

COMPARATIVE ANALYSIS OF RAW AND ACTIVATED *Moringa oleifera* BASED BIOSORBENTS FOR SUSTAINABLE DYE REMOVAL FROM TEXTILE EFFLUENT

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Abstract: Dyes are extensively used in industries such as textiles, food, leather, and plastics and their discharge into the environment causes serious ecological hazards. Dye-contaminated water alters color, depletes dissolved oxygen, and disrupts aquatic ecosystems. This study investigates the adsorption potential of *Moringa oleifera* seed and flower powders, in both raw and activated forms, for the removal of textile dyes from industrial effluents. These plant-derived biosorbents were prepared and thermally activated to enhance surface characteristics and functional group availability, thereby improving dye interaction. Adsorption experiments were systematically performed under varying pH, adsorbent dosage, and contact time to establish optimal operational conditions. Results indicated that the activated biosorbents exhibited notably higher dye removal efficiency than their raw counterparts, attributed to enhanced surface area, porosity, and active functional sites. Total Dissolved Solids (TDS) analysis further validated the results, showing a marked reduction in dissolved contaminants and improvement in water quality after treatment.

This study thus demonstrates that thermal activation significantly improved the adsorption performance and surface reactivity of *Moringa oleifera*-based biosorbents. Due to their low cost, renewability, and environmental safety, these biosorbents present a sustainable and effective alternative for treating dye-contaminated textile effluents, contributing to eco-friendly wastewater management and sustainable industrial practices.

Keywords: *Moringa oleifera*, Biosorbents, Activated Carbon, Dye removal, Textile effluent, Adsorption

I. INTRODUCTION

Moringa oleifera Lam., commonly known as the drumstick tree, horseradish tree, or ben oil tree, is a fast-growing perennial species belonging to the family Moringaceae, native to the Indian subcontinent. It is now widely cultivated across tropical and subtropical regions of the world, including Africa, South and Central America, Mexico, Hawaii, and Southeast Asia [1,2]. The plant derives its common names from its key characteristics, as the immature pods resemble drumsticks, the roots have a pungent flavor similar to horseradish, and the seeds yield a high-quality oil known as ben oil.

Nearly every part of the plant including the leaves, flowers, seeds, bark, and roots contains an array of bioactive compounds such as phenolics, flavonoids, alkaloids, terpenoids, tannins, glucosinolates, and isothiocyanates, which contribute to its antioxidant, antimicrobial, and therapeutic properties [3,4]. Due to this rich biochemical composition and multifaceted utility, *M. oleifera* is often regarded as a “Miracle tree” of immense nutritional, medicinal, and biotechnological importance [2].

Among the various parts of *Moringa oleifera*, the seeds and flowers exhibit distinct morphological features that influence their suitability as natural biosorbents.

The fruits of *Moringa oleifera* are long, three-lobed pods (20–60 cm) that split open on drying to release multiple seeds enclosed within a hull bearing three papery wings arranged at approximately 120° intervals. A mature tree can produce 15,000–25,000 seeds annually, with an average seed weight of 0.3 g and a kernel-to-hull ratio of 75:25 [5].

The flowers are borne in axillary, drooping panicles (10–25 cm) and are white to cream with yellow markings at the base. Each flower consists of five sepals, five petals, five stamens, and five staminodes, with all petals reflexed except the lower one. The species is known for its prolific flowering and adaptability to semi-arid regions [5,6,7].

1.1 Need for Sustainable Water Treatment

Rapid industrialization, particularly in the textile sector, has resulted in the continuous discharge of dye-laden effluents into aquatic systems, leading to serious environmental and health concerns [8,9]. Conventional wastewater treatment methods such as coagulation, oxidation, and chemical precipitation are often limited by high operational costs and incomplete dye removal [10,11]. In contrast, biosorption using plant-based materials has emerged as a sustainable, eco-friendly, and cost-effective alternative for the removal of contaminants from wastewater [12,13]. Among potential biosorbents, *Moringa oleifera*, an abundant and renewable plant, has gained attention due to its multifunctional properties and suitability for environmental applications.

In this context, the present study investigates the use of *Moringa oleifera* seed and flower powders, in both raw and activated forms, as biosorbents for the removal of textile dyes from effluent water. The primary objective is to evaluate the adsorption efficiency of activated carbon derived from these plant materials for dye degradation. The performance of the biosorbents was assessed under varying operational parameters, including contact time, adsorbent dosage, pH, and adsorption capacity. Additionally, water quality parameters such as Total Dissolved Solids (TDS) were analyzed to determine the overall treatment efficiency, providing a comprehensive evaluation of the potential of *Moringa oleifera*-based materials in sustainable wastewater management.

II. MATERIALS AND METHODS

This study evaluated the adsorption and decolorization efficiency of *Moringa oleifera* seed and flower derived adsorbents for treating textile effluent. Experimental procedures included the synthesis of activated carbon, physicochemical characterization, and adsorption studies under controlled laboratory conditions.

2.1 Preparation of Samples

2.1.1 Collection of Plant Material

Fresh seeds and flowers of *Moringa oleifera* were collected from local farms in Erode, Tamil Nadu. The plant material was authenticated by the Tamilnadu Agricultural University, Coimbatore, Tamil Nadu. Samples were transported to the laboratory under ambient conditions for further processing.

2.1.2 Processing of Adsorbents

Collected samples were thoroughly washed with tap water to remove surface impurities and then shade-dried at ambient temperature. The dried materials were pulverized into fine powder using a mechanical blender and sieved to obtain a uniform particle size. The powders were stored in airtight containers until further use.

2.1.3 Preparation of Extracts

Powdered seed and flower samples were mixed with distilled water in a 1:10 ratio (w/v) and agitated on a rotary shaker for 24 h. The mixtures were filtered through Whatman No. 1 filter paper, and the filtrates were stored at 4°C for subsequent analysis.

2.1.4 Preparation of Activated Carbon

The dried plant powders were impregnated with phosphoric acid at a ratio of 1:2 (acid:material, w/w) and soaked for 24 h at room temperature. The impregnated samples were carbonized in a muffle furnace at 500°C for 1 h under limited air supply. The resultant material was cooled, repeatedly washed with distilled water until neutral pH was reached, and dried at 110°C for 12 h. The prepared activated carbon was stored in airtight containers for adsorption experiments.

2.2 Adsorption Studies

2.2.1 Collection of Effluent

Textile effluent samples were collected from a local dyeing and printing industry in Erode, Tamil Nadu, and stored at 4°C before use.

2.2.2 Physicochemical Properties of Effluent

The pH of the effluent was measured using a calibrated digital pH meter, and temperature was recorded using a calibrated thermometer. Each measurement was performed in triplicate to ensure accuracy.

2.3 Optimization of Adsorption Parameters

2.3.1 Effect of Adsorbent Dosage

Aliquots (25 mL) of dye-containing effluent were treated with 0.5 g, 1 g, 1.5 g, 2 g, and 2.5g of seed and flower derived adsorbents in separate conical flasks. The mixtures were agitated at 180 rpm using an orbital shaker. After incubation, samples were centrifuged, and absorbance was measured at 670 nm using a UV-Vis spectrophotometer. Adsorption efficiency was calculated using the formula:

$$\% \text{ of Adsorption} = \frac{C_i - C_f}{C_i} \times 100$$

where C_i and C_f are the initial and final dye concentrations, respectively.

2.3.2 Effect of Contact Time

Effluent samples (25 mL) containing 2 g of adsorbent were incubated under shaking conditions (180 rpm) and analyzed at 1, 2, 4, and 24 h intervals. The percentage adsorption was calculated as described above.

2.3.3 Effect of pH

To evaluate pH influence, effluent samples (25 mL) containing 2 g of adsorbent were adjusted to pH 5, 7, 9, 12 and 14 using dilute acid or base. Samples were incubated under shaking conditions (180 rpm), and dye removal efficiency was measured spectrophotometrically at 670 nm.

2.4 Determination of Total Dissolved Solids (TDS)

TDS values of treated and untreated effluents were determined using a digital TDS meter after calibration with a standard solution. Measurements were taken in triplicate and reported as mean values.

III. RESULTS AND DISCUSSION

3.1 Evaluation of *Moringa oleifera* Seed and Flower Biosorbents

The biosorption potential of *Moringa oleifera* seed and flower powders was evaluated for the removal of dye contaminants from textile effluent. Both raw and activated forms were studied to compare their adsorption efficiencies. The activated biosorbents exhibited higher dye removal capacity than their raw counterparts, suggesting that activation enhanced the surface area, porosity, and availability of active sites responsible for adsorption.

3.2 Preparation and Activation of Biosorbents

The biosorbents were prepared by cleaning, drying, and grinding *Moringa oleifera* seeds and flowers into fine, uniform powder suitable for adsorption studies. A portion of each sample was subjected to controlled thermal activation to obtain activated carbon. The activation process altered the physical and chemical properties of the biosorbents, improving their dye binding potential and overall performance in wastewater treatment applications.

3.3 Adsorption Studies on Dye Removal from Textile Wastewater

3.3.1 Physical Properties of Effluent Water

The textile effluent exhibited a highly alkaline pH of 12, which can strongly influence the adsorption behavior by altering both the adsorbent surface charge and the ionization state of dye molecules. The recorded temperature of 60°C may further affect adsorption kinetics and dye-adsorbent interactions.

3.4 Optimization of Adsorption studies

Optimization of operational parameters is essential to enhance dye degradation efficiency. Key factors such as pH, adsorbent dosage, initial dye concentration, and contact time were systematically studied to determine their influence on adsorption performance and to establish optimal conditions for maximum decolorization.

3.4.1 Effect of Adsorbent Concentration

Adsorbent dosage plays a critical role in determining dye removal efficiency. The decolorization potential of activated *Moringa oleifera* seed and flower powders was evaluated at varying concentrations (Table 3).

Activated Moringa seed achieved the highest dye removal efficiency of 88% at 0.5 g of adsorbent, whereas the activated Moringa flower exhibited maximum decolorization of 86% at 1.5 g. A further increase in dosage resulted in minimal improvement, indicating possible surface site saturation at higher concentrations.

S.No	Concentration of Adsorbents (g)	% of Decolorisation			
		Raw <i>M. oleifera</i> Seed Powder	Activated <i>M. oleifera</i> Seed Powder	Raw <i>M.oleifera</i> Flower Powder	Activated <i>M.oleifera</i> Flower Powder
1	0.5	51 ± 2.4	88 ± 4.6	11 ± 0.4	83 ± 4.4
2	1	34 ± 1.8	85 ± 4.2	32 ± 1.5	84 ± 5.4
3	1.5	43 ± 1.9	84 ± 3.8	47 ± 1.8	86 ± 4.2
4	2	31 ± 1.6	86 ± 4.4	11 ± 0.6	84 ± 4.7
5	2.5	11 ± 0.4	83 ± 3.9	13 ± 0.9	82 ± 3.8

Table 3. Effect of Adsorbent Concentration on Adsorption of Treated Effluent Samples

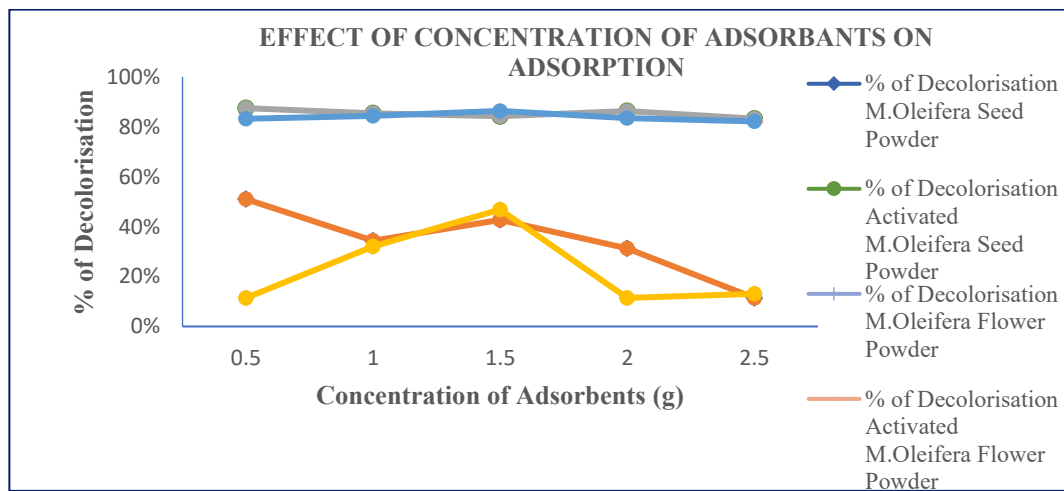


Fig 3. Effect of Adsorbent Concentration on Adsorption of Treated Effluent Samples

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3.4.2 Effect of pH on Adsorption

Solution pH markedly affects the adsorption process by influencing both the surface charge of the adsorbent and the ionization state of dye molecules. Activated Moringa seed exhibited maximum adsorption efficiency at pH 5 (88%), while activated Moringa flower showed optimal decolorization at pH 5 (84%). These findings highlight the strong dependence of dye removal efficiency on electrostatic interactions governed by solution pH (Table 4).

S.No	pH	% of Decolorisation			
		Raw <i>M. oleifera</i> Seed Powder	Activated <i>M. oleifera</i> Seed Powder	Raw <i>M.oleifera</i> Flower Powder	Activated <i>M.oleifera</i> Flower Powder
1	5	72 ± 3.7	88 ± 5.1	51 ± 3.2	84 ± 5.4
2	7	74 ± 4.4	64 ± 3.8	31 ± 1.8	79 ± 4.8
3	9	67 ± 3.4	52 ± 3.4	75 ± 3.7	79 ± 5.2
4	12	69 ± 3.9	43 ± 2.8	43 ± 2.9	73 ± 4.6
5	14	65 ± 3.2	12 ± 1.2	11 ± 0.9	78 ± 4.8

Table 4. Effect of pH on Adsorption of Treated Effluent Samples

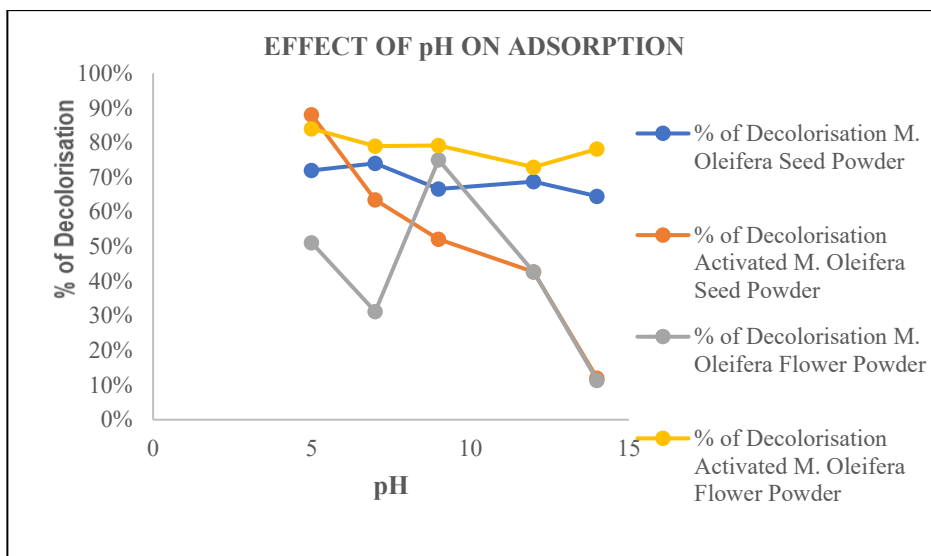


Fig 4. Effect of pH on Adsorption of Treated Effluent Samples

Similar observations were reported by Sivakumar et al. [14] and Adebayo et al. [15], who found that adsorption efficiency is maximized under pH conditions that promote electrostatic attraction between dye molecules and biosorbent surfaces.

3.4.3 Effect of Contact Time on Adsorption

Contact time is a key parameter in adsorption dynamics, governing the rate and extent of dye removal. The adsorption process typically involves an initial rapid uptake due to the abundance of active surface sites, followed by a slower phase as equilibrium is approached. Time-dependent studies with Moringa seed and flower adsorbents followed this pattern, confirming efficient initial adsorption and subsequent stabilization at equilibrium.

S.No	Contact Time	% of Decolorisation			
		Raw <i>M. oleifera</i> Seed Powder	Activated <i>M.oleifera</i> Seed Powder	Raw <i>M.oleifera</i> Flower Powder	Activated <i>M.oleifera</i> Flower Powder
1	1 hour	41 ± 2.8	55 ± 3.2	39 ± 2.7	45 ± 3.2
2	2 hour	86 ± 6.1	92 ± 6.2	80 ± 5.6	87 ± 6.5
3	4 hour	90 ± 5.9	96 ± 6.1	85 ± 5.8	92 ± 6.2
4	24 hours	68 ± 4.8	69 ± 4.4	60 ± 3.8	74 ± 5.4

Table 5. Effect of Contact Time on Adsorption of Treated Effluent Samples

The results (Table 5) confirm that activation of *Moringa oleifera* seed and flower powders significantly enhances their adsorption potential for dye removal. The maximum decolorisation efficiency was achieved within 2 to 4 hours of contact time, beyond which no substantial improvement was observed. This indicates that equilibrium was attained within this duration. The activated biosorbents demonstrated consistently higher efficiency than the raw forms, suggesting that surface activation improves the availability of active sites and strengthens dye-adsorbent interactions. The enhanced adsorption observed in activated samples further confirms that thermal activation improves surface area and accessibility of functional groups, facilitating faster dye-adsorbent interaction.

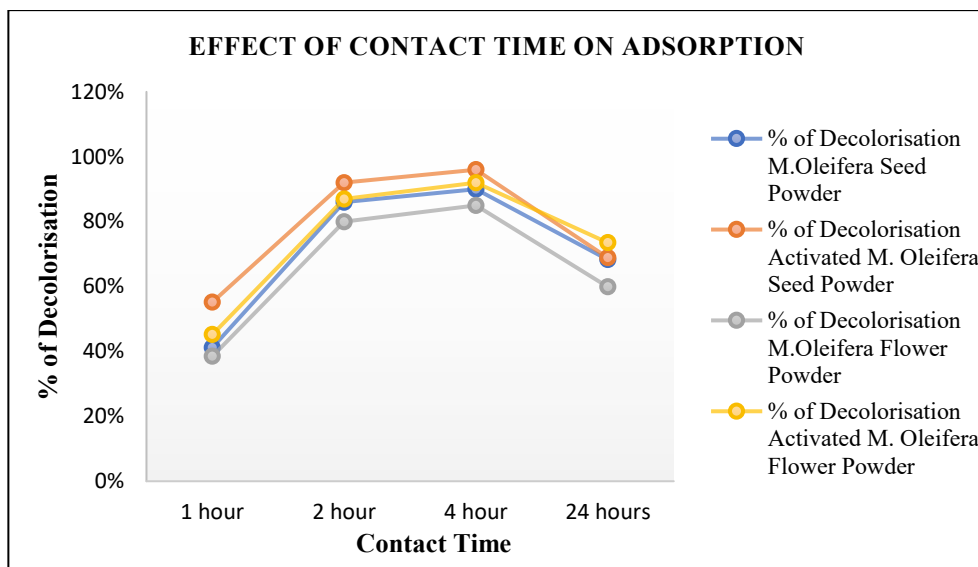


Fig 5. Effect of Contact Time on Adsorption of Treated Effluent Samples

3.5 Total Dissolved Solids (TDS) Analysis

Total Dissolved Solids (TDS) are a key indicator of water quality, reflecting the concentration of dissolved organic and inorganic constituents. Elevated TDS levels compromise water usability and quality, making their reduction a critical objective in wastewater treatment.

S.No	Sample	TDS (PPM)
1	Effluent water sample	2000 ± 140
2	<i>Moringa Oleifera</i> Seed Powder treated Effluent Sample	889 ± 54
3	<i>Moringa Oleifera</i> Flower Powder treated Effluent Sample	900 ± 60
4	Activated <i>Moringa Oleifera</i> Seed Powder treated Effluent Sample	667 ± 42
5	Activated <i>Moringa Oleifera</i> Flower Powder treated Effluent Sample	746 ± 48

Table 6. Analysis of Total Dissolved Solids (TDS) value in Treated Effluent Water samples

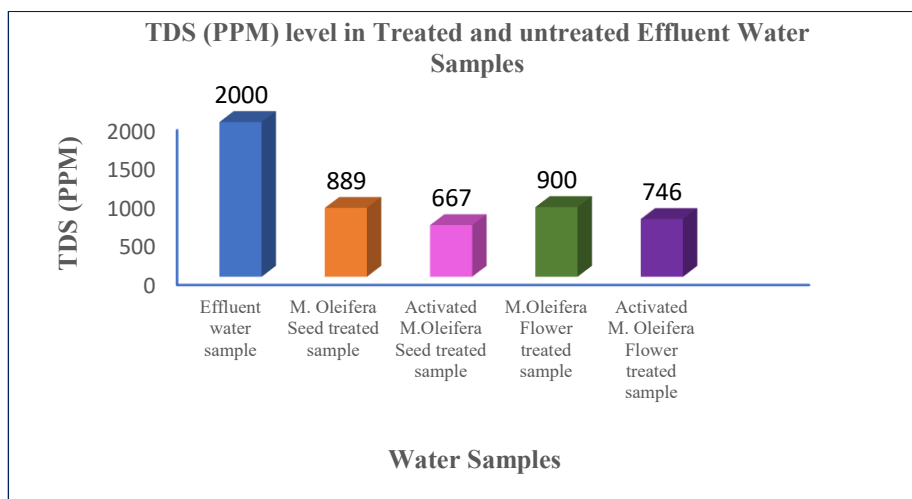


Fig 6. Analysis of Total Dissolved Solids (TDS) value in Treated Effluent Water samples

In this study, the raw textile effluent exhibited a TDS value of 2000 ppm, indicating a substantial presence of dissolved impurities. All four biosorbent formulations effectively reduced TDS levels, confirming their potential in improving

water quality. Among the tested adsorbents, activated Moringa seed achieved the lowest TDS value of 667 ppm, followed by activated Moringa flower at 746 ppm, demonstrating the superior performance of the activated forms in removing dissolved contaminants. This is consistent with the results of Aravind et al. [16], who demonstrated that activation significantly enhances adsorption characteristics in biomass-derived adsorbents.

The results (Table 6) collectively confirm the efficacy of *Moringa oleifera* based biosorbents in reducing dissolved solids and dye content, thereby enhancing overall water quality. The significant reduction observed across all formulations underscores their promise as eco-friendly and sustainable materials for textile effluent treatment. Further optimization and scaling studies could enhance adsorption capacity and enable practical application in industrial wastewater remediation.

Overall, the results establish that activation markedly improves the surface functionality, porosity, and adsorption potential of *Moringa oleifera* seed and flower powders. The enhanced adsorption performance, coupled with substantial TDS reduction, highlights the feasibility of utilizing activated *Moringa oleifera* biosorbents as eco-friendly materials for large-scale textile effluent management.

IV. CONCLUSION

In conclusion, *Moringa oleifera* seed and flower powder, particularly in their activated carbon forms, serve as highly efficient, cost-effective, and environmentally friendly biosorbents for dye removal from industrial effluent. Their adsorption potential, characterized by functional group analysis and optimized treatment parameters demonstrates their viability as sustainable alternatives to conventional chemical adsorbents. Given their biodegradable and non-toxic nature, these biosorbents offer a promising approach to wastewater treatment.

Future research should focus on large-scale implementation, regeneration potential, and improving adsorption efficiency through advanced material modifications to enhance industrial applicability and long-term sustainability.

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Conflicts of Interest

The authors declare no conflict of interest.

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