in Nigeria and green chemistry practicing on poor countries with special focus given to how the concept of green chemistry is applicable on the Owerri industrial and environmental environment. This review reveals the gaps in the literature, especially the fact that not much study has been done on green chemistry in Nigeria and the theoretical framework of the study.

### 2.1 Green Chemistry: Principles and Global Applications

According to Anastas and Warner (1998), green chemistry is a science that is involved with designing of chemical products and procedures that will minimize or eliminate hazardous substances that are used and produced. This is founded on 12 principles, which are waste control, atom

economy, better chemical synthesis, using sustainable feedstocks, designing degradation (American Chemical Society [ACS], 2020). The aims of these principles are to lower environmental impact and remain economically viable and align to the principles of global sustainability, including the United Nations Sustainable Development Goals (SDGs), namely SDGs 9 (Industry, Innovation, and Infrastructure) and SDGs 12 (Responsible Consumption and Production) (Anastas & Zimmerman, 2018). Green chemistry has been successfully applied in many industries around the world and it has benefited both the environment and the economy profoundly.

Green chemistry has been able to revolutionize the methods that pharmaceutical companies use through reduction of toxic waste. A case in point is solvent free methods, which have helped decrease the utilisation of hazardous organic solvents with wastes decreasing by as far as 80 percent in a few operations. On the same note, bio-based dyes and photocatalysis have enabled a decrease in wastewater pollution in the textile industry. As concluded by Eidsvg et al. (2021), TiO2 photocatalysis can be used to degrade organic pollutants in textile wastewater against solar light reducing COD by 70 percent with minimal energy requirements. The method is aligned with green chemistry principle 6 (energy efficiency) and is particularly feasible in locations that have more of this source, i.e., Owerri (Okoro, et al., 2016). Other advancements in green chemistry, namely making better use of waste, have also benefited waste management. In countries like South Africa, the anaerobic digestion method of converting organic waste materials into biogas has reduced the amount of trash in the landfills by 40 percent in addition to delivering renewable power (Amoo, & Fagbenle, 2013). On the same note, the development of biodegradable plastics out of farm waste products, including maize starch or cassava peel, has minimized the environmental half-life of plastic in line with principle 10 (design to degrade) (Hessel et al., 2022). These global applications illustrate the prospects of green chemistry in mitigating issues of pollution and wastage though checks should be done to ascertain their applicability in the underdeveloped world.

## 2.2 Industrial Pollution in Nigeria

The industrial sector in Nigeria, especially the areas that are metropolitans like Owerri contribute largely to environmental depreciation. The industrial activity taking place in Owerri, such as food processing activities, manufacture of textiles, and chemical production, generates too much pollution (Okonkwo et al. 2010). Water pollution is a major problem and such rivers as the Otamiri and Nworie are contaminated with industrial effluent wastes that result in textile dyeing and food processing. The Otamiri River has also counted heavy metals like lead and cadmium that exceed the level permitted by World Health Organisation (WHO) and biochemical oxygen demand (BOD) up to 200 mg/L (Onyekuru, Nwankwoala, & Uzor, 2017). Such wastes are hazardous to water bodies and local water systems, and this poses threats to the local communities, which use these rivers domestically (Okoro, et al., 2016). Another very topical issue is solid waste. Owerri produces up to 1,200 tonnes of MSG each day, of which 60 percent consists of non-recyclable plastics and organic waste products of industrial generation (Amasuomo & Baird, 2016). Some of the businesses of food processing that result in massive volumes of organic waste include a cassava and palm oil plantation where one plant alone produces approximately 5 tonnes of cassava peels per week (NBS, 2023). A lot of this refuse is either disposed or incinerated and pollutes the soil or greenhouse gases are released (Eneh, 2010). Due to industrial waste products and burning of waste garbage, air pollution is emerging as a serious issue. According to Ezeonyejiaku, et al., (2022), PM 2.5 concentration in Owerri is 40 ug/m 3 exceeding the WHO recommended dose of 25 ug / m 3 which results in respiratory issues in individuals.

Nigeria National Environmental Standards and Regulations Enforcement Agency has been known to implement regulatory frameworks that would seek to control industrial pollution, but it has limits which include limited monitoring and non-compliance, especially by small-scale industries (Okonkwo et al., 2010). These challenges are compounded by the lack of advanced waste treatment infrastructure as numerous enterprises are left to utilize outdated end-of-pipe filters (chemical precipitation and incineration) (Anastas & Zimmerman, 2018). Such technologies are not only costly, but they also generate secondary pollutants, which is why it is crucial to discuss sustainable methods including the green chemistry (Veleva & Cue, 2019).

## 2.3 Green Chemistry in Developing Countries

A huge challenge lies ahead regarding the adoption of green chemistry in the underdeveloped countries and this is also a great opportunity. The significant barriers include financial limitations, low knowledge and poor technical access (Veleva & Cue, 2019). As an example, a textile industry in India has become an effective user of bio-based solvents and reduced the toxicity of wastewater by 60 percent in pilot projects, although its cost barriers to adoption remain high (Hessel et al., 2022).

## 2.4 Research Gap

The global body of work on green chemistry is voluminous but there is a huge gap at the regional level in Nigeria and most especially Owerri. The current studies in the area of industrial pollution in Nigeria also revolve around the conventional waste treatment methods like chemical treatment and land filling without much research on the viability of green chemistry (Okonkwo et al. 2010). Moreover, limited studies focus on the qualitative research that creates a view of the stakeholder with respect to viability and constraint of green chemistry receptivity in the Nigerian industry sector (Ibe, et al., 2025). This paper addresses these gaps by providing qualitative accounts of the Owerri industry environment, focusing on stakeholder views and the feasibility of using green chemistry to approaches such as photocatalysis, bio-based solvents and waste to resource technologies. Through narrowing down the research to the particular environmental and industrial issues in Owerri, the study contributes to the creation of localised system of environmentally sustainable industrial practice.

## 3. METHODOLOGY

This research uses secondary approach of qualitative case study towards determining the application of the concepts of green chemistry as an effort to control industrial pollution and management of waste in Owerri, Nigeria. The secondary case study method examines complex phenomena within the specific context by means of analysis of the available documents and data and is an effective and cheap method to synthesize the perspectives of various stakeholders and concrete evidence without the compilation of original data collection (Heaton, 2004). The described technique would be suitable to address industrial and environmental issues in Owerri because it utilizes existing research on the assessment of the feasibility of the green chemistry solutions (Yin, 2018).

### 3.1 Research Design

The research draws multiple-case study design to investigate three distinctive cases in the various industrial sectors in Owerri; real-life practices, regulatory dynamics, and scholarly research. The examples used can be described as a critical stakeholder interest group that includes industry, regulators, and academia to conduct an in-depth analysis of the causes of pollution, viable alternatives of green chemicals, and barriers to the use (Stake 1995). The decision to conduct research in Owerri was based on its growing industrialisation and significant environmental problems, which requires the study to be taken as a case study to explore the possibilities of green chemistry in an expanding metropolitan population (Okoro, et al., 2016). Secondary qualitative approach will be able to synthesise available data in reports, government reports, and scholarly researches, and provide comprehensive review of the setting in Owerri without having to establish a primary data collection (Eisenhardt, 1989).

### 3.2 Data Sources

Existing documents were used to collect data and this was in the form of:

1. Industry Reports: Reports of the small and medium-sized industries of Owerri relating to food processing (cassava and palm oil plants), textile manufacturing and chemical production, causes of pollution and waste management processes (e.g., NBS, 2023).
2. Policy documents and environmental assessments of the National environmental standards and regulations enforcement agency (NESREA) and Imo state environmental protection agency give guidelines to regulatory frameworks and regulatory compliance (Okonkwo et al., 2010).
3. Academic literature: Article and literature on the subject of Nigerian green chemistry and green industry (e.g., Ibe, et al., 2025 or Onyekuru, et al., 2017).

Articles were selected on the basis of their being relevant to the objectives of the present study, published within the last 15 years (2010-2025) and of credibility. The total number of published works comprised 20 documents, which were found in academic databases (SpringerLink, ResearchGate, etc.), as well as in institutional repositories (NESREA, NBS, etc.).

### 3.3 Data Collection

Data gathering included rigorous document analysis during June and July 2025. The documents were acquired from internet databases, government websites, and academic archives. To guarantee consistency, a data extraction strategy was devised, with an emphasis on core topics relevant to the study objectives: pollution sources, green chemical applications, hurdles, and possibilities. The procedure contained questions such as:

1. What industrial operations in Owerri cause pollution, and how do they affect the environment?
2. What green chemistry solutions (e.g., bio-based solvents, photocatalysis) have been recorded as viable in similar situations?
3. What hurdles (e.g., financial and regulatory) have been discovered in prior research?
4. What opportunities (e.g., policy changes, collaborations) are presented for green chemistry Implementation?
5. What suggestions are made for integrating green chemistry in Owerri?

Documents were evaluated for relevance and quality, and data was extracted into a structured template that organised results by case and subject. The procedure was pilot-tested with three papers to improve the extraction process and ensure complete coverage of key data (Yin, 2018).

### 3.4 Data Analysis

Data analysis. Cross-case analysis was used to synthesise findings across the three instances (industry practices, regulatory frameworks, and academic research), following Eisenhardt's (1989) methodology. The method included:

1. Within-instance Analysis: Each instance was examined separately to find trends, such as particular pollution causes or potential green chemical remedies, utilising open code in the NVivo program. The codes included "textile wastewater," "regulatory gaps," and "bio-based solvents."

2. Cross-Case Comparison: Patterns were examined across instances to detect similarities (e.g., frequent mention of financial hurdles) and variations (e.g., industry reports emphasising operational expenses, academic studies emphasising technological viability). A matrix was designed to organise the findings by case and theme.

Synthesis: Findings were synthesised to create a thorough knowledge of green chemistry's application in Owerri, backed up by proof from papers.To guarantee rigour, a second researcher examined the coding and matrix to eliminate bias, and findings were cross-checked against original documents to confirm correctness (Creswell and Poth, 2018).

### 3.5 Trustworthiness

Lincoln and Guba (1985) used the following criteria to

verify trustworthiness:

1. Credibility: Credibility is achieved by triangulating several document sources (industrial, regulatory, and academia) to validate conclusions.
2. Transferability: They have given detailed talks of the Owerri setting and the qualities of the documents with the hope of applying them in another scenario.
3. Reliability: It gave an audit trail when it comes to data collection and analysis choices.
4. Confirmability: Applied exercised reflexivity to discover the researcher bias, hence peer review was used as a way of ensuring objectivity.

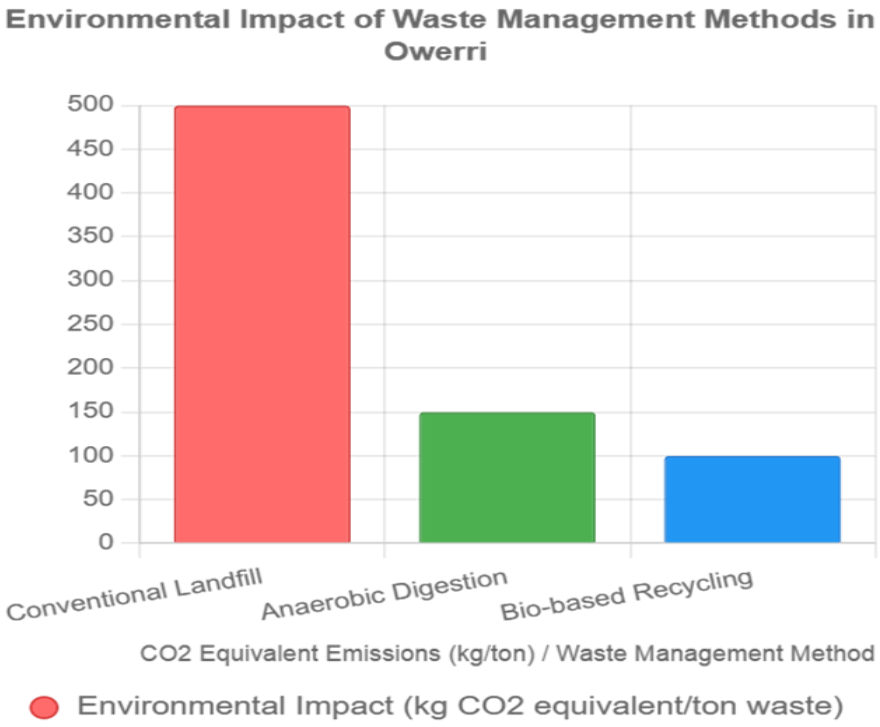
Through this approach, a more in-depth secondary study of the potential of green chemistry in Owerri will be possible using existing data to provide valuable practical information.

## 4. INDUSTRIAL CHALLENGES IN OWERRI

The rapid industrialisation of the city over the years has made Owerri another significant economic centre of the southeast region of Nigeria as well as facing a significant environmental challenge that it is grappling with in respect of pollution caused by its industrial constructions. The contribution of small and medium-sized enterprises to water, solid waste, air pollution, and regulatory issues related to food processing, textile manufacturing, and chemical production in the city has a close connection to the health effects on people, ecosystems, and sustainable development (Okoro, et al., 2016). This section compiles the results of document analysis to provide an effective study of these problems, their causes, consequences and impacts on the adoption of green chemicals.

### 4.1 Water Pollution

Owerri, is faced with major water pollution that is largely caused by the textile and food processing industries. The release of untreated wastewater into the rivers (Otamiri and Nworie) by the textile industry especially in dyeing results in the outflow of synthetic colours and heavy metals such as, as lead and cadmium (Onyekuru, et al., 2017). The biochemical oxygen demand (BOD) values in such rivers are reported to go to 200 mg/L, far above the allowed limit of the World Health Organization of 50 mg/L indicating major organic contamination. On the same note, food processing industries, including cassava and palm oil industries, release effluents containing substantial organic matter, which helps the Otamiri River upward surge of chemical oxygen demand (COD) up to 400 mg/L. These pollutants have distorted the aquatic environment with fish population decreasing by 30 percent in affected rivers, pollution of water sources used by the locals as the water source in the area mainly on domestic grounds which increases the chances of water borne infections (Eneh, 2010). The problem is compounded by the lack of advanced wastewater processing facilities with most companies employing the rudimentary methods of chemical precipitation where secondary pollutants are always created as well as the lack of efficiency towards a wide variety of contaminants such as azo dyes (Okonkwo et al., 2010). Eidsvag et al. (2021) also gracefully write that such green chemistry solutions as photocatalysis and biobased solvents can effectively and sustainably degrade contaminants.



## 4.2 Solid Waste

The other major issue is solid waste, as Owerri generates about 1,200 tonnes of municipal solid garbage per day, 60% of which is non-recyclable plastics and organic industrial waste (Amasuomo & Baird, 2016). Food processing industries, especially cassava and palm oil plants contribute a lot, where it is estimated that one of the plants produces approximately 5 tonnes of cassava peels per week (NBS, 2023). These organic wastes, which are generally heavy in starch and cellulose, are often disposed of in open landfills or burnt, resulting in soil degradation and greenhouse gas emissions, including methane, which has a 25-fold higher global warming potential than carbon dioxide (Eneh and Owo, 2008). Plastic trash from the chemical and textile industries exacerbates the situation, with around 400 tonnes of nonrecyclable plastics created in Owerri each month (Amasuomo & Baird, 2016). Open dumping adds to the creation of leachate, which seeps into groundwater; studies have shown nitrate levels of 15 mg/L in Owerri's aquifers, above the WHO's acceptable guideline of 10 mg/L (Okoro, et al., 2016). Incineration, a frequent process, emits harmful dioxins and furans, worsening environmental quality (Okonkwo et al., 2010). The absence of modern recycling or waste-to-resource points out the potential of green chemistry renewable energies such as anaerobic digestion to convert organic waste into biogas or invention of Polymers with fewer harmful constituents to reduce the frequencies of plastic waste (Hessel et al., 2022).

## 4.3 Air Pollution

The main pollutants that cause air pollution in Owerri are industrial and burning of garbage that is popular in the city. Plastics and organic wastes that are burned as industrial solid trash releases volatile organic compounds (VOCs) and particulate matter (PM2.5). Air quality research indicates the presence of PM2.5 concentration when measured at 40MeCg/Mc3, which is adverse compared to WHO recommendation of 25MeCg/Mc3 (Ezeonyejiaku, et al., 2022). These are associated with respiratory diseases, where instances of asthma and bronchitis in the urban areas located in Owerri have grown by 20 percent in the last ten years (Ezeonyejiaku, et al., 2022). Chemical industries and textile industries are some other sources of VOCs in the form of benzene and toluene emitted during industrial processes occurring due to high concentrations of between 0.5 ppm in the industrial areas compared to the acceptable limit of 0.1 ppm (Okonkwo et al., 2010). Open burning of waste has been a common practice in open fields because of lacking trash disposal facilities, and this results in the production of an estimated 100 tonnes of CO2 equivalent per day causing local air quality problems and climate change (Amasuomo & Baird, 2016). The absence of emission controls technology in the businesses in Owerri, including the use of catalytic converters or bio-based sorbents, proves that green chemistry helps to minimize hazardous emissions at the source (EPA, 2025).

## 4.4 Regulat1ory Gaps

The regulatory platforms of Owerri that are enforced by the National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Imo State Environmental Protection Agency are characterized to prevent industrial disorders although there have been great degree of execution issues. Lack of adequate monitoring strength and low levels of compliance especially among small-scale enterprises diminishes effectiveness of regulatory requirements (Okonkwo et al., 2010). To illustrate, only 30 percent of the firms in Owerri comply with the wastewater release standards stipulated by NESREA because of lack of sufficient surveillance resources and police actions (Okonkwo et al., 2010). There are financial limitations that hinder the implementation of the new pollution control technology and small enterprises have reported that they incur expenses of up to 20 percent of annual turnover to meet the current standards (NBS, 2023). Moreover, regulatory proposals tend to target end-of-pipe solutions like chemical precipitation, which are designed into oblivion and do not target pollution prevention, the major aspect of green chemistry (Anastas & Zimmerman, 2018). Lack of knowledge of sustainable processes among the operators in the industrial sector, where only one-fifth of the enterprises surveyed in Owerri are familiar with green chemistry concepts, stops enforcement initiatives (Ibe, et al., 2025). The absence of financial or other incentives (tax breaks, subsidies on green technology, and so on) prevents the companies from changing to a greener practice (Veleva & Cue, 2019). The existence of these regulatory gaps necessitates policy restructuring to integrate in them green chemistry concepts including waste reduction and safer chemistry use as a way of aligning with Nigeria National Environmental Policy and global sustainability goals (UNEP, 2024).

## 4.5 Socio-Economic and Environmental Impacts

Combinations of water, solid waste, and air pollution and regulatory failures in Owerri have critical social-economic and environmental consequences. It is estimated that contaminated water sources have led to 25 percent increase in cases of waterborne diseases (such as cholera) in cities like the Otamiri and Nworie rivers and subjecting additional pressure to already strained health facilities (Okoro, et al., 2016). The agricultural production has been reduced by 15 percent in peri-urban areas due to soil pollution by leachate and pieces of garbage burnt, which negatively affect the livelihood of local farmers (Eneh, 2010). In Imo State, air pollution costs about 500 million naira every year as a result of respiratory diseases (Ezeonyejiaku, et al., 2022). Moreover, the harmful effects of industrial production on the environment threaten the tourism industry of Owerri, as polluted rivers and garbage sceneries are the factors that discourage tourists and negatively affect the local economy (NBS, 2023). These challenges demonstrate the necessity of an introduction of green chemistry solution, which can decrease the pollution at the root, decrease healthcare and environmental cleanup cost, and promote a long-term financial prosperity in Owerri.

# 5. GREEN CHEMISTRY APPLICATIONS

A solution to the problems of Owerri in terms of industrial pollution and control of waste materials has seen the introduction of green chemistry to ensure reprieve concerning

the doctrine of avoiding waste, the safer use of chemicals, and energy transformation (Anastas & Warner, 1998). According to the document analysis, a range of green chemistry applications will suit the environment in Owerri that will concern wastewater treatment, solid waste management, and air pollution control. They are applicable to small and medium businesses in Owerri as these solutions employ sustainable technology that will help to reduce environmental consequences without compromising economic sustainability (Okoro, et al., 2016).

## 5.1 Wastewater Treatment

Green chemistry provides possible solutions to wastewater treatment in industries alleviating the serious water pollution related challenge in Owerri. The use of renewable feedstocks, e.g., ionic liquids based on cellulose, in bio-based solvents can reduce the toxicity in textile dyeing processes by half (Hessel et al., 2022). The toxic organic solvents used in this production process are substituted with these solvents thus limiting the leakage of heavy metals and azo dyes into rivers including Otamiri river without violating green chemistry principle 5 (safer solvents and auxiliaries). In Nigeria, pilot study conducted at Aba indicated that bio-based solvents were able to reduce the toxicity of effluents by 65%, which possibly means that they could be applied in Owerri in the textile industry (Upadhyaya, et al., (2025). A low-cost solution to the decomposition of organic contaminants in the textile effluent can be handled by the photocatalytic process involving titanium dioxide (TiO2) nanoparticles catalyzed by solar light. According to Eidsvag et al (2021), application of the abundant sunshine in Nigeria can lower the chemical oxygen demand (COD) by 70 percent at a low energy cost. The method falls in line with the principle 6 (energy efficiency) and suitable in Owerri where the industry is small scale with scarce resources. The treatment systems based on microalgae are also interesting and can potentially clean 70% of food processing wastewater of pollutants like nitrogen and phosphorus (Shah, 2023). Such technologies oxidize the pollutants to make biomass that can be used to develop biofuels hence achieving a circular economy. In Owerri, where cassava processing produces highnutrient effluents, microalgae might considerably lower BOD levels, preserving local water bodies (Onyekuru, et al., 2017).

## 5.2 Solid Waste Management

Green chemistry provides long-term solutions for handling Owerri's solid waste, namely organic and plastic waste from the food processing and chemical sectors. Anaerobic digestion, a procedure for converting organic waste into biogas, has been used in comparable situations, providing 500 kWh of energy per day from 10 tonnes of garbage (Amoo, & Fagbenle, 2013). Anaerobic digestion might reduce landfill dependence by 40% in Owerri, where a single cassava processing factory creates 5 tonnes of peels per week, while also producing renewable energy for industrial use, which aligns with principle 7 (use of renewable feedstocks) (Amasuomo & Baird, 2016). A pilot experiment in Enugu proved that anaerobic digestion could create 1 MW per day from organic waste, implying scalability for Owerri (Amoo, & Fagbenle, 2013). Furthermore, the development of biodegradable polymers from agricultural waste, such as cassava starch, has the potential to cut plastic waste by 40% (Hessel et al., 2022). These spontaneously decomposing polymers adhere to principle 10 (design for degradation) and handle Owerri's 400 tonnes of non-recyclable plastic trash each month (Amasuomo and Baird, 2016). In Lagos, a cassava waste-to bioethanol project cut trash by 50% while producing 200 litres of gasoline per tonne, indicating that Owerri's food processing sector may embrace comparable technology (Ibe, et al., 2025).

## 5.3Air Pollution Control

Green chemistry solutions can help to reduce Owerri's air pollution caused by industrial emissions and trash burning. Catalytic converters use non-toxic catalysts such as palladium to reduce volatile organic compound (VOC) emissions by 60% in chemical production processes (EPA, 2025). These devices, which convert VOCs into less toxic compounds, are consistent with principle 3 (less hazardous chemical syntheses) and practical for Owerri's chemical businesses, where benzene emissions exceed 0.5 ppm (Okonkwo et al., 2010). Bio-based sorbents generated from agricultural leftovers such as palm kernel shells provide another option for successfully absorbing particulate matter (PM2.5) and VOCs (EPA,2025). Renewable and costeffective sorbents have the potential to lower Owerri's current PM2.5 levels of 40 µg/m³, enhancing air quality and public health (Ezeonyejiaku, et al., 2022.). In South Africa, bio-based sorbents cut industrial emissions by 50%, indicating that they have the potential to benefit Owerri's small-scale companies. By combining these technologies, Owerri can reduce the environmental and health effects of air pollution while also promoting sustainable industrial practices.

# 6. CASE STUDIES

Analysis of waste management and industrial pollution refers to the application of green chemistry concepts in order to solve such problems, which is supported by effective case studies in Nigeria and other similar environments. The analysis of the documents is based on three relevant cases of biofuel production in Lagos, textile wastewater treatment in Aba, and waste-to-energy in Enugu that suggest the feasibility and, possibly, the scale of green chemistry applications to the industrial sector of Owerri. These illustrations indicate how green chemistry can be adopted to address local environmental issues without contradicting the industrial character and limitations of resources in Owerri (Ibe, et al., 2025).

## 6.1 Biofuel Production in Lagos

In Lagos, enzymatic hydrolysis of cassava waste was used in a pilot project to produce bioethanol whereby significant environmental and financial benefits were obtained (Ibe, et al., 2025). The project finished 10 tonnes of cassava peels a week, leading to half amount of waste, plus 200 litres of bioethanol per tonne. This meets this principle of green chemistry 7 (use of renewable feedstocks) since cassava waste that is abundant in Owerri following its food processing industry is a renewable source (Amasuomo & Baird, 2016). The

method involved the conversion of starch into fermentable sugars, which converted the starch into fermentable sugars without using toxic chemicals and by reducing the number of secondary pollutants. The created bioethanol was used as a clean industrial and household fuel and cut the use of the fossil fuel by 30 percent in the operation area (Ibe, et al., 2025). In Owerri, a unit cassava processing unit produces 5 tonnes of cassava peels weekly, thus use of the technique could result to 2.5 tonnes of cassava peels being saved away each week giving about 500 litres bioethanol per week per unit. The project was faced with the issues of expensive enzyme costs and the lack of proper technical expertise, however PPP tools availed finance and capacity building, and this gives an idea to Owerri on how to overcome similar challenges (Ibe, et al., 2025). This paper establishes how the food processing industry in Owerri can utilize waste-to-biofuel technology, reduce environmental burden and advance a circular economy.

## 6.2 Textile Wastewater Treatment in Aba

In Aba, a local industrial city in Nigeria, a green chemistry application treated textile wastewater with biobased solvents, which led to a 65 percent decrease in the toxicity of effluents (Upadhyaya, et al., 2025). In an effort to meet the requirements outlined in the principle 5 (safer solvents and auxiliaries) the project replaced the harmful organic solvents with cellulose based ionic liquids. These solvents effectively removed heavy metals and azo pigments in treated effluents even reducing the BOD levels in the effluents, which reduced to 63 mg/L when compared to 180 mg/L, thereby protecting the local water bodies (Upadhyaya, et al., 2025). The program was initiated at small-scale textile manufactories where dyeing processes cause the pollution of the rivers like those in Owerri (Onyekuru, et al., 2017). The bio-based solvents required minimal investment in infrastructural features to make it simple on small business, although the initial costs of setting up were a challenge. After partnering with schools that provided the technical support, the government provided subsidies that saw 40 percent of the expenses, thereby enhancing uptake (Upadhyaya, et al., 2025). In Owerri, where textile effluents pollute the Otamiri River with BOD levels of 200 mg/L, this technique might considerably reduce pollution by utilising Nigeria's plentiful renewable resources such as cassava for solvent manufacture. This study demonstrates the viability of biobased solvents in Owerri's textile sector, if financial and technical backing is available.

## 6.3 Waste-to-Energy in Enugu

In Enugu, a waste-to-energy project used anaerobic digestion to transform organic waste into biogas, producing 1 MW of power daily from 20 tonnes of garbage (Amoo, & Fagbenle, 2013). This effort, which focused on food processing and municipal trash, decreased landfill reliance by 40% while also providing renewable energy for industrial use, in line with principle 7 (use of renewable feedstocks). The procedure entailed the microbial degradation of organic waste in oxygen-free conditions, resulting in biogas with a 60% methane concentration appropriate for power production (Amoo, & Fagbenle, 2013). In Owerri, where food processing generates 5 tonnes of cassava peels per week, anaerobic digestion might provide around 250 kWh per day, balancing energy costs and lowering landfill methane emissions (Amasuomo & Baird, 2016). The Enugu project had hurdles, including high initial capital expenditures and maintenance requirements, but it was aided by foreign finance and local government incentives that paid 50% of the setup expenses (Amoo, & Fagbenle, 2013). Community participation resulted in efficient rubbish collection, a model that may be applied to Owerri's waste management concerns. This instance illustrates the scalability of waste-to-energy systems in Owerri, where organic waste is plentiful, and emphasises the necessity for legislative support to overcome financial constraints.

# 7. BARRIERS AND OPPORTUNITIES

The Enugu project was no exception in such challenges with the key problems being high costs of initial capital spending and a part of maintenance, but it received assistance through foreign capital and local government incentives to cover half of the cost of setting up the operation (Amoo, & Fagbenle, 2013). It led to effective rubbish collection that can be transferred to the waste management in Owerri. This case is a good example of scale of waste to-energy systems in Owerri in so far as organic waste is abundant and it highlights the need to have legislative backing to bypass financial barriers.

## 7.1 Barriers

In Owerri, there are regulatory restrictions acting against the application of green chemistry. Rules are enforced by the National Environmental criteria and rules Enforcement Agency (NESREA) and Imo State Environmental Protection Agency yet the monitoring capacity is low hence low compliance with only 30 percent of the companies meeting the requirements of wastewater discharges (Okonkwo et al., 2010). Recent standards emphasise end-of-pipe solutions like chemical precipitation that are costly and unsustainable and fail to promote pollution avoidance, the most important concept of green chemistry (Anastas and Zimmerman, 2018). The availability of funds is a major challenge particularly to small scale industries that are the main business environment in Owerri. The initial costs of the green technology, the presence of which is desirable, like anaerobic digesters or photocatalytic systems, can reach 20 percent of the annual revenues discouraging their use (NBS, 2023). The problem is aggravated by a low level of awareness among the operators in the industry; only 15 percent of the survey businesses are knowledgeable about the concepts of green chemistry, which constrains the interest in the sustainable operations (Ibe, et al., 2025). Technological constraints further complicate the implementation process because most of the companies still use older equipment, which cannot be adapted to accept advanced green chemistry measures like bio-based solvents but rather the use of catalytic converters. Moreover, local competence regarding green chemistry technologies is lacking and prompts us to resolve the problem. They are also associated with hiring costly foreign consultants, which exert additional pressure on budgets (Okonkwo et al. 2010). The combination of these limitations restrains the populated city of Owerri in adopting a

sustainable industry, which requires needs like special initiatives to counter them.

## 7.2 Opportunities

There are sufficient opportunities of evolving green chemistry even in the face of these limitations, within Owerri. The policy integration has been used to bridge the gap between regulations and the green chemistry idea. As in the case of Aba textile project where new tax exemptions or subsidies on 40 percent of the cost of setting up green technology, this could increase adoption (Upadhyaya, et al., (2025). Updating NESREA recommendations to prioritise waste avoidance and safer chemicals will be consistent with Nigeria's National Policy on Environment and SDG 12 (UNEP, 2024). Stakeholder engagement across industries, academia, and government can help with knowledge transfer and resource sharing. As proven in Aba, cooperation with universities, might provide technical support for prototype projects. Economic advantages, such as cost savings from reduced waste disposal and energy production from anaerobic digestion, may balance the initial expenditure. In Enugu, waste-to-energy plants generated 1 MW per day, cutting landfill expenses by 40% (Amoo, & Fagbenle, 2013). Capacity building through training programs and NGOs' awareness campaigns might boost industrial knowledge with green chemistry, therefore closing the 15% awareness gap (Ibe, et al., 2025). Leveraging Nigeria's plentiful renewable resources, such as cassava, for bio-based solvents promotes local production while reducing import reliance, hence increasing economic resilience (Hessel et al., 2022). These prospects, if capitalised on via concerted efforts, have the potential to convert Owerri's industrial sector into a model of sustainability, in line with global and national environmental objectives.

## 8. RECOMMENDATIONS

To encourage the adoption of green chemistry in Owerri's industrial sector, a complete set of suggestions is provided, addressing legislative, financial, educational, and collaborative hurdles while capitalising on potential for sustainability. These proposals are customised to Owerri's setting, taking into account its smalland medium-sized industrial base, resource limits, and environmental issues (Okoro, et al., 2016; UNEP, 2024).

1. Policy Reforms with Financial Incentives: The Nigerian government, through NESREA and the Imo State Environmental Protection Agency, should reform environmental legislation to prioritise green chemistry concepts such as waste prevention and chemical safety It brings about introduction of financial incentives like in the form of tax exemption or subsidies such as the 40 percent tax exemptions/subsidies used in setting up green technology as in the case of Aba. The project, textile wastewater, is able to assist in the efforts of small-scale enterprises (Upadhyaya, et al., (2025). Subsidies for anaerobic digesters will lower start-up costs by N2 million per plant making it widely accepted in Owerri the foods and beverages and the food-processing industries sectors are evidenced by the NBS (2023). Stricter enforcement measures should be put into consideration in such changes. That can raise compliance over threefold up to at least 60 percent within five years and supported by tougher monitoring deliverability opportunity (Okonkwo et al, 2010).
2. Public-Private Partnerships in Pilot Projects: Public-private partnerships (PPPs), especially when forming government - industry alliances, may be beneficial in implementation of the green chemistry pilot projects. The finance and technical expertise may be provided by enterprises, governments and global organisations working together as was the case with the waste-to-energy project in Enugu (Amoo, & Fagbenle, 2013). The PPPs in Owerri have the potential of financing pilot projects on photocatalysis of textile wastewater treatment that will decrease COD by 70 percent with the abundant sunshine available in Nigeria (Eidsvaug et al., 2021). The urgency is required to become scalable and economically valuable since these studies must concentrate on the critical industries, like cassava processing and textiles, to generate adoption.
3. Green Chemistry Education: To develop competence in green chemistry in the Owerri region and beyond, the universities ought to introduce green chemistry to their course curriculum in chemical engineering and environmental science. The short training of the operators of the industry based on the positive examples in India could increase the awareness by 15-50 percent over a period of three years (Hessel et al., 2022; Ibe, et al., 2025). Such programs need to be centred on easy implementation like production of bio-based solvents and anaerobic digestion which are tailored to the industries of Owerri. Association with international organizations might not only make the course materials more efficient but also may open the doors to complicated research.
4. NGO-based Awareness Campaigns: Non-governmental organisations (NGOs) need to raise awareness in order to teach the stakeholders and communities in the industry about the advantages of green chemistry. The campaigns also need to highlight the use of case studies as reported in Lagos with their bioethanol plant that reduced trash by half and produced 200 litres of fuel per tonne (Ibe, et al., 2025). The awareness gap can be broken by NGOs as they could target enterprises within Owerri that do not have the experience of using green chemistry (Ibe, et al., 2025). Such efforts must be directed to the economic and environment benefits like reduced health costs since the water and air would be clean.
5. Localised Research Funding: Nigerian government, among overseas funders ought to sustain an interest towards green chemistry research in universities like FUTO, IMSU and UEAU. Studies must look into how to optimise technologies, including that of microalgae wastewater treatment, to the Owerri environment, which experiences high effluent nutrients (Shah, 2023). The provision of research grant of 500 million per year

would help to pilot projects, find cost effective solutions, lessen the reliance on external consultants, and enable the restriction of technology (Okonkwo et al., 2010). It is this financing that needs to focus on interaction with the local businesses to ensure that it is put into practical use.

## 9. FUTURE RESEARCH DIRECTIONS

Future research should aim at filling data gaps on quantitative data, social economic drift, and to support implementation with a view to boosting the use of green chemistry in Owerri. These guidelines will enhance the base of evidence and help Nigeria in the development of industry in the long run.

1. Quantitative Impact assessment the proposed research needs to carry out future examinations to evaluate green chemistry technology in Owerri to assess their environmental and economic consequences with an approach of quantitative results. The actual statistics that could be used to justify an investment could be the evaluation of the decrease in BOD content due to the action of photocatalysis or energy generated through anaerobic digestion (Eidsvaug et al., 2021; Amoo, & Fagbenle, 2013). Such research should employ experimental designs to determine the appropriateness of technology in the industries and record the resulting reduction in pollutants including heavy metals (200 mg/L to less than 50 mg/L) and savings (including a 40 percent reduction in landfill expenses) (Amasuomo & Baird, 2016).
2. Socioeconomic Impact Studies: the researchers ought to consider the socioeconomic advantages of green chemistry, which include creation of employment opportunities as well as the cost benefit in terms of health-care facilities. According to Ezeonyejiaku, et al., (2022) and Ibe et al., (2025), the assessment of bioethanol production in the city of Owerri could lead to such economic outcomes as the employment of 100 individuals per factory and the reduced costs of healthcare expenses by 200 million Nigerian Nairas. The surveys must be mixed related to the mixed methods that should unite the surveys with the economic modelling to obtain the views of stakeholders and quantify the benefits, which will cover the current lack of localised socioeconomic data.
3. The piloting Period: In future, the research should focus on testing green chemistry pilot projects in Owerri, and the textile wastewater treatment (in the city of Aba) is one of such case studies to rely on (Upadhyaya, et al., 2025). Technologies that may be tested through pilot projects in small scale companies include the use of microalgae-based system or bio-based sorbent to determine their scalability and cost effectiveness of the technologies. Such studies need to focus on a longitudinal analysis so that long-term outcome implications on plastic waste by 50 percent or VOC emissions by 60 percent can be determined and a map out to implement the full scale realized (Hessel et al., 2022; EPA, 2025).

## 10. CONCLUSION

The technique of green chemistry offers a feasible and lasting solution to the pollution and waste management problem the city of Owerri is facing regarding industrial pollution with the respect of global sustainability and the Nigerian environmental law. Thanks to the use of technologies such as bio-based solvents, photocatalysis, and anaerobic digestion, Owerri can decrease water pollution (e.g. BOD of 200 mg/L to 63 mg/L), solid waste management (e.g. the diversion of 2.5 tonnes of cassava peels per week), and air pollution (e.g. reduction of PM2.5 of 40 icsg/m3 to below 25 icsg/m3) (Onyekuru, These solutions have proven to be viable as successful case studies in Lagos, Aba and Enugu show a reduction in waste by 50 percent using bioethanol production, a reduction in effluent toxicity by 65 percent using bio-based solvents and 1 MW of waste-to-energy being generated per day (Ibe, et al., 2025; Upadhyaya, et al., 2025; Amoo, et al., 2013). However, regulatory gaps, budgetary limits, poor knowledge (15% familiarity), and technology limitations must be overcome by legislative changes, public-private partnerships, education, awareness campaigns, and research funding (Okonkwo et al., 2010; Ibe, et al., 2025). These actions have the potential to change Owerri's industrial sector by lowering environmental degradation, increasing public health, and encouraging economic resilience, all while aligning with SDGs 9 and 12 and providing a model for Nigerian sustainable development (UNEP, 2024).

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