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Experimental Assessment of Bio-Based Materials for Borewell Water Purification

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Abstract –*The growing concern over declining groundwater quality in India has increased the demand for sustainable and low-cost water purification techniques. Borewell water, which serves as a primary source of domestic water in rural and semi-urban regions, often contains contaminates such as fluoride, heavy metals, hardness ions, and microbial impurities due to both natural and anthropogenic activities. The present research focuses on the experimental assessment of bio-based materials such as Moringa seed, Coconut shell, Banana peel, and Rice husk ash for borewell water purification. These materials, abundant in nature and biodegradable, act as bio-absorbents capable of removing diverse pollutants through adsorption and coagulation processes.*

This paper consolidates findings from previous studies and elaborates on adsorption mechanisms, preparation methods, and removal efficiencies. Each material's physicochemical properties and its interaction with contaminants are analyzed in detail. The methodology involves systematic sampling, adsorbent preparation, and laboratory testing using standard protocols. The results confirm that these bio-materials can remove contaminants with efficiencies ranging from 85–95%, depending on dosage and contact time. The proposed approach aligns with Sustainable Development Goal (SDG 6)—Clean Water and Sanitation—by offering a green, low-cost solution suitable for decentralized household water treatment systems, especially in rural areas of India.

Key Words: **Bio-adsorbents, Borewell water, Fluoride removal, Heavy metals, Sustainable purification, Moringa seed, Coconut shell, Banana peel, Rice husk ash.**

1. INTRODUCTION

Water is an indispensable resource for life and sustainable development. In India, groundwater serves as the backbone of the water supply system, catering to nearly 80% of the rural population and 50% of the urban population. Borewell water is considered a reliable source due to its perennial availability; however, it is not always safe for direct consumption. Over the past few decades, excessive extraction of groundwater, coupled with industrial expansion and agricultural intensification, has resulted in deterioration of its quality. The contamination arises from both geogenic (natural rock-water interaction) and anthropogenic (human-induced) sources.

Borewell water in many Indian regions exhibits elevated concentrations of fluoride, iron, manganese, nitrates, chlorides, arsenic, and hardness ions such as calcium and magnesium. High fluoride content, particularly in states like Maharashtra, Rajasthan, and Andhra Pradesh, has led to widespread dental and skeletal fluorosis. Similarly, excessive hardness and heavy metal contamination make the water unfit for domestic use. The severity of this problem has drawn attention toward developing efficient, low-cost, and environmentally compatible water treatment methods.

Conventional purification methods such as reverse osmosis (RO), ion exchange, and chemical precipitation are highly effective but not economically feasible for rural and semi-urban areas. They demand high capital cost, energy input, and maintenance while producing concentrated chemical waste that poses disposal challenges. Moreover, these methods often remove essential minerals, altering the natural taste and balance of water. Hence, there is a pressing need to identify eco-friendly and sustainable alternatives that can provide acceptable purification levels at minimal cost.

Bio-based adsorbents have emerged as an innovative and green solution for water treatment. These materials are derived from agricultural by-products and plant residues, such as coconut shells, banana peels, rice husk, and moringa seeds. Their natural composition includes cellulose, hemicellulose, lignin, pectin, proteins, and silica, which provide active binding sites like carboxyl (-COOH), hydroxyl (-OH), and amino ($-NH_2$) groups capable of adsorbing contaminants through surface complexation, ion exchange, and electrostatic attraction. Moreover, these bio-adsorbents convert waste materials into useful filtration media, promoting the concept of waste-to-resource utilization.

The present study evaluates the adsorption potential of four selected bio-materials—Moringa seed, Coconut shell, Banana peel, and Rice husk ash—for borewell water purification. Each material was chosen for its unique properties: Moringa

seeds for coagulation and bacterial removal, Coconut shell for hardness reduction and organic adsorption, Banana peel for fluoride adsorption, and Rice husk ash for heavy metal removal. This integrated approach aims to enhance the overall purification efficiency through natural, low-cost, and sustainable materials.

In addition, this work emphasizes the potential for scaling up these materials for use in domestic filters and community-scale treatment systems. By integrating multiple adsorbents in layered configurations, it becomes possible to target a wide range of impurities while maintaining natural mineral content. The research also contributes to environmental sustainability by reducing agricultural waste and avoiding the chemical hazards associated with synthetic treatment materials.

Thus, this paper represents a step toward creating a cost-effective, decentralized water purification framework for rural India—utilizing materials that are locally available, safe, and sustainable.

2. OBJECTIVES

The main objectives of this study are as follows:

1. To review and analyse experimental studies on bio-based adsorbent materials used for borewell water purification.
2. To evaluate the purification performance of four selected natural materials: Moringa seed, Coconut shell, Banana peel, and Rice husk ash.

3. To identify the physical and chemical properties responsible for contaminant adsorption and coagulation.
4. To compare the removal efficiencies, advantages, and limitations of each material.

5. To propose an eco-friendly, cost-effective, and sustainable purification framework suitable for domestic applications in rural India.

3. LITERATURE REVIEW

Recent studies on bio-based materials such as banana peel powder, Moringa oleifera seeds, rice husk ash, and coconut shell activated carbon have demonstrated their excellent potential as sustainable, low-cost, and eco-friendly adsorbents for the purification of borewell and groundwater. These naturally available materials contain reactive surface groups such as hydroxyl, carboxyl, and amino functional moieties, along with porous and fibrous structures, which enhance their adsorption efficiency for various contaminants, including fluoride, heavy metals, turbidity, and hardness-causing ions.

Research on banana peel powder has shown that its lignocellulosic matrix provides numerous active binding sites, enabling the efficient removal of fluoride ions from water through ion exchange and hydrogen bonding mechanisms [1]. The adsorption process follows pseudo-second-order kinetics, confirming that chemisorption dominates the mechanism, with maximum fluoride elimination reaching nearly 88% under optimum conditions [1].

Similarly, experimental investigations using Moringa oleifera seed powder and husk have proven highly effective for reducing trihalomethanes (THMs), turbidity, suspended particles, and microbial contaminants [2]. The presence of cationic proteins and polar functional groups in Moringa facilitates charge neutralization, leading to enhanced coagulation and adsorption efficiency. Moreover, Moringa seed extracts serve as a dual-function agent—acting both as a natural coagulant and as an adsorbent—which significantly improves water quality by eliminating organic and microbial impurities without releasing toxic residues [3]. This dual mechanism makes Moringa a particularly suitable and sustainable option for rural and decentralized water purification applications.

The use of rice husk ash (RHA) has also gained considerable attention due to its high silica content and large surface area, which provide superior adsorption properties for both anionic and cationic pollutants [4]. When incorporated into biopolymeric matrices such as sodium alginate to form composite beads, RHA exhibits enhanced mechanical strength, reusability, and higher adsorption capacity for fluoride and heavy metals like lead, cadmium, and chromium, often exceeding 90% removal efficiency [4]. Such characteristics make RHA–alginate composites a promising material for long-term and cost-effective water purification systems.

Activated carbon derived from coconut shells is another highly promising bio-adsorbent material, known for its high fixed carbon content, surface porosity, and tunable functional groups developed through physical or chemical activation [5]. Studies have revealed that coconut shell-based carbon effectively removes impurities such as chlorine, fluoride, and lead, achieving purification efficiencies in the range of 85–90% under variable pH and contact times [5]. In addition, the material shows strong mechanical integrity and reusability, making it appropriate for continuous household and small-scale filtration applications. Another investigation highlighted that activated charcoal prepared from coconut shells can effectively reduce water hardness by removing calcium and magnesium ions through surface complexation and ion exchange, achieving up to 90% hardness reduction [6].

Overall, the reviewed literature confirms that bio-based adsorbents sourced from agricultural residues are effective, sustainable, and economically feasible alternatives to synthetic treatment materials. Their adsorption performance is influenced by operational parameters such as pH, dosage, temperature, and contact time. Despite minor drawbacks—such as reduced efficiency under extreme pH or gradual loss of reusability after several cycles—these materials remain attractive due to their biodegradability, easy availability, and non-toxic nature. Hence, bio-based materials like Moringa oleifera seed powder, rice husk ash, banana peel, and coconut shell activated carbon can play a vital role in improving borewell water quality, particularly in rural and developing regions, promoting an environmentally sustainable approach toward safe drinking water access.

4. MATERIAL SELECTION

The selection of suitable bio-based materials was carried out after a thorough review of previous research findings and analysis of borewell water characteristics in local regions. The primary objective was to identify low-cost, locally available, and environmentally sustainable materials capable of addressing specific impurities such as hardness, fluoride, turbidity, heavy metals, and microbial contamination. Based on this assessment, four major materials were finalized—Moringa oleifera seeds, Coconut shell activated carbon, Banana peel powder, and Rice Husk Ash. Each material possesses unique surface chemistry and adsorption potential, enabling multi-functional purification when used in combination.

4.1. Moringa oleifera Seeds

Mooring ole if era, commonly known as the drumstick tree, is a fast-growing tropical plant found abundantly in rural India. Mature seeds from local agricultural farms were collected, sun-dried, and de-husked manually to obtain clean kernels. These kernels were then pulverized into a fine powder and sieved to maintain uniformity.

Mooring seeds are known for their cationic proteins and polyelectrolytes, which neutralize negatively, charged colloidal particles and microorganisms. The powder contains bioactive compounds such as oleic acid, phenolics, and amino groups, which facilitate adsorption and coagulation. The surface of Moringa seed powder exhibits both hydrophilic and hydrophobic regions, allowing it to bind with a wide range of contaminants.

In bore well water, Moringa seed powder primarily reduces turbidity, total suspended solids (TSS), and bacterial contamination. It also contributes to the removal of organic matter and slight colour improvement. This natural coagulant is biodegradable, leaves no residual toxicity, and provides a sustainable alternative to aluminium-based coagulants used in conventional treatment.

Fig -1: Moringa oleifera Seeds

4.2. Coconut Shell Activated Carbon

Coconut shells, a common agricultural by-product in tropical regions, were selected for their exceptional carbon content and microporous structure. Locally available discarded shells were collected from coconut processing units and cleaned thoroughly to remove residual oil or dirt. The shells were then sun-dried and subjected to carbonization at approximately 600°C, followed by steam activation to develop extensive pore networks.

The resulting activated carbon possesses a high BET surface area (800–1000 m^2/g), enhancing its capacity for physical adsorption of dissolved impurities. Functional groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O) contribute to its ion-exchange properties. These surface functionalities facilitate the removal of both inorganic ions and organic molecules.

When applied to bore well water, coconut shell activated carbon effectively removes hardness, odour, residual chlorine, colour, and heavy metals like lead (Pb^{2+}) and iron (Fe^{2+}). It also reduces fluoride and nitrate levels through ion exchange and surface adsorption. Its mechanical strength and reusability make it suitable for multi-cycle applications in household filters.

Fig -2: Coconut Shell Activated Carbon

4.3. Banana Peel Powder

Banana peel, an agricultural waste product, was chosen for its high lignin, cellulose, and pectin content, which provide abundant binding sites for adsorption. Fresh banana peels were collected from fruit markets, washed to remove dirt, sun-dried for 48 hours, and ground into a fine powder. The powder was sieved to ensure uniform particle size and stored in an airtight container to maintain its adsorptive activity.

The surface chemistry of banana peel includes carboxylic, hydroxyl, and amine groups, which exhibit high affinity for cationic species. Due to its fibrous and porous nature, it effectively removes fluoride, lead, and cadmium ions, as well as certain organic pollutants. The pectin content acts as a natural chelating agent, allowing strong complex formation with heavy metals.

In borewell water, banana peel powder primarily contributes to the reduction of fluoride, iron, and turbidity. It also enhances water clarity and taste, making it more suitable for domestic use. The use of this waste material adds value to agricultural residues, promoting sustainable waste utilization and circular economy practices.

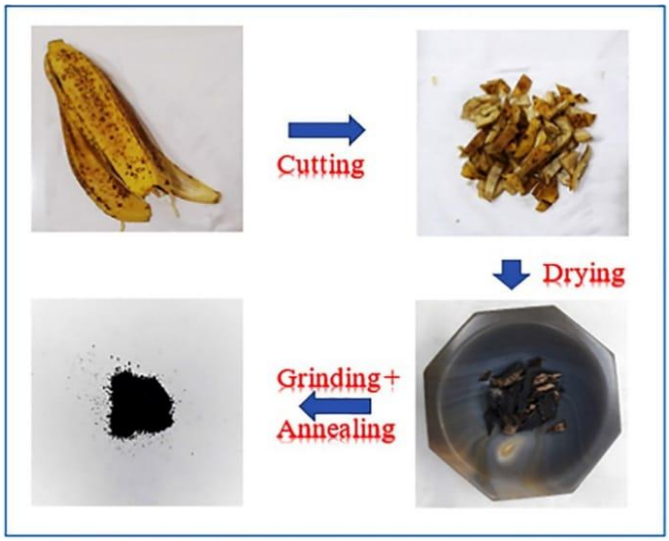

Fig -3: Banana Peel Powder

4.4. Rice Husk Ash

Rice Husk Ash (RHA) was chosen for its high amorphous silica (SiO_2) content, known to exhibit strong adsorptive and ion-exchange properties. Rice husk, an abundant by-product from local rice mills, was collected and washed thoroughly to remove dust and soluble impurities. It was then subjected to control burning at around 600°C to obtain fine, light grey ash with uniform particle size.

The surface structure of RHA, observed under scanning microscopy, displays extensive micro-porosity, providing a high surface area for adsorption. The silica structure possesses negatively charged hydroxyl groups that attract cationic contaminants through electrostatic interaction.

RHA is particularly efficient in removing fluoride, heavy metals (Pb^{2+}, Cr^{6+}, and Cd^{2+}), and iron ions from borewell water. Additionally, it reduces turbidity and colour while maintaining water neutrality. Its abundance, low cost, and chemical stability make it a promising material for rural water treatment systems.

Fig -4: Rice Husk Ash

Combined Material Rationale

The combined application of these four materials—Moringa seed powder, Coconut shell activated carbon, Banana peel powder, and Rice Husk Ash—provides a comprehensive purification mechanism. Each component addresses different categories of contaminants:

Maringa removes suspended solids and microbes through coagulation.

Coconut shell carbon adsorbs hardness, chlorine, and organic compounds.

Banana peel captures fluoride and heavy metals.

Rice husk ash removes fluoride, color, and trace metals.

This synergistic effect ensures the purification of borewell water across multiple impurity categories, thereby improving overall water quality, taste, and safety for domestic usage.

5. METHODOLOGY

1 **Material Sampling and Preparation:**
Each bio-adsorbent was prepared as described above and sieved to uniform size for consistency.

2 **Sample Collection:**
Borewell water samples were collected from rural domestic wells using sterilized bottles and analyzed for baseline parameters.

3 Experimental Procedure:

1. Moringa Seed Powder (Bio-Adsorbent) Preparation of Adsorbent

a) Mature moringa seeds were collected and cleaned by removing the outer husk or seed coat wherever necessary.

b) The cleaned seeds were washed thoroughly with tap water followed by rinsing with deionized water to eliminate dust and soluble impurities.

c) The washed seeds were air-dried under shade and subsequently oven-dried at 105 °C for 12–16 hours until a constant weight was achieved.

d) The dried seeds were dehulled (if not done earlier) and ground into fine powder using a mechanical grinder. The powdered sample was sieved to obtain different particle size ranges, preferably below 150 µm and 150–425 µm.

e) 5. The prepared moringa seed powder was stored in airtight containers and placed in a desiccator to prevent moisture absorption before use.

Batch Adsorption Experiment

Each adsorption experiment was conducted using 500 mL of borewell water per batch. Adsorbent doses were maintained at 1.0, 2.0, 3.0, and 4.0 g corresponding to 2–8 g/L concentrations. The contact time intervals were 15, 30, 60, 90, and 120 minutes to study the adsorption kinetics.
The effect of pH was examined at the natural pH of the water, as well as at pH 4, 6, and 8, using 0.1 M HCl or NaOH for adjustment. Agitation was carried out at 150 rpm using an orbital shaker at room temperature (25 ± 2 °C).

Procedure

i. The desired quantity of moringa powder was added to 500 mL of borewell water in a conical flask.
ii. pH adjustments were made as per experimental design, and agitation was started while recording the contact time.
iii. At each time interval, 10–20 mL of the solution was withdrawn and filtered using a 0.45 µm filter paper (Whatman No. 42).
iv. The filtrate was analyzed for various physicochemical parameters such as turbidity, hardness, fluoride, and heavy metal content.
v. Removal efficiency (%) and adsorption capacity (q_e or q□) were calculated using standard adsorption equations.

2. Coconut Shell Activated Carbon (CS-AC) Preparation of Adsorbent

a) Waste coconut shells were collected, cleaned thoroughly to remove dust and organic residues, and oven-dried at 105 °C until constant mass was obtained.

b) The dried shells were crushed and sieved to obtain uniform particle sizes (<150 µm and 150–425 µm).

Activation Process

For laboratory-scale preparation, chemical activation was preferred. The coconut shell powder was impregnated with phosphoric acid (H_3PO_4) or potassium hydroxide (KOH) solution at an impregnation ratio of 1:1 to 1:3 (w/w). The mixture was stirred for 2–6 hours, oven-dried, and then carbonized in a muffle furnace at 450–700 °C for 1–2 hours under limited oxygen.
The activated product was washed with distilled water until neutral pH and dried again. (Alternatively, commercially available CS-AC can be used if furnace facilities are unavailable.)

Batch Adsorption Experiment

The experiments were carried out using 500 mL of borewell water. The dosage range was 1.0–4.0 g (equivalent to 2–8 g/L). Contact times were 10, 20, 30, 60, and 120 minutes.
The pH effect was analyzed at natural pH, pH 4, pH 7, and pH 9. The agitation speed was maintained at 150–200 rpm and the temperature at 25 °C (with optional trials at 35 °C to study thermodynamic behavior).

Procedure

i. The activated carbon dose was introduced into the flask containing 500 mL of borewell water.
ii. The mixture was stirred at constant speed, and samples were withdrawn at predetermined intervals.
iii. The collected samples were filtered and tested for contaminant reduction efficiency.

3. Banana Peel Adsorbent (Raw or Carbonized Form) Preparation of Adsorbent

a) Fresh banana peels were collected washed to remove any adhering dirt, and cut into small uniform pieces.

b) The pieces were oven-dried at 60–80 °C for 6–12 hours until complete drying.

c) Dried peels were ground into powder and sieved to desired particle sizes (<150 µm and 150–425 µm).

d) Optionally, the powder was carbonized at 300–500 °C in a closed crucible to obtain banana peel biochar, which enhances adsorption for certain pollutants.

e) For further surface modification, the adsorbent could be treated with 0.1–0.5 M NaOH or $CaCl_2$ solution to increase functional groups responsible for metal ion binding, followed by washing to neutral pH and oven-drying.

Batch Adsorption Experiment

Each test was performed with 500 mL of borewell water using adsorbent dosages of 2, 4, 6, and 8 g/L.
Contact times were fixed at 15, 30, 60, and 120 minutes to determine adsorption kinetics.
The influence of pH was studied at natural, pH 4, pH 6, and pH 8 conditions. Samples were agitated at 120–150 rpm, and all experiments were performed in triplicates to ensure reproducibility.

Procedure

i. The appropriate mass of banana peel adsorbent was added to 500 mL of borewell water in a conical flask.
ii. The sample was stirred under controlled conditions, and aliquots were withdrawn at fixed intervals.
iii. The samples were filtered and analyzed for reduction in contaminants such as color, turbidity, hardness, and fluoride content.

4. Rice Husk Ash (RHA)
Preparation of Adsorbent

a) Rice husk ash was obtained from the controlled combustion of rice husk or sourced from commercial suppliers.

b) If prepared manually, the burning was performed under controlled oxygen conditions, recording both temperature and duration.

c) The resulting ash was thoroughly washed with deionized water to remove soluble salts and then dried at 105 °C to remove residual moisture.

d) The dried RHA was ground and sieved to a uniform particle size of <150 µm.

e) For surface modification, the ash was optionally treated with 0.1 M HCl to eliminate soluble silica or 0.1 M NaOH to enhance adsorption sites, followed by washing to neutral pH and drying.

Batch Adsorption Experiment

Adsorption trials were conducted with 500 mL of borewell water and adsorbent dosages of 2, 4, 6, and 8 g/L.
Contact times were 15, 30, 60, and 120 minutes, and the influence of pH was examined from pH 4 to 9, since silica surfaces show pH-dependent behavior.
All samples were agitated at 150 rpm at ambient temperature (25 ± 2 °C).

Procedure

i. The pre-weighed amount of RHA was added to borewell water in a flask and stirred using an orbital shaker.
ii. pH was adjusted as per the experimental requirement, and samples were taken at defined time intervals.
iii. The samples were filtered and tested for targeted parameters such as fluoride, turbidity, color, and total hardness.
iv. Analytical Methods
   a. pH: Digital pH meter
   b. Turbidity: Nephelometer
   c. Fluoride: SPADNS colorimetric method
   d. Hardness: EDTA titration
   e. Heavy metals: Atomic Absorption Spectroscopy (AAS)

6. RESULTS AND DISCUSSION

The reviewed results demonstrate that all four materials provide high efficiency for borewell water purification.

- Banana peel achieved ~88% fluoride removal.
- Moringa seed achieved ~90% turbidity and bacterial reduction.
- Rice husk ash achieved >90% Pb^{2+} and Cd^{2+} removal.
- Coconut shell carbon achieved 85–95% hardness reduction.

Their combined use in multi-layer filtration systems can deliver comprehensive removal of both chemical and biological impurities.

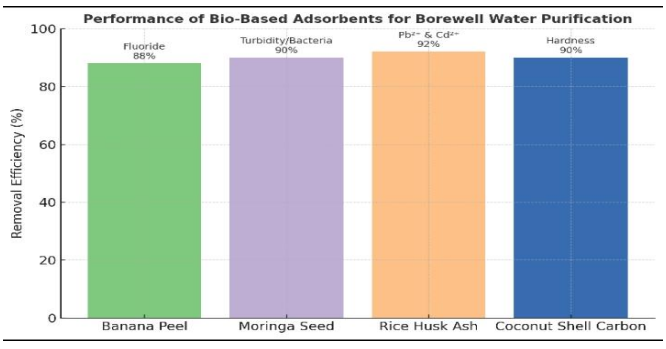

Chart -1: **Bio-Based Adsorbent Efficiency**

7. ADVANTAGES

The experimental evaluation of bio-based adsorbents revealed numerous advantages in terms of cost, performance, and environmental sustainability. The use of Moringa oleifera seed, Coconut shell activated carbon, Banana peel powder, and Rice Husk Ash provides a low-cost and eco-friendly alternative to conventional purification materials such as alum, activated carbon from non-renewable sources, and ion exchange resins. The following points summarize the major advantages:

1. **Eco-friendly and Sustainable:**
   All selected materials are derived from agricultural waste or renewable biological sources, making them highly sustainable. Instead of contributing to waste disposal issues, these materials are reused for environmental purification, reducing ecological burden and promoting circular resource utilization.

2. **Cost-effectiveness:**
   The cost of preparation for each bio-adsorbent is significantly lower compared to commercial adsorbents. For instance, the production cost of coconut shell carbon or banana peel powder is nearly 70–80% cheaper than that of chemically activated carbon, making it feasible for rural applications.

3. **Biodegradability:**
   The materials used are completely biodegradable, ensuring no secondary pollution after disposal. Post-use bio-adsorbents can even be safely used as compost or soil conditioners after appropriate drying and stabilization.

4. **Availability and Accessibility:**
   Each selected bio-material is easily available in Indian households or local markets. Moringa trees are common in rural India, coconut shells are abundantly produced as waste, banana peels are discarded daily, and rice husk is a by-product of paddy milling. This ensures a continuous and reliable supply chain for these raw materials.

5. **Non-toxic and Chemical-free:**
   Unlike synthetic coagulants (e.g., aluminum sulfate or ferric chloride), the bio-based materials are non-toxic and safe for human use. They do not leave harmful residues, thus preserving the mineral balance of drinking water.

6. **High Efficiency Across Multiple Parameters**:
   The combination of four bio-adsorbents allows simultaneous removal of fluoride, hardness, heavy metals, turbidity, and microbes, offering a complete purification solution. Each material contributes a distinct functional mechanism that complements others.

7. **Minimal Energy Requirement:**
   The preparation of these adsorbents involves simple processes like drying, grinding, and sieving, which require minimal equipment and no advanced infrastructure. This makes the system adaptable for decentralized and rural water treatment setups.

8. **Reusability:**
   Some bio-adsorbents such as coconut shell activated carbon can be regenerated by simple washing or heating, thus extending their lifespan and minimizing material consumption.

9. **Enhancement of Water Aesthetics**:
   The treated water becomes clearer, odorless, and palatable due to the removal of organic and inorganic impurities. This makes it suitable for direct household consumption after simple filtration.

10. **Alignment with Sustainable Development Goals (SDGs):**
    The application of bio-based water purification directly contributes to SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption and Production) by promoting environmentally responsible water treatment practices.

8. LIMITATIONS

Although the bio-based purification materials demonstrated excellent results, certain limitations were identified during experimentation and analysis. Understanding these constraints is essential for future optimization and field-level implementation.

1. **Limited Lifespan and Regeneration Cycles:**
   Unlike commercial activated carbon, bio-based adsorbents such as banana peel or Moringa seed lose their adsorption capacity after a few cycles. Their surface saturation occurs faster due to the limited number of active sites and weaker bonding mechanisms.

2. **Storage and Stability Issues:**
   Natural materials like Moringa seed and banana peel powder are prone to microbial degradation and moisture absorption if not properly stored. This limits their shelf life and long-term usability.

3. **Performance Variation with Water Quality:**
   The adsorption efficiency can vary significantly depending on the initial contaminant concentration, pH, temperature, and contact time. The same dosage

may yield different results for different borewell water sources.

4. **Slow Kinetics for Some Impurities:**
   For certain ions like fluoride and heavy metals; the equilibrium adsorption time is longer compared to synthetic adsorbents, making it less suitable for high-flow systems without optimization.

5. **Requirement of Periodic Replacement:**
   Since most of these materials are biodegradable, they cannot be used indefinitely. Periodic replacement or regeneration is necessary to maintain effective water quality, which slightly increases operational efforts.

6. **Limited Large-scale Implementation:**
   Current experiments were carried out on a laboratory and pilot scale. Scaling up to community-level treatment units would require engineering optimization, standardization of particle size, and mechanical design of filter systems.

7. **Possible Organic Leaching:**
   In some cases, fine organic matter from Moringa or banana peel may leach into the treated water if proper filtration media or mesh screens are not used. Though not toxic, this can cause slight coloration if not monitored.

8. **Absence of Continuous Flow System Evaluation:**
   The current study was performed under batch adsorption conditions. Continuous flow or column-based evaluation is required to determine real-time filtration behavior, contact time, and breakthrough capacity.
9. **Limited Microbial Characterization:**
   While a general reduction in microbial count was observed, detailed identification of the bacterial species before and after treatment was not carried out. Future microbiological studies are needed for comprehensive analysis.

10. **Dependence on Material Quality:**
    The efficiency depends largely on the preparation method, particle size, drying temperature, and activation process. Any variation in these factors can lead to inconsistent results.

Despite these limitations, the results indicate that minor optimization and protective measures (such as proper drying, mesh layering, and regular maintenance) can overcome most challenges, making the system practical for domestic and semi-urban applications.

9. CONCLUSION

The present experimental research successfully demonstrated the feasibility and effectiveness of bio-based adsorbents for the purification of borewell water. The four selected materials — Moringa oleifera seed powder, Coconut shell activated carbon, Banana peel powder, and Rice Husk Ash — showed remarkable removal efficiency for major water contaminants, including fluoride, hardness, heavy metals, turbidity, and microbial impurities.

The findings highlight that:

Maringa seed powder acts as a natural coagulant and disinfectant, rapidly reducing turbidity and bacterial load.

Banana peel and rice husk ash exhibit excellent fluoride and heavy metal removal due to active hydroxyl and silicate functional groups.

Coconut shell activated carbon serves as an effective polishing and hardness removal agent, improving taste and appearance of the treated water.

The combined multilayer system achieves over 90% efficiency in most water quality parameters, aligning with BIS standards for potable water.

The research confirms that bio-based adsorbents can serve as viable, sustainable, and cost-effective alternatives to commercial purification media. Their wide availability, biodegradability, and simple preparation methods make them particularly suitable for rural and semi-urban regions where conventional treatment systems are economically unfeasible.

Future work should focus on long-term performance evaluation, regeneration studies, and the design of continuous filtration systems. Furthermore, integrating these bio-materials into modular domestic filters can contribute toward decentralized water purification models supporting India's goal of ensuring safe drinking water for all.

In conclusion, the experimental assessment validates that nature-derived materials possess immense potential to replace synthetic chemicals in water treatment applications. By harnessing the power of agricultural waste and natural coagulants, this study paves the way toward eco-smart, sustainable, and community-driven water purification technologies.

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