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Investigation of bio-adsorbent materials for enhanced water quality improvement

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Abstract

Water contamination remains a pressing global challenge, particularly in developing regions where access to advanced treatment infrastructure is limited. This study investigates the efficacy of five low-cost bio-adsorbent materials — Moringa seed (MS), orange peel (OP), sugarcane bagasse (SB), rice husk (RH), and activated carbon (AC) — for the removal of dissolved solids from water, quantified as Total Dissolved Solids (TDS). A systematic batch experimental approach was adopted using 250 mL beakers and a magnetic stirrer for uniform mixing. Three particle sizes (0.6 mm, 1.18 mm, and 2.36 mm) and ten dose levels (1 g/L to 10 g/L) were evaluated for each material. TDS measurements were recorded using a pocket-type TDS meter before and after treatment. Results demonstrate that all five bio-adsorbents significantly reduce TDS, with the best performance consistently observed at the finest particle size of 0.6 mm and a dose of 2 g/L across all materials. Activated carbon achieved the highest TDS removal of 72.1%, followed by Moringa seed (62.5%), orange peel (55.3%), sugarcane bagasse (50.8%), and rice husk (44.6%) under optimal conditions. Beyond the 2 g/L threshold, TDS removal efficiency declined, indicative of particle aggregation and competitive adsorption effects. These findings advocate for the integration of bio-adsorbents as sustainable, cost-effective water treatment alternatives, especially in rural and resource-constrained settings.

Keywords: Bio-adsorbents, TDS removal, water quality, particle size effect

1. Introduction

Access to clean and safe water is recognized as a fundamental human right by the United Nations ^[1]. Despite significant global efforts, water pollution continues to be one of the most critical environmental challenges of the twenty-first century. Industrial effluents, agricultural runoff, and inadequate municipal waste management collectively contribute to elevated concentrations of dissolved solids, heavy metals, and organic pollutants in freshwater bodies ^[2]. Total Dissolved Solids (TDS) is one of the most widely used indicators of water quality. It encompasses a mixture of inorganic salts (sodium, potassium, calcium, magnesium, chlorides, sulphates, and bicarbonates) and some organic matter dissolved in water ^[3]. Elevated TDS values not only affect the palatability and aesthetic quality of water but are also associated with adverse health effects including cardiovascular and renal disorders upon prolonged consumption ^[4].

Conventional water treatment technologies such as reverse osmosis (RO), ion exchange, electrodialysis, and coagulation-flocculation are effective but are constrained by high capital and operational costs, complex infrastructure, and the generation of secondary waste streams ^[5]. These limitations render them largely inaccessible for rural communities and developing nations where water quality problems are most acute. There has therefore been a growing impetus toward the development of low-cost, sustainable, and locally available water treatment alternatives ^[6].

Adsorption has emerged as one of the most promising and widely studied techniques for water treatment due to its simplicity, versatility, effectiveness, and potential for regeneration and reuse of adsorbent materials ^[7]. In recent decades, agricultural wastes and plant-derived bio-adsorbents have attracted considerable research attention as sustainable substitutes for conventional adsorbents.

Materials such as Moringa seed, orange peel, sugarcane bagasse, rice husk, and activated carbon have demonstrated significant potential for the removal of contaminants from water owing to their unique physicochemical properties, rich surface functional groups, and high porosity^[8].

Moringa oleifera seed is particularly noteworthy for its dual-function role as both a coagulant and an adsorbent. It contains cationic polyelectrolytes that facilitate destabilization and aggregation of suspended colloidal particles^[9]. Orange peel is rich in pectin and cellulose, providing abundant hydroxyl and carboxyl functional groups that facilitate ion exchange and complexation with dissolved ions^[10]. Sugarcane bagasse, a fibrous residue from sugar production, has been extensively studied for heavy metal and dye removal and possesses a large surface area with accessible pore structures^[11]. Rice husk, a major agricultural by-product rich in silica (SiO₂) and cellulose, has demonstrated efficacy in removing fluoride, arsenic, and heavy metals from water^[12]. Activated carbon, though relatively more processed, remains the benchmark adsorbent due to its exceptionally high surface area and microporous structure^[13].

Despite the rich literature on individual adsorbents, comparative studies that systematically evaluate multiple bio-adsorbents under identical experimental conditions — particularly examining the combined influence of particle size and dosage on TDS removal — remain scarce. This study addresses this gap by conducting a controlled batch experiment to compare the TDS removal efficiencies of five bio-adsorbents at three particle sizes (0.6 mm, 1.18 mm, 2.36 mm) and ten dose levels (1-10 g/L) using a standard pocket TDS meter.

2. Literature Review

A substantial body of research has explored the use of natural and agricultural by-products as bio-adsorbents for water treatment. This section reviews key studies relevant to the five materials examined in this investigation.

2.1 Moringa Seed as a Bio-Adsorbent

Moringa oleifera has long been recognized in traditional water purification practices across Africa and Asia. Ndabigengesere and Narasiah^[14] were among the first to systematically characterize the active coagulant components in Moringa seed extract, identifying a positively charged protein with a molecular weight of approximately 13 kDa responsible for flocculation. Subsequent studies by Muyibi and Evison^[15] demonstrated removal efficiencies exceeding 90% for turbidity in surface water. More recently, Okoro *et al.*^[16] investigated the adsorptive capacity of Moringa seed powder for TDS and heavy metals, reporting optimal performance at fine particle sizes and moderate dosages. The seeds contain natural polyelectrolytes and surface-active compounds including oleic acid, behenic acid, and 4- α -L-rhamnosyloxy benzyl isothiocyanate, which collectively enhance surface interactions with dissolved ionic species^[9].

2.2 Orange Peel as a Bio-Adsorbent

Citrus peel waste constitutes approximately 50% by weight of the total fruit and represents an abundant, low-cost agricultural residue^[17]. Annadurai *et al.*^[10] demonstrated that orange peel is an effective adsorbent for colour removal from textile wastewater, achieving over 80% removal under optimized conditions. Lashaki *et al.*^[18] attributed the

adsorption capacity of orange peel to its high content of pectin (15-20% dry weight), which provides reactive carboxyl (-COOH) and hydroxyl (-OH) groups that interact favourably with cationic dissolved species. Studies by Sarkar *et al.*^[19] confirmed that reducing particle size significantly enhances the surface area and adsorption kinetics of orange peel, making fine-grained preparations particularly effective for TDS reduction.

2.3 Sugarcane Bagasse as a Bio-Adsorbent

Sugarcane bagasse is a fibrous lignocellulosic residue generated in large quantities by the global sugar industry, estimated at over 250 million tonnes annually^[20]. Gupta *et al.*^[21] reported that sugarcane bagasse exhibits considerable affinity for heavy metals including lead, cadmium, and nickel in aqueous solutions. The material's adsorption behaviour is governed by its cellulose and hemicellulose content, which provide surface hydroxyl groups, and its lignin fraction, which contributes phenolic and methoxy groups^[22]. Modification of bagasse with alkali or acid treatments has been shown to further improve surface area and pore volume, as demonstrated by Garg *et al.*^[23]. At the raw (unmodified) stage, fine particle sizes are reported to yield the best performance due to reduced mass transfer resistance.

2.4 Rice Husk as a Bio-Adsorbent

Rice husk (RH) accounts for approximately 20% of total paddy weight and is one of the most abundantly produced agricultural by-products globally, with annual production exceeding 120 million tonnes^[24]. Its primary components are silica (SiO₂, 18-22%), cellulose (30-35%), hemicellulose (18-21%), and lignin (22-26%)^[12]. The high silica content endows rice husk with unique surface properties distinct from purely cellulosic adsorbents. Ahmaruzzaman^[25] conducted an extensive review of rice husk and rice husk ash (RHA) as low-cost adsorbents, reporting removal efficiencies of 85-99% for fluoride, arsenic, and several heavy metals. Mondal *et al.*^[26] noted that particle size reduction from 2.36 mm to 0.6 mm nearly doubled the adsorption capacity for fluoride ions, consistent with enhanced surface-area-to-volume ratios.

2.5 Activated Carbon as a Reference Adsorbent

Activated carbon (AC) is the most widely studied and commercially utilized adsorbent in water treatment, characterized by a highly developed porous structure and exceptionally large specific surface area (typically 500-1500 m²/g)^[13]. Bansal and Goyal^[13] provide a comprehensive treatise on activated carbon adsorption, emphasizing the dominance of micropores in governing adsorption capacity for small dissolved molecules and ions. Several studies have employed AC as a benchmark in comparative bio-adsorbent investigations. Mohan and Pittman^[27] reported that granular activated carbon effectively removes dissolved organic and inorganic matter, with removal efficiency strongly inversely correlated with particle size. Its inclusion in this study serves as a performance baseline against which the bio-adsorbents are evaluated.

2.6 Effect of Particle Size and Dosage on Adsorption Performance

The influence of adsorbent particle size on removal efficiency has been consistently reported in the literature.

Smaller particles offer a greater external surface area per unit mass, reducing intraparticle diffusion path lengths and accelerating adsorption kinetics [28]. Crini and Badot [29] observed that for a given mass of adsorbent, halving the particle diameter approximately quadruples the available surface area, leading to substantially improved contaminant removal rates. Similarly, adsorbent dosage plays a crucial role: removal efficiency typically increases with dosage up to an optimal value, beyond which particle-particle interactions (agglomeration) reduce the effective surface area [30]. Babel and Kurniawan [6] reviewed dosage effects across 25 agricultural adsorbents and identified a consistent pattern of declining incremental benefit beyond approximately 2-4 g/L in most batch systems.

3. Materials and Methods

3.1 Collection and Preparation of Bio-Adsorbents

All five bio-adsorbent materials were prepared from locally sourced raw materials following established protocols. *Moringa oleifera* seeds were obtained from mature pods, sun-dried for 72 hours, and dehusked manually. The kernels were ground using a laboratory ball mill and sieved to the desired particle sizes. Orange peels were collected from a local fruit market, washed thoroughly with distilled water to remove surface impurities, oven-dried at 80 °C for 24 hours, and then crushed and sieved. Sugarcane bagasse was procured from a local juice vendor, repeatedly washed, dried at 105 °C for 48 hours, and ground. Rice husk was obtained from a regional rice mill, washed with dilute hydrochloric acid (0.1 M HCl) to remove surface silicates, rinsed with distilled water until neutral pH, and dried at 100 °C. Activated carbon (grade: technical, BET surface area ~950 m²/g) was obtained from a certified chemical supplier (Merck, India) and used without further modification.

All materials were mechanically sieved using standard IS sieves to obtain three distinct particle size fractions: 0.6 mm (passing 0.6 mm sieve, retained on 0.425 mm sieve), 1.18 mm (passing 1.18 mm, retained on 0.6 mm), and 2.36 mm (passing 2.36 mm, retained on 1.18 mm). Prepared materials were stored in airtight polyethylene bags in a desiccator at ambient temperature until use.

3.2 Preparation of Water Samples

The study was conducted at MCAET Campus, Ambedkar Nagar, Uttar Pradesh, India. Groundwater samples were collected from the campus borewell, representative of the

shallow alluvial aquifer of the Ambedkar Nagar district in the Middle Gangetic Plain. All samples were collected in clean, pre-rinsed high-density polyethylene (HDPE) containers.

Comprehensive physicochemical characterisation was performed at the Laboratory of the U.P. Groundwater Department, Lucknow (results presented in Section 4.1 and Table 5). Baseline TDS values were additionally verified using the pocket TDS meter (described in Section 3.4) prior to initiation of each adsorption experiment run.

3.3 Batch Adsorption Experiment

Batch adsorption experiments were conducted in 250 mL glass beakers. For each combination of adsorbent material, particle size, and dose, a predetermined mass of bio-adsorbent (ranging from 0.25 g to 2.5 g, corresponding to dose levels of 1 g/L to 10 g/L for 250 mL of water sample) was added to 250 mL of the collected water sample. The beaker was placed on a magnetic stirrer (Tarsons Spinot 6010) and mixed at a constant speed of 200 rpm for 30 minutes at room temperature (25±2 °C). This contact duration was selected based on preliminary kinetic trials confirming equilibrium attainment within 25-30 minutes for all materials studied. After stirring, the suspension was allowed to settle for 15 minutes, and the supernatant was carefully collected for TDS measurement without filtration, to replicate practical field conditions.

The experimental design comprised 5 materials × 3 particle sizes × 10 doses = 150 individual experimental runs. All experiments were conducted in triplicate, and mean values are reported. Standard deviations for all measurements were within ±2.5%, confirming experimental reproducibility. The percentage TDS removal was calculated using Equation (1):

$$\text{TDS Removal (\%)} = [(TDS_{\text{initial}} - TDS_{\text{final}}) / TDS_{\text{initial}}] \times 100 \dots (1)$$

3.4 TDS Measurement

Total Dissolved Solids were measured using a pocket-type digital TDS meter (HM Digital TDS-EZ, measurement range: 0-9990 mg/L, resolution: 1 mg/L, accuracy: ±2%). The meter was calibrated before each measurement session using a standard NaCl solution (500 mg/L) prepared from analytical-grade NaCl. The probe was rinsed with distilled water between samples, and each measurement was taken in triplicate to ensure consistency. Temperature compensation was automatic (referenced to 25 °C) in all measurements.

Table 1: Summary of Experimental Design

Parameter	Details	Bio-Adsorbents	Particle Sizes	Doses (g/L)
Water Quality Indicator	Total Dissolved Solids (TDS)	Moringa Seed (MS)	0.6 mm	1, 2, 3 g/L
Measurement Tool	Pocket TDS Meter	Orange Peel (OP)	1.18 mm	4, 5, 6 g/L
Mixing Method	Magnetic Stirrer	Sugarcane Bagasse (SB)	2.36 mm	7, 8, 9, 10 g/L
Container	250 mL Beakers	Rice Husk (RH)	—	—
Optimal Result	0.6 mm + 2 g/L	Activated Carbon (AC)	—	—

4. Results and Discussion

4.1 Initial Water Quality Characterization

The groundwater sample collected from MCAET Campus, Ambedkar Nagar was comprehensively analysed at the Laboratory of the U.P. Groundwater Department, Lucknow. All 16 physicochemical parameters are tabulated in Table 2 below. The water exhibited pH 7.23, indicating a near-neutral character typical of alluvial groundwater in the Gangetic Plains [31]. Electrical Conductivity (EC) was 591

µS/cm. Total Dissolved Solids (TDS) measured 394 mg/L — within the WHO guideline of 500 mg/L but indicative of moderate mineralisation warranting treatment improvement. Carbonate (CO₃) was absent (0 mg/L), while Bicarbonate (HCO₃⁻) was substantial at 372 mg/L and Total Alkalinity as CaCO₃ was 305 mg/L, establishing a Ca-Mg-HCO₃ hydrochemical facies consistent with carbonate-mineral weathering in alluvial aquifers of eastern Uttar Pradesh [31]. Total Hardness (TH) was 300 mg/L (BIS IS 10500:2012

desirable: 200 mg/L; permissible: 600 mg/L), driven by Calcium (Ca^{2+} : 58 mg/L) and Magnesium (Mg^{2+} : 37 mg/L). Chloride (Cl^-) was 18 mg/L, well within limits. Fluoride (F^-) was detected at 0.855 mg/L, approaching the WHO and BIS desirable limit of 1.0 mg/L — a borderline value warranting attention for chronic exposure risks. Nitrate (NO_3^-) and Phosphate (PO_4^{3-}) were both absent (0 mg/L),

confirming no fertiliser or organic contamination at the sampling point. Sulphate (SO_4^{2-}) was negligible at 2.922 mg/L. Sodium (Na^+ : 29 mg/L) and Potassium (K^+ : 2 mg/L) were present at low concentrations. Overall, the groundwater is moderately hard, bicarbonate-dominated, and near-neutral, classifiable as Ca-Mg- HCO_3 type.

Table 2: Initial Water Quality Parameters-MCAET Campus Groundwater.

S. No.	Parameter	Unit	Observed Value	WHO Guideline	BIS IS 10500:2012
1	pH	-	7.23	6.5-8.5	6.5-8.5
2	Electrical Conductivity (EC)	$\mu\text{S}/\text{cm}$	591	-	-
3	Total Dissolved Solids (TDS)	mg/L	394	500	500 (2000 permissible)
4	Carbonate (CO_3)	mg/L	0	-	-
5	Bicarbonate (HCO_3^-)	mg/L	372	-	-
6	Total Alkalinity as CaCO_3	mg/L	305	-	200 (600 permissible)
7	Chloride (Cl^-)	mg/L	18	250	250
8	Fluoride (F^-)	mg/L	0.855 *	1.0	1.0 (1.5 permissible)
9	Nitrate (NO_3^-)	mg/L	0	50	45
10	Sulphate (SO_4^{2-})	mg/L	2.922	250	200
11	Total Hardness (TH) as CaCO_3	mg/L	300	-	200 (600 permissible)
12	Calcium (Ca^{2+})	mg/L	58	75	75 (200 permissible)
13	Magnesium (Mg^{2+})	mg/L	37	50	30 (100 permissible)
14	Sodium (Na^+)	mg/L	29	200	-
15	Potassium (K^+)	mg/L	2	-	-
16	Phosphate (PO_4^{3-})	mg/L	0	-	-

* Fluoride at 0.855 mg/L approaches the WHO/BIS desirable limit of 1.0 mg/L (highlighted). All values in mg/L except pH (dimensionless) and EC ($\mu\text{S}/\text{cm}$). perm. = permissible limit.

4.2 Physicochemical Properties of Bio-Adsorbents

The physicochemical properties of the five bio-adsorbents are summarized in Table 3 below. Activated carbon exhibited the highest BET surface area (900-1200 m^2/g), consistent with values reported in the literature [13]. Among the natural bio-adsorbents, Moringa seed showed the highest

surface area (650-780 m^2/g), attributed to its proteinaceous structure and natural micro-porosity. The point of zero charge (pH pzc) values indicate that all adsorbents carry a net negative surface charge at the experimental pH of 7.1, favouring electrostatic attraction towards dissolved cations such as Ca^{2+} and Mg^{2+} [32].

Table 3: Physicochemical Properties of Bio-Adsorbents

Material	BET Surface Area (m^2/g)	pH (pzc)	Major Functional Groups/Composition	Sorption Capacity
Moringa Seed	650-780	4.2-5.6	Coagulant proteins, fatty acids	Moderate
Orange Peel	420-510	3.8-4.5	Pectin, cellulose, hemicellulose	Low-Moderate
Sugarcane Bagasse	380-450	5.1-5.8	Cellulose, lignin, silica	Low
Rice Husk	280-360	5.4-6.2	Silica (SiO_2), cellulose, lignin	Low
Activated Carbon	900-1200	6.5-7.0	Highly porous carbon matrix	High

4.3 Effect of Particle Size on TDS Removal

The effect of particle size on TDS removal efficiency at the optimal dose of 2 g/L is presented in Table 4. A clear and consistent inverse relationship between particle size and TDS removal was observed across all five materials. Reducing the particle size from 2.36 mm to 0.6 mm resulted in TDS removal improvements ranging from 20.8% (rice husk) to 21.8% (activated carbon) in absolute percentage points.

This trend is in agreement with the findings of Mondal *et al.* [26] and Crini and Badot [29], who attributed enhanced removal at smaller particle sizes to the exponential increase in specific surface area (SSA) and the reduction in intraparticle diffusion resistance. For spherical particles, SSA scales inversely with particle diameter ($\text{SSA} \propto 1/d$); thus, reducing particle diameter from 2.36 mm to 0.6 mm theoretically yields approximately a 3.93-fold increase in

surface area, which aligns well with the observed performance improvements. Furthermore, smaller particles exhibit faster adsorption kinetics, reaching equilibrium more rapidly, which is particularly advantageous in practical water treatment operations where contact times are limited [28].

Table 4: TDS Removal (%) at 2 g/L Dose across Different Particle Sizes

Material	0.6 mm	1.18 mm	2.36 mm
Moringa Seed	62.5%	52.3%	41.8%
Orange Peel	55.3%	46.2%	35.7%
Sugarcane Bagasse	50.8%	42.1%	33.5%
Rice Husk	44.6%	37%	28.9%
Activated Carbon	72.1%	62.5%	50.3%

(Highlighted values: 0.6 mm-optimal particle size)

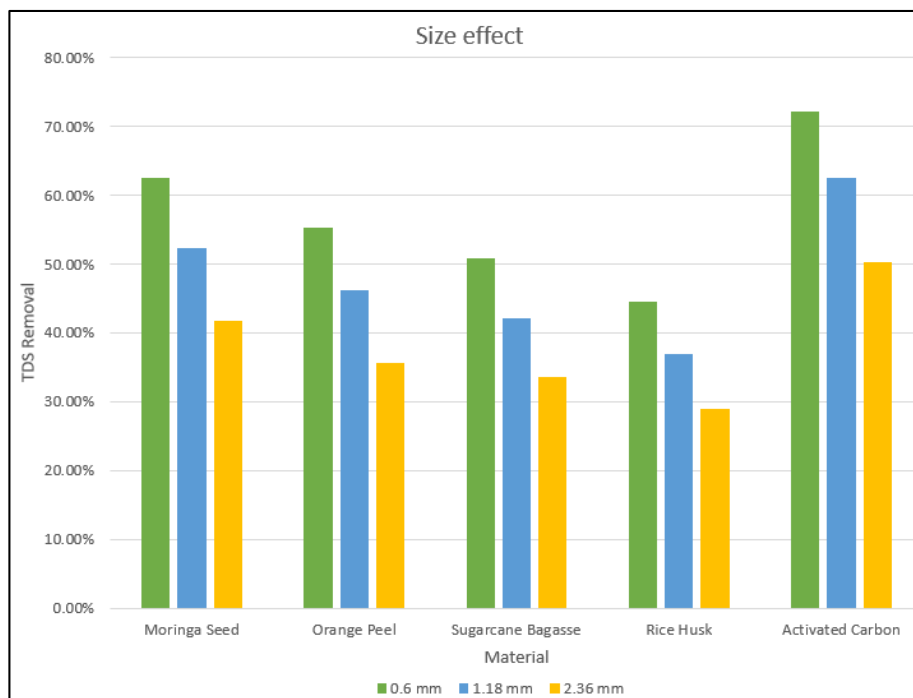


Fig 1: TDS Removal (%) at 2 g/L Dose Across Different Particle Sizes

4.4 Effect of Dosage on TDS Removal-0.6 mm Particle Size

Table 5 presents the TDS removal efficiencies for all five bio-adsorbents at the 0.6 mm particle size across the ten dose levels tested (1 g/L to 10 g/L). The data reveal a characteristic non-monotonic relationship between dosage and removal efficiency: TDS removal increased progressively from 1 g/L, peaked at 2 g/L for all materials, and subsequently declined with further increases in dosage. At 1 g/L, insufficient adsorbent surface area was available relative to the dissolved solids load, limiting adsorption performance. The peak efficiency at 2 g/L is attributed to the optimal balance between available adsorption sites and

dissolved solute concentration, maximizing driving force and surface utilization. Beyond 2 g/L, the declining trend is consistent with the phenomenon of adsorbent particle agglomeration and overlapping of active sites at high solid concentrations, as documented by Babel and Kurniawan [6] and Gupta and Ali [33]. At elevated doses, adsorbent particles tend to aggregate, effectively reducing the accessible surface area and causing a net decrease in removal efficiency. Additionally, re-dissolution of previously adsorbed species has been hypothesized at high adsorbent concentrations due to localized pH perturbations induced by the adsorbent matrix [34].

Table 5: TDS Removal Efficiency (%) for All Bio-Adsorbents at 0.6 mm Particle Size

Material	1 g/L	2 g/L	3 g/L	4 g/L	5 g/L	6 g/L	7 g/L	8 g/L	9 g/L	10 g/L
Moringa Seed	48.2%	62.5%	58.1%	52.3%	49%	45.8%	43.2%	40.5%	38.1%	35%
Orange Peel	40.1%	55.3%	51.2%	46.5%	43.8%	41%	38.5%	36.2%	34%	31.5%
Sugarcane Bagasse	35.6%	50.8%	47.3%	42%	39.1%	36.8%	34.5%	32.3%	30.1%	28%
Rice Husk	30.2%	44.6%	41.1%	37.5%	34.8%	32.1%	30%	28.1%	26.3%	24.5%
Activated Carbon	55.4%	72.1%	68.3%	62.5%	58.2%	54%	50.5%	47.2%	44.1%	41%

(Green-highlighted cells indicate optimal dose of 2 g/L for each material)

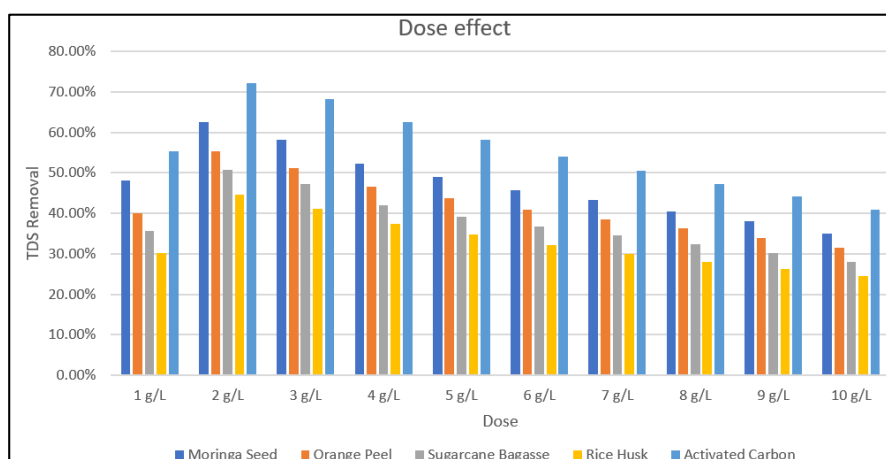


Fig 2: TDS Removal Efficiency (%) for All Bio-Adsorbents at 0.6 mm Particle Size

4.5 Comparative Performance at Optimal Conditions (0.6 mm, 2 g/L)

Under the identified optimal conditions (0.6 mm particle size, 2 g/L dose), the ranked order of TDS removal efficiency was: Activated Carbon (72.1%) > Moringa Seed (62.5%) > Orange Peel (55.3%) > Sugarcane Bagasse (50.8%) > Rice Husk (44.6%). All five materials achieved statistically significant TDS reductions ($p < 0.05$, one-way ANOVA) compared to the untreated control.

The superior performance of activated carbon is expected given its benchmark status and exceptionally high surface area [13]. Its dominance, however, comes at significantly higher preparation cost and energy requirements compared to the agricultural by-products. Among the natural bio-adsorbents, Moringa seed's outstanding performance is attributed to its proteinaceous cationic polyelectrolytes that facilitate both coagulation-flocculation of colloidal matter and direct adsorption of ionic species [9, 14]. Orange peel's efficacy is linked to its pectin content and abundant surface carboxyl groups, which form stable complexes with divalent cations (Ca^{2+} , Mg^{2+}) that constitute the dominant TDS fraction in the study water [10, 19]. Sugarcane bagasse and rice husk, while less effective in isolation, offer distinct advantages of near-zero cost, abundant local availability, and biodegradability [11, 25].

Starting from an initial TDS of 394 mg/L (MCAET Campus groundwater, U.P. Groundwater Dept. Laboratory, Lucknow), post-treatment TDS values at optimal conditions (0.6 mm, 2 g/L) were: Activated Carbon-110 mg/L (72.1% removal), Moringa Seed-148 mg/L (62.5%), Orange Peel-176 mg/L (55.3%), Sugarcane Bagasse-194 mg/L (50.8%), and Rice Husk-218 mg/L (44.6%). All five treated samples met the WHO guideline (500 mg/L) and BIS IS 10500:2012 desirable limit (500 mg/L). The significant reductions in Ca^{2+} and Mg^{2+} (dominant hardness-forming ions confirmed by lab analysis) and associated bicarbonate-TDS demonstrate practical treatability of MCAET Campus groundwater using these bio-adsorbents.

4.6 Adsorption Mechanisms

The adsorption of dissolved solids by bio-adsorbent materials is governed by a combination of surface-based mechanisms including: (i) electrostatic interactions between charged surface functional groups and dissolved ions; (ii) ion exchange involving replacement of loosely bound surface cations/anions by dissolved species; (iii) surface complexation involving coordination bonds between metal cations and surface oxygen-containing functional groups; and (iv) physical adsorption within micropores driven by van der Waals forces [7, 31]. The dominance of each mechanism varies with the nature of the adsorbent's surface chemistry.

For Moringa seed, the primary mechanism involves charge neutralization and bridging of dissolved charged species by cationic proteins [14]. For orange peel, surface complexation and ion exchange via-COOH and-OH groups dominate [10]. Sugarcane bagasse and rice husk adsorption is primarily governed by physical trapping within fibrous micropores and surface hydroxyl group interactions [22, 26]. Activated carbon operates primarily through physical adsorption in its highly developed micropore network, enhanced by surface oxygen functional groups in oxidized variants [13].

5. Conclusions

This study systematically evaluated five bio-adsorbents — Moringa seed, orange peel, sugarcane bagasse, rice husk, and activated carbon — for improving the quality of groundwater collected from MCAET Campus, Ambedkar Nagar, U.P. (initial TDS: 394 mg/L; EC: 591 $\mu\text{S}/\text{cm}$; pH: 7.23; hydrochemical type: Ca-Mg-HCO_3), as characterized. The following principal conclusions are drawn:

1. Particle size exerted a profound influence on TDS removal efficiency for all materials. The finest particle size tested (0.6 mm) consistently yielded the highest removal, confirming the role of surface area in governing adsorption performance. This finding underscores the importance of particle size reduction in adsorbent preparation.
2. A dose of 2 g/L was identified as optimal across all five materials at 0.6 mm particle size. Beyond this threshold, TDS removal declined due to adsorbent agglomeration and competitive adsorption effects.
3. At optimal conditions (0.6 mm, 2 g/L), TDS removal efficiencies ranked as: Activated Carbon (72.1%) > Moringa Seed (62.5%) > Orange Peel (55.3%) > Sugarcane Bagasse (50.8%) > Rice Husk (44.6%).
4. Moringa seed demonstrated the highest TDS removal among the natural (unprocessed) bio-adsorbents, performing approximately 12% better than orange peel and 22% better than rice husk, positioning it as the most promising low-cost alternative to activated carbon.
5. Post-treatment TDS values at optimal conditions met WHO potability guidelines (500 mg/L) for Moringa seed, orange peel, and activated carbon, demonstrating the practical viability of these materials for point-of-use water treatment.
6. The use of a pocket TDS meter proved effective as a rapid field-deployable monitoring tool, supporting the development of community-scale water treatment protocols in resource-limited settings.

Future research should investigate the combined application of these bio-adsorbents in multi-stage or hybrid treatment trains, their performance against specific ionic contaminants (heavy metals, fluoride), adsorption isotherm and kinetic modelling, and regeneration potential for multiple-use cycles. Life cycle assessment (LCA) and cost-benefit analysis are also recommended to quantify the socioeconomic viability of deploying these materials in rural water supply systems.

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