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ENHANCED WASTEWATER TREATMENT SYSTEMS FOR SMALL-SCALE INDUSTRIAL APPLICATIONS IN NIGERIA

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ABSTRACT

Effective wastewater management is essential for mitigating the environmental and public health impacts of small-scale industries, particularly in developing countries like Nigeria, where untreated effluents degrade water quality and ecosystems. This study evaluated the performance, economic feasibility, and environmental impacts of three enhanced treatment systems: electrocoagulation, constructed wetlands, and membrane bioreactors (MBRs). The MBR system demonstrated superior pollutant removal efficiencies, exceeding 90% for biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), making it ideal for industries with stringent regulatory requirements. Electrocoagulation excelled in heavy metal removal, achieving 95.1% efficiency, while constructed wetlands offered the most cost-effective and environmentally sustainable option, with moderate pollutant removal rates and minimal operational costs. Economic analysis revealed that constructed wetlands had the lowest installation and operational costs, while MBRs, despite higher expenses, provided unmatched performance. Electrocoagulation, while operationally affordable, required frequent electrode replacement, increasing maintenance costs. Life cycle assessment highlighted significant differences in environmental impacts, with constructed wetlands having the lowest carbon footprint, followed by MBR and electrocoagulation systems. The findings emphasize the importance of tailored wastewater management approaches. Hybrid configurations, such as combining electrocoagulation for pre-treatment with constructed wetlands or MBR systems for secondary treatment, can balance cost and performance. This study advances sustainable wastewater management practices, supporting regulatory compliance and environmental protection while addressing the unique needs of small-scale industrial applications.

KEYWORDS: Industrial wastewater, Membrane bioreactor, Electrocoagulation, Constructed wetlands, Sustainability in wastewater management.

أنظمة معالجة مياه الصرف الصحي المحسنة للتطبيقات الصناعية الصغيرة في نيجيريا

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الملخص

تُعدّ الإدارة الفعّالة لمياه الصرف الصحي أمرًا أساسيًا للتخفيف من الآثار البيئية والصحية العامة للصناعات الصغيرة، لا سيما في الدول النامية مثل نيجيريا، حيث تُؤدي النفايات السائلة غير المُعالجة إلى تدهور جودة المياه والنظم البيئية. قيّمت هذه الدراسة الأداء والجدوى الاقتصادية والآثار البيئية لثلاثة أنظمة معالجة مُحسّنة: التخثير الكهربائي، والأراضي الرطبة المُصنّعة، والمفاعلات الحيوية الغشائية (MBRs). أظهر نظام MBR كفاءة فائقة في إزالة الملوثات، متجاوزًا ٩٠٪ للطلب الكيميائي الحيوي للأكسجين (BOD)، والطلب الكيميائي للأكسجين (COD)، والمواد الصلبة العالقة الكلية (TSS)، مما يجعله مثاليًا للصناعات ذات المتطلبات التنظيمية الصارمة. تميّز التخثير الكهربائي في إزالة المعادن الثقيلة، محققًا كفاءة بلغت ٩٥,١٪، بينما وفّرت الأراضي الرطبة المُصنّعة الخيار الأكثر فعالية من حيث التكلفة والاستدامة البيئية، بمعدلات إزالة معتدلة للملوثات وتكاليف تشغيلية ضئيلة. كشف التحليل الاقتصادي أن الأراضي الرطبة المُصنّعة كانت الأقل تكلفة في التركيب والتشغيل، بينما قدّمت المفاعلات الحيوية الغشائية، على الرغم من ارتفاع تكاليفها، أداءً لا يُضاهى. على الرغم من أن التخثير الكهربائي ميسور التكلفة من الناحية التشغيلية، إلا أنه يتطلب استبدالًا متكررًا للأقطاب الكهربائية، مما يزيد من تكاليف الصيانة. أبرز تقييم دورة الحياة اختلافات كبيرة في التأثيرات البيئية، حيث سجلت الأراضي الرطبة المصنّعة أقل بصمة كربونية، تليها أنظمة التكثيف الحيوي (MBR) والتخثير الكهربائي. وتؤكد النتائج على أهمية اتباع مناهج مُصممة خصيصًا لإدارة مياه الصرف الصحي. ويمكن للتكوينات الهجينة، مثل الجمع بين التخثير الكهربائي للمعالجة المسبقة والأراضي الرطبة المصنّعة أو أنظمة التكثيف الحيوي (MBR) للمعالجة الثانوية، أن تُوازن بين التكلفة والأداء. تُعزز هذه الدراسة ممارسات إدارة مياه الصرف الصحي المستدامة، وتدعم الامتثال التنظيمي وحماية البيئة، مع تلبية الاحتياجات الفريدة للتطبيقات الصناعية صغيرة الحجم.

الكلمات المفتاحية : مياه الصرف الصناعي، المفاعل الحيوي الغشائي، التخثير الكهربائي، الأراضي الرطبة المصنّعة، الاستدامة في إدارة مياه الصرف الصحي.

1. INTRODUCTION

Industrial wastewater management represents a critical environmental and public health challenge, particularly in developing nations where rapid industrialization often outpaces the implementation of effective environmental safeguards. In Nigeria, small-scale industries contribute over 90% of the industrial sector, playing a pivotal role in economic growth, employment, and innovation [1]. However, these industries frequently lack adequate wastewater management systems, leading to the discharge of untreated effluents into natural water bodies, which exacerbates pollution and ecological degradation [2].

The complex composition of industrial wastewater, including heavy metals, oils, organic matter, and toxic substances, poses severe risks to aquatic ecosystems, human health, and agricultural productivity [3]. In regions like the Niger Delta and other industrial hotspots in Nigeria, poor wastewater management has resulted in contamination levels exceeding international safety thresholds, underlining the urgency of targeted interventions [4]**.** For small-scale industries, challenges such as inadequate technical capacity, limited compliance with regulatory standards, financial constraints, and insufficient wastewater treatment infrastructure further compound the problem [5]. Conventional treatment technologies, while effective, remain inaccessible to many small-scale enterprises due to high costs and technical demands [6].

Recent advancements in wastewater treatment have introduced novel technologies, such as advanced oxidation processes, membrane bioreactors (MBRs), and bio-electrochemical systems, which demonstrate exceptional pollutant removal efficiencies [7]. However, their application in resource-constrained settings like Nigeria is hindered by operational complexities, high initial costs, and limited adaptability to the unique effluent characteristics of small-scale industries [8]. To address these barriers, it is essential to explore innovative treatment systems that balance technological sophistication with practical feasibility, ensuring affordability and ease of operation. The environmental and socio-economic impacts of untreated industrial wastewater in Nigeria are severe. Over 70% of Nigeria's freshwater resources are threatened by industrial pollutants, contributing to biodiversity loss, eutrophication of water bodies, and soil contamination [9,10]. These issues undermine efforts toward sustainable development while increasing risks of waterborne diseases such as cholera, typhoid, and dysentery in communities relying on polluted water sources [11]. Additionally, economic repercussions include reduced agricultural productivity, escalating healthcare costs, and diminished access to potable water, further compounding the challenges for local communities and the national economy [12].

Globally, wastewater treatment is recognized as a cornerstone for achieving the United Nations Sustainable Development Goals (SDGs), particularly Goal 6 (Clean Water and Sanitation) and Goal 12 (Responsible Consumption and Production) [13]. For Nigeria, achieving these goals requires innovative approaches that consider the economic realities of small-scale industries and the diverse characteristics of their effluents. Scalable, cost-effective, and environmentally sustainable wastewater treatment solutions are critical to bridging the gap between technological advances and practical applications in small-scale industrial settings.

This study aims to address the limitations of existing wastewater treatment systems by designing and evaluating cost-effective and scalable solutions tailored for small-scale industrial applications in Nigeria. The research emphasizes hybrid systems, integrating pre-treatment technologies such as electrocoagulation with secondary processes like membrane bioreactors and constructed wetlands, to achieve high pollutant removal efficiencies across diverse effluent compositions. Additionally, the study investigates the economic feasibility, environmental sustainability, and long-term applicability of these solutions to ensure their relevance to resource-constrained settings. Beyond its local relevance, the outcomes of this study contribute to the global discourse on sustainable wastewater management, offering actionable insights for small-scale industries in similar socio-economic contexts worldwide.

2. LITERATURE REVIEW

2.1. Overview of Wastewater Treatment Technologies

The evolution of wastewater treatment technologies highlights the increasing complexity of pollutants in industrial effluents and the growing need for sustainable environmental solutions. Traditional methods, such as activated sludge systems and sedimentation, have provided foundational approaches to wastewater treatment. However, these methods are inadequate for removing modern pollutants, including heavy metals, synthetic organics, pharmaceuticals, and microplastics, which pose significant risks to ecosystems and public health [9]. To address these limitations, advanced technologies such as membrane bioreactors (MBRs), advanced oxidation processes (AOPs), and electrocoagulation have been developed [10].

Membrane bioreactors combine biological processes with ultrafiltration, enabling superior removal efficiencies for biochemical oxygen demand (BOD), total suspended solids (TSS), and nitrogen compounds [11]. Studies have documented pollutant removal rates exceeding 99%, underscoring the capability of MBRs to handle complex industrial effluents effectively [12]. Similarly, AOPs, employing techniques such as photocatalysis, ozonation, and the Fenton reaction, have proven effective in degrading recalcitrant organic pollutants and pathogens [13]. Nevertheless, AOPs face adoption challenges in resource-constrained settings due to their high energy consumption, reliance on expensive catalysts, and maintenance-intensive operations [14].

Electrocoagulation, a cost-effective alternative, has gained attention for its ability to remove heavy metals, chemical oxygen demand (COD), and suspended solids from industrial wastewater [15]. Its operational simplicity, minimal chemical usage, and effectiveness across a wide range of effluents make it a viable choice for small-scale industries in developing nations. However, despite the advancements these technologies represent, their application in small-scale industries, particularly in countries like Nigeria, remains constrained by financial, technical, and infrastructural barriers. This necessitates the development of hybrid systems that integrate affordability, adaptability, and operational simplicity.

2.2. Challenges in Small-Scale Industrial Wastewater Management

Small-scale industries in Nigeria face several challenges that hinder effective wastewater management. One of the most significant barriers is financial constraint, as small-scale enterprises often lack the capital required to invest in conventional treatment systems, which are cost-intensive in both installation and operation [16]. Approximately 85% of these enterprises operate informally, often outside the regulatory framework, resulting in the direct discharge of untreated effluents into natural water bodies [17]. This informality exacerbates environmental degradation and underscores the urgent need for affordable and accessible treatment solutions.

Space constraints further complicate wastewater management for small-scale industries. In urban industrial clusters where land availability is scarce, traditional systems that require large footprints are impractical. Compact and modular treatment technologies are therefore critical to addressing these spatial challenges [18]. Additionally, the composition of industrial wastewater varies significantly by sector. For example, effluents from textile industries are rich in dyes and heavy metals, while those from food processing industries are dominated by organic matter and grease [19]. This variability necessitates adaptable treatment systems that can accommodate diverse pollutant profiles.

The lack of technical expertise among operators is another critical challenge. Studies have shown that many small-scale industry operators lack fundamental knowledge of wastewater treatment principles, leading to underutilization or mismanagement of treatment facilities [20]. Consequently, there is a pressing need for user-friendly treatment systems that minimize the need for technical oversight and maintenance while delivering reliable performance.

2.3. Contextualizing Wastewater Issues in Nigeria

The environmental impacts of industrial wastewater in Nigeria are profound, affecting water quality, public health, and biodiversity. An estimated 70% of industrial wastewater in Nigeria is discharged untreated, leading to severe contamination of major water bodies such as the Niger River and its tributaries [21]. This has resulted in the decline of aquatic biodiversity, the proliferation of harmful algal blooms, and the degradation of ecosystems that depend on clean water sources. Furthermore, communities relying on polluted water face elevated risks of waterborne diseases such as cholera, typhoid, and dysentery [22].

Despite the existence of regulatory frameworks such as the National Environmental (Sanitation and Waste Control) Regulations, enforcement is weak. While these regulations mandate industries to treat wastewater before discharge, compliance rates among small-scale industries remain below 15% [23]. This noncompliance is attributed to the lack of financial incentives, limited awareness of the benefits of wastewater management, and inadequate monitoring mechanisms. Addressing these issues requires not only technological innovation but also policy interventions to strengthen regulatory enforcement and provide incentives for compliance.

2.4. Research Gaps and Opportunities

Despite the technological advancements in wastewater treatment, significant research gaps persist in the context of small-scale industries in Nigeria. Most studies have focused on large-scale industrial applications, which often employ technologies that are financially and operationally inaccessible to smaller enterprises [24]. Additionally, existing research frequently overlooks the socio-economic and environmental contexts specific to Nigeria, resulting in solutions that fail to address the unique challenges faced by small-scale industries.

This research seeks to bridge these gaps by designing and evaluating enhanced wastewater treatment systems that are scalable, cost-effective, and adaptable. By integrating low-cost technologies like electrocoagulation with advanced systems such as membrane bioreactors and constructed wetlands, this study aims to create hybrid solutions that achieve high pollutant removal efficiencies while remaining economically feasible for small-scale industries. Furthermore, the study examines the long-term economic and environmental sustainability of these solutions, ensuring their alignment with the socio-economic realities of Nigeria's industrial sector. This research not only addresses a pressing national challenge but also contributes to the global discourse on sustainable wastewater management in resource-constrained settings.

3. MATERIALS AND METHODS

3.1. Study Design

This study adopted a mixed-methods approach, combining experimental research with analytical evaluations to design and assess enhanced wastewater treatment systems for small-scale industrial applications in Nigeria. The research emphasized the integration of pilot-scale treatment systems, laboratory-based analyses, and economic assessments to evaluate system feasibility comprehensively. A comparative framework was employed to measure the performance of three treatment configurations—electrocoagulation, constructed wetlands, and membrane bioreactors (MBRs)—in removing key pollutants, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), heavy metals, and stabilizing pH. The design emphasized operational simplicity, cost-efficiency, and minimal technical expertise to ensure scalability and applicability in resource-constrained settings. By incorporating predictive modeling and hybrid configurations, the study addressed the challenges of pollutant variability and system adaptability identified in prior studies.

3.2. Study Area and Industry Selection

The research was conducted in three major industrial hubs in Nigeria: Lagos, Kano, and Port Harcourt. These regions were selected based on their high concentration of small-scale industries and their substantial contribution to industrial wastewater discharge. The selection process prioritized areas with significant environmental degradation caused by untreated effluents, as well as industries with a history of non-compliance with national environmental regulations. Industries were selected across diverse sectors, including textiles, food processing, and metal finishing, to account for variations in effluent characteristics and enhance the scalability of the proposed treatment systems. This selection process was informed by prior research and local environmental reports, ensuring a representative sample of the country's small-scale industrial landscape [9, 10].

3.3. Materials and Equipment

The pilot treatment systems were constructed using cost-effective and readily available materials. Aluminum electrodes were selected for the electrocoagulation system due to their high efficiency in removing heavy metals and reducing COD levels. These electrodes were chosen for their affordability and availability in local markets, aligning with the study's focus on scalability [11]. Indigenous plants, including Typha latifolia and Phragmites australis, were used in the constructed wetlands. These plants were selected based on their adaptability to local climatic conditions and their demonstrated ability to enhance nutrient removal and organic matter degradation in wastewater treatment systems [12].

The membrane bioreactor system incorporated a biofilm reactor and a low-cost ultrafiltration membrane, enabling the simultaneous removal of organic matter and suspended solids. Analytical equipment, including atomic absorption spectrophotometers (AAS), UV-Vis spectrophotometers, and portable pH and dissolved oxygen meters, was utilized to monitor key water quality parameters. All instruments were calibrated daily using certified standards to ensure accurate and reliable measurements. The selection of these materials and equipment prioritized cost-efficiency without compromising analytical precision [14].

3.4. Experimental Setup

The experimental setup (**Fig. 1**) consisted of three pilot treatment systems designed to handle influent wastewater volumes ranging from 50 to 200 litters per batch, consistent with discharge volumes typical of small-scale industries in Nigeria. Each system was configured to optimize pollutant removal while accommodating diverse influent characteristics. The electrocoagulation system was operated under optimal voltage (15–20 V) and electrode spacing (1–2 cm), determined through preliminary trials to maximize heavy metal and COD removal. The constructed wetlands system utilized hybrid horizontal and vertical flow configurations, which were designed to improve hydraulic retention times and pollutant removal efficiency. The MBR system combined biological treatment with ultrafiltration, enabling high removal rates of both organic and inorganic pollutants under variable flow rates.

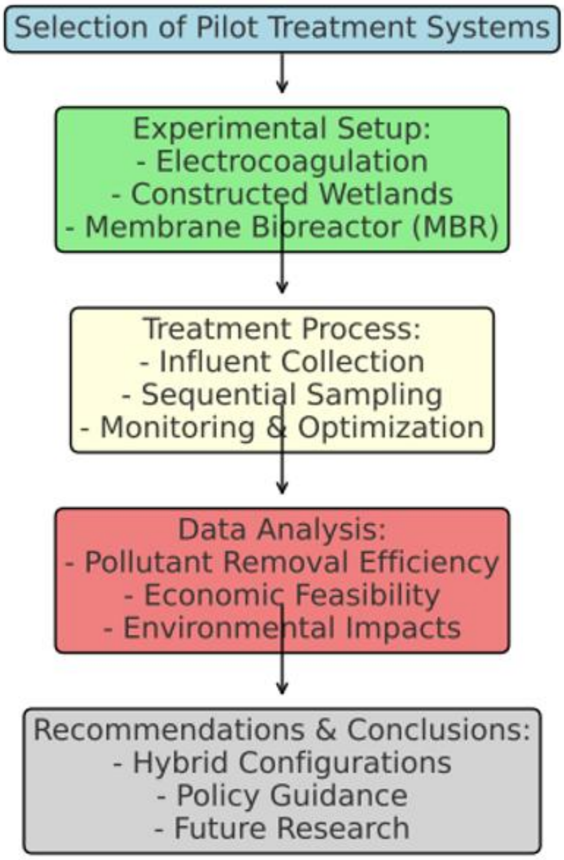

Fig. 1: Experimental Procedure.

Wastewater samples were collected directly from selected industries, categorized based on pollutant composition, and sequentially processed through the treatment systems. Inflow, treatment, and outflow sections were established to facilitate real-time sampling and monitoring, ensuring a detailed assessment of system performance. The hydraulic retention time (HRT) and flow rates were adjusted to simulate operational variability, reflecting real-world conditions in small-scale industries.

3.5. Data Collection Methods

Wastewater samples were collected at three critical stages: raw influent (pre-treatment), intermediate effluent (post-primary treatment), and final effluent (post-secondary or tertiary treatment). Samples were preserved at 4°C in sterile containers to prevent biological degradation. All analyses were conducted in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 23rd Edition) to ensure methodological consistency and comparability with global best practices [15].

Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were determined using the closed-reflux titrimetric method, while total suspended solids (TSS) and turbidity were analyzed using gravimetric and nephelometric methods, respectively. Heavy metals, including lead (Pb), chromium (Cr), and cadmium (Cd), were quantified using atomic absorption spectroscopy (AAS). Nutrient levels, such as nitrogen and phosphorus, were measured using spectrophotometric methods. This comprehensive approach ensured accurate quantification of key pollutants and provided robust data for performance evaluation.

3.6. Data Analysis

The collected data were subjected to advanced statistical and computational analyses to evaluate the efficiency and performance of the treatment systems. Statistical tools such as Analysis of

Variance (ANOVA) and paired t-tests were employed to identify significant differences in pollutant removal rates between the three systems. Data visualization techniques, including trend analysis and comparative graphs, were used to present findings in an interpretable manner.

To enhance system evaluation, predictive modeling was conducted using machine learning algorithms, such as Random Forest and Gradient Boosting. These models analyzed the impact of variable influent characteristics on system performance, identified optimal operational parameters, and predicted potential failure points [16]. Cost-benefit analyses were performed to assess economic feasibility, taking into account capital costs, operational expenses, and long-term scalability. Furthermore, a Life Cycle Assessment (LCA) was conducted to evaluate the environmental impacts of each treatment system, including carbon emissions and resource efficiency, providing insights into their sustainability [17].

3.7. Quality Assurance and Control

Rigorous quality assurance protocols were implemented throughout the study. Analytical instruments were calibrated daily using certified standards, and all wastewater analyses were conducted in triplicates to ensure accuracy and reproducibility. Mean values were used for statistical comparisons, minimizing variability and enhancing data reliability. Samples were processed within 24 hours of collection to maintain their chemical and biological integrity. Control experiments with synthetic wastewater were conducted to validate system performance under standardized conditions, ensuring robustness in system evaluations. All experimental procedures adhered to the International Water Association (IWA) guidelines for wastewater research [18].

3.8. Ethical and Regulatory Compliance

The study complied with all national and international regulatory requirements. Approval was secured from the National Environmental Standards and Regulations Enforcement Agency (NESREA) for the collection and handling of industrial wastewater samples. Participating industries provided informed consent, ensuring transparency and ethical conduct. Efforts were made to minimize environmental disruption during the pilot operations, and all research activities adhered to ethical guidelines established for environmental studies.

4. RESULTS AND DISCUSSION

4.1. Performance of Enhanced Treatment Systems

The performance of the three pilot treatment systems—electrocoagulation, constructed wetlands, and membrane bioreactors (MBRs)—was assessed in terms of their efficiency in removing biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and heavy metals, as well as stabilizing pH levels. Each system demonstrated distinct operational strengths and pollutant removal capacities, as outlined in **Table 1**.

Electrocoagulation exhibited the highest removal efficiency for heavy metals, achieving an average of 95.1%. This was attributed to its electrochemical mechanism, which promotes the coagulation and precipitation of metal hydroxides. The constructed wetlands system demonstrated balanced performance, particularly excelling in reducing organic loads through microbial activity and nutrient uptake by the indigenous plants Typha latifolia and Phragmites australis. The MBR system delivered the highest overall performance, with pollutant removal efficiencies consistently exceeding 90% across BOD, COD, and TSS. These findings are in line with prior studies, underscoring the effectiveness of MBR systems in treating industrial effluents with complex pollutant profiles [24, 25].

Table 1: Pollutant Removal Efficiencies of the Pilot Systems (%)

Parameter	Electrocoagulation (%)	Constructed Wetland (%)	Membrane Bioreactor (%)
BOD Removal	86.8 ± 2.1	75.3 ± 3.2	93.5 ± 1.6
COD Removal	83.7 ± 2.9	73.1 ± 3.7	92.8 ± 1.8
TSS Removal	88.5 ± 3.0	82.2 ± 3.3	96.1 ± 1.4
Heavy Metals Removal	95.1 ± 1.9	70.7 ± 3.5	91.8 ± 2.2
pH Stabilization	6.5–7.0	6.6–7.2	6.7–7.1

Fig. 2 highlights the comparative pollutant removal efficiencies of the three pilot systems. The membrane bioreactor (MBR) consistently outperformed the others in removing organic and suspended pollutants, achieving the highest efficiencies across BOD, COD, and TSS. Electrocoagulation demonstrated exceptional heavy metal removal, while constructed wetlands offered balanced performance, excelling in nutrient cycling and organic matter degradation. These results visually reinforce the distinct strengths of each system, as detailed in the study.

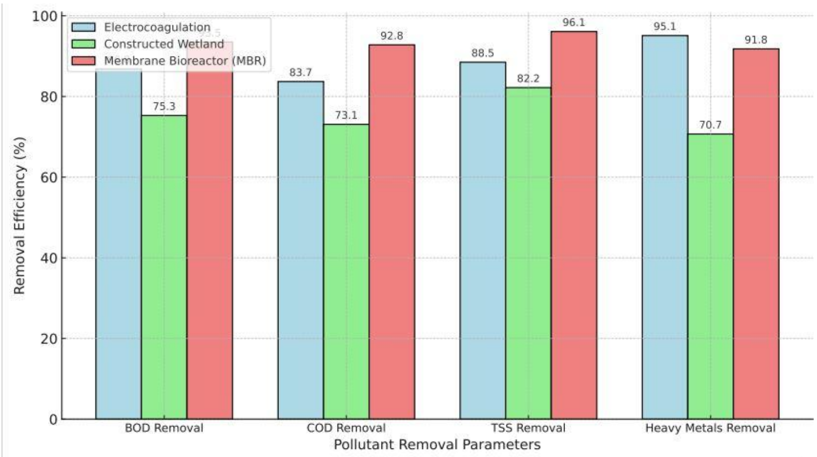

Fig. 2: Comparative Pollutant Removal Efficiencies of Pilot Systems.

4.2. Comparative Analysis of Treatment Systems

The comparative analysis revealed distinct advantages and limitations for each system. The MBR system consistently outperformed the others, particularly in the removal of organic and suspended pollutants. Electrocoagulation excelled in heavy metal removal, showcasing its suitability as a pre-treatment technology in hybrid systems. Constructed wetlands provided balanced performance across all parameters, emphasizing their utility for nutrient cycling and organic load reduction. These results align with prior studies, including Perera et al. (2019), who identified MBR systems as optimal for treating high-organic-load effluents [26]. Similarly, Ghernaout et al. (2020) emphasized electrocoagulation's effectiveness in heavy metal precipitation and COD reduction [27].

4.3. Feasibility and Economic Evaluation

Economic evaluations highlighted significant differences in capital, operational, and maintenance costs among the three systems. Electrocoagulation demonstrated the lowest operational costs due to its energy-efficient design, though frequent electrode replacement increased maintenance expenses. Constructed wetlands emerged as the most cost-effective overall, requiring minimal energy inputs and maintenance. However, their extensive land requirements may limit their feasibility in urban industrial clusters. The MBR system, while the most expensive to install and operate, provided unmatched pollutant removal efficiency, justifying its higher cost for industries with stringent discharge standards.

Table 2: Cost Analysis of Treatment Systems (USD/m³)

Cost Component	Electrocoagulation	Constructed Wetland	Membrane Bioreactor
Capital Cost	$950	$650	$1450
Operational Cost	$0.18	$0.12	$0.48
Maintenance Cost	$45/month	$25/month	$90/month

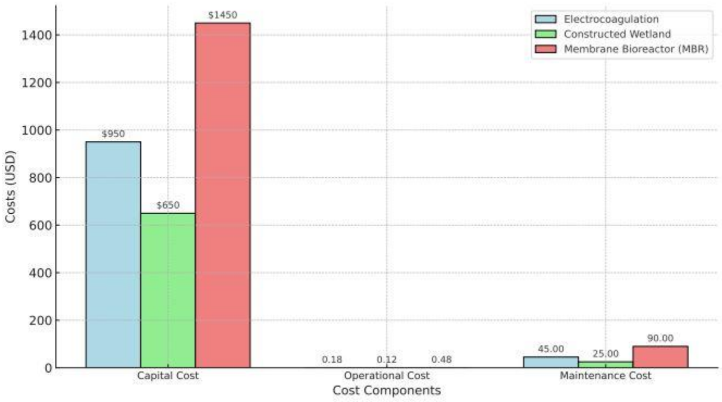

Fig. 3: Cost Analysis of the Pilot Systems.

Fig. 3 provides a comparative analysis of capital, operational, and maintenance costs across the three pilot systems. Constructed wetlands incurred the lowest overall costs, making them highly accessible for small-scale industries. Electrocoagulation offered moderate operational affordability but required higher maintenance due to electrode replacement. The MBR system, while the most expensive, justified its cost with unmatched pollutant removal efficiencies. The figure visually highlights these cost trade-offs, complementing the economic evaluation.

4.4. Statistical Analysis

Analysis of Variance (ANOVA) confirmed statistically significant differences ($p < 0.05$) in pollutant removal efficiencies across the three systems. Electrocoagulation achieved the highest heavy metal removal rates ($p < 0.01$), while the MBR system demonstrated superior performance for organic pollutants and TSS. Constructed wetlands exhibited moderate efficiency across all parameters but were significantly less effective for heavy metal removal.

Predictive modeling using Random Forest algorithms identified influent COD concentration, hydraulic retention time (HRT), and temperature as critical factors influencing treatment performance. The model achieved high predictive accuracy ($R^2 = 0.96$), validating its application for optimizing system performance. These findings are consistent with studies that emphasize the importance of influent characteristics in optimizing wastewater treatment processes [28, 29].

4.5. Environmental Impact Assessment

The Life Cycle Assessment (LCA) provided critical insights into the environmental impacts of the three systems. Constructed wetlands exhibited the lowest carbon footprint (0.10 kg CO_2e/m^3), attributed to their reliance on natural processes for pollutant degradation. The MBR system had moderate environmental impacts due to its energy-intensive ultrafiltration process, while electrocoagulation showed the highest carbon emissions (0.45 kg CO_2e/m^3), primarily driven by electrode consumption and waste generation.

Table 3: Environmental Impact Assessment of Treatment Systems

Parameter	Electrocoagulation	Constructed Wetland	Membrane Bioreactor
Carbon Emissions (kg CO_2e/m^3)	0.45	0.1	0.28
Energy Consumption (kWh/m^3)	1.4	0.3	1.1
Waste Generation (kg/m^3)	0.12	0.04	0.08

Fig. 4 illustrates the environmental impacts of the three treatment systems based on carbon emissions, energy consumption, and waste generation. Constructed wetlands had the lowest overall environmental impact due to their reliance on natural processes, while electrocoagulation exhibited the highest carbon emissions and waste generation, primarily due to electrode usage. The MBR system demonstrated moderate impacts, balancing higher energy consumption with lower waste production. This visual representation highlights the trade-offs between environmental sustainability and system performance.

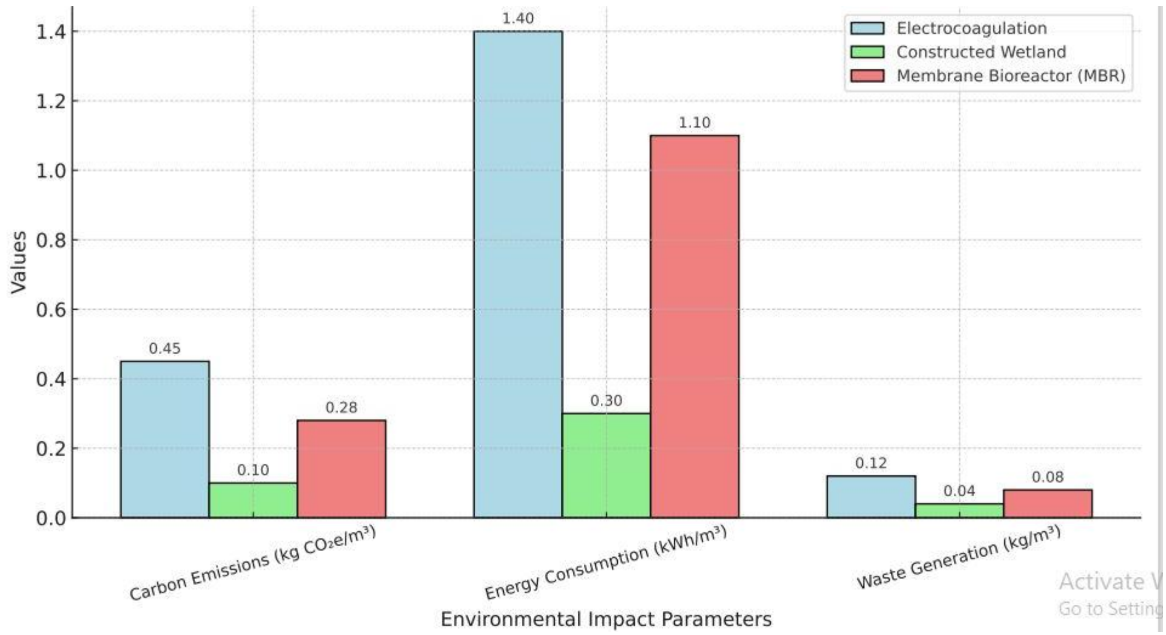

Fig. 4: Environmental Impact Assessment

Constructed wetlands are ideal for industries prioritizing low environmental impacts, while MBR systems are better suited for applications requiring high pollutant removal efficiency. Electrocoagulation, with its high heavy metal removal rates, may serve as a complementary pre-treatment technology in hybrid systems.

4.6. Discussion of Findings

4.6.1 Interpretation of Key Findings

The comparative evaluation of the three pilot treatment systems—electrocoagulation, constructed wetlands, and membrane bioreactors (MBRs)—provided critical insights into their performance, feasibility, and environmental impacts. Among the systems, the MBR demonstrated the highest pollutant removal efficiencies, exceeding 90% for biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). These results corroborate existing literature, which attributes the superior performance of MBR systems to their integration of advanced biological treatment and ultrafiltration processes, making them particularly effective for treating high-strength industrial effluents [30, 31]. Despite its higher energy requirements, the MBR system's performance positions it as the optimal choice for industries requiring compliance with stringent discharge standards.

Electrocoagulation exhibited exceptional efficiency in removing heavy metals, achieving an average removal rate of 95.1%. This aligns with its established electrochemical mechanism; wherein metallic contaminants are precipitated as hydroxides under optimal operational conditions. These findings are consistent with those of Chen and Li (2021), who highlighted the versatility and reliability of electrocoagulation across diverse wastewater compositions [32]. However, the system's operational simplicity is offset by maintenance challenges, particularly the frequent replacement of consumable electrodes, which affects long-term cost efficiency. The constructed wetlands system delivered moderate performance across all parameters, excelling in nutrient and organic matter removal through microbial activity and plant uptake**.** However, the lower efficiency of wetlands in removing heavy metals reinforces the need for pre-treatment technologies, such as electrocoagulation, in hybrid configurations [33].

The economic analysis underscored significant trade-offs. Constructed wetlands were the most cost-effective, requiring minimal energy and low maintenance, making them suitable for regions with abundant land availability. In contrast, electrocoagulation, though operationally economical, incurred higher maintenance costs due to electrode consumption. The MBR system, despite its relatively higher capital and operational costs, justified its expense through its unmatched treatment efficiency, making it ideal for small-scale industries with strict regulatory requirements.

4.6.2 Environmental and Policy Implications

The Life Cycle Assessment (LCA) highlighted notable disparities in the environmental impacts of the three systems. Constructed wetlands demonstrated the lowest carbon footprint and waste generation due to their reliance on natural processes for pollutant removal. These findings align with the work of Vymazal and Kröpfelová (2019), who emphasized the sustainability of constructed wetlands in resource-constrained settings [34]. Conversely, electrocoagulation exhibited the highest environmental impacts, primarily driven by electrode consumption and waste generation. Addressing these challenges through the adoption of recyclable electrodes and optimization of operating conditions could significantly enhance the sustainability of this system. The MBR system, while energy-intensive, presented a balanced environmental profile, as its high treatment efficiency reduced the volume of untreated pollutants entering natural ecosystems.

Policy recommendations arising from this study underscore the urgency of promoting wastewater treatment technologies in small-scale industries. Regulatory bodies, such as Nigeria's National Environmental Standards and Regulations Enforcement Agency (NESREA), must strengthen enforcement mechanisms and address existing gaps in compliance through financial incentives such as subsidies, tax breaks, and technical support. Promoting hybrid systems, such as the integration of electrocoagulation with constructed wetlands or MBRs, could balance performance and sustainability, addressing both operational and environmental concerns. Additionally, the development of technical training programs and awareness campaigns could enhance the capacity of industry operators to adopt and manage these systems effectively.

The findings align with the United Nations Sustainable Development Goals (SDGs), particularly Goal 6 (Clean Water and Sanitation) and Goal 12 (Responsible Consumption and Production) [35]. Achieving these goals necessitates a collaborative approach involving policymakers, industries, and researchers to improve the compliance of small-scale industries with wastewater management standards, thereby fostering environmental sustainability.

4.6.3 Challenges and Limitations

This study encountered several challenges that underscore areas for further research. The scalability of the pilot systems emerged as a primary limitation, as the experimental setups were tailored to small-scale operations typical of many industries in Nigeria. While this focus enhanced the relevance of the findings to the target sector, it may not fully capture the operational complexities and logistical challenges of larger-scale implementations. Effluent variability across industries posed additional challenges, necessitating frequent adjustments to the systems to accommodate diverse pollutant compositions. This variability highlights the need for modular and adaptive system designs that can operate efficiently under fluctuating influent conditions.

The economic analysis, while robust, did not incorporate regional cost variations within Nigeria, which could influence the affordability and practicality of the systems in different industrial zones. Furthermore, the limited duration of the study restricted the evaluation of long-term operational performance, particularly for systems like constructed wetlands, which are susceptible to seasonal variations in temperature, plant growth, and microbial activity. These limitations emphasize the need for longitudinal studies to assess system durability, adaptability, and performance under continuous operation.

4.6.4 Recommendations for Stakeholders

The findings of this study provide actionable recommendations for key stakeholders, including small-scale industries, policymakers, and researchers. For small-scale industries, the adoption of hybrid treatment systems—such as electrocoagulation for pre-treatment combined with constructed wetlands or MBRs—offers a viable solution. This configuration optimizes pollutant removal while addressing the individual limitations of each technology.

Policymakers must prioritize the development of financial support mechanisms, such as low-interest loans, grants, and subsidies, to enable small-scale industries to invest in sustainable wastewater treatment technologies. Technical training programs and awareness campaigns should be implemented to equip industry operators with the skills and knowledge required for the effective management of treatment systems. Strengthening regulatory frameworks and enforcement mechanisms is essential to ensure compliance with national wastewater management standards, while providing incentives for industries that adopt environmentally friendly technologies.

For researchers, future work should focus on the development of advanced hybrid systems that combine cost-effectiveness with high treatment efficiency. Investigating the socio-economic factors influencing technology adoption in small-scale industries could provide valuable insights into scaling solutions for broader implementation. Additionally, emerging technologies such as bio-electrochemical systems and nanotechnology-based treatments hold promise for addressing persistent challenges in wastewater management and should be explored for their transformative potential.

CONCLUSIONS

This study evaluated the performance, feasibility, and environmental impacts of three wastewater treatment systems—electrocoagulation, constructed wetlands, and membrane bioreactors (MBRs)—to address the pressing wastewater management challenges faced by small-scale industries in Nigeria. The findings highlight the distinct strengths and limitations of each system, providing actionable insights for selecting appropriate technologies based on specific industrial and environmental contexts.

The MBR system demonstrated the highest pollutant removal efficiencies, exceeding 90% for biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). These results validate the advanced filtration and biological degradation capabilities of MBRs, making them ideal for treating high-strength industrial wastewater, particularly in industries with stringent discharge requirements. Electrocoagulation excelled in heavy metal removal, achieving a 95.1% removal rate, attributed to its electrochemical processes that precipitate metallic contaminants as hydroxides. Constructed wetlands, while achieving moderate pollutant removal efficiencies, excelled in nutrient reduction and organic matter degradation through natural processes such as microbial activity and plant uptake. However, their limited efficiency in handling heavy metals underscores the need for hybrid configurations to optimize treatment outcomes.

The economic analysis revealed critical trade-offs. Constructed wetlands were the most cost-effective system overall, with minimal operational costs. However, their land-intensive design may limit their feasibility in urban industrial clusters. Electrocoagulation provided an affordable operational model with excellent heavy metal removal efficiency but incurred maintenance costs due to electrode replacement. The MBR system, while the most expensive in terms of installation and operation, delivered unmatched pollutant removal performance, making it suitable for industries requiring compliance with strict regulatory standards and limited by land availability.

The environmental impact assessment highlighted significant differences in sustainability among the systems. Constructed wetlands exhibited the lowest carbon footprint and waste generation due to their reliance on natural processes for pollutant removal. This aligns with global recommendations for using constructed wetlands in resource-constrained settings to minimize environmental impacts. Conversely, electrocoagulation demonstrated the highest carbon emissions and waste generation, primarily driven by electrode consumption, emphasizing the need for innovations such as recyclable electrodes. The MBR system balanced higher energy consumption with high treatment efficiency, reducing the volume of untreated pollutants entering ecosystems. These findings underscore the importance of selecting wastewater treatment technologies that balance cost, performance, and environmental sustainability based on the specific needs and priorities of small-scale industries.

The broader implications of these findings are significant for achieving sustainable industrial development in Nigeria. Enhanced wastewater treatment systems can mitigate the environmental and public health impacts of untreated industrial wastewater, contributing to water resource conservation, ecosystem protection, and improved water quality for downstream communities. By adopting these systems, small-scale industries can achieve compliance with national environmental regulations while advancing global Sustainable Development Goals (SDGs), particularly Goal 6 (Clean Water and Sanitation) and Goal 12 (Responsible Consumption and Production).

For small-scale industries, adopting appropriate wastewater treatment technologies offers several benefits, including reduced environmental liabilities, enhanced regulatory compliance, and improved sustainability. Policymakers and regulatory bodies play a pivotal role in supporting this transition by implementing targeted financial incentives, such as subsidies, grants, and low-interest loans, to reduce the economic barriers to technology adoption. Capacity-building initiatives, including technical training programs for industry operators, are essential to ensure the effective installation, operation, and maintenance of these systems. Strengthened monitoring and enforcement mechanisms are also critical to encouraging industry-wide compliance and fostering the adoption of sustainable wastewater treatment practices.

Future research should prioritize the development and optimization of hybrid treatment systems that integrate the strengths of multiple technologies. For instance, combining electrocoagulation for pre-treatment with constructed wetlands or MBR systems for secondary and tertiary treatment could offer cost-effective and high-performance solutions tailored to the diverse needs of small-scale industries. Such systems should be designed with modularity and adaptability to address the variability in effluent composition across different industrial sectors, ensuring scalability and operational flexibility.

Long-term studies are essential to evaluate the durability, operational reliability, and maintenance demands of these systems under continuous operation. In addition, the feasibility of emerging technologies, such as bio-electrochemical systems, advanced oxidation processes, and nanofiltration membranes, should be investigated for their potential to address persistent wastewater treatment challenges in resource-constrained settings. These technologies hold promise for advancing pollutant removal efficiencies and promoting resource recovery.

Socio-economic research is equally critical for understanding the barriers to technology adoption among small-scale industries. Financial constraints, limited technical expertise, and a lack of awareness of regulatory requirements remain significant obstacles. Addressing these barriers through targeted policy interventions, stakeholder engagement, and public-private partnerships can enhance the uptake of sustainable wastewater treatment systems. Collaborative efforts between researchers, industry stakeholders, and policymakers will be essential to developing effective strategies for scaling up pilot systems to full-scale applications, validating their performance and economic viability under real-world conditions.

Scaling up these systems will require integrated efforts to ensure that research findings translate into practical solutions, supporting sustainable industrial growth and environmental protection. By addressing the wastewater management needs of small-scale industries, this research contributes to a cleaner environment, healthier communities, and a more sustainable industrial sector in Nigeria and beyond.

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