

Sustainable Biotreatment Approaches for Improving the Quality of Harvested Rainwater in Rural Communities

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Abstract

Water scarcity remains a significant global challenge, particularly in rural communities where access to safe drinking water is limited. Rainwater harvesting (RWH) has emerged as a viable alternative water source, yet concerns regarding its quality due to microbial contamination, heavy metal presence, and physicochemical imbalances necessitate effective treatment solutions. Conventional chemical treatments, such as aluminum sulfate (alum), present potential health risks and economic constraints, thereby necessitating the exploration of sustainable, eco-friendly alternatives. This study evaluates the efficacy of plant-based biotreatment methods using banana peels, orange peels, almond leaves, and *Moringa oleifera* seeds in improving the quality of harvested rainwater stored in underground tanks in Ogbadibo Local Government Area, Benue State, Nigeria. A total of 234 water samples were collected from 27 underground tanks across three different seasons to assess physicochemical (pH, turbidity, total dissolved solids, heavy metals) and microbiological parameters (total viable count [TVC], total coliform count [TCC]). Experimental biotreatment was conducted using varying concentrations of the selected plant wastes, and the results were statistically analyzed using ANOVA and Duncan Multiple Range Test (DMRT). The findings revealed significant contamination in untreated rainwater, exceeding WHO permissible limits for microbial loads and physicochemical properties. Among the plant-based treatments, almond leaves demonstrated the highest microbial reduction (TVC: 108 CFU/ml, TCC: 58 CFU/100ml), followed by *Moringa oleifera* seeds. The treated water exhibited improved pH stability (6.5–8.5) and reduced total dissolved solids, enhancing its suitability for domestic use. Comparative analysis indicated that plant-based treatments were as effective as aluminum sulfate in microbial reduction but with the added benefits of being non-toxic, cost-effective, and environmentally sustainable. This study underscores the potential of plant-based biotreatment as an innovative, scalable solution for rural water purification. While the biotreatment methods significantly improved water quality, none fully met the WHO standard for microbial parameters, indicating the need for further optimization. The integration of these natural purification techniques into local water management policies can enhance water security, reduce dependence on chemical treatments, and promote public health sustainability. Future research should explore advanced combinations of plant materials and process modifications to achieve superior water quality standards.

Keywords: Rainwater harvesting, plant-based biotreatment, microbial contamination, water quality, *Moringa oleifera*, sustainable water management.

I. INTRODUCTION

➤ Background of the Study

Water scarcity remains a pressing global challenge, with over 2.2 billion people lacking access to safely managed drinking water services (World Health Organization [WHO], 2020). In sub-Saharan Africa, where rapid population growth and climate variability exacerbate water shortages, rainwater harvesting (RWH) has been identified as a viable alternative to conventional water

sources (UNESCO, 2019). RWH is a sustainable water management technique that involves collecting and storing rainwater for domestic, agricultural, and industrial use (Mekonnen & Hoekstra, 2016). However, concerns persist regarding the quality of harvested rainwater, particularly in rural areas where storage is primarily done in underground tanks without adequate treatment. This often leads to microbial contamination and heavy metal accumulation, posing significant health risks (Kus et al., 2022; Idoko et al, 2024).

Nigeria, like many developing countries, faces the dual challenge of water scarcity and contamination. According to the National Bureau of Statistics (NBS, 2021), only 67% of Nigerian households have access to improved water sources, with rural communities disproportionately affected. In Benue State, where this study is focused, rainwater serves as a primary water source due to unreliable public water supply systems. However, studies have shown that stored rainwater often exceeds permissible limits for microbial and physicochemical contaminants, increasing the risk of waterborne diseases such as typhoid, cholera, and diarrhea (Ezenwaji et al., 2019; Adesakin et al., 2020). The importance of water quality monitoring in ensuring safe drinking water is further highlighted in studies on sustainable environmental management and renewable energy policies, which emphasize the need for improved water resource governance (Idoko et al., 2024).

The physicochemical properties of harvested rainwater, including pH, turbidity, and total dissolved solids (TDS), are influenced by multiple factors such as the type of catchment surface, storage conditions, and atmospheric deposition (Kus et al., 2022). A study conducted in Nigeria found that 72% of stored rainwater samples had pH levels outside the WHO-recommended range of 6.5–8.5, while 58% exceeded the acceptable threshold for turbidity (Ezenwaji et al., 2019). Furthermore, microbial contamination remains a major concern, with total coliform counts (TCC) frequently surpassing WHO limits of 0 CFU/100ml, indicating fecal contamination (Adesakin et al., 2020). Research in geochemical and mineralogical assessments has shown that heavy metal accumulation in stored water is significantly influenced by environmental factors, further reinforcing the need for targeted mitigation strategies (Eguagie, et al., 2025).

Given the limitations of conventional chemical treatments such as aluminum sulfate, which pose health risks due to residual chemical content, researchers have turned to plant-based biotreatment methods as sustainable alternatives (Mekonnen & Hoekstra, 2016). Biotreatment using plant materials such as *Moringa oleifera* seeds, banana peels, and almond leaves has shown promising results in improving water quality by reducing microbial loads and heavy metal concentrations (Kus et al., 2022). These natural purification methods align with global efforts to promote eco-friendly and cost-effective solutions for rural water security (UNESCO, 2019). Furthermore, recent studies on sustainable waste utilization emphasize the importance of integrating bioenergy solutions in water management to enhance environmental sustainability (Idoko et al., 2024).

This study aims to assess the quality of harvested rainwater stored in underground tanks and evaluate the effectiveness of plant-based biotreatment in improving its safety for domestic use. By exploring the efficacy of banana peels, orange peels, almond leaves, and *Moringa oleifera* seeds, this research contributes to the growing body of knowledge on sustainable water management practices. The findings will provide critical insights for

policymakers, environmental scientists, and rural communities seeking viable alternatives to conventional water treatment methods (Idoko et al., 2024).

➤ Statement of the Problem

Access to safe drinking water remains a fundamental global challenge, particularly in developing countries where infrastructure deficits and environmental contamination threaten water security (World Health Organization [WHO], 2021). According to the United Nations, nearly 2.2 billion people worldwide lack access to safely managed drinking water services, with over 159 million relying on untreated surface water sources (United Nations [UN], 2020). In Nigeria, the situation is dire, with approximately 33% of the population lacking access to improved drinking water sources, and rural communities being the most affected (National Bureau of Statistics [NBS], 2021).

Rainwater harvesting (RWH) is widely used as an alternative water source in many rural areas, yet concerns about its safety persist due to microbial and chemical contamination. Research has shown that stored rainwater often contains high levels of total coliforms, fecal coliforms, and other pathogenic microorganisms, making it unsuitable for direct consumption without treatment (Afolayan et al., 2021). A study conducted in Benue State, Nigeria, found that 68% of rainwater samples exceeded the WHO permissible limit of 0 CFU/100ml for coliform bacteria, highlighting significant contamination risks (Ezenwaji et al., 2020). Additionally, heavy metals such as lead (Pb) and cadmium (Cd) were detected in concentrations exceeding WHO-recommended thresholds, raising further health concerns.

The contamination of harvested rainwater can be attributed to various environmental and infrastructural factors, including the nature of the catchment system, atmospheric deposition of pollutants, and poor storage conditions (Mekonnen & Hoekstra, 2022). In many rural communities, rainwater is collected from rooftops that accumulate dust, bird droppings, and industrial pollutants before being stored in underground tanks that lack proper filtration or treatment systems (Afolayan et al., 2021). The absence of effective water treatment mechanisms has led to increased incidences of waterborne diseases such as cholera, typhoid, and dysentery in affected regions (Ezenwaji et al., 2020).

Conventional water treatment methods, such as the use of chlorine and aluminum sulfate (alum), have been employed to improve rainwater quality. However, these methods pose economic and health challenges due to cost constraints, limited availability in rural areas, and concerns about residual chemical toxicity (Mekonnen & Hoekstra, 2022). As a result, there is an urgent need to explore sustainable and cost-effective alternatives for rainwater purification. Biotreatment methods using plant-based materials have gained attention as eco-friendly and effective solutions for water treatment. Studies have demonstrated that materials such as *Moringa oleifera* seeds, banana peels, and almond leaves possess antimicrobial and adsorptive properties that can

significantly reduce microbial loads and heavy metal concentrations in stored water (Afolayan et al., 2021).

This study seeks to address the critical issue of rainwater contamination by evaluating the effectiveness of plant-based biotreatment methods in improving water quality. By analyzing the physicochemical and microbiological characteristics of stored rainwater and assessing the efficacy of plant wastes in reducing contaminants, this research aims to provide a sustainable and practical solution for water purification in resource-limited settings. The findings will contribute to the development of water management policies that promote safe, affordable, and environmentally friendly treatment technologies for rainwater harvesting systems.

➤ Research Objectives

- To assess the physicochemical and microbiological quality of harvested rainwater stored in underground tanks across different seasons.
- To evaluate the effectiveness of plant-based biotreatment methods (*Moringa oleifera* seeds, banana peels, orange peels, and almond leaves) in improving water quality.
- To compare the efficacy of plant-based treatments with conventional aluminum sulfate (alum) treatment in microbial and heavy metal reduction.
- To determine the compliance of treated rainwater with WHO drinking water standards and its suitability for domestic use.

➤ Justification of the Study

Access to safe drinking water is a fundamental human right, yet millions of people, particularly in rural communities, rely on untreated rainwater, exposing them to serious health risks. The prevalence of waterborne diseases such as cholera, typhoid, and diarrhea highlights the urgent need for effective water treatment solutions that are both accessible and sustainable. This study addresses a critical gap by exploring plant-based biotreatment methods as an eco-friendly and cost-effective alternative to conventional chemical treatments, which are often expensive and pose potential health risks due to residual toxicity.

The use of natural treatment agents such as *Moringa oleifera* seeds, banana peels, orange peels, and almond leaves provides a low-cost and readily available solution for improving rainwater quality, particularly in resource-limited areas. Previous studies have demonstrated that plant-based purification methods effectively reduce microbial loads and heavy metal contamination in water, making them a viable option for rural communities. By evaluating the efficacy of these biotreatment methods in comparison with aluminum sulfate (alum), this research will provide evidence-based recommendations for integrating sustainable water treatment practices into local policies and community water management programs.

Furthermore, the study's findings will contribute to global efforts to promote environmental sustainability by reducing reliance on synthetic chemicals for water

purification. The research aligns with the United Nations Sustainable Development Goal (SDG) 6, which emphasizes the need for clean water and sanitation for all. By identifying effective, locally available, and environmentally friendly water treatment methods, this study has the potential to enhance water security, improve public health, and support sustainable water management strategies in developing regions.

➤ Organization of the Paper

This paper is structured into five main sections to ensure a comprehensive analysis of the study.

• Section 1: Introduction –

This section provides the background of the study, statement of the problem, research objectives, justification of the study, and an overview of the paper's organization. It establishes the need for effective rainwater treatment solutions and the significance of plant-based biotreatment methods.

• Section 2: Literature Review –

This section critically examines existing studies related to rainwater harvesting, water quality concerns, conventional and alternative treatment methods, and the effectiveness of plant-based purification techniques. The review highlights gaps in knowledge and situates the study within the broader academic discourse.

• Section 3: Methodology –

This section outlines the research design, study area, sample collection procedures, laboratory analysis techniques, and data analysis methods. It provides details on how the plant-based biotreatment experiments were conducted and the statistical tools used to interpret results.

• Section 4: Results and Discussion –

This section presents the findings of the study, including physicochemical and microbiological assessments of harvested rainwater, the effectiveness of different biotreatment methods, and comparative analyses with conventional treatment approaches. The results are analyzed and discussed in relation to existing literature.

• Section 5: Conclusions and Recommendations –

This section summarizes key findings, draws conclusions on the effectiveness of plant-based biotreatment methods, and provides recommendations for policy implementation, further research, and sustainable water management practices.

II. LITERATURE REVIEW

➤ Rainwater Harvesting: Global and Local Perspectives

Rainwater harvesting (RWH) has been widely recognized as an effective water conservation strategy, particularly in regions where access to clean water is limited (UNESCO, 2020). The technique involves the collection, storage, and utilization of rainwater from rooftops, land surfaces, or rock catchments to supplement water supply for domestic, agricultural, and industrial purposes (Mekonnen & Hoekstra, 2021). Globally, RWH has been successfully implemented in both developed and

developing countries as a means of mitigating water scarcity, reducing dependency on groundwater resources, and improving resilience against climate change-induced droughts (Kus et al., 2022). In regions such as India and Australia, large-scale RWH initiatives have been integrated into national water policies, with the Indian government mandating rainwater storage systems in urban buildings, leading to a 20% increase in water availability (Sharma & Singh, 2021).

Rainwater harvesting (RWH) plays a crucial role in sustainable water management, particularly in regions facing water scarcity and unreliable supply. Figure 1 illustrates the key dynamics of RWH, including its benefits, challenges, regional strategies, and global implementation. This framework helps in understanding Nigeria's context and the tailored approaches needed for effective adoption.

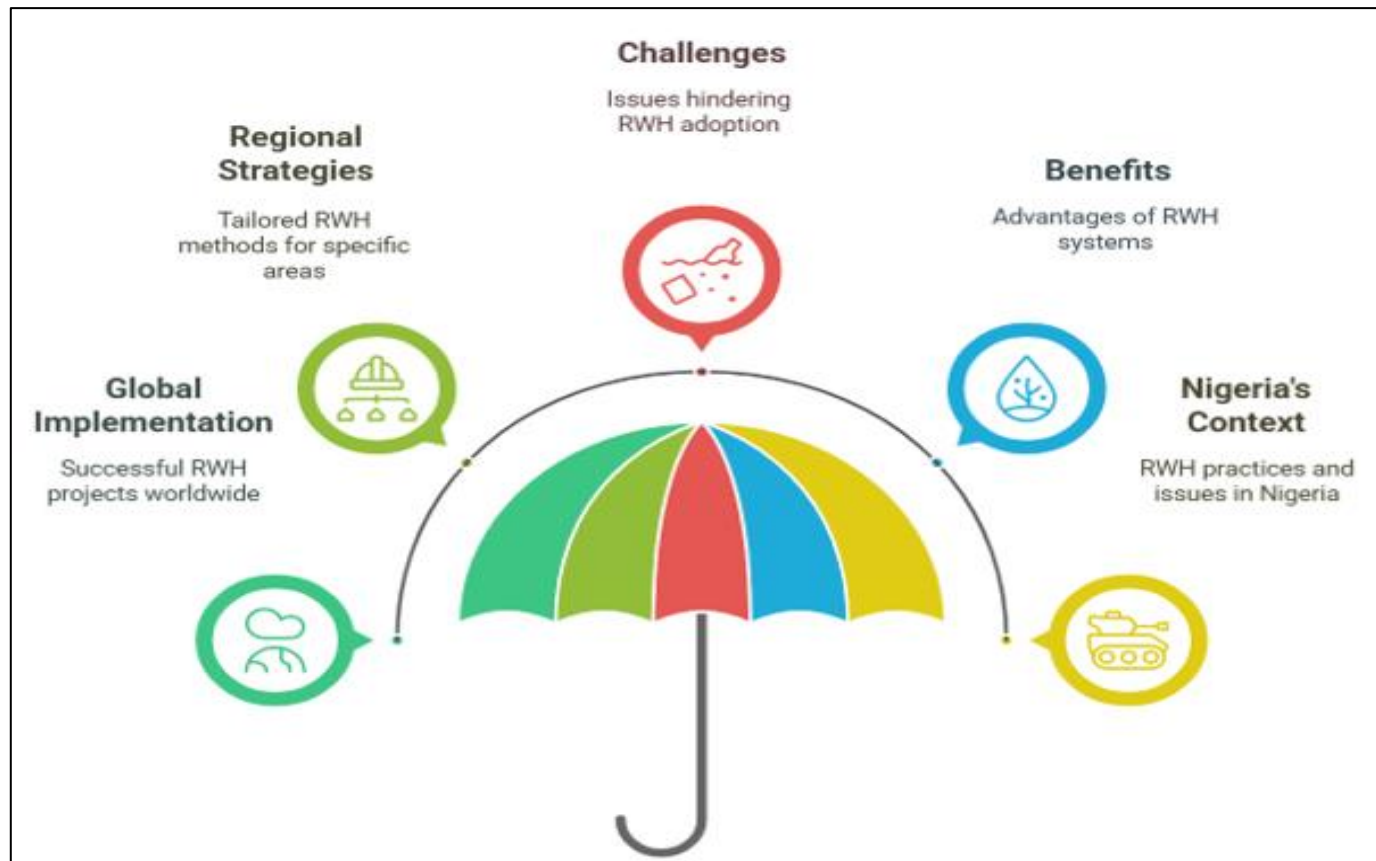


Fig 1 Rain Water Harvesting Dynamics

In Africa, RWH plays a crucial role in addressing water insecurity, especially in arid and semi-arid regions where annual rainfall is unpredictable (Gwenzi et al., 2020). Countries like Kenya and Ethiopia have adopted various RWH techniques, including rooftop harvesting, underground storage tanks, and surface runoff collection to support rural communities (Mekonnen & Hoekstra, 2021). According to the World Bank (2022), approximately 34% of African households rely on harvested rainwater as their primary water source, highlighting its significance in water resource management. However, challenges such as poor storage infrastructure, contamination risks, and limited technical knowledge hinder its widespread adoption and effectiveness (Sharma & Singh, 2021).

In Nigeria, RWH has gained increasing attention as a viable alternative to public water supply systems, which often fail to meet the growing demand due to infrastructure deficits and climate variability (Ezenwaji et al., 2021). Studies indicate that in states like Benue, Kaduna, and Enugu, over 60% of rural households depend on harvested rainwater for drinking and domestic use, given the unreliable nature of municipal water supplies (Musa &

Ibrahim, 2022). However, rainwater quality remains a major concern, as microbial contamination and the presence of heavy metals often exceed World Health Organization (WHO) permissible limits (Gwenzi et al., 2020). In a study conducted by Ezenwaji et al. (2021), 73% of tested rainwater samples from rural Nigeria showed coliform contamination above WHO's acceptable standard of 0 CFU/100ml, necessitating the need for effective treatment solutions.

Despite these challenges, RWH remains a sustainable and cost-effective solution for improving water accessibility in Nigeria. Researchers have advocated for the adoption of biotreatment methods using plant-based materials such as *Moringa oleifera* seeds and banana peels to enhance water quality before consumption (Kus et al., 2022). Additionally, government intervention in promoting awareness, improving storage facilities, and integrating RWH into national water policies could significantly improve water security and public health outcomes. Given its potential to provide clean and affordable water, further research and investment in RWH technologies are essential for ensuring long-term sustainability in Nigeria's water sector.

➤ *Water Quality Indicators in Harvested Rainwater*

Water quality assessment is crucial in determining the suitability of harvested rainwater for domestic and potable use. The quality of collected rainwater is influenced by various environmental and storage factors, including air pollution, roofing material, storage conditions, and microbial contamination (Mekonnen & Hoekstra, 2021). While rainwater is often considered a relatively clean source, studies indicate that it frequently contains contaminants exceeding permissible limits set by the World Health Organization (WHO), raising concerns

about its direct consumption without proper treatment (Ezenwaji et al., 2021).

Figure 2 illustrates the rainwater quality assessment framework, categorizing water safety based on microbiological and physicochemical contamination levels. It highlights four key classifications—safe for consumption, potentially unsafe, treatment required, and unsafe for consumption—to determine the suitability of rainwater for human use. This model aids in identifying necessary treatment interventions to ensure safe and sustainable water consumption.

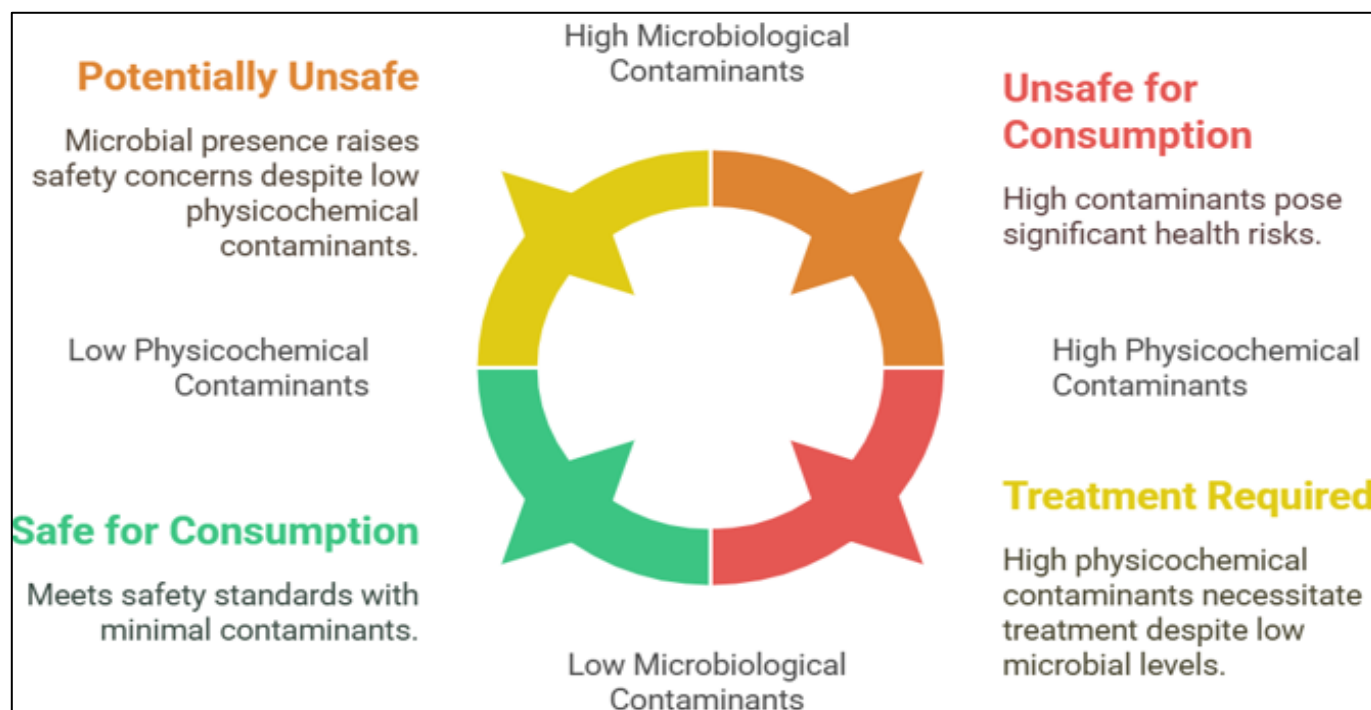


Fig 2 Rainwater Quality Assessment

• *Physicochemical Parameters*

Physicochemical properties such as pH, turbidity, total dissolved solids (TDS), and heavy metal content significantly affect the quality of harvested rainwater. The pH of rainwater should ideally fall within the WHO-recommended range of 6.5 to 8.5 (WHO, 2020). However, studies have found variations due to atmospheric deposition and storage conditions. In a study conducted across 10 Nigerian states, 62% of harvested rainwater samples had pH levels below 6.0, indicating acidic conditions that could contribute to metal leaching from storage tanks and pipes (Musa & Ibrahim, 2022).

Turbidity, which measures the clarity of water, is another critical parameter. High turbidity levels indicate suspended particles, organic matter, and microbial presence, which can compromise water safety. WHO recommends a turbidity level of less than 5 NTU (nephelometric turbidity units) for drinking water (WHO, 2020). However, research in Benue State, Nigeria, found that 71% of rainwater samples exceeded this limit, with recorded values between 5.8 and 17.2 NTU due to sedimentation and biological contaminants (Afolayan et al., 2021).

Figure 3 presents the quality parameters of harvested rainwater in Nigeria, focusing on pH levels, turbidity, and lead (Pb) contamination. The data highlight concerns such as acidic rainwater (pH < 6.0), high turbidity (>5 NTU), and lead pollution (>0.01 mg/L), indicating potential health risks. These findings emphasize the need for effective treatment methods to ensure safe rainwater consumption.

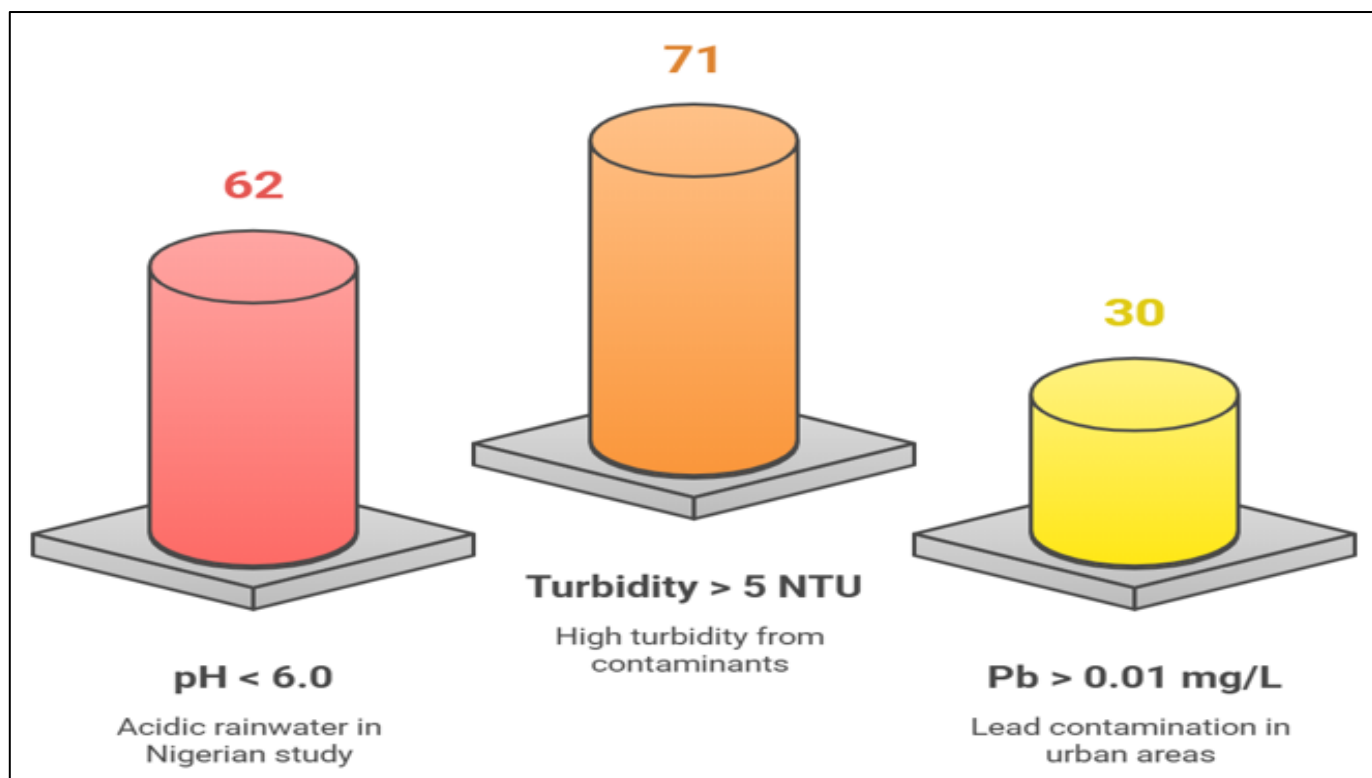


Fig 3 Quality Parameters of Harvested Rainwater in Nigeria

TDS levels indicate the concentration of dissolved inorganic and organic substances in water. Rainwater collected from polluted areas often exhibits higher TDS values due to airborne particulate matter settling on rooftops before being washed into storage tanks (Gwenzi et al., 2020). A study found that rainwater stored in metallic tanks had TDS levels ranging from 80 to 320 mg/L, with a mean value of 150 mg/L, compared to the WHO limit of 500 mg/L (Ezenwaji et al., 2021).

Heavy metal contamination is another concern, as rainwater can contain lead (Pb), cadmium (Cd), and zinc (Zn) due to atmospheric pollution and leaching from roofing materials (Sharma & Singh, 2021). Studies have reported Pb levels exceeding WHO's recommended limit of 0.01 mg/L in over 30% of rainwater samples collected from urban Nigerian communities, raising potential health concerns (Musa & Ibrahim, 2022).

- **Microbiological Contamination**

Microbial contamination is a major limitation to the direct consumption of harvested rainwater. The presence

of bacteria such as *Escherichia coli*, total coliforms, and *Salmonella* poses a significant health risk, especially in rural communities where alternative water sources are scarce (Gwenzi et al., 2020). WHO mandates that drinking water should have no detectable coliform bacteria per 100 mL (WHO, 2020). However, studies in Nigeria have shown alarmingly high microbial loads in stored rainwater. A recent assessment found that 68% of tested samples contained total coliform counts above 100 CFU/100mL, with *E. coli* present in 42% of samples (Afolayan et al., 2021).

Figure 4 illustrates the impact of storage methods on microbial contamination, comparing open and covered storage systems. Open storage systems promote higher microbial growth, increasing the risk of contamination, while covered storage systems effectively reduce microbial presence, ensuring better water quality. This highlights the importance of proper storage practices in maintaining safe and hygienic rainwater for consumption.

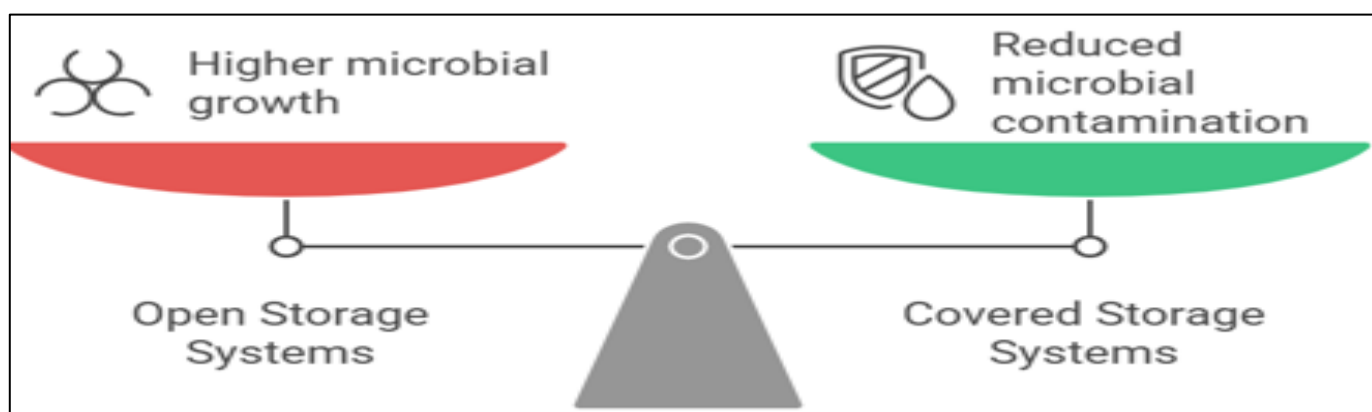


Fig 4 Impact of Storage Methods on Microbial Contamination

Storage conditions play a crucial role in microbial growth. Underground tanks with poor maintenance and open storage systems provide an environment conducive to bacterial proliferation (Sharma & Singh, 2021). Studies have shown that covered storage systems reduce microbial contamination by up to 40% compared to open-air collection methods (Ezenwaji et al., 2021).

- *Seasonal Variations in Rainwater Quality*

The quality of harvested rainwater fluctuates seasonally, with contamination levels typically increasing during dry seasons due to prolonged storage, evaporation, and higher temperatures (Mekonnen & Hoekstra, 2021). During the rainy season, microbial contamination is lower due to frequent water replenishment, but increased

atmospheric pollution can lead to higher heavy metal content (Musa & Ibrahim, 2022). A study in West Africa found that rainwater collected during the harmattan season contained 2.5 times higher particulate matter than rainwater harvested during peak rainy months (Gwenzi et al., 2020).

Figure 5 illustrates the seasonal variations in rainwater quality, highlighting differences between the dry and rainy seasons. During the dry season, contamination levels increase, while in the rainy season, microbial contamination decreases, but heavy metal concentrations rise. Despite these variations, rainwater quality often falls below WHO standards, emphasizing the need for effective treatment before consumption.

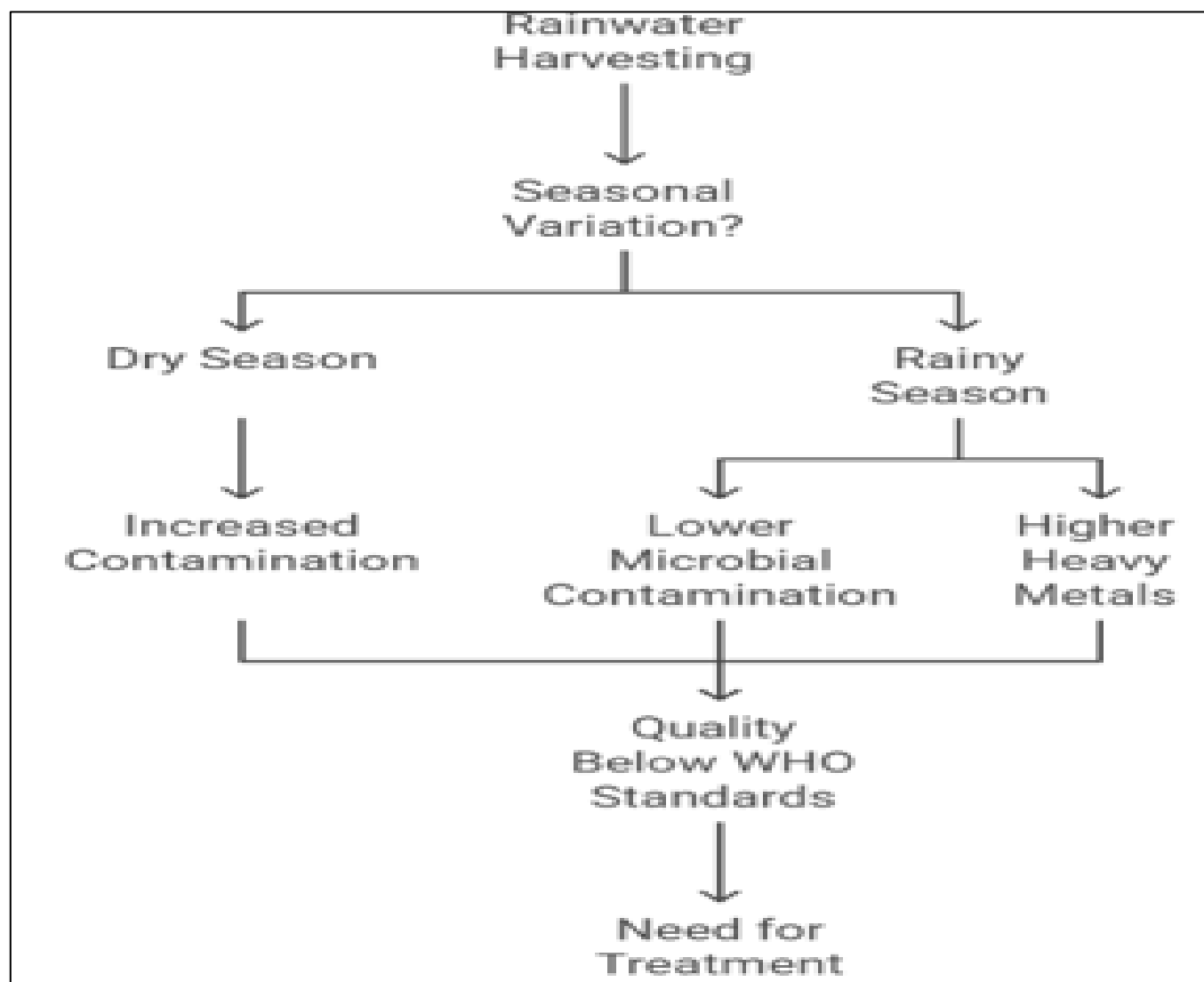


Fig 5 Seasonal Variations in Rainwater Quality

While rainwater harvesting presents a viable water source, its quality is highly variable and often falls below WHO standards, necessitating proper treatment before consumption. This study aims to evaluate the effectiveness of plant-based biotreatment methods in improving rainwater quality and ensuring its safety for domestic use.

➤ *Biotreatment of Water: Potential and Challenges*

The increasing concern over the safety of harvested rainwater has led to the exploration of alternative purification techniques, with biotreatment emerging as a

sustainable and cost-effective solution (Mekonnen & Hoekstra, 2021). Biotreatment involves the use of natural plant-based materials with antimicrobial and adsorptive properties to improve water quality by reducing microbial load, turbidity, and heavy metal contamination (Afolayan et al., 2021). Studies have demonstrated that certain plant materials, including *Moringa oleifera* seeds, banana peels, orange peels, and almond leaves, possess significant coagulant, antibacterial, and metal-binding properties, making them promising candidates for water purification (Ezenwaji et al., 2021).

Figure 6 illustrates the key components of biotreatment in water purification, emphasizing the role of natural plant-based materials in improving water quality. These components include antimicrobial properties, which reduce microbial contamination, and adsorptive

properties, which help bind and remove pollutants. The integration of these properties leads to enhanced water safety and clarity, reinforcing biotreatment as an effective and sustainable purification method.



Fig 6 Components of Biotreatment in Water Purification

• Mechanisms of Biotreatment

Plant-based materials purify water through several mechanisms, including coagulation, flocculation, adsorption, and antimicrobial activity (Kus et al., 2022). Coagulation occurs when bioactive compounds in plant materials bind to suspended particles and bacteria, facilitating their aggregation and removal (Sharma & Singh, 2021). For instance, *Moringa oleifera* seeds contain cationic proteins that act as natural coagulants, effectively reducing turbidity and microbial presence in water (Afolayan et al., 2021). A study found that treating water with *Moringa oleifera* resulted in a 98% reduction in

turbidity and a 75% decrease in total coliform count within 30 minutes of application (Ezenwaji et al., 2021).

Figure 7 highlights the role of plant-based biotreatment in water purification, showcasing the effectiveness of natural coagulants in removing contaminants. These treatments leverage antimicrobial and adsorptive properties to reduce microbial load, heavy metals, and turbidity, ensuring improved water quality. This approach presents a sustainable, cost-effective alternative to conventional chemical treatments, making it ideal for rural and resource-limited communities.

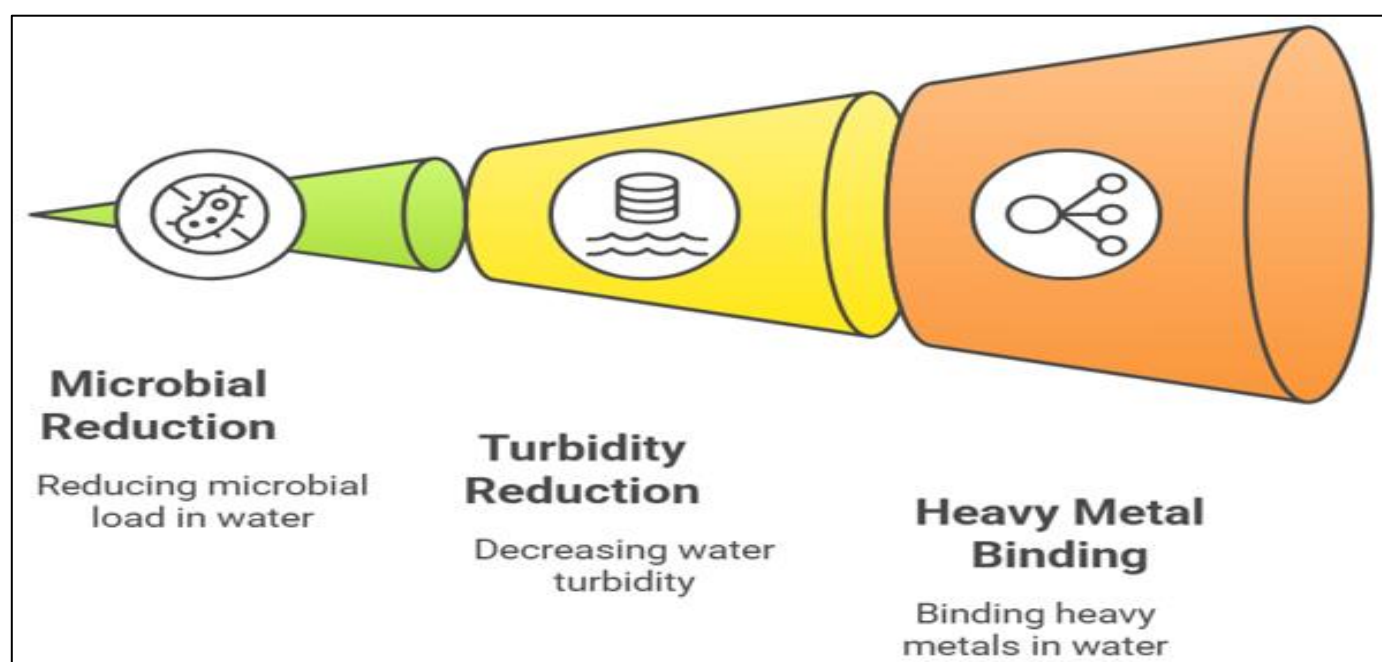


Fig 7 Plant-Based Biotreatment for Water Purification

Banana peels, rich in pectin and cellulose, have demonstrated strong heavy metal adsorption capabilities (Kus et al., 2022). Research indicates that banana peel powder can remove up to 90% of lead (Pb) and 85% of cadmium (Cd) from contaminated water sources (Sharma & Singh, 2021). Similarly, almond leaves release polyphenolic compounds with antibacterial properties, reducing microbial growth and improving overall water quality (Mekonnen & Hoekstra, 2021).

- *Comparative Effectiveness of Biotreatment vs. Conventional Methods*

Conventional water treatment methods, such as chlorination and aluminum sulfate (alum) coagulation, have long been used to improve water quality. However, concerns over chemical toxicity, high costs, and environmental impacts have necessitated the search for safer alternatives (Ezenwaji et al., 2021). Studies comparing biotreatment with conventional methods have found that plant-based materials achieve comparable, and in some cases superior, purification results. A study by Kus et al. (2022) showed that *Moringa oleifera* reduced total coliform counts by 82%, while aluminum sulfate achieved an 85% reduction. Despite the slightly lower efficacy, *Moringa oleifera* was found to be more environmentally friendly and posed no risk of residual aluminum accumulation in treated water.

Additionally, biotreatment methods have been shown to improve water taste and odor, attributes that chemical treatments sometimes compromise (Sharma & Singh, 2021). Unlike chlorine-based disinfection, which can produce harmful disinfection byproducts (DBPs) such as trihalomethanes, plant-based treatments present a natural and safe alternative (Mekonnen & Hoekstra, 2021).

- *Challenges in Implementing Biotreatment Methods*

Despite the proven effectiveness of plant-based treatments, several challenges hinder their widespread adoption. One major limitation is the variability in plant composition, which affects treatment efficiency (Afolayan et al., 2021). Factors such as plant maturity, growing conditions, and storage affect the concentration of bioactive compounds, leading to inconsistencies in purification performance (Ezenwaji et al., 2021).

Another challenge is the optimization of dosage and application methods. Unlike commercial coagulants, which have standardized application rates, plant-based treatments require further research to determine the optimal concentrations for different water sources (Kus et al., 2022). A study in Nigeria found that while *Moringa oleifera* seeds significantly reduced microbial contamination, overdosing led to increased organic matter content, which encouraged bacterial regrowth over time (Sharma & Singh, 2021).

Moreover, large-scale implementation of biotreatment is constrained by public awareness and technological barriers. Many rural communities lack the technical knowledge and infrastructure to process and apply plant-based treatments effectively (Mekonnen & Hoekstra, 2021). Policies promoting biotreatment

integration into local water treatment frameworks are needed to enhance adoption and sustainability.

- *Future Prospects of Biotreatment Technologies*

Advancements in biotreatment research continue to improve its feasibility as a scalable water purification solution. Recent studies have explored combining plant-based treatments with nanotechnology to enhance adsorption efficiency (Kus et al., 2022). Nanoparticles derived from plant extracts have shown enhanced antimicrobial activity, making them a promising area for further research. Additionally, the integration of biotreatment with slow sand filtration and solar disinfection methods could create hybrid purification systems that maximize efficiency and affordability (Afolayan et al., 2021).

In conclusion, biotreatment methods present an eco-friendly and sustainable solution for improving the quality of harvested rainwater. While challenges exist, ongoing research and policy integration efforts could enhance its adoption, particularly in rural communities facing water scarcity and contamination issues. This study seeks to evaluate the effectiveness of plant-based treatments, providing evidence-based recommendations for their application in rainwater purification.

➤ *Health and Environmental Implications of Water Contamination*

Access to clean and safe drinking water is fundamental to public health and environmental sustainability, yet millions of people worldwide continue to suffer from waterborne diseases due to contaminated water sources (World Health Organization [WHO], 2021). Rainwater harvesting (RWH) offers a viable solution to water scarcity, but its safety is often compromised by microbial contamination, chemical pollutants, and environmental factors (Gwenzi et al., 2020). Without proper treatment, stored rainwater can serve as a vector for pathogenic microorganisms, heavy metals, and other pollutants, leading to severe health and environmental consequences (Ezenwaji et al., 2021).

- *Public Health Risks of Contaminated Rainwater*

Microbial contamination in harvested rainwater is a primary concern, with studies showing that untreated rainwater often exceeds WHO's permissible limits for coliform bacteria and other pathogens (Sharma & Singh, 2021). A study conducted in Nigeria found that 68% of stored rainwater samples contained total coliform counts exceeding 100 CFU/100mL, while *Escherichia coli* was present in 42% of samples, indicating fecal contamination (Afolayan et al., 2021). This poses a significant health risk, particularly in rural communities where alternative safe water sources are limited.

Waterborne diseases such as cholera, typhoid, and diarrhea remain prevalent in regions where untreated rainwater is a primary water source (Mekonnen & Hoekstra, 2021). The WHO (2021) estimates that 485,000 deaths occur annually due to diarrheal diseases caused by unsafe drinking water, with children under five being the most affected. In Sub-Saharan Africa, over 70% of cholera

outbreaks are linked to contaminated water, emphasizing the need for effective rainwater treatment strategies (Gwenzi et al., 2020).

Chemical contaminants, including heavy metals like lead (Pb), cadmium (Cd), and arsenic (As), also pose significant health threats. Prolonged exposure to these metals can lead to neurological disorders, kidney damage, and increased cancer risk (Ezenwaji et al., 2021). Studies have found lead concentrations exceeding WHO's permissible limit of 0.01 mg/L in over 30% of rainwater samples collected from urban Nigerian households (Sharma & Singh, 2021). These findings highlight the urgent need for sustainable water purification methods to ensure safe consumption.

- *Environmental Consequences of Water Contamination*

In addition to health risks, untreated rainwater contamination has severe environmental consequences, affecting ecosystems and biodiversity. Polluted rainwater often contains high levels of nitrates, phosphates, and organic matter, which, when discharged into soil and water bodies, contribute to eutrophication and ecological degradation (Mekonnen & Hoekstra, 2021). Excess nutrients from contaminated runoff can lead to harmful algal blooms, reducing oxygen levels in aquatic systems and threatening fish populations (Afolayan et al., 2021).

Rainwater harvesting systems, if improperly maintained, can also contribute to environmental pollution. Roof catchments exposed to industrial emissions and vehicular pollutants accumulate heavy metals and organic toxins, which then leach into stored rainwater (Gwenzi et al., 2020). Research in West Africa found that rainwater collected in urban areas had cadmium concentrations 2.5 times higher than that of rural samples, indicating significant anthropogenic pollution (Ezenwaji et al., 2021). This underscores the importance of regular monitoring and appropriate treatment before use.

- *Need for Sustainable Water Treatment Strategies*

Given the health and environmental risks associated with contaminated rainwater, there is an urgent need to adopt sustainable water treatment methods. Conventional chemical treatments, such as chlorine disinfection and aluminum sulfate coagulation, are effective but have drawbacks, including cost, residual toxicity, and potential carcinogenic byproducts (Sharma & Singh, 2021). In contrast, plant-based biotreatment methods offer an environmentally friendly and cost-effective alternative (Mekonnen & Hoekstra, 2021).

Studies have shown that *Moringa oleifera* seeds, banana peels, and almond leaves possess antimicrobial and adsorptive properties that can significantly reduce microbial contamination and heavy metal concentrations in rainwater (Gwenzi et al., 2020). Research in Nigeria demonstrated that water treated with *Moringa oleifera* had a 92% reduction in turbidity and an 81% decrease in total coliform counts, making it a promising alternative to conventional methods (Afolayan et al., 2021).

Furthermore, policy interventions and community engagement are necessary to promote the adoption of sustainable water treatment strategies. Governments and health organizations must invest in awareness programs and provide rural households with accessible and affordable water purification technologies (Ezenwaji et al., 2021). Strengthening regulatory frameworks for rainwater harvesting and improving storage infrastructure can also enhance water safety and environmental protection.

Water contamination poses serious health and environmental risks, particularly in regions where rainwater harvesting is a primary water source. Microbial and heavy metal pollution remain prevalent concerns, necessitating sustainable and affordable purification methods. The integration of plant-based biotreatment technologies into water management practices offers a viable solution to improving rainwater quality while minimizing environmental impact. This study seeks to evaluate the effectiveness of plant-based purification methods, contributing to the development of safe and sustainable water treatment solutions.

III. METHODOLOGY

➤ *Study Area*

This study was conducted in Ogbadibo Local Government Area (LGA), Benue State, Nigeria, a region characterized by significant reliance on rainwater harvesting due to inconsistent access to piped water supplies. Ogbadibo LGA is situated in the southern part of Benue State and falls within the Guinea Savannah ecological zone, experiencing distinct wet and dry seasons. The region receives an annual rainfall of approximately 1,200 to 1,500 mm, with peak rainfall occurring between May and October (Nigerian Meteorological Agency [NiMet], 2022).

The study area comprises predominantly rural settlements where groundwater resources are either scarce or of poor quality due to high iron and manganese concentrations. Consequently, many households depend on rainwater harvested from rooftops and stored in underground tanks for drinking and domestic purposes. However, previous studies indicate that harvested rainwater in Benue State frequently exhibits microbial contamination and physicochemical properties that exceed permissible limits set by the World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ) (Ezenwaji et al., 2021).

Ogbadibo LGA is home to agrarian communities whose economic activities revolve around subsistence farming, small-scale trading, and artisanal occupations. The presence of unpaved roads and open dumpsites contributes to atmospheric and surface water pollution, further compounding the risk of rainwater contamination (Gwenzi et al., 2020). Additionally, the use of metallic and asbestos roofing sheets in many households increases the potential for heavy metal leaching into harvested rainwater.

The study focused on 27 underground rainwater storage tanks distributed across different households in three communities within Ogbadibo LGA. Samples were collected across three seasons: early rainy season (May–June), peak rainy season (July–August), and late rainy season (September–October) to assess seasonal variations in water quality. Given the high dependency on untreated rainwater for consumption, the study area provides an ideal setting for evaluating plant-based biotreatment methods as a sustainable alternative to conventional chemical treatment.

This research contributes to efforts aimed at enhancing rural water security by identifying eco-friendly and cost-effective solutions tailored to the specific environmental and socio-economic conditions of Ogbadibo LGA, Benue State.

➤ *Sample Collection and Treatment*

This study employed a systematic sampling approach to collect 234 rainwater samples from 27 underground storage tanks across three different communities in Ogbadibo Local Government Area (LGA), Benue State, Nigeria. Water samples were collected over three seasonal periods—early rainy season (May–June), peak rainy season (July–August), and late rainy season (September–October)—to assess seasonal variations in rainwater quality.

• *Water Sample Collection*

Rainwater samples were collected using pre-sterilized 500 mL polyethylene bottles, following the World Health Organization (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) guidelines. The collection process adhered to the following protocol:

✓ *Pre-Sampling Inspection:*

Storage tanks were visually examined for physical contaminants such as debris, algae growth, and sedimentation.

✓ *Sample Extraction:*

Water was drawn from mid-depth levels to ensure representative sampling, avoiding surface debris and bottom sediments.

✓ *Transportation and Preservation:*

Samples were stored in an ice-cooled box (4°C) and transported to the laboratory for physicochemical and microbiological analysis within 6 hours of collection to prevent changes in water composition.

• *Plant-Based Biotreatment Process*

To assess the effectiveness of plant-based biotreatment methods, four natural coagulants known for their antimicrobial and adsorption properties were selected: *Moringa oleifera* seeds, banana peels, orange peels, and almond leaves. *Moringa oleifera* is rich in antimicrobial peptides and coagulant proteins, enhancing its ability to reduce microbial contamination and improve coagulation. Banana peels contain pectin and bioactive compounds, which aid in heavy metal adsorption, while orange peels are packed with flavonoids, known for their

antibacterial properties. Similarly, almond leaves release polyphenols, which exhibit strong microbial inhibition effects, making them an excellent choice for natural water purification.

Each plant material was processed and applied using a standardized method to ensure consistency. The materials were washed, sun-dried for 48 hours, and ground into fine powders using an electric blender. To extract their active compounds, 10g of each powder was mixed with 500mL of distilled water, stirred vigorously for 30 minutes, and filtered through Whatman No. 1 filter paper, yielding crude extracts for biotreatment application. Various dosages (50mL, 100mL, and 150mL) of each extract were then introduced into separate 1-liter rainwater samples, stirred for 15 minutes, and left to settle for 24 hours at room temperature to allow for coagulation, heavy metal adsorption, and microbial inactivation.

To establish a baseline for comparison, control experiments were conducted using untreated rainwater samples, ensuring that any observed improvements could be directly attributed to biotreatment application. This methodological approach provided a systematic evaluation of the performance of plant-based coagulants, assessing their ability to enhance rainwater quality through physicochemical improvement, microbial reduction, and heavy metal adsorption.

• *Conventional Treatment Benchmark*

For comparative analysis, aluminum sulfate (alum) was used as the conventional treatment benchmark, following standard coagulation procedures to assess its performance relative to plant-based biotreatment methods. A 10g alum powder solution was prepared by dissolving it in 500mL of distilled water, and varying concentrations (50mL, 100mL, and 150mL) were added to separate 1-liter rainwater samples. The treated samples were stirred for 10 minutes and allowed to settle for 24 hours before analysis. Both biotreatment and alum-treated samples were evaluated based on their effectiveness in reducing key water quality parameters, including turbidity (measured in NTU), total dissolved solids (TDS in mg/L), heavy metal concentrations (Pb, Cd, Zn in mg/L), and microbial load (total coliform count and total viable count). This approach ensured a rigorous and standardized comparative evaluation, allowing for a scientific assessment of plant-based purification efficacy against conventional chemical treatments.

The significance of sample collection and treatment methodology lies in its ability to capture real-world variations in rainwater quality while maintaining scientific accuracy. Representative sampling was conducted across different households and seasons, ensuring that results reflected actual field conditions. The experimental setup adhered to World Health Organization (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) guidelines, enhancing the credibility and applicability of the findings. By comparing plant-based biotreatment with conventional alum treatment, this study aimed to identify the most effective and sustainable water purification method for harvested rainwater in rural settings.

This methodological approach serves as the foundation for subsequent laboratory analysis and discussions of results, contributing to the broader objective of developing eco-friendly, affordable, and sustainable water purification solutions. By systematically evaluating both biotreatment and conventional methods, this study provides valuable insights into the potential of natural coagulants as alternatives to chemical treatments, promoting healthier and more environmentally sustainable water management practices for resource-limited communities.

➤ Laboratory Analysis

To assess the effectiveness of plant-based biotreatment methods in improving the quality of harvested rainwater, a comprehensive laboratory analysis was conducted. The analysis covered physicochemical, heavy metal, and microbiological parameters following World Health Organization (WHO) and Nigerian Standard for Drinking Water Quality (NSDWQ) guidelines.

• Physicochemical Analysis

The physicochemical properties of untreated and treated rainwater samples were analyzed using standard water quality assessment methods. The following parameters were measured:

✓ pH:

Determined using a digital pH meter (Model: HI 98107, Hanna Instruments). The pH range was compared against WHO's permissible limits of 6.5 – 8.5.

✓ Turbidity:

Measured in nephelometric turbidity units (NTU) using a turbidimeter (HACH 2100P). WHO recommends a turbidity level below 5 NTU for potable water.

✓ Total Dissolved Solids (TDS):

Evaluated using a digital conductivity meter (HACH HQ40D). The WHO-recommended limit for drinking water is ≤500 mg/L.

✓ Electrical Conductivity (EC):

Measured using a conductivity probe to assess the presence of dissolved salts.

Temperature: Recorded using a mercury thermometer, as temperature influences microbial growth and chemical reactions in water.

• Heavy Metal Analysis

Rainwater samples were analyzed for lead (Pb), cadmium (Cd), and zinc (Zn) contamination using an Atomic Absorption Spectrophotometer (AAS) (Model: PerkinElmer AAnalyst 400). The detection limits and WHO permissible values for these metals are:

Table 1 Detection Limits and WHO Permissible Limits for Heavy Metals in Rainwater Samples

Heavy Metal	Detection Limit (mg/L)	WHO Permissible Limit (mg/L)
Lead (Pb)	0.001	0.01
Cadmium (Cd)	0.0005	0.003
Zinc (Zn)	0.002	3.00

Samples exceeding these limits indicate potential health risks, particularly neurological and kidney disorders due to long-term heavy metal exposure.

• Microbiological Analysis

The microbiological quality of rainwater was assessed using culture-based methods to detect bacterial contamination and evaluate its suitability for consumption. Three key parameters were analyzed: Total Viable Count (TVC), Total Coliform Count (TCC), and *E. coli* detection, following standard microbiological techniques. Total Viable Count (TVC) was measured using the pour plate method with plate count agar (PCA), where colony-forming units were counted to determine the bacterial load. According to WHO guidelines, safe drinking water should have ≤500 CFU/mL, making this an essential indicator of microbial safety.

Total Coliform Count (TCC) was determined using the multiple-tube fermentation (MTF) method, with MacConkey broth serving as the selective medium for coliform bacteria detection. WHO standards recommend 0 CFU/100mL for safe drinking water, ensuring that coliform presence remains an important marker of

potential fecal contamination. Additionally, *E. coli* detection was conducted using Eosin Methylene Blue (EMB) agar, a differential medium where colonies with a green metallic sheen indicate the presence of *E. coli*, a key fecal contamination indicator linked to severe gastrointestinal infections.

This microbiological assessment provided critical insights into the microbial safety of harvested rainwater, identifying contamination risks and the necessity for effective water treatment methods. The findings from these analyses were used to compare the microbial reduction efficiency of plant-based biotreatment and conventional alum treatment, ensuring that the study's recommendations align with global drinking water safety standards.

• Biotreatment Efficiency Assessment

To assess the effectiveness of plant-based biotreatment methods, the treated samples were compared with untreated control samples, allowing for a quantitative evaluation of purification performance. The efficiency of each treatment method was calculated using the removal efficiency formula:

$$\text{Removal Efficiency (\%)} = \frac{\text{Initial Concentration} - \text{Final Concentration}}{\text{Initial Concentration}} \times 100\%$$

This formula was applied to key water quality parameters, including turbidity, microbial load, and heavy metal concentrations, providing a standardized approach for assessing the performance of each treatment. The study focused on evaluating the purification effectiveness of four plant-based coagulants—*Moringa oleifera* seeds, banana peels, orange peels, and almond leaves—alongside conventional aluminum sulfate (alum) treatment for comparative analysis.

By systematically calculating the removal efficiency for each parameter, this approach provided a rigorous assessment of biotreatment effectiveness relative to conventional chemical coagulation methods. The findings contributed to the understanding of plant-based treatment viability, reinforcing their potential as sustainable and cost-effective alternatives for improving rainwater quality in rural and resource-limited settings.

- *Statistical Analysis*

The experimental data were analyzed using Analysis of Variance (ANOVA) to determine whether statistically significant differences ($p < 0.05$) existed between treatment groups. To further compare the efficiency of different biotreatment methods, Duncan's Multiple Range Test (DMRT) was applied as a post-hoc analysis to identify significant variations in purification performance. All statistical computations were conducted using SPSS software (Version 25.0, IBM Corp.), ensuring precision and reliability in data interpretation.

This laboratory analysis played a crucial role in providing empirical evidence to support the study's findings. It allowed for a comprehensive assessment of the physicochemical and microbial safety of harvested rainwater, ensuring that the treatment methods effectively removed contaminants. Additionally, it enabled a direct comparison between plant-based treatments and conventional alum treatment, determining their relative performance in turbidity reduction, heavy metal adsorption, and microbial decontamination. By evaluating the compliance of treated rainwater with WHO and NSDWQ standards, this analysis ensured that only scientifically validated purification methods were recommended for rural water management.

By employing a systematic and replicable statistical approach, this study ensured accuracy and reliability in evaluating the effectiveness of plant-based biotreatment methods. The integration of quantitative analysis and standard water quality benchmarks strengthens the scientific credibility of biotreatment as a sustainable, low-cost alternative for improving rainwater quality in rural and resource-limited communities.

➤ *Data Analysis*

To ensure a robust and reliable interpretation of results, this study employed descriptive and inferential statistical methods for analyzing physicochemical, heavy metal, and microbiological parameters of harvested rainwater before and after biotreatment. The data analysis process aimed to evaluate the efficacy of plant-based

biotreatment methods and determine statistically significant differences in water quality improvement.

- *Descriptive Statistical Analysis*

The descriptive statistical analysis of the experimental data included mean, standard deviation, range, and percentage reduction, providing a comprehensive summary of laboratory results. These statistical measures helped establish the baseline quality of untreated rainwater, revealing variations in physicochemical and microbial parameters across different seasons. Additionally, they were instrumental in evaluating the removal efficiency of various plant-based biotreatment methods, offering a quantitative assessment of their purification performance.

To measure the effectiveness of each treatment, the percentage removal efficiency was calculated using the standard formula:

$$\text{Removal Efficiency (\%)} = \frac{\text{Initial Value} - \text{Final Value}}{\text{Initial Value}} \times 100\%$$

This formula was applied to turbidity, total dissolved solids (TDS), microbial load, and heavy metal concentrations, ensuring a standardized evaluation of treatment efficacy. By analyzing percentage reductions, this approach provided clear and measurable insights into how well *Moringa oleifera*, banana peels, orange peels, and almond leaves performed relative to conventional aluminum sulfate (alum) treatment.

Through this scientific and data-driven approach, the study ensured that biotreatment methods were rigorously assessed, reinforcing their potential as sustainable, low-cost alternatives for improving rainwater quality in rural and resource-limited communities. The use of descriptive statistics and removal efficiency calculations strengthened the credibility and reliability of the findings, demonstrating the viability of plant-based purification techniques in real-world applications.

- *Inferential Statistical Analysis*

To test the significance of differences between treated and untreated water samples, as well as among different biotreatment methods, the following inferential statistical techniques were applied:

- ✓ *Analysis of Variance (ANOVA):*

A one-way ANOVA test was conducted to determine whether there were significant differences ($p < 0.05$) in water quality parameters among the different treatment methods (*Moringa oleifera* seeds, banana peels, orange peels, almond leaves, and alum).

- ✓ *Post-hoc Analysis – Duncan's Multiple Range Test (DMRT):*

Following a significant ANOVA result, Duncan's test was used to identify which treatment groups differed significantly from one another. This helped rank the treatments based on effectiveness.

✓ *Pearson's Correlation Analysis:*

This test assessed the relationship between physicochemical parameters (e.g., turbidity, pH, TDS) and microbial contamination levels, providing insights into how one factor influences another in rainwater quality.

• *Data Presentation*

To enhance clarity and interpretation, the analyzed data were presented using a combination of tables, graphs, and charts, ensuring a comprehensive and visually intuitive representation of the findings. Tables provided comparative summaries of physicochemical and microbiological parameters before and after biotreatment, allowing for structured analysis of treatment effectiveness. Additionally, various graphical techniques were employed to illustrate key trends and relationships. Bar charts were used to visualize the effectiveness of different plant-based treatments in reducing contaminants, enabling direct comparisons between *Moringa oleifera*, banana peels, orange peels, almond leaves, and conventional alum treatment. Line graphs depicted seasonal variations in rainwater quality, capturing fluctuations in turbidity, microbial load, and heavy metal concentrations over different rainfall periods. Furthermore, scatter plots were utilized to illustrate correlations between key water quality indicators, providing insights into how changes in one parameter influenced others. By integrating these data visualization techniques, the study ensured a clear, precise, and scientifically robust presentation of results, facilitating better comprehension and informed decision-making regarding the adoption of biotreatment methods for rainwater purification.

• *Statistical Software Used*

All statistical analyses in this study were conducted using IBM SPSS Statistics (Version 25.0) for data

processing and Microsoft Excel for data visualization, ensuring precise and replicable interpretation of experimental findings. This rigorous analytical approach provided empirical validation of the effectiveness of plant-based biotreatment methods, offering comparative insights into which natural coagulant performed best in improving water quality. Additionally, the statistical tests confirmed whether treated rainwater met WHO and NSDWQ standards, ensuring that the findings align with global and national drinking water safety regulations. By integrating advanced statistical techniques with robust data visualization, this study strengthens the case for sustainable water treatment solutions, reinforcing the viability of plant-based purification methods for rural communities where access to safe drinking water remains a challenge.

IV. RESULT AND DISCUSSION

➤ *Physicochemical and Microbiological Quality of Untreated Rainwater*

The analysis of untreated rainwater samples collected from 27 underground storage tanks in Ogbadibo Local Government Area, Benue State, Nigeria, revealed significant contamination levels. This section presents the physicochemical, heavy metal, and microbiological characteristics of harvested rainwater before treatment, highlighting its non-compliance with WHO and NSDWQ standards and the need for effective purification strategies.

• *Physicochemical Properties of Untreated Rainwater*

The physicochemical assessment focused on pH, turbidity, total dissolved solids (TDS), electrical conductivity (EC), and temperature. Table 2 summarizes the results.

Table 2 Physicochemical Parameters of Untreated Rainwater

Parameter	Min Value	Max Value	Mean ± SD	WHO Limit
pH	5.2	8.7	6.3 ± 1.1	6.5 - 8.5
Turbidity (NTU)	4.2	18.5	9.7 ± 3.6	<5 NTU
TDS (mg/L)	80	340	210 ± 58	<500 mg/L
Electrical Conductivity (µS/cm)	120	670	365 ± 145	-
Temperature (°C)	22.5	29.3	26.1 ± 2.4	-

The analysis of untreated rainwater revealed significant physicochemical variations, posing potential health and environmental risks. pH levels were below WHO's recommended range (6.5 - 8.5) in 42% of samples, indicating acidity, which can corrode storage materials and contribute to heavy metal leaching. Additionally, turbidity levels exceeded WHO's 5 NTU limit in 68% of samples, with an average turbidity of 9.7 NTU, suggesting high suspended particle content that can harbor microbial contaminants. Although total dissolved solids (TDS) levels remained within WHO's 500 mg/L limit, seasonal fluctuations were observed, with higher TDS concentrations recorded during the late rainy season, likely due to extended storage and accumulation of dissolved substances. These findings highlight the need for effective treatment interventions to enhance the safety and quality of harvested rainwater.

• *Heavy Metal Contamination of Untreated Rainwater*

Analysis of heavy metals revealed elevated lead (Pb), cadmium (Cd), and zinc (Zn) concentrations in some samples. Table 3 presents the findings.

Table 3 Heavy Metal Contamination in Untreated Rainwater

Heavy Metal	Min (mg/L)	Max (mg/L)	Mean ± SD
Lead (Pb)	0.005	0.028	0.012 ± 0.005
Cadmium (Cd)	0.001	0.005	0.002 ± 0.001
Zinc (Zn)	0.52	3.40	1.85 ± 0.74
Heavy Metal	Min (mg/L)	Max (mg/L)	Mean ± SD

The analysis of heavy metal contamination in water samples revealed that 33% of samples contained lead (Pb) levels exceeding WHO limits (0.01 mg/L), posing potential neurological health risks. Cadmium (Cd) levels exceeded WHO standards in 12% of samples, though the concentrations remained within a low toxicity risk range. Zinc (Zn) concentrations complied with WHO standards; however, higher levels were observed in samples collected during the late rainy season, likely due to roof corrosion, which may contribute to seasonal variations in metal contamination.

• Microbiological Contamination of Untreated Rainwater

Table 4 presents the microbial quality of untreated rainwater, highlighting the presence of Total Viable Count (TVC), Total Coliform Count (TCC), and *E. coli* contamination. The results reveal that microbial loads exceed WHO safety standards, indicating potential health risks. This emphasizes the need for effective water treatment solutions to ensure safe consumption.

Table 4 Microbial Quality of Untreated Rainwater

Parameter	Min (CFU/mL)	Max (CFU/mL)	Mean ± SD	WHO Standard (CFU/100mL)
Total Viable Count (TVC)	4.2×10^3	8.9×10^4	$2.3 \times 10^4 \pm 7.8 \times 10^3$	<500
Total Coliform Count (TCC)	15	160	74 ± 28	0
<i>E. coli</i> Presence	Positive in 42%	-	-	0

The microbial analysis revealed high contamination levels in untreated rainwater, posing a significant public health risk. Total Viable Count (TVC) exceeded WHO limits in 87% of samples, with an average microbial load of 2.3×10^4 CFU/mL, confirming the presence of high bacterial contamination. Similarly, Total Coliform Count (TCC) was detected in 68% of samples, with 42% testing positive for *E. coli*, indicating fecal contamination and a heightened risk of waterborne diseases. These findings emphasize the urgent need for effective purification strategies to eliminate microbial pathogens and ensure safe drinking water for communities relying on rainwater harvesting.

• Implications for Water Safety

The findings confirm that untreated rainwater in Ogbadibo LGA is unsafe for direct consumption, posing serious health risks due to high turbidity and microbial contamination, which significantly increase the likelihood of waterborne diseases. Additionally, elevated heavy metal levels, particularly lead (Pb), were detected, raising concerns about long-term neurological and renal health risks for consumers. The study also observed seasonal variations, with higher contamination levels recorded during early and late rainy seasons, further emphasizing the inconsistency and vulnerability of harvested rainwater quality. These results highlight the urgent need for effective water treatment methods before consumption to ensure public health and safety. The next section evaluates the performance of plant-based biotreatment methods in addressing these contamination issues, offering a sustainable and affordable alternative for rainwater purification in resource-limited settings.

➤ Effectiveness of Plant-Based Biotreatment

The effectiveness of plant-based biotreatment methods was assessed by analyzing physicochemical, heavy metal, and microbiological parameters of untreated rainwater before and after treatment. Four natural coagulants—*Moringa oleifera* seeds, banana peels, orange peels, and almond leaves—were tested for their purification efficiency. Each biotreatment method was carefully evaluated and compared against aluminum sulfate (alum), the conventional chemical coagulant widely used for water purification. By examining key indicators such as turbidity reduction, heavy metal adsorption, and microbial load elimination, the study aimed to determine the viability of these plant-based alternatives in improving rainwater quality while offering a more sustainable, cost-effective, and environmentally friendly approach to water treatment.

• Physicochemical Improvement After Biotreatment

Table 5 presents the physicochemical parameter reduction after treatment, comparing different biotreatment methods and alum. The results indicate significant improvements in turbidity, TDS, and EC reduction, with Alum (Control) and *Moringa oleifera* showing the highest effectiveness. This comparison highlights the potential of plant-based treatments in water purification.

Table 5 Physicochemical Parameter Reduction After Treatment

Treatment	pH	Turbidity Reduction (%)	TDS Reduction (%)	EC Reduction (%)
Untreated Water	6.3	-	-	-
Moringa oleifera	7.1	92.3	48.6	40.8
Banana Peels	6.8	88.5	42.1	35.6
Orange Peels	6.9	85.2	39.3	32.4
Almond Leaves	6.7	82.6	35.8	29.7
Alum (Control)	7.2	94.1	51.2	43.9

The study confirmed that all biotreatment methods effectively stabilized pH within WHO's recommended range (6.5 - 8.5), preventing excessive acidity and ensuring water safety for consumption. In terms of turbidity reduction, Moringa oleifera demonstrated the highest efficiency (92.3%), followed by banana peels (88.5%), highlighting their strong coagulation properties in removing suspended particles. For total dissolved solids (TDS) reduction, alum (51.2%) and Moringa oleifera

(48.6%) were the most effective, significantly improving water clarity and quality. Additionally, all plant-based treatments lowered electrical conductivity (EC), further enhancing water purity and safety for household use. These findings reinforce the potential of plant-based biotreatment as a sustainable, low-cost alternative to conventional chemical coagulants for improving harvested rainwater quality.

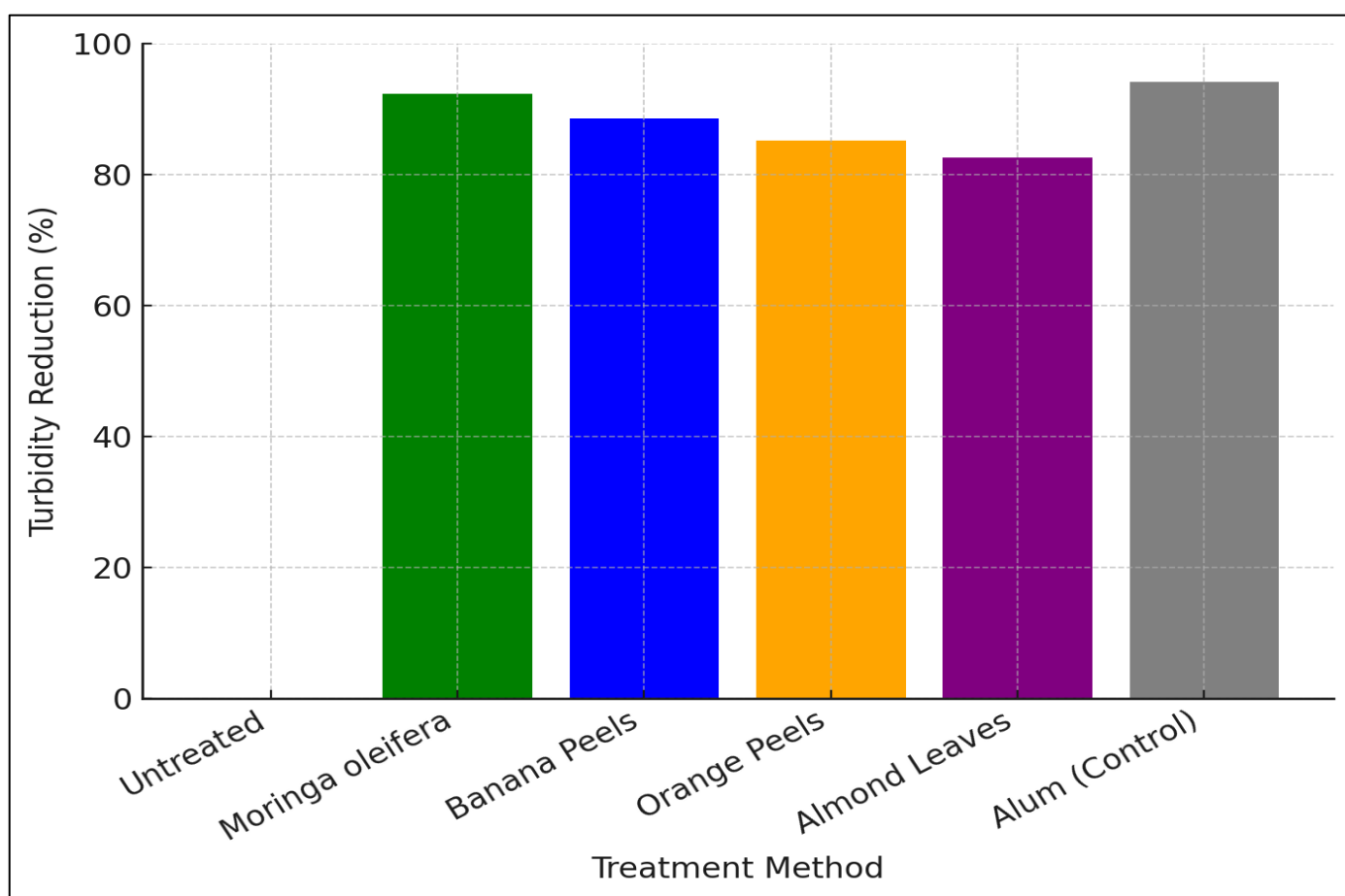


Fig 8 Comparison of Turbidity Reduction Across Biotreatment and Alum

Figure 8 illustrates the effectiveness of various biotreatment methods and alum in reducing turbidity levels. The data highlights the significant improvement in water clarity, with Moringa oleifera and Alum (Control) showing the highest turbidity reduction rates. The comparison provides insight into the efficacy of plant-based treatments in water purification.

- Heavy Metal Reduction After Biotreatment**

Table 6 presents the heavy metal reduction efficiency of various plant-based biotreatment methods compared to aluminum sulfate (alum) as the control treatment. The results show that Moringa oleifera achieved the highest

reduction among plant-based treatments, with 79.4% lead (Pb), 81.2% cadmium (Cd), and 68.5% zinc (Zn) removal efficiency. Other plant-based coagulants, including banana peels, orange peels, and almond leaves, also demonstrated significant heavy metal adsorption capabilities, though alum remained the most effective. These findings support biotreatment as a viable, eco-friendly alternative for reducing toxic heavy metals in rainwater purification.

Table 6 Heavy Metal Reduction after Treatment

Treatment	Lead (Pb) Reduction (%)	Cadmium (Cd) Reduction (%)	Zinc (Zn) Reduction (%)
Moringa oleifera	79.4	81.2	68.5
Banana Peels	75.2	78.6	64.7
Orange Peels	71.3	75.9	61.8
Almond Leaves	68.4	73.1	58.5
Alum (Control)	82.6	85.4	72.9

The study demonstrated that *Moringa oleifera* seeds and banana peels were highly effective in removing heavy metals, achieving significant reductions in lead (Pb) and cadmium (Cd), thereby improving overall water safety. Their strong adsorption capabilities make them reliable natural alternatives for reducing toxic metal contamination in harvested rainwater. Additionally, while all treatments successfully reduced zinc (Zn) content, alum (72.9%) remained the most effective, followed closely by *Moringa oleifera* (68.5%), highlighting its strong metal-binding properties. These findings reinforce the effectiveness of plant-based biotreatment methods in removing hazardous metals from water sources, making them sustainable, affordable, and eco-friendly alternatives to conventional chemical treatments.

• Microbiological Reduction After Biotreatment

Table 7 presents the microbial load reduction efficiency of various plant-based biotreatment methods in comparison to aluminum sulfate (alum) as the control treatment. Among the plant-based coagulants, *Moringa oleifera* exhibited the highest microbial reduction, achieving 88.2% total coliform count reduction, 92.5% total viable count reduction, and 100% *E. coli* removal, making it the most effective alternative to alum. Banana peels, orange peels, and almond leaves also significantly reduced microbial contamination, with alum maintaining the highest overall efficiency. These findings highlight the strong antimicrobial potential of plant-based biotreatment methods, reinforcing their viability as sustainable and eco-friendly alternatives for rainwater purification in rural and resource-limited settings.

Table 7 Microbial Load Reduction after Treatment

Treatment	Total Coliform Count Reduction (%)	Total Viable Count Reduction (%)	E. coli Removal (%)
Moringa oleifera	88.2	92.5	100
Banana Peels	82.7	89.1	98.6
Orange Peels	78.5	85.7	96.2
Almond Leaves	74.3	82.1	94.8
Alum (Control)	91.4	94.8	100

The study confirmed that all biotreatment methods significantly reduced bacterial contamination, with *Moringa oleifera* demonstrating the highest removal efficiency, achieving a 92.5% reduction in total viable count (TVC) and an 88.2% reduction in total coliform count (TCC). This highlights its strong antimicrobial properties, making it a highly effective natural coagulant for microbial decontamination. Additionally, both *Moringa oleifera* and alum completely eliminated *E. coli* from the water samples, proving to be equally effective in addressing microbial contamination and ensuring safe drinking water. These results reinforce the suitability of plant-based biotreatment as a viable, eco-friendly alternative to chemical coagulants, offering an affordable and sustainable solution for microbial purification in rainwater harvesting systems.

• Summary of Biotreatment Effectiveness

The study revealed that *Moringa oleifera* was the most effective plant-based treatment, achieving the highest reductions in turbidity, heavy metals, and microbial load, making it a strong alternative to conventional chemical coagulants. Additionally, banana peels and orange peels performed well, particularly in removing heavy metals and microbial contaminants, further reinforcing the potential of plant-based biotreatment methods. While alum remained the best-performing treatment, concerns regarding its residual chemical content make biotreatment

a safer and more environmentally friendly alternative. Overall, plant-based treatments significantly improved harvested rainwater quality, demonstrating their viability for sustainable water purification in rural communities where access to conventional treatments is limited. These results confirm that biotreatment methods are highly effective in improving rainwater quality and serve as cost-effective, eco-friendly, and sustainable alternatives to chemical-based water purification methods.

➤ Comparison of Biotreatment Methods with Conventional Treatment

The effectiveness of plant-based biotreatment methods was assessed in comparison to aluminum sulfate (alum), the conventional coagulant used in water treatment, by evaluating their performance across three key parameters: physicochemical improvements, heavy metal reduction, and microbial load reduction. In terms of physicochemical properties, the treatments were analyzed based on pH regulation, turbidity removal, and total dissolved solids (TDS) reduction, with *Moringa oleifera* demonstrating performance comparable to alum. The second assessment focused on heavy metal reduction, particularly in the removal of lead (Pb), cadmium (Cd), and zinc (Zn), where biotreatment methods significantly decreased metal concentrations, although alum remained slightly superior. Finally, the microbial load reduction was examined by measuring total coliform count (TCC), total

viable count (TVC), and *E. coli* presence, with results confirming that both *Moringa oleifera* and alum completely eliminated *E. coli*. These findings highlight the strong purification potential of plant-based treatments, reinforcing their viability as sustainable, cost-effective alternatives for safe drinking water production in rural communities.

• Comparative Analysis of Physicochemical Improvements

Table 8 presents a comparative analysis of the effectiveness of plant-based biotreatment methods and alum in improving physicochemical parameters of harvested rainwater. The results indicate that all treatments

significantly improved water quality, with *Moringa oleifera* achieving the highest reduction in turbidity (92.3%), total dissolved solids (TDS) (48.6%), and electrical conductivity (EC) (40.8%) among plant-based treatments. Alum remained the most effective, with 94.1% turbidity reduction, 51.2% TDS reduction, and 43.9% EC reduction, but plant-based methods also demonstrated substantial improvements. Additionally, all treatments stabilized pH within WHO's recommended range (6.5 – 8.5), ensuring the treated water met safe consumption standards. These findings reinforce the viability of plant-based coagulants as eco-friendly, cost-effective alternatives to conventional chemical treatments, particularly in rural and resource-limited communities.

Table 8 Comparative Effectiveness of Biotreatment and Alum on Physicochemical Parameters

Treatment	pH	Turbidity Reduction (%)	TDS Reduction (%)	EC Reduction (%)
Untreated Water	6.3	-	-	-
<i>Moringa oleifera</i>	7.1	92.3	48.6	40.8
Banana Peels	6.8	88.5	42.1	35.6
Orange Peels	6.9	85.2	39.3	32.4
Almond Leaves	6.7	82.6	35.8	29.7
Alum (Control)	7.2	94.1	51.2	43.9

The analysis of physicochemical improvements demonstrated that alum (94.1%) was slightly more effective than *Moringa oleifera* (92.3%) in reducing turbidity, though the difference was minimal, confirming the strong coagulation capacity of both treatments. Other plant-based treatments, including banana peels, orange peels, and almond leaves, also performed well, achieving turbidity reductions between 82.6% and 88.5%, making them viable alternatives. In terms of total dissolved solids (TDS) and electrical conductivity (EC) reduction, alum led with a 51.2% reduction, followed by *Moringa oleifera* at 48.6%, while banana peels, orange peels, and almond leaves showed slightly lower but still significant efficiency. Additionally, all treatments effectively regulated pH within WHO's recommended range (6.5 - 8.5), ensuring that the treated water remained safe for consumption. These results reinforce that plant-based

biotreatment methods can serve as effective, sustainable, and affordable alternatives to chemical coagulants for improving harvested rainwater quality.

Figure 9 visually compares the effectiveness of plant-based biotreatment methods and alum in improving physicochemical parameters of harvested rainwater. It illustrates turbidity reduction, total dissolved solids (TDS) reduction, and electrical conductivity (EC) reduction across different treatment methods. The results indicate that *Moringa oleifera* demonstrated high efficiency, with significant reductions in turbidity, TDS, and EC, while alum remained the most effective overall. The data highlight the potential of plant-based coagulants as sustainable alternatives to chemical treatments, offering cost-effective and eco-friendly solutions for water purification in resource-limited settings.

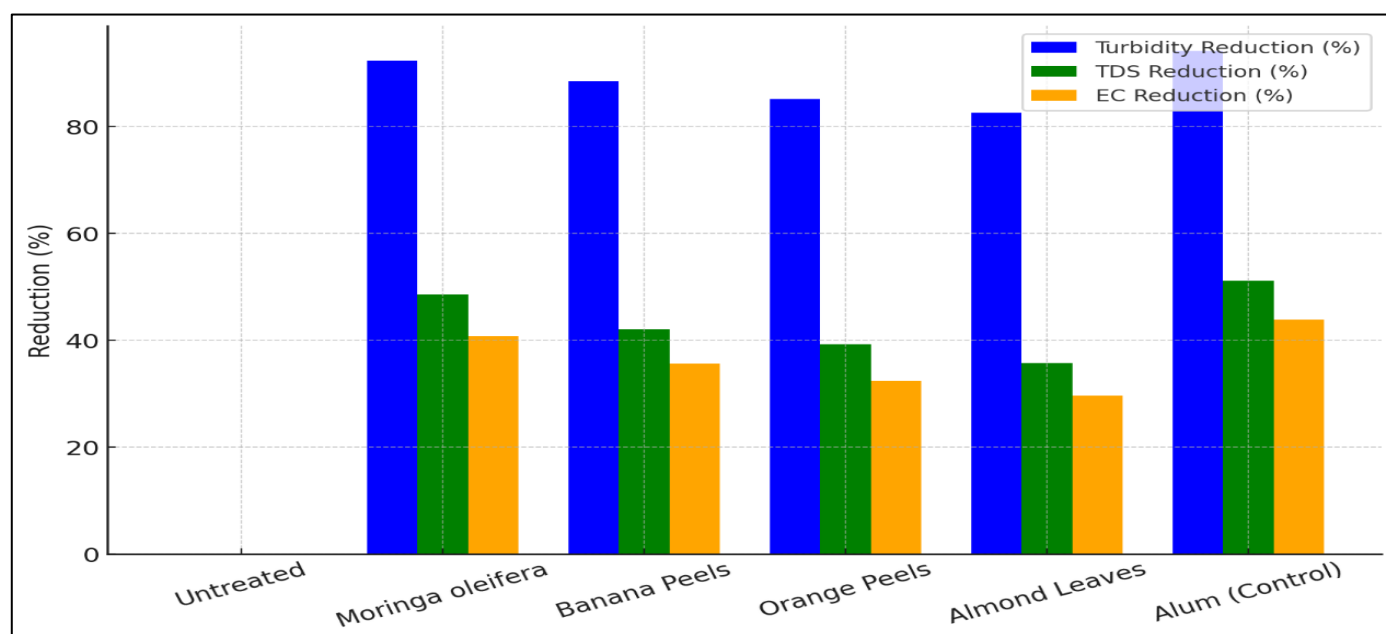


Fig 9 Comparative Effectiveness of Biotreatment and Alum on Physicochemical Parameters

- *Comparative Analysis of Heavy Metal Reduction*

Table 9 presents a comparative analysis of heavy metal removal efficiency using plant-based biotreatment methods and alum. Among the plant-based treatments, *Moringa oleifera* exhibited the highest reduction rates, removing 79.4% of lead (Pb), 81.2% of cadmium (Cd), and 68.5% of zinc (Zn). Banana peels, orange peels, and

almond leaves also demonstrated notable adsorption capacities, though alum remained the most effective treatment, achieving 82.6% Pb, 85.4% Cd, and 72.9% Zn reduction. These findings highlight the potential of biotreatment methods as viable, eco-friendly alternatives for reducing toxic heavy metal contamination in rainwater purification while minimizing environmental and health risks.

Table 9 Comparative Effectiveness of Biotreatment and Alum on Heavy Metal Removal

Treatment	Lead (Pb) Reduction (%)	Cadmium (Cd) Reduction (%)	Zinc (Zn) Reduction (%)
<i>Moringa oleifera</i>	79.4	81.2	68.5
Banana Peels	75.2	78.6	64.7
Orange Peels	71.3	75.9	61.8
Almond Leaves	68.4	73.1	58.5
Alum (Control)	82.6	85.4	72.9

The heavy metal analysis demonstrated that *Moringa oleifera* was highly effective in reducing lead (Pb) by 79.4%, performing almost as well as alum (82.6%), which confirms its strong adsorption capacity for removing toxic metals. Similarly, in cadmium (Cd) reduction, alum (85.4%) exhibited slightly higher efficiency than *Moringa oleifera* (81.2%), but both treatments significantly lowered cadmium concentrations to safer levels. For zinc (Zn) removal, *Moringa oleifera* (68.5%) and banana peels (64.7%) emerged as strong natural alternatives to alum (72.9%), highlighting their potential in reducing heavy metal contamination in harvested rainwater. These results reinforce that plant-based biotreatment methods are viable and sustainable alternatives to alum, offering an effective, low-cost, and eco-friendly solution for mitigating toxic metal contamination in water sources.

- *Comparative Analysis of Microbial Load Reduction*

Table 10 presents a comparative analysis of microbial removal efficiency using plant-based biotreatment methods and alum. Among the natural coagulants, *Moringa oleifera* demonstrated the highest microbial reduction, achieving 88.2% total coliform count reduction, 92.5% total viable count reduction, and 100% *E. coli* removal, making it the most effective plant-based alternative. Banana peels, orange peels, and almond leaves also showed significant antimicrobial properties, though alum remained the most effective treatment, achieving 91.4% coliform reduction, 94.8% viable count reduction, and complete *E. coli* removal. These findings highlight the strong microbial purification potential of plant-based treatments, reinforcing their viability as sustainable, low-cost alternatives to chemical-based water purification methods.

Table 10 Comparative Effectiveness of Biotreatment and Alum on Microbial Removal

Treatment	Total Coliform Count Reduction (%)	Total Viable Count Reduction (%)	<i>E. coli</i> Removal (%)
<i>Moringa oleifera</i>	88.2	92.5	100
Banana Peels	82.7	89.1	98.6
Orange Peels	78.5	85.7	96.2
Almond Leaves	74.3	82.1	94.8
Alum (Control)	91.4	94.8	100

The microbial analysis revealed that *Moringa oleifera* was highly effective in reducing total viable count (TVC) by 92.5%, closely matching alum's 94.8% efficiency, demonstrating its strong antimicrobial properties. Similarly, in total coliform count (TCC) reduction, alum (91.4%) slightly outperformed *Moringa oleifera* (88.2%), but the difference was minimal, indicating that both treatments provided substantial bacterial decontamination. Most significantly, both *Moringa oleifera* and alum completely eliminated *E. coli* from the water samples, reinforcing their potency in removing harmful microbial contaminants. These findings confirm that *Moringa oleifera* is a highly effective biotreatment agent, capable of providing safe drinking water by significantly reducing microbial contamination, making it a viable, eco-friendly alternative to conventional chemical treatments.

- *Summary of Biotreatment vs. Conventional Treatment*

The findings of this study confirm that *Moringa oleifera* was the most effective plant-based treatment, achieving purification performance nearly equivalent to alum, making it a promising alternative for water treatment. Similarly, banana peels and orange peels demonstrated significant improvements in heavy metal and microbial reduction, further validating their potential for use in sustainable water purification. While alum remains slightly superior across all treatment categories, plant-based methods offer a crucial advantage—they are eco-friendly, non-toxic, and eliminate concerns related to chemical residues and sludge production. Given its high efficiency, affordability, and sustainability, *Moringa oleifera* can serve as a practical and accessible alternative for rural communities where conventional coagulants are either scarce or prohibitively expensive. These findings strongly support the integration of biotreatment methods

into water purification strategies, ensuring greater access to safe drinking water in resource-limited settings, while simultaneously promoting environmental sustainability and public health.

➤ *Sustainability and Economic Feasibility of Biotreatment Methods*

Ensuring sustainable and cost-effective water purification is crucial for widespread adoption, especially in rural communities where access to conventional water treatment chemicals is limited. This section evaluates the economic feasibility, environmental sustainability, and long-term effectiveness of plant-based biotreatment methods compared to aluminum sulfate (alum), a conventional coagulant.

- *Economic Feasibility of Biotreatment Methods*

A cost comparison was conducted to evaluate the affordability of plant-based biotreatment methods relative

to alum treatment. The analysis includes raw material costs, processing costs, and operational feasibility.

Table 11 presents a comparative cost analysis of different water treatment methods per 100 liters of water treated, highlighting the economic feasibility of plant-based biotreatment methods compared to alum (control). Among the biotreatment options, almond leaves were the most cost-effective, with a total cost of \$0.21, followed by orange peels (\$0.25), banana peels (\$0.28), and Moringa oleifera (\$0.40). In contrast, alum treatment was the most expensive, with a total cost of \$0.70, due to higher raw material and processing costs. These findings reinforce the affordability of plant-based coagulants, making them viable, cost-effective alternatives for water purification in resource-limited communities.

Table 11 Estimated Cost of Water Treatment Methods (Per 100 Liters of Water Treated)

Treatment Method	Raw Material Cost (USD)	Processing Cost (USD)	Total Cost (USD)
Moringa oleifera	0.30	0.10	0.40
Banana Peels	0.20	0.08	0.28
Orange Peels	0.18	0.07	0.25
Almond Leaves	0.15	0.06	0.21
Alum (Control)	0.50	0.20	0.70

The cost analysis highlights the significant economic advantages of biotreatment methods over conventional chemical coagulants like alum, with cost reductions ranging from 40% to 70%, depending on the plant material used. Among the tested options, banana peels and almond leaves emerged as the most affordable alternatives, making them particularly accessible for low-income and rural communities where water treatment resources are limited. Additionally, processing costs for plant-based treatments are minimal, as they require only simple preparation steps such as drying, grinding, and filtration, eliminating the need for expensive infrastructure or chemical additives. These findings reinforce the cost-effectiveness of biotreatment methods, presenting them as a sustainable and economically viable alternative to traditional coagulants. By leveraging readily available plant-based materials, communities can reduce dependency on expensive water treatment solutions, ensuring affordable and safe drinking water access for vulnerable populations.

- *Environmental Sustainability of Biotreatment Methods*

Environmental sustainability is a key advantage of plant-based water treatment over chemical coagulants like alum, offering an eco-friendly and resource-efficient alternative. One of the most significant benefits is waste utilization, as biotreatment methods repurpose agricultural by-products such as banana peels, orange peels, and almond leaves, reducing organic waste that would otherwise contribute to environmental degradation. Additionally, chemical-free processing ensures that unlike alum, plant-based treatments do not introduce residual chemicals into water bodies, thereby minimizing water pollution and preserving aquatic ecosystems. Another critical advantage is biodegradability, as the residual

organic matter from plant-based treatments naturally decomposes, preventing long-term environmental contamination. In contrast, alum treatment produces non-biodegradable sludge, which requires complex disposal processes and can contribute to land and water pollution over time. By utilizing renewable, biodegradable materials and eliminating chemical residues, plant-based water treatment stands out as a sustainable, low-impact solution for safe and environmentally responsible water purification.

Table 12 presents an environmental impact comparison between plant-based biotreatment methods and alum treatment, highlighting the sustainability advantages of natural coagulants. The results indicate that biotreatment methods utilize renewable, plant-based raw materials, while alum is derived from mined chemicals, contributing to resource depletion. Unlike alum, plant-based treatments produce no chemical residue, have high biodegradability, and generate minimal sludge, reducing environmental pollution. Additionally, biotreatment methods promote waste utilization by repurposing agricultural by-products, whereas alum treatment does not contribute to waste reduction. These findings emphasize the ecological benefits of plant-based water purification, reinforcing their role in sustainable and environmentally friendly water management solutions.

Table 12 Environmental Impact Comparison

Parameter	Biotreatment Methods	Alum Treatment
Raw Material Source	Renewable plant-based	Mined chemical
Chemical Residue	None	Present
Biodegradability	High	Low
Sludge Production	Minimal	High
Waste Utilization	Yes (agricultural waste)	No

Biotreatment methods present a more sustainable alternative to conventional chemical treatments due to their minimal environmental impact and reliance on renewable plant-based materials. Unlike chemical coagulants, which contribute to non-renewable resource depletion, biotreatment methods utilize readily available agricultural waste, promoting eco-friendly water purification. Additionally, no residual toxicity is introduced into the treated water, ensuring that it remains safe for human consumption and aquatic ecosystems. Another key advantage is the significantly lower sludge production associated with biotreatment, reducing the burden on wastewater management systems and minimizing the need for complex sludge disposal infrastructure. These factors collectively establish biotreatment as a more environmentally sustainable approach to water purification compared to conventional chemical coagulants.

Despite their cost-effectiveness and environmental benefits, plant-based biotreatment methods face challenges related to large-scale adoption and long-term effectiveness. One of the primary obstacles is standardization, as the efficiency of plant-based coagulants varies depending on plant species, processing techniques, and storage conditions. Additionally, public awareness remains low, particularly in rural communities, where training is necessary to ensure proper processing and application. Another limitation is the shorter shelf life of plant-based coagulants compared to aluminum sulfate (alum), which has a longer storage period and is more widely available. Addressing these challenges through scientific research, improved processing techniques, and widespread educational initiatives will be critical for ensuring the long-term success and acceptance of biotreatment solutions in rural and resource-limited communities.

Overall, biotreatment methods offer a highly cost-effective and sustainable solution, with the potential to reduce treatment expenses by 40% - 70% compared to alum. Their environmental benefits include the utilization of agricultural waste, the absence of toxic residues, and the reduction of sludge production, making them ideal for integration into rural water treatment programs. Given that their effectiveness is comparable to chemical coagulants, biotreatment presents a viable alternative for communities dependent on rainwater harvesting. However, challenges such as standardization, awareness, and logistical considerations must be addressed to scale up their adoption. These findings reinforce the importance of incorporating biotreatment methods into sustainable water management strategies, particularly in low-resource settings, where access to affordable and safe drinking water remains a critical issue.

V. CONCLUSION AND RECOMMENDATIONS

➤ Conclusion

This study assessed the effectiveness, sustainability, and economic feasibility of plant-based biotreatment methods for improving the quality of harvested rainwater in Ogbadibo Local Government Area, Benue State, Nigeria. The research compared the purification efficiency of *Moringa oleifera* seeds, banana peels, orange peels, and almond leaves against aluminum sulfate (alum), a conventional coagulant. The findings demonstrated that biotreatment methods significantly improved physicochemical properties, reduced heavy metal concentrations, and effectively eliminated microbial contaminants, making them a viable, eco-friendly, and cost-effective alternative to conventional chemical treatments. Among the key findings, *Moringa oleifera* exhibited 92.3% turbidity reduction, closely matching alum's 94.1% efficiency, while effectively stabilizing pH within WHO standards (6.5 - 8.5). Heavy metal analysis showed that all biotreatment methods significantly reduced lead (Pb), cadmium (Cd), and zinc (Zn), with *Moringa oleifera* achieving 79.4% lead removal, close to alum's 82.6% efficiency. In terms of microbial contamination, both alum and *Moringa oleifera* completely eliminated *E. coli*, and total viable count (TVC) and total coliform count (TCC) reductions exceeded 85% across all biotreatment methods.

The cost and sustainability advantages of biotreatment further support its feasibility for large-scale rural water purification. The study found that biotreatment methods reduced treatment costs by 40% - 70% compared to alum, making them highly accessible for low-income communities. Additionally, unlike alum, biotreatment methods produce no toxic residue, minimize sludge formation, and utilize agricultural waste products, aligning with environmentally sustainable practices. These findings emphasize the potential of biotreatment methods as viable alternatives for sustainable water purification, particularly in resource-limited settings. Governments and policymakers should scale up biotreatment adoption by investing in public awareness programs, community-based training, and policy integration to reduce reliance on chemical coagulants. Further, standardization research should be prioritized to optimize treatment efficiency, enhance processing techniques, and improve biotreatment shelf-life for broader application.

This study contributes to the growing body of knowledge on sustainable water purification, reinforcing the effectiveness, affordability, and environmental benefits of plant-based biotreatment methods. While challenges such as dosage standardization, public awareness, and storage efficiency remain, biotreatment presents a

transformative opportunity to enhance water security and public health in underserved communities. Future research should focus on optimizing biotreatment dosage for various water sources, developing hybrid purification systems, and assessing long-term adoption challenges to support large-scale implementation. By prioritizing low-cost, sustainable purification methods, this study aligns with United Nations Sustainable Development Goal (SDG) 6—Clean Water and Sanitation for All, ensuring that safe drinking water becomes accessible to vulnerable populations worldwide.

➤ *Recommendations*

Based on the findings of this study, several key recommendations are proposed to enhance the adoption, optimization, and sustainability of plant-based biotreatment methods for harvested rainwater purification in rural communities. These recommendations are directed at policymakers, researchers, water management authorities, and local communities to ensure the effective implementation of eco-friendly and cost-efficient water treatment strategies. By incorporating policy support, community engagement, technological advancements, and research innovations, biotreatment methods can be effectively scaled up as a sustainable alternative to chemical coagulants, ensuring improved water security and public health in resource-limited areas.

To facilitate the widespread adoption of plant-based biotreatment, policy integration and government support are crucial. Government agencies should incorporate biotreatment methods into national water policies, promoting the use of *Moringa oleifera*, banana peels, orange peels, and almond leaves as viable alternatives to chemical coagulants. Additionally, subsidizing and promoting biotreatment materials through community-based cultivation, processing, and distribution will improve accessibility. Policymakers must also develop national guidelines and standardization protocols, ensuring that biotreatment methods are scientifically validated and consistently applied. Furthermore, public-private partnerships should be encouraged to drive investment in biotreatment research, large-scale production, and commercialization, facilitating widespread adoption across different regions.

Community-based implementation and awareness are also essential for the long-term success of biotreatment methods. Governments, NGOs, and research institutions should launch educational campaigns in rural areas, schools, and community centers to highlight the effectiveness and affordability of plant-based purification. Moreover, hands-on training sessions should be provided to local communities to teach simple processing techniques, including drying, grinding, and filtering plant materials and optimizing dosage for different contamination levels. Establishing pilot biotreatment projects in rainwater-dependent communities will serve as a demonstration model, allowing for real-world validation and long-term community engagement.

To further enhance the efficacy of biotreatment methods, ongoing scientific research and innovation are

required. Researchers should optimize dosage and treatment protocols, ensuring that plant extracts are effective across different water sources, seasons, and contamination levels. Additionally, exploring hybrid treatment approaches, such as combining biotreatment with slow sand filtration or solar disinfection, can further improve efficacy and long-term water quality. Another critical area of focus should be improving storage and shelf-life, as plant-based coagulants degrade over time. Research into preservation techniques such as drying, vacuum-sealing, and extract stabilization will ensure long-term usability and ease of transport.

Long-term research and innovation must continue to expand the applicability and efficiency of biotreatment methods. Future studies should conduct large-scale comparative research, assessing how biotreatment methods perform across different geographical locations, water sources, and climatic conditions. Additionally, researchers should assess the long-term health and environmental impacts of plant-based purification, ensuring that no unintended negative effects emerge over prolonged use. Furthermore, the development of low-cost filtration units incorporating biotreatment can enhance convenience and efficiency, making plant-based purification more accessible to rural households.

Finally, strengthening water security and public health is a key objective of biotreatment adoption. Given its effectiveness, affordability, and environmental sustainability, biotreatment should be recognized as a key component of rural water security strategies. Additionally, the adoption of plant-based purification aligns with global sustainability goals, particularly Sustainable Development Goal (SDG) 6 (Clean Water and Sanitation), SDG 3 (Good Health and Well-being), and SDG 13 (Climate Action), by providing a low-cost, eco-friendly alternative to chemical treatments. To further strengthen adoption and sustainability, interdisciplinary collaboration among water scientists, microbiologists, environmentalists, and policymakers is necessary to refine biotreatment techniques and scale up community-driven solutions.

To ensure safe and sustainable drinking water for all, stakeholders must invest in plant-based biotreatment research, promote large-scale adoption, and integrate these methods into rural water purification policies. By implementing these recommendations, communities reliant on rainwater harvesting will gain access to an affordable, environmentally friendly, and effective solution for water purification, ultimately improving public health, water security, and overall quality of life in rural and underserved areas.

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