Sustainable Wastewater Treatment Technologies: Advancements For Environmental Sustainability In Nigeria

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ABSTRACT : *The global challenge of managing wastewater is becoming more urgent, driven by climate change, rapid urban growth, and rising environmental concerns. As urban populations grow and industries expand, traditional wastewater treatment methods, such as activated sludge processes and chemical treatments, remain widely used. While these methods effectively reduce pollutants, they often consume a lot of energy, rely on significant chemical inputs, and create byproducts that can harm the environment. Their dependence on fossil fuels and chemicals results in a substantial environmental footprint, worsening climate change, water pollution, and resource depletion issues. In response, there is a global trend toward more sustainable wastewater treatment technologies that offer environmentally friendly and resource-efficient options. Technologies like constructed wetlands, biological filtration systems, and resource recovery methods are gaining attention for their ability to improve upon traditional systems. These innovative solutions utilize natural processes, such as microbial degradation and plant-based filtration, to treat wastewater effectively while recovering valuable resources like nutrients, biogas, and clean water. These methods can lessen the environmental impact of wastewater treatment, cut operational costs, and support a circular approach to resource use by recycling nutrients, water, and energy.*
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KEYWORDS: *Environmental Sustainability, Wastewater Treatment, Climate Change, Green Infrastructure, Urbanization, Biological Filtration*

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I.　INTRODUCTION

Managing wastewater has become a critical issue worldwide due to increasing urbanization, population growth, and industrial activities. Discharging untreated or poorly treated wastewater into the environment pollutes water bodies, harms ecosystems, and leads to various public health problems. Traditional wastewater treatment methods, while necessary, are expensive, consume a lot of energy, and often generate large volumes of sludge and other waste. Additionally, using chemicals in these processes can have harmful environmental effects, as they can release toxic byproducts.

In response to these issues, there has been a shift towards more sustainable approaches to wastewater treatment that focus on protecting the environment, reducing costs, and recovering resources. Sustainable technologies like constructed wetlands, biological filtration systems, and nutrient recovery processes have emerged as viable alternatives. These methods not only improve wastewater quality but also provide significant ecological and economic benefits. They decrease energy use, support biodiversity, and recover nutrients and other resources, thus contributing to a circular economy.

This paper explored these emerging technologies in detail and evaluate their applicability in various situations, from rural areas to urban centers. It will discuss the potential of these technologies to reduce the environmental impact of wastewater treatment while boosting overall sustainability. Furthermore, it will highlight the relevance of these technologies in both developed and developing countries, including specific case studies from Nigeria and other regions.

A.   PRINCIPLES OF SUSTAINABLE WASTEWATER TREATMENT

Sustainable wastewater treatment is an approach that prioritizes environmental protection, resource conservation, and community well-being. It goes beyond just removing pollutants to consider the potential for resource recovery and minimizing negative impacts on ecosystems. Unlike conventional systems that often rely on energy-intensive and chemical-heavy processes, sustainable methods prioritize ecological balance, energy efficiency, and circularity. These systems are designed to support broader goals of environmental sustainability, public health, and climate resilience.

CORE PRINCIPLES:

1. **Low Energy Consumption:**
Sustainable systems focus on using passive or low-energy technologies, often leveraging gravity flow, natural processes, or renewable energy sources like solar or biogas (Langergraber, 2013; Lettinga, 2001; Ogunjimi et al., 2022). This approach contrasts with traditional activated sludge systems that often require a lot of energy for aeration and mechanical operations.

2. **Resource Recovery:**
Modern sustainable wastewater treatment goes beyond pollutant removal to include resource recovery. Technologies increasingly aim to reclaim valuable materials such as nitrogen, phosphorus, organic matter (as compost or biogas), and clean water. This method supports the circular economy by turning waste into resources for agriculture, energy production, and industrial (Moelants, Awuah, & Buamah, 2008).

3. **Minimal Chemical Use:**
Chemical additives in traditional treatment can have negative environmental and health effects, both during treatment and through the creation of secondary sludge. Sustainable treatment methods focus on biological, physical, or nature-based processes that limit or eliminate chemical dependency, using methods like phytoremediation, microbial digestion, or membrane bioreactors (Moelants, Awuah, & Buamah, 2008). .

B.   ROLE IN ACHIEVING ENVIRONMENTAL SUSTAINABILITY

Sustainable wastewater treatment is essential for advancing environmental sustainability by tackling key issues like water pollution, climate change, and resource scarcity. By reducing greenhouse gas emissions linked to conventional treatment and encouraging the reuse of water and nutrients, these systems help achieve Sustainable Development Goals (SDGs), particularly:
• SDG 6: Ensuring availability and sustainable management of water and sanitation for all.
• SDG 13: Taking urgent action to combat climate change and its impacts.
• SDG 12: Ensuring sustainable consumption and production patterns.

In regions like Nigeria, where infrastructure gaps and environmental pressures are serious, sustainable wastewater solutions provide a path to long-term ecological health, better water quality, and improved resilience to climate change. They also lighten the load on overwhelmed municipal systems and encourage decentralized, community-based management strategies.

OBJECTIVES:
1. To explore innovative, sustainable technologies in wastewater treatment that support environmental sustainability.
2. To assess the effectiveness and efficiency of constructed wetlands, biological filtration systems, and resource recovery methods in treating wastewater.
3. To examine the environmental, social, and economic benefits of these technologies, focusing on their potential to reduce pollution and promote resource recycling.
4. To identify challenges and limitations in implementing and scaling these technologies, particularly in urban and industrial settings.
5. To provide practical recommendations for integrating these technologies into national development plans to ensure they align with broader environmental and economic goals.

II.   LITERATURE REVIEW

1. Global Wastewater Management Challenges

Wastewater management is crucial for protecting water resources and involves the collection, treatment, and reuse of wastewater. Problems in wastewater collection networks can lead to various issues. Managing wastewater has become a pressing global concern due to rapid population growth, urbanization, industrialization, and climate change. Conventional systems, like activated sludge processes and chemical methods, have traditionally been used to remove organic matter, pathogens, and nutrients from sewage and industrial waste. However, these methods are often energy-hungry, depend on chemicals, and create harmful byproducts, compromising their environmental sustainability (Tchobanoglous et al., 2014; UN Water, 2020).

2. Environmental Impacts of Conventional Systems

Environmental degradation refers to the deterioration of the environment through resource depletion, ecosystem destruction, and wildlife extinction (Choudhary et al., 2015). Traditional wastewater treatment technologies significantly contribute to environmental degradation. Their reliance on fossil fuels, excessive chemical inputs, and harmful sludge and secondary pollutants contradict the purpose of protecting the environment (Smith & Scott, 2017). Moreover, many of these systems are not suitable for decentralized or rural areas due to their high costs, limiting their use in developing countries.

3. Emergence of Sustainable Wastewater Treatment Technologies

Sustainable treatment technologies aim to minimize negative environmental impacts while effectively treating materials. In response to the limits of traditional systems, sustainable technologies have become more popular. These methods focus on reducing environmental impact, improving efficiency, and enhancing resource recovery. Technologies like constructed wetlands, biofiltration, anaerobic digestion, and membrane bioreactors use natural or low-energy processes to treat wastewater (Langergraber, 2013; Kadlec & Wallace, 2009). These systems not only treat wastewater but also recover valuable resources, including nutrients, biogas, and reusable water, which are crucial for the circular economy (Lettinga, 2001). In developed countries like Germany, resource recovery systems have been integrated into wastewater treatment infrastructure. Fuchs et al. (2019) explain that Germany's wastewater treatment plants have adopted these technologies as part of a broader effort to promote sustainability and lessen environmental impacts. The biogas produced often powers the treatment plant, and excess energy may be fed into the local grid.

4. Constructed Wetlands and Natural Treatment Systems

Wetlands and natural treatment systems, especially constructed wetlands, are engineered systems that harness natural processes like vegetation, soil, and microbial activity to purify water. Constructed wetlands replicate natural wetland ecosystems, using vegetation, microbial communities, and substrate media to treat wastewater. They are cost-effective, low-maintenance, and particularly suitable for rural or peri-urban areas. Evidence from studies shows their effectiveness in removing nutrients, pathogens, and heavy metals. They also help with habitat growth and boost biodiversity (Brix, 1997; Vymazal, 2011). Research consistently shows that constructed wetlands are effective in reducing various contaminants in wastewater. For instance, Vymazal (2013) notes that these systems are adept at removing organic matter, nitrogen, phosphorus, and heavy metals, which are common pollutants in domestic and industrial wastewater. Constructed wetlands also improve water quality and support biodiversity by creating valuable habitats for wildlife. In developing areas like Nigeria, constructed wetlands have proven to be a promising wastewater treatment solution, especially in communities where access to conventional methods is limited. Eze (2020) highlights the rising interest in constructed wetlands for treating domestic wastewater in Nigeria, where they have been successfully used in small-scale applications. Case studies in Nigeria and other African countries show that constructed wetlands are particularly effective for treating wastewater from small communities, including both domestic and agricultural runoff. Ogunjimi et al. (2022) discuss various case studies proving the feasibility of using constructed wetlands for decentralized wastewater treatment in rural areas, where they can significantly lower pollution levels and improve public health.

5. Biological Filtration and Anaerobic Systems

Biological filtration refers to using beneficial bacteria to cleanse water on a molecular level. Biological filtration systems, including trickling filters and biofilm reactors, depend on microbial communities to break down organic pollutants. Anaerobic digesters, often used in industrial and agricultural settings, produce biogas that can be harnessed for energy, closing the energy loop and reducing the system's carbon footprint (Lettinga, 2001; Tchobanoglous et al., 2014). According to Ng et al. (2017), biological filtration systems offer key advantages over traditional methods. One significant advantage is their low energy consumption. As these systems mainly rely on microbial processes, they require less external energy than energy-intensive methods like activated sludge treatment. In Nigeria, biological filtration systems, especially biofilters, have shown potential for treating industrial wastewater. Igbinosa and Okoh (2017) detail successful biofilter applications in Nigerian industrial wastewater treatment plants, particularly for

handling effluents with high organic loads. These systems effectively reduce pollutants in wastewater, and their use in industries such as food processing, textiles, and manufacturing has enhanced environmental protection and public health. The implementation of biofilters in industrial settings demonstrates that biological filtration can be a cost-effective and sustainable solution for managing wastewater in developing regions like Nigeria.

6. Application in Developing Countries and the Nigerian Context

Sustainable wastewater technologies aim to minimizing environmental impact while maximizing resource recovery and water reuse. Although these technologies have gained traction in developed countries, their uptake in developing countries, including Nigeria, remains limited. Challenges such as poor infrastructure, weak regulatory frameworks, lack of technical knowledge, and limited public awareness have hindered their progress (Adewumi et al., 2018). While several pilot projects have shown the feasibility of these systems in sub-Saharan Africa, large-scale implementation remains uncommon. Zhang et al. (2018) highlight the potential of wastewater treatment to promote a circular economy, where wastewater is seen not as waste but as a valuable resource that can be reused. In a circular economy, the idea of "waste" is reduced. Materials such as water, nutrients, and energy are recycled continuously. Wastewater treatment plants can help reduce environmental pollution, conserve natural resources, and support sustainability by using resource recovery methods.

7. Integration of Technologies:

Combining different wastewater treatment technologies is a new strategy that can improve the effectiveness, sustainability, and cost-efficiency of wastewater treatment systems. Several studies show that using various methods, such as constructed wetlands, biological filtration systems, and resource recovery technologies, can provide a layered approach to treat wastewater more effectively and recover valuable resources like biogas, nutrients, and clean water while reducing environmental impact.

One effective combined approach involves using constructed wetlands alongside biological filtration systems and resource recovery methods. Constructed wetlands rely on natural processes with plants, soils, and microbes to treat wastewater and have been proven to reduce organic pollutants, nutrients, and pathogens. However, they often need large spaces and can struggle with highly polluted wastewater or large volumes of it. In contrast, biological filtration systems, such as trickling filters or moving bed biofilm reactors (MBBRs), offer more compact and energy-efficient solutions by using microbial activity to break down organic matter and nutrients such as nitrogen and phosphorus. Integrating constructed wetlands with biological filtration allows these technologies to complement each other, efficiently treating both organic and nutrient pollutants across different types of wastewater.

Moreover, integrating resource recovery methods like anaerobic digestion, nutrient recovery, and biogas production with these treatment systems can create a closed-loop system. This means wastewater is treated and also used for generating resources. Anaerobic digestion produces biogas from organic matter and can work alongside constructed wetlands and biological filters to recover energy while treating wastewater. Similarly, nutrient recovery technologies, like struvite precipitation, can extract valuable nutrients like phosphorus and nitrogen, which can then be used as fertilizers in agriculture. This layered approach promotes a circular economy model where wastewater treatment focuses on generating resources rather than just disposal, which helps reduce reliance on non-renewable resources and lowers the environmental impact of wastewater management.

Zhang et al. (2018) point out that integrating multiple technologies not only leads to better wastewater treatment but also improves energy use in treatment plants. Combining methods like anaerobic digestion with biological filtration or constructed wetlands can lessen the need for external energy inputs, making these systems more energy-efficient. For instance, the biogas produced in anaerobic digestion can generate energy for the treatment process, potentially allowing the treatment plant to be energy-neutral or even energy-positive. Additionally, this integration can reduce the demand for external chemicals typically used in traditional treatment processes, lowering operational costs and improving the overall sustainability of the system.

While the theoretical benefits of integrating these technologies are well-known, practical implementation is still developing, especially in poorer countries. Many areas, especially rural and peri-urban regions in developing nations, lack the needed infrastructure and resources to use these complex integrated systems on a large scale. However, joint pilot projects between local governments, NGOs, and international development agencies show promise in demonstrating the potential of integrated systems to meet the wastewater treatment and resource recovery needs of these communities (Moelants, Awuah, & Buamah, 2008).

For example, pilot projects in sub-Saharan Africa, such as in Nigeria, have demonstrated that integrated systems combining constructed wetlands and resource recovery technologies can offer cost-effective, sustainable solutions for rural and peri-urban areas with limited access to traditional wastewater treatment infrastructure. These pilot projects often act as demonstration sites where local stakeholders, including community members, government agencies, and international partners, work together to design, implement, and assess these integrated systems. These projects highlight the technical feasibility of these systems while building local capacity and raising awareness about the benefits of combined wastewater treatment and resource recovery.

Kagimba et al. (2021) emphasize that collaboration is crucial for the success of these integrated systems. They argue that partnerships among local governments, NGOs, and development agencies are vital to overcoming barriers to adoption in developing countries, such as financial limitations, lack of technical know-how, and insufficient infrastructure. These collaborations can provide the needed support in funding, expertise, and capacity-building, helping pilot projects scale up and replicate in other areas. Furthermore, these projects demonstrate how to integrate multiple treatment technologies and yield valuable data on their performance and sustainability.

While challenges persist, such as high initial costs and technological complexity, these pilot initiatives offer proof of concept and insights for future efforts. In many cases, integrating multiple technologies leads to a complete approach to wastewater treatment that focuses on not just meeting environmental standards but also recovering valuable resources that can help offset treatment costs and contribute to the local economy (Zhang, Liu, & Chen, 2018).

In conclusion, the integration of technologies like constructed wetlands, biological filtration systems, and resource recovery methods shows great promise for creating more effective, sustainable, and cost-efficient wastewater treatment systems. By combining these technologies, treatment plants can reduce pollutants and recover resources like biogas, nutrients, and water, advancing a circular economy model. While the adoption of integrated systems is still early in many areas, especially in developing countries, collaborative pilot projects are providing important insights and demonstrating the potential of such systems to meet the needs of rural and peri-urban communities in water treatment and resource recovery. Going forward, ongoing collaboration, innovation, and expanding these technologies will be crucial for achieving sustainable, efficient wastewater management solutions worldwide.

III.   RESEARCH GAP

Although there has been significant progress in sustainable wastewater technologies globally, Nigeria is behind in both research and application. While research on individual sustainable wastewater treatment technologies is growing, there is a major gap in studies evaluating the combined application of these technologies in urban and industrial environments. Furthermore, existing research often emphasizes the technical aspects of these systems, while the socio-economic and policy factors influencing their broad adoption receive less attention. In addition, there is a lack of research on how to practically integrate resource recovery systems with traditional wastewater treatment plants, particularly in developing countries like Nigeria, where infrastructural constraints persist. Addressing these gaps will help Nigeria move toward environmentally responsible wastewater management and align with global climate resilience and sustainable development goals.

IV.   LIMITATIONS

1. Geographic Constraints: The success and efficiency of these technologies are affected by geographic factors such as climate, land availability, and local water quality. For instance, constructed wetlands may not work well in dry regions due to water scarcity, while biological filtration systems might not meet the needs of large urban populations. In Nigeria, for example, geographic and climatic conditions influence how these technologies can be applied in different regions (Ogunjimi et al., 2022).

2. Economic Barriers: The initial investment required for establishing sustainable wastewater treatment technologies, particularly for resource recovery systems, can be unreasonably high for many municipalities or rural areas with limited financial resources. Although these technologies can provide long-term savings and environmental benefits, the intial costs often make their adoption difficult. This is especially true in developing countries, where funding for infrastructure development is limited.

3. Operational and Maintenance Challenges: Although these systems are generally low-maintenance, they still require specialized knowledge and expertise to operate. Biological systems, in particular, depend heavily on the health of microbial communities, which can change due to environmental factors and need constant monitoring. In Nigeria, a shortage of skilled labor and inadequate training in advanced wastewater treatment technologies complicates the operation and maintenance of these systems (Igbinosa & Okoh, 2017).

4. Regulatory and Institutional Barriers: Regulatory structures may not always support adopting new wastewater treatment technologies. In some areas, traditional methods are heavily regulated, and new systems may not fit within existing frameworks, making widespread use difficult. The need to create regulations that enable sustainable wastewater management is evident in many developing nations, including Nigeria (Obi et al., 2018).

V.   SUMMARY OF RESEARCH

This study examined advancements in sustainable wastewater treatment technologies, focusing on constructed wetlands, biological filtration systems, and resource recovery methods. Each of these technologies shows promise in improving wastewater quality while minimizing environmental impact and promoting sustainability. Constructed wetlands, for instance, effectively remove nutrients and have low energy needs, making them ideal for rural or peri-urban areas.

Biological filtration systems offer scalable solutions for urban wastewater treatment, while resource recovery methods align with circular economy principles by converting wastewater into valuable resources like biogas and nutrients.

However, adopting and scaling these technologies face several challenges, including land requirements, high initial costs, and technical complexities. Further, integrating these systems into existing infrastructure calls for substantial policy and regulatory support. This paper concludes that successfully implementing these technologies requires a complete approach that considers technical, economic, and social factors.

VI. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

1. This study greatly enhances the existing knowledge of sustainable wastewater treatment technologies by carefully analyzing their use, advantages, and weaknesses within Nigeria's environmental, infrastructural, and socio-economic
2. context. While much of the global discussion on wastewater treatment focuses on advanced economies, this research fills a crucial gap by emphasizing the adoption and localization of environmentally sustainable technologies in developing countries.
3. By synthesizing recent advancements such as constructed wetlands, anaerobic digesters, biofiltration systems, and nutrient recovery methods, the study provides a relevant framework for implementing low-cost, energy-efficient, and eco-friendly treatment systems tailored to Nigeria's needs. It broadens understanding by examining how natural ecological processes can be designed to tackle urban wastewater challenges with minimal carbon and chemical footprints.
4. Additionally, the research offers new insights into how to scale and integrate these technologies within existing, often inadequate, wastewater infrastructures in Nigeria. It identifies key technical, institutional, and policy barriers to adoption and provides practical recommendations for overcoming these challenges through strategic planning, public-private partnerships, and community engagement.
5. This work also builds a valuable evidence base for policymakers, environmental engineers, and urban planners by highlighting the co-benefits of sustainable wastewater technologies not only for pollution control and resource recovery but also for enhancing climate resilience, improving public health, and supporting circular economy practices. By doing so, the study advances both academic discussions and practical solutions, serving as a foundational reference for future research, implementation strategies, and policy development in Nigeria and similar developing countries.

B. RECOMMENDATIONS

1. Governments should establish supportive policies that encourage the adoption of sustainable wastewater treatment technologies. This could include subsidies, tax incentives, and funding for research and development to reduce the initial costs of these technologies.
2. More funding for research and development is essential to improve the scalability and economic feasibility of these technologies. The focus should be on creating low-cost, high-efficiency solutions suitable for both urban and rural areas.
3. Urban planners and civil engineers should prioritize integrating sustainable wastewater treatment systems within broader urban water management plans. This could involve mixing various technologies for better performance, including combining resource recovery systems with existing infrastructure.
4. Public awareness campaigns and community engagement initiatives should be launched to educate stakeholders about the benefits of sustainable wastewater management. Cooperation between governments, the private sector, and local communities is crucial for the successful implementation of these technologies.

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