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Article

Addressing wastewater treatment challenges in developing nations: A standardized framework for sustainable adsorption techniques in small and medium industries

Nnaemeka Chinedu[1], Queensley C. Chukwudum[2,*]

[1] Department of Chemical Engineering, Lakehead University, Thunder Bay, ON P7B 5E1, Canada
[2] Department of Insurance and Risk Management, University of Uyo, Uyo 520003, Nigeria
*** Corresponding author:** Queensley C. Chukwudum, queensleyv@yahoo.com

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Abstract: Water pollution has become a major challenge for many low-income and developing countries, leading to a shortage of clean water for daily activities. The review section of this study merges findings from different studies on wastewater treatment, which explored various techniques categorized primarily into physical, biological, and chemical methods. Among these, adsorption—a physical method was identified as the most cost-effective and environmentally friendly approach, primarily because the materials needed for it are widely available in nature. A major gap observed in all the studies reviewed was the lack of the application of the adsorption technique on an industrial scale, which stems mainly from the absence of standardization, as the study reveals. To bridge this gap, we develop a standardized framework for adsorption techniques in small and medium industries with clear guidelines on how to implement adsorption-based wastewater treatment. It incorporates sustainable practices, climate change considerations, and water risk management to ensure long-term environmental and economic benefits.

Keywords: adsorption techniques; low-cost adsorbents; water risk management; agricultural waste utilization; organic pollutant removal; unified standards; climate adaptation measure

1. Introduction

According to the United Nations, over 80% of the world's wastewater is released into the environment without undergoing treatment or reuse, with the percentage exceeding 95 in some of the least-developed countries. In developing nations, the quality of water significantly affects healthcare facilities. Unsanitary conditions heighten the risk of disease transmission for both patients and staff. Worldwide, 15% of patients acquire an infection during their hospital stay, with a significant portion of these cases occurring in low-income countries [1]. Research conducted by the World Health Organization indicates that many infections are attributed to inadequate access to clean water and poor hygiene practices [2]. Around 3.2 million children lose their lives each year due to unsafe drinking water and inadequate sanitation. Additionally, it is estimated that nearly half of all hospital beds are filled with patients recuperating from illnesses related to water contamination.

Due to inadequate funding, many developing nations are compelled to use water bodies as open sewers for waste. A notable example is the Ganges River in India, which is polluted with over 1.3 billion liters of domestic waste, 260 million liters of industrial waste, runoff from 6 million tons of fertilizer, 9000 tons of pesticides, and many animal carcasses [3].

Various research studies have been done on the different methods of cleaning wastewater, each with their advantages and disadvantages. Adsorption has been one of the most common techniques chosen because of its cost-effectiveness and environmental friendliness. The materials required to make the adsorbents are readily available in nature as agricultural wastes or sometimes as household wastes. The objective of this study is to briefly review wastewater treatment techniques for developing countries and further develop a standardized framework for adsorption techniques in small and medium industries with clear guidelines on how to implement adsorption-based wastewater treatment.

2. Literature review

There have been many contributions to literature in this field. However, adsorption techniques have received little attention due to their limited use at industrial scales. For instance, Ali et al. [4] investigated different types of low-cost waste materials/adsorbents that have been employed by various other authors. Their aim was to showcase the effectiveness of inexpensive materials in cleaning polluted water while retaining the quality of the water. This is particularly useful in low- to middle-income countries. The materials comprise fruit waste, coconut shells, discarded tires, bark and various tannin-rich substances, sawdust and other types of wood materials, rice husk, petroleum byproducts, fertilizer residues, fly ash, waste from the sugar industry, blast furnace slag, chitosan and seafood processing leftovers, seaweed and algae, peat moss, clays, red mud, zeolites, sediment and soil, ore minerals, and more. Nishat et al. [5] reviewed the different categories under which wastewater treatment techniques fall. The importance of the review hinged on the problems faced with the high levels of water pollution leading to water scarcity and the lack of an updated comprehensive categorization of existing wastewater treatment techniques. The categories covered were biological, physical, and chemical methods. Their functionalities, scope, mechanisms, advantages, and limitations were highlighted. Adsorption emerged as an efficient, cost-effective, and non-destructive technique for treating wastewater, capable of eliminating various pollutants, thus promoting environmental sustainability. They further suggested a combined application of traditional techniques merged with cutting-edge approaches where a biological step and an adsorption step go hand in hand. This will be significantly better than just a single technique.

The emerging issues with water pollution and how it is a challenge globally were addressed by [6]. Various methods of wastewater treatment were discussed in their study, namely chemical techniques, including Fenton oxidation and electrochemical oxidation; physical methods, including adsorption and membrane filtration; and various biological approaches. Adsorption was picked as the most simple, cost-effective, versatile, sustainable, and environmentally friendly technique in wastewater treatment. The research gaps mentioned related to pilot and large-scale systems and a wide range of applications. Additionally, Tsoutsa et al. [7] investigated the adsorption and coagulation procedures. Their in-depth review was aimed at showcasing how the production of natural adsorbents from agricultural products is more effective than synthetic materials because they can achieve the same levels of removal efficiency while being biodegradable and reusable. The problem highlighted was the degree of effectiveness, which was seen to vary depending on the concentration of the contaminants, with most requiring pre-treatment or modification to improve their removal rates.

Ngeno et al. [8] examined waste materials as cost-effective adsorbents for water and wastewater treatment in Africa, while Bekchanov et al. [9] investigated the functionalization of natural polymers like chitosan and cellulose for wastewater treatment. The former highlighted several waste-based adsorbents, including agricultural and industrial byproducts, and their performance in removing pollutants such as dyes and heavy metals. The latter demonstrated that functionalization enhanced the materials' adsorption efficiency and selectivity for contaminants, such as heavy metals and organic pollutants. Ngeno et al. [8] identified gaps in research related to scalability, regeneration, and localized applications. They recommended further exploration of waste valorization and government policies to promote sustainable practices in emerging economies. Bekchanov et al. [9] emphasized eco-friendliness and renewability, positioning functionalized natural polymers as a sustainable alternative for large-scale wastewater treatment.

Wang et al. [10] reviewed the applications of lignin-based adsorbents in wastewater treatment, focusing on their natural abundance, cost-effectiveness, and high adsorption potential for heavy metals and dyes. The study also explored methods for lignin modification to enhance adsorption efficiency and proposed further research into its industrial-scale applications. Regarding the potential of tea waste as a natural adsorbent for removing toxic pollutants such as dyes and heavy metals from wastewater [11] demonstrated its high removal efficiency, attributing it to the tea waste's natural porosity and surface functionality. They recommended scaling up its application and exploring hybrid adsorption systems. Abdulredha et al. [12] further examined the effectiveness of zeolite as a natural adsorbent for nitrogenous compounds in water treatment. The study detailed the material's ion-exchange properties and high adsorption capacity, which makes it particularly suitable for removing ammonia and nitrates. Challenges in regeneration and cost-effectiveness were identified as areas for improvement. Membrane-based adsorbents, which are a more recent form of adsorbents, were compared with powdered adsorbents in [13]. The authors’ findings indicated that the former, which are mostly based on polymeric membranes, are easier to handle, and they pose fewer recovery problems when compared to the latter.

From the studies examined, all the experiments undertaken by the researchers showed that adsorption is the most cost-effective and environmentally friendly technique for treating wastewater. There is also a recurring echo on the need for industrial-scale applications. However, the specific type of raw material to use varies with the type of pollutant in the water. This drastically limits the use of adsorption at the industrial scale. Different adsorbents from agricultural waste products have their shortcomings and areas where they are very active and versatile. **Table 1** presents the different approaches, limitations, and discrepancies in the existing adsorption raw materials used in the literature.

Table 1. Comparing different adsorption processes based on the type of waste material.

Classification of waste	Examples	Contaminants/Pollutants	Discrepancies based on some identified factors
Household waste	Fruit waste: banana peel [14], orange peel, and palm fruit bunch.	Fruit waste is used to remove dyes like Methylene blue, Orange II, Crystal Violet and Victoria Blue.	Factors are adsorption efficiency and size. Specifically for banana peel and orange, the findings have: 1) Adsorption efficiency: Banana peel of 12 g/L removed 72% of Malachite Green dye, while orange peel of 14 g/L removed 70% in 100 min.
	Coconut-coconut shell [15,16]	Coconut waste is used in the removal of phenol, hydrogen sulphides, and hydrogen peroxides	Factors are chemicals, temperature, and surface area. Differences are as follows: 1) Chemicals used in impregnation and treatment: $ZnCl_2$ impregnated coconut shell, H_3PO_4 impregnated coconut shell and NH_3 and $(NH_4)_2S_2O_8$ modified activated carbon; 2) Temperature: Activation at 900 °C and 450 °C; 3) Surface area: 800 m^2g^{-1} and 1200 m^2g^{-1}.
	Scrap tyres [17–19]	Scrap tires are used in the removal of phenol, Orange II and Acid Black 24 dyes	Factors are temperature and surface area. Differences are as follows: 1) Temperature: 400 to 700 °C; 2) Surface area: 320 m^2g^{-1} and 1260 m^2g^{-1}.
Agricultural waste	Tree bark [20,21]	Phenol, Acid Blue and Reactive Blue 4	Factors are chemical, time for heating, temperature, and surface area. Differences are as follows: 1) Temperature: 672 °C and 800 °C; 2) Surface area: 332 m^2g^{-1}; 3) Chemicals: N_2 and CO_2; 4) Time for heating: 6.5 h and 1 h.
	Sawdust [22]	Telon and Astrazone blue dyes	Factors are temperature, adsorption efficiency, and relationship type. Differences are as follows: 1) Adsorption efficiency: 82.2 mg dye/g of wood at 25 °C to 105.7 mg dye/g of wood at 80 °C. Given this adsorption efficiency, the authors get 3.29mg dye/g per 1 °C, which should give an expected value of 263.04 mg dye/g for 80 ºC. However, the experiment gives 105.7 mg dye/g. This suggests a non-linear relationship and not a linear one.
	Rice husk [23]	Methylene blue	Factors are types of activation and temperature. Differences are as follows: Chemical activation: At 600 °C, it had capacities of 0.24–0.72 mM for methylene blue. Steam activation: At 900 °C, it had capacities of 0.05 mM to 0.28 mM.
Soil and ore materials	Clays [24]	Phenol, Basic, and Acid blue	Factors are efficiency of activation and chemical. Differences are as follows: Chemicals: H_2O_2 AND HCl Activation efficiency: H_2O_2 was greater by 23% and 13% in the case of Blue 69 and Basic Red 22, respectively, while the efficiency of activation with HCl was greater by 30% and 16% when compared to natural clay.
	Zeolite [25]	Bisphenol, pyridine, and quinoline	Factors are chemicals. Differences are as follows: Chemical: Hexadecyltrimethylammonium and NaCl

A common limitation identified across all the studies reviewed is that the adsorption technique's feasibility for large-scale implementation is still quite poor. Hence, industries/factories or the government cannot utilize the technique in cleaning their wastewater or polluted water bodies.

Drawing from **Table 1**, one of the key factors limiting the large-scale use of these raw, cost-effective, and environmentally friendly materials is the lack of standardization in the processes. A general framework, thus, can support the usage of adsorption on an industrial scale. Moreover, in developing countries, most of the industries are of small or medium scale, making it more feasible to implement the adsorption techniques. We also observe that the use of the agriculture-related rubber seed husks as activated carbon has received very limited attention. This raw material is abundantly available in Nigeria, given the rubber plantations in different parts of the country. Chinedu [26] focused on the removal of phenol and Congo red dye from wastewater using rubber seed husks. Assessed on the following factors—initial dye concentration, temperature, pH, and adsorbent dosage—the adsorption capacity observed was 90 mg/g, which was among the top 6 adsorbents when compared to other adsorbents, as shown in **Table 2**.

Table 2. Adsorbents and their respective Adsorption capacities.

	Adsorbent	**Adsorbate (Dyes)**	**Adsorption capacity (mg/g)**
1	Neem Bark	Malachite green	0.36
2	Mango Bark	Malachite green	0.5
3	Core pith	Congo red	2.6
4	Palm shells	Reactive(blue/red)	14–24.7
5	Pine cone	Congo red	19.18
6	Orange peel	Aid violet	19.88
7	Banana peel	Basic blue	20.8
8	Rice husk	Acid yellow	36–86.9
9	Sugarcane bagasse	Congo red	38
10	Saw dust	Methylene blue	40
11	Date stones	Methylene blue	43.5
12	Papaya seeds	Congo red	71
13	Almond shells	Direct red	80–90.9
14	Rubber seed shell	Congo red	90
15	Coffee waste	Toluidine blue	142.5
16	Garlic peel	Methylene blue	142.9

3. Proposed standardized framework

This standardized framework offers a clear pathway for small and medium industries to adopt adsorption techniques in a uniform and sustainable manner, promoting both environmental and economic benefits while addressing pressing water and climate challenges.

3.1. The conceptual framing

The general summarized structure of our proposed framework is represented diagrammatically in **Figure 1**. The conceptual design illustrates a logical flow, starting with an overarching framework overview that leads into the identification of key components, including climate change integration and environmental considerations for sustainability. These components feed into a system of monitoring, reporting, and continuous improvement, ultimately culminating in a conclusion and implementation pathway that provides actionable steps for adopting adsorption techniques in small and medium industries, thus providing a holistic guide.

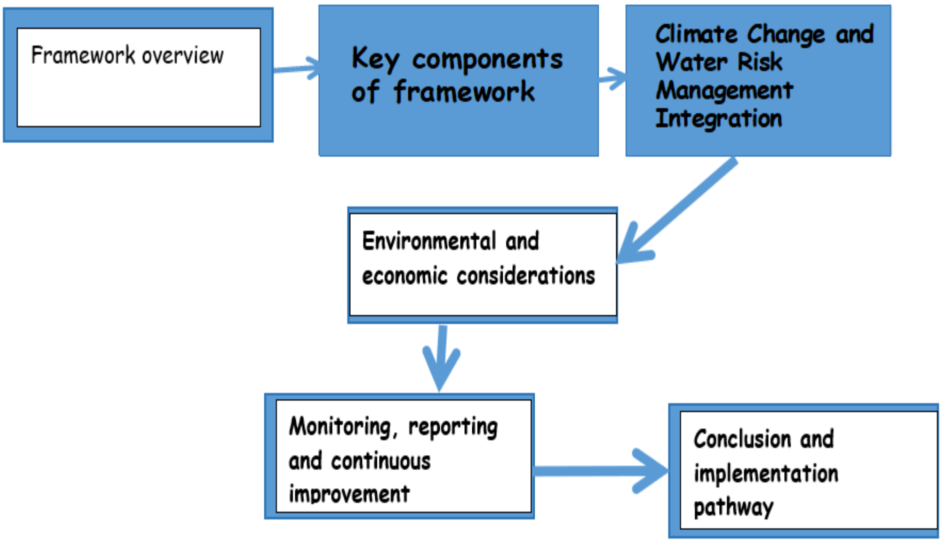

Figure 1. General design of the standardized framework.

3.2. A comprehensive outline of the standardized framework

Table 3 provides a granular perspective of the various components of the standardized framework.

Table 3. Standardized framework for adopting adsorption techniques at industrial scale.

Step 1. Framework Overview **Objective** **To create a uniform, scalable, and environmentally friendly approach to wastewater treatment using adsorption techniques, tailored for small and medium industries in developing countries. The framework emphasizes the use of locally sourced, low-cost adsorbents and includes guidelines on implementation, monitoring, and climate resilience.**		
Step 2. Key Components of the Framework		
2.1. Selection of Adsorbent Materials Criteria for adsorbents Must be **locally available**, low-cost, and preferably derived from agricultural or industrial waste. Examples include **rubber seed husk**, coconut shell, rice husk, fruit peels, and other biodegradable materials. Adsorbents should have the capacity for **high adsorption efficiency** for the specific contaminants in the wastewater. • **Evaluation and testing** Conduct **preliminary testing** to determine adsorption capacity for specific pollutants (e.g., dyes, heavy metals, phenols). Adsorbents should undergo **standardized lab testing** to assess properties such as **surface area, porosity, and reusability**.	**2.2.** Designing the Adsorption Process • **Adsorption system** Design modular adsorption units that can be scaled depending on the size of the industry. Ensure systems allow for the **reusability** and **regeneration** of adsorbents where possible. Integrate pre-treatment stages (e.g., filtration) to optimize adsorption efficiency. • **Process parameters** **Initial concentration of pollutants**: Standardize testing for different concentrations to ensure adsorbent effectiveness. **Adsorbent dosage**: Determine the optimal amount of adsorbent required for specific pollutants based on contaminant levels. **Contact time**: Define the time required for the adsorbent to interact with the contaminants effectively. **pH and temperature**: Standardize the operating pH and temperature for maximum adsorption capacity, considering variability in wastewater composition.	**2.3.** Implementation Guidelines • **Installation** Install **adsorption columns** or batch reactors designed for ease of maintenance and operation, ensuring scalability for small and medium-sized operations. Establish a **simple layout** that can be replicated across industries, regardless of local conditions. • **Monitoring and maintenance** Ensure regular monitoring of **adsorbent performance** through pollutant concentration testing before and after treatment. Develop **regeneration cycles** for adsorbents, where feasible, to increase material lifespan and reduce costs. Train staff to operate and maintain the system efficiently, ensuring the process is understood and repeatable.

Table 3. (*Continued*).

Step 3. Climate Change and Water Risk Management Integration	
3.1. Climate-Resilient Design • **Energy efficiency** Use **low-energy adsorption systems** that rely on gravity flow or minimal pumping to reduce the carbon footprint. Explore options for **renewable energy** (e.g., solar power) to support system operations in regions vulnerable to power outages. • **Water risk adaptation** In areas prone to drought, design systems that **minimize water usage** in pre-treatment processes, making them more resilient to water scarcity. Ensure the systems are adaptable to varying water qualities and pollutant loads that may fluctuate due to changing climate conditions.	**3.2.** Water Recycling and Reuse • **Circular water economy** Encourage industries to adopt **closed-loop systems**, where treated water can be reused in industrial processes or irrigation, reducing overall water consumption. Develop **guidelines** on reusing treated wastewater based on pollutant levels and water quality standards. • **Contingency plans** Incorporate **disaster preparedness** by designing systems that can handle **sudden increases in pollution** or **extreme weather events** like flooding, which may introduce additional contaminants.
Step 4. Environmental and Economic Considerations	
4.1. Sustainability and Compliance • **Environmental compliance** Ensure industries using adsorption techniques comply with **local environmental regulations** for wastewater discharge. Encourage collaboration with **government agencies** to establish water quality standards for different industries. • **Carbon footprint minimization** Use **natural, biodegradable adsorbents** to reduce waste and avoid the environmental impacts of synthetic materials. Encourage industries to periodically assess the environmental impact of their adsorption systems using **life cycle assessment (LCA)**.	**4.2.** Cost-Benefit Analysis • **Cost-effective solutions** Provide detailed cost assessments for adsorption systems, highlighting the **low initial investment** and **affordable maintenance** costs compared to other methods. Promote government subsidies or **public-private partnerships** to support the adoption of these systems in small and medium-sized enterprises (SMEs). • **Local economic impact** Encourage the **sourcing of adsorbents** from local farmers and suppliers, boosting local economies and reducing material transportation costs. Support the development of small-scale businesses focused on **adsorbent production** and **system maintenance**, creating jobs and fostering sustainability.
Step 5. Monitoring, Reporting, and Continuous Improvement	
5.1. Performance Monitoring • **Regular testing** Implement a **schedule for testing** the effectiveness of the adsorption process, including pollutant levels, system efficiency, and adsorbent degradation. Encourage industries to maintain **digital logs** of water quality data for reporting and future optimization.	**5.2.** Continuous Improvement • **Research and development** Promote **collaborative research** between academia, industries, and government on enhancing adsorbent materials, particularly focusing on locally sourced alternatives. Encourage ongoing experimentation with **hybrid systems** combining adsorption with other treatment techniques, such as **biological treatments**. • **Feedback mechanism** Establish a feedback loop for industries to share challenges and innovations in adsorption systems, helping improve the overall framework through shared knowledge.

Table 3. (*Continued*).

Step 6. Conclusion and Implementation Pathway	
6.1. Summary Unified Standards: This framework ensures uniformity across industries by establishing guidelines for material selection, process design, and performance monitoring.	**6.2. Implementation Pathway** 1. Pilot Programs: Collaborate with local governments and NGOs to launch pilot programs in regions with water scarcity issues. 2. Capacity Building: Provide training workshops for industry workers on the implementation and maintenance of adsorption systems. 3. Policy Integration: Advocate for the integration of the framework into national water management policies, promoting sustainable wastewater treatment practices.

4. Conclusion

The result of this review study shows that adsorption is the most cost-effective and environmentally friendly method of wastewater treatment. The raw materials can easily be gotten from agricultural products and used to treat wastewater safely in the environment. Such inexpensive ways of water treatment will greatly alleviate the water scarcity being experienced in many parts of Africa. For example, given that the rubber seed husk is a waste product that is very common in Nigeria, owing to the many rubber plantations in several states, key industrial stakeholders in Nigeria and the government need to pay keen attention to the adsorbing potential of rubber seed husk material for small- to medium-scale industrial purposes.

In general, the government, industries, and factories in developing countries should consider using the raw cheap, and indigenous materials that they have in their various regions and further design country-wise standardization frameworks to deploy adsorption techniques on a larger scale towards cleaning polluted water.

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