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Preliminary study of *Tamarindus indica* seeds as potential adsorbent for turbidity removal in wastewater

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The search for low-cost and sustainable water treatment materials has turned attention toward agro-waste as a renewable resource. In this study, *Tamarindus indica* seeds were explored as a precursor for activated carbon (AC) synthesis, aiming to enhance turbidity removal in wastewater. Seeds were chemically activated with phosphoric acid and carbonized under controlled heating regimes. The resulting AC was systematically characterized: FTIR revealed enriched hydroxyl and carboxyl functionalities; XRD confirmed an amorphous carbon matrix favorable for adsorption; and SEM micrographs displayed well-developed mesopores. Performance testing against kaolin-based synthetic wastewater demonstrated that the 2 mm AC fraction achieved a maximum turbidity removal efficiency of 84.66%, closely approaching that of commercial AC. These findings establish *Tamarindus indica* seed-derived AC as an effective, eco-friendly, and economically viable adsorbent. Beyond its immediate application, this work underscores the broader potential of agricultural residues in circular bioeconomy frameworks, where waste valorization can yield scalable materials for decentralized water purification and sustainable environmental remediation.

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1. Introduction

Water pollution resulting from rapid urbanization, industrial discharge, and agricultural runoff has become a pressing global concern, particularly in developing countries where wastewater treatment infrastructure may be inadequate [1]. Among various water quality parameters, turbidity is of major concern due to its direct link to the presence of suspended solids, pathogens, and colloidal impurities. Traditional turbidity removal strategies rely on chemical coagulants such as aluminium sulfate (alum), which, despite their effectiveness, pose significant environmental and health risks, including the potential association with neurotoxicity and Alzheimer's disease [2]. These challenges have accelerated the shift toward eco-friendly, biodegradable, and sustainable alternatives in water treatment technologies.

Activated carbon (AC) is widely recognized for its porous structure, high surface area, and excellent adsorption capabilities, making it suitable for removing turbidity, heavy metals, organic compounds, and dyes from water [3]. While commercial AC is typically derived from coal or coconut shells, these sources are either non-renewable or relatively expensive. Consequently, attention has turned to low-cost, abundant biomass sources for AC production, particularly agro-waste materials. *Tamarindus indica*, commonly known as tamarind, is a tropical leguminous tree belonging to the Fabaceae family. It is widely cultivated in South and Southeast Asia, Africa, and South America for its edible pulp, but its seeds—often treated as agricultural waste—hold significant potential as a value-added resource. The seeds are typically hard, glossy brown, and oval, consisting of approximately 35–40% endosperm, rich in polysaccharides, polyphenols, and lignocellulosic matter suitable for carbonization [4].

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These seed properties make *Tamarindus indica* a promising precursor to produce activated carbon (AC). The high content of lignin and cellulose in the seed coat structure facilitates the development of porous surfaces during thermal and chemical activation [5]. Moreover, the seeds possess inherent antioxidant and antimicrobial components, further enhancing their relevance in environmental and biomedical applications [6]. Recent studies have shown that *Tamarindus indica* seed-derived activated carbon exhibits excellent performance in removing turbidity, methylene blue, phenols, and heavy metals such as lead and cadmium from aqueous solutions [7].

Beyond *Tamarindus indica*, other species within or related to the genus—such as *Acacia nilotica, Prosopis juliflora,* and *Albizia lebbeck*—have also demonstrated efficacy in wastewater treatment applications due to their abundant phenolic groups, surface functionalization capacity, and low-cost availability [8]; [9]. These natural adsorbents share similar characteristics with *Tamarindus indica*, suggesting a broader applicability of Fabaceae species in sustainable environmental remediation. Moreover, tamarind seed extract has been explored not only for its adsorptive capabilities but also for its coagulant properties, offering a dual mechanism—coagulation and adsorption—for pollutant removal [10]. Such multifunctional potential reinforces the relevance of *Tamarindus indica* in addressing turbidity and other physicochemical issues in wastewater management.

Despite their potential, tamarind seeds remain largely underutilized in most processing industries, typically discarded or used as low-value biomass. This aligns with the goals of circular bioeconomy frameworks, which emphasize the conversion of agro-waste into functional materials for environmental remediation. This study aims to harness the waste-to-resource potential of *Tamarindus indica* seeds by synthesizing activated carbon through controlled heat and chemical treatment. The physical and chemical properties of the resulting AC was characterized using Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR). The turbidity removal efficiency of the AC was evaluated using synthetic kaolin-based wastewater, with comparative analysis against commercial activated carbon (CAC). Through this investigation, the study intends to establish *Tamarindus indica* as a viable, cost-effective, and environmentally sustainable alternative in wastewater treatment.

2. Methodology

2.1. Preparation of *Tamarindus indica* seeds as adsorbents

Mature *Tamarindus indica* seeds were collected from a local supplier and thoroughly washed with tap water followed by distilled water to remove adhering dust and impurities. The seeds were air-dried for 24 hours and subsequently oven-dried at 80 °C for another 24 hours to eliminate residual moisture. Once dried, the seeds were mechanically crushed using a hammer and ground into fine particles. The ground material was sieved to obtain three particle size fractions: 4 mm, 2 mm, and 250 μm. Each size fraction was soaked in 1.0 M phosphoric acid (H_3PO_4) for 24 hours to facilitate chemical activation. The acid-treated samples were then filtered and subjected to thermal treatment in two stages. First, the samples were pre-heated in a hot air oven at 130 °C for 24 hours. Second, carbonization was carried out in a muffle furnace at 400 °C for different durations depending on the particle size: 6 hours (4 mm), 4 hours (2 mm), and 2 hours (250 μm). The activated carbon (AC) samples were allowed to cool in a desiccator before use in further analysis.

2.3. Characterization of adsorbents

2.3.1. Fourier transform infrared spectroscopy (FTIR)

FTIR analysis was performed using a Shimadzu IRTracer-100 spectrometer to identify functional groups present on the surface of raw and activated samples. Spectra were recorded in the mid-infrared range (4000–400 cm^{-1}) using the KBr pellet technique.

2.3.2. X-ray diffraction (XRD)

XRD analysis was conducted using a Rigaku MiniFlex II X-ray diffractometer to assess the crystalline or amorphous nature of the carbon structure. The diffraction patterns were collected in the 2θ range of 10°–80° with Cu Kα radiation.

2.3.3. Scanning electron microscopy (SEM)

The surface morphology and pore characteristics of the raw and activated samples were observed using a JEOL JSM-6360LA SEM. Samples were gold-coated to improve conductivity and examined under an accelerating voltage range of 0.02–30 kVp.

2.2. Preparation of synthetic wastewater

A stock suspension of synthetic wastewater was prepared by dispersing 10 g of kaolin powder in 1 L of distilled water. The suspension was stirred continuously for 1 hour using a magnetic stirrer to ensure uniform dispersion. It was then allowed to hydrate and settle for 24 hours at room temperature. The resulting kaolin suspension was used as a model turbid solution for adsorption testing.

2.4. Turbidity removal efficiency test

The turbidity removal performance of the prepared *Tamarindus indica* seed-based activated carbon (AC) was quantitatively assessed using a Thermo Orion AQ3010 Turbidity Meter, which operates on the principle of nephelometry. The instrument measures light scattered at a 90° angle from a light source passing through the sample, and results are expressed in Nephelometric Turbidity Units (NTU). Turbidity is a key water quality parameter that indicates the presence of suspended solids, colloidal particles, and organic matter, which can adversely affect aquatic ecosystems.

For each turbidity test, 0.1 g of activated carbon from each particle size fraction (4 mm, 2 mm, and 250 µm) was added to 50 mL of the synthetic kaolin wastewater in a 100 mL beaker. The initial turbidity of the solution (T_0) was recorded prior to AC addition. The mixture was stirred continuously using a magnetic stirrer for 20 minutes at a constant speed to ensure homogeneous dispersion and maximize adsorbent–adsorbate interaction. During the treatment period, turbidity readings were recorded at 1-minute intervals to monitor the rate of turbidity reduction over time. After 20 minutes, the final turbidity value (T_f) was recorded. The Turbidity Removal Percentage (TRP) was then calculated using the following formula:

$$\text{TRP (\%)} = \left(\frac{T_0 - T_f}{T_0}\right) \times 100 \tag{1}$$

where:

- T_0= Initial turbidity of the wastewater (NTU)
- T_f= Final turbidity after treatment (NTU)

This equation provides a normalized percentage that reflects the efficiency of turbidity reduction by each AC sample. A higher TRP value indicates better performance of the adsorbent in removing suspended and colloidal particles from the wastewater. Comparative TRP values among different particle sizes and activation durations allowed for the identification of optimal synthesis parameters.

3. Results and discussion

3.1. Characterization of adsorbents

3.1.1. Fourier transform infrared spectroscopy (FTIR)

FTIR spectroscopy was employed to identify the functional groups present on the surface of *Tamarindus indica*-based activated carbon (AC) before and after activation as shown in Table 1, below. The FTIR spectrum of the raw seed sample revealed characteristic peaks indicating the presence of hydroxyl (–OH), carboxyl (–COOH), ester (C=O), and aliphatic hydrocarbon (–CH) groups. Notably, a broad and intense absorption band around 3288 cm^{-1} corresponded to the O–H stretching vibration, indicating the presence of hydroxyl groups commonly found in lignocellulosic biomass. A strong absorption peak near 1744 cm^{-1} was attributed to C=O stretching of carboxylic acids and esters. The presence of C–O stretching vibrations at 1209 cm^{-1} and 960 cm^{-1} further supports the presence of alcohol or ether functionalities. In the lower wavenumber region, peaks around 740–495 cm^{-1} were indicative of CH_2 bending vibrations, commonly associated with aliphatic chains in hemicellulose and lignin structures [11].

Table 1. FTIR spectral characteristics of Tamarindus indica seed adsorbents (raw vs activated).

Wavenumber (cm^{-1})	Intensity / Band Type	Functional Group	Vibration Mode	Sample Type
~3288	Broad & intense	O–H (hydroxyl)	O–H stretching	Raw
~3090–3010	Weak to moderate	=C–H (aromatic/aliphatic)	C–H stretching (sp^2/sp^3 hybrid)	Raw & Activated
~2978–2770	Medium	C–H (aliphatic CH_3, CH_2)	Asymmetric/symmetric C–H stretch	Raw & Activated
~2324	Sharp (minor)	Possibly CO_2 or C≡N	Triple bond stretching	Activated
~1743–1562	Strong	C=O (carbonyl, ester, acid)	C=O stretching	Raw & Activated
~1465–1380	Medium	C=C (aromatic ring)	C=C ring stretching	Raw
~1200–900	Strong, sharp	C–O (alcohol, ether)	C–O stretching	Raw & Activated
~819–638	Moderate	Aromatic ring or C–Cl stretch	C–H bending or C–X stretch	Activated
~474–459	Weak to medium	CH_2 bending	Out-of-plane CH_2 wagging	Raw & Activated

After activation, the FTIR spectrum showed a notable enhancement in the intensity of the –COOH and –OH bands, suggesting successful development of surface oxygen-containing functional groups during phosphoric acid activation and thermal treatment. These functional groups are known to contribute significantly to adsorption capacity through hydrogen bonding and electrostatic interactions with pollutants [12]. Similar FTIR findings have been reported in the literature for other adsorbents derived from Tamarindus species and related Fabaceae family members. For instance, Abdu Nasara et al. (2023) observed prominent hydroxyl and carboxylic acid peaks in the FTIR spectra of AC synthesized from *Tamarindus indica* seed coats, emphasizing their role in adsorption of cationic dyes and heavy metals. Likewise, Rajan & Anish (2024) reported FTIR spectra of tamarind shell-derived carbon with characteristic O–H and C=O peaks, attributing their high adsorption potential to these polar groups.

The generation of such functional groups during chemical activation using phosphoric acid is well-documented and is attributed to the acid's dehydrating action, which facilitates the breakdown of hemicellulose and lignin while introducing phosphate groups [13]. These surface modifications not only increase porosity but also enhance the chemical reactivity of the AC surface, making it more effective for turbidity and contaminant removal. The retention and enhancement of oxygen-containing groups in the activated samples suggest that *Tamarindus indica*-based AC can effectively participate in adsorption mechanisms such as ion exchange, complexation, and π–π interactions—especially relevant for removing colloidal particles and organic matter in turbid water [14];[15]. These findings align with studies using other natural precursors such as *Prosopis juliflora* and *Acacia nilotica*, which also exhibit similar FTIR signatures and adsorption behavior [16]. Overall, the FTIR analysis confirms that chemical activation of *Tamarindus indica* seeds significantly enhances the development of adsorption-active functional groups on the carbon surface, positioning this biosorbent as a viable, sustainable material for water purification.

3.2. X-ray diffraction (XRD) analysis

X-ray diffraction (XRD) analysis was conducted to examine the crystalline or amorphous nature of the synthesized activated carbon (AC) derived from *Tamarindus indica* seeds. The diffraction patterns for both the *Tamarindus indica* AC and the commercial activated carbon (CAC) were compared within the 2θ range of 10°–60° as shown in Figure 1. The XRD spectrum of *Tamarindus indica* AC showed a broad diffraction peak centered around 2θ = 24°, corresponding to the (002) reflection plane of graphitic carbon structures. This broad peak is characteristic of amorphous carbonaceous materials with disordered lattice structures and poor graphitization [3]. Notably, the absence of sharp, well-defined peaks indicates that the carbon produced from *Tamarindus indica* seeds lacks long-range crystalline order, which is typical of activated carbons derived from lignocellulosic biomass. Such an amorphous structure is highly favorable for adsorption processes, as it suggests the presence of an irregular pore structure and high surface heterogeneity—both of which increase surface area and provide more active sites for pollutant uptake [8].

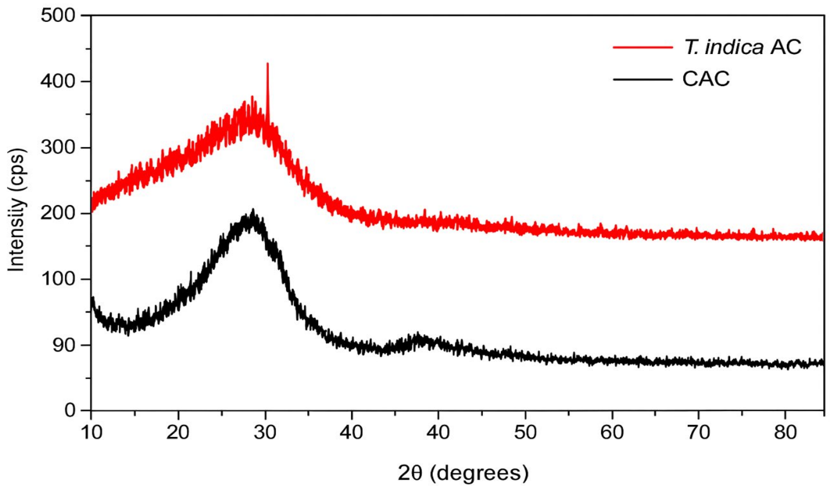


Fig. 1. X-ray diffraction (XRD) patterns of activated carbon derived from Tamarindus indica seeds and commercial activated carbon (CAC).

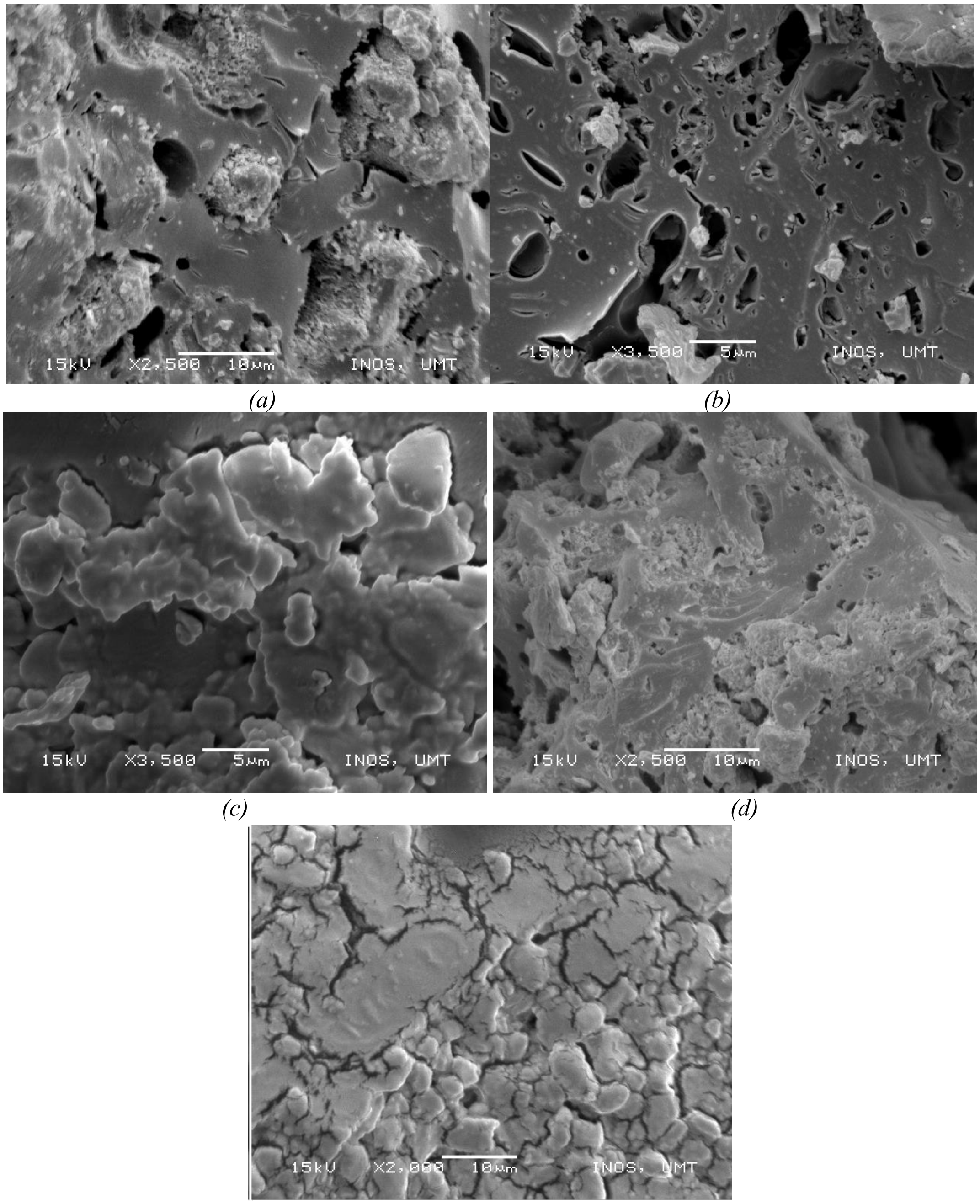
Comparative studies using *Tamarindus indica* shells or seeds have reported similar XRD patterns. For instance, Rajan & Anish (2024) found that tamarind shell-derived AC exhibited a dominant amorphous structure, with a broad peak between 22° and 26°, indicating the presence of turbostratic carbon layers. Abdu Nasara et al. (2023) also confirmed the amorphous nature of *T. indica*-based AC with similar diffraction profiles, attributing the structural disorder to phosphoric acid activation, which hinders the alignment of carbon microcrystallites. In the present study, comparison with commercial activated carbon (CAC) revealed similar broad peaks in the same region, although CAC exhibited slightly higher intensity, likely due to a more controlled activation and carbonization process. Nevertheless, the structural similarity in terms of amorphous nature supports the potential of *Tamarindus indica* seed-derived AC as an effective alternative to CAC.

Amorphous AC materials have been shown to exhibit better adsorption capacities compared to crystalline materials due to their greater accessibility of internal pores and flexible surface chemistry [13]. This structural disorder enhances diffusion and facilitates the adsorption of macromolecules and colloids, making *Tamarindus indica*-based AC particularly suitable for turbidity removal from wastewater.

3.3. Scanning electron microscopy (SEM) analysis

SEM analysis was conducted to examine the surface morphology, pore structure, and textural differences between raw and activated *Tamarindus indica* seed samples. The micrographs revealed clear morphological transformations resulting from chemical activation and thermal treatment which was depicted in Figure 3. The raw *Tamarindus indica* seed (Figure 3e) exhibited a relatively smooth and compact surface with minimal porosity. This structure is typical of uncarbonized lignocellulosic biomass and reflects low adsorptive potential due to the absence of accessible internal cavities or voids [11].

Upon activation, the morphology changed significantly. The 2 mm AC sample (Figure 3a) displayed a porous surface structure with well-formed macropores and mesopores, indicative of successful pore development. These features are desirable for turbidity removal due to enhanced surface area and increased adsorption sites [8]. The 4 mm AC (Figure 3b) also exhibited well-developed pores, although with slightly larger and less uniformly distributed openings compared to the 2 mm sample. This may be attributed to the longer thermal exposure required for larger particles, which encourages the expansion of existing pore walls but may limit uniform development [17].



(a) *(b)* *(c)* *(d)* *(e)*

Fig. 2. SEM micrographs of (a) 2 mm activated carbon (AC) from Tamarindus indica, (b) 4 mm AC, (c) 250 µm AC, (d) commercial activated carbon (CAC), and (e) raw Tamarindus indica seed.

The 250 µm AC (Figure 3c) showed smaller, less pronounced surface porosity, with lower pore visibility than in the larger particle sizes. The limited pore development is likely due to the shorter heating duration, which restricts the full breakdown of volatile compounds and hinders micropore and mesopore formation. This observation corresponds to its lower Turbidity Removal Percentage (TRP) in prior results, suggesting insufficient activation at this particle scale ([7]). The conventional activated carbon sample (Figure 3d) exhibited a relatively smooth texture interspersed with defined pores. Despite being industrially optimized, its morphology was comparable to that of the 2 mm *Tamarindus indica* AC, reinforcing the potential of *Tamarindus indica* -derived adsorbents as a viable alternative. Previous studies on tamarind shell and seed-based carbons reported similar morphological transformations, supporting their efficiency for dye and metal removal applications [15]; [18].

Similar SEM results have been reported for *Tamarindus indica*-derived adsorbents. Rajan & Anish (2024) observed the formation of deep, irregular pores in tamarind shell AC after phosphoric acid activation, attributing the surface morphology to volatile matter release during carbonization. Abdu Nasara et al. (2023) also highlighted the role of heating duration in developing mesopores critical for capturing suspended solids in wastewater. Moreover, plant-based AC materials like those derived from *Acacia nilotica* and *Prosopis juliflora* have shown comparable morphological patterns, emphasizing the effectiveness of acid-thermal activation routes in producing high-performance adsorbents from Fabaceae biomass [12]. In conclusion, SEM analysis confirmed that activation significantly enhanced the surface roughness and porosity of *Tamarindus indica* seed-derived AC, thereby improving its capacity for turbidity reduction. *Tamarindus indica* seed-derived adsorbent with the 2 mm particle size, with its optimal pore architecture, emerged as the most effective configuration for wastewater treatment applications.

3.4. Turbidity removal efficiency analysis

The effectiveness of activated carbon (AC) derived from *Tamarindus indica* seeds in turbidity reduction was evaluated using a Thermo Orion AQ3010 Turbidity Meter, with results expressed in Nephelometric Turbidity Units (NTU). Turbidity—caused by suspended particles such as silt, clay, and organic matter—is a critical parameter in water quality assessment. High turbidity not only impairs aesthetics but also serves as a vector for microbial contaminants and disinfectant-resistant pathogens [19]. Hence, turbidity removal is essential in any primary or tertiary water treatment protocol.

The 2 mm *Tamarindus indica* AC sample, activated for 4 hours, demonstrated the highest TRP, with values reaching up to 84.66%, indicating its superior adsorption capability as shown in Table 2. This performance is attributed to its optimal surface morphology, as evidenced in the SEM analysis, which displayed well-distributed mesopores (~2–3 µm). The mesoporous structure increases surface area and facilitates efficient physical adsorption of suspended solids [8]. The 4 mm AC sample showed a slightly lower TRP (average 80.15%), likely due to its broader but less uniformly distributed pores. The 250 µm sample, with only 2 hours of activation, achieved the lowest TRP (average 45.27%), suggesting that smaller particles with shorter heating durations are less effective due to underdeveloped porosity and insufficient exposure to thermal degradation processes [16].

Table 2. Turbidity removal efficiency of activated carbon (AC) derived from Tamarindus indica seeds and commercial AC at different grain sizes and dosages after 5 minutes of treatment.

Sample	**Volume of kaolin synthetic wastewater (ml)**	**Mass of Conventional AC (g)**	**Highest TRP (%)**	**Average TRP (%)**
4 mm AC	50	0.05	84.25	80.15
250 µm AC	50	0.10	45.39	45.27
2 mm AC	50	0.02	84.66	69.20
CAC	50	0.02	95.83	95.70
CAC	50	0.05	99.95	99.93

Comparative analysis with commercial activated carbon (CAC) revealed that the best-performing CAC sample achieved up to 99.93% TRP under identical conditions. Although CAC outperformed *Tamarindus indica* AC, the latter's performance is considered satisfactory given its low cost, local availability, and environmental benefits. The adsorption efficiency of plant-based activated carbon is often correlated with surface oxygen functionalities (–OH, –COOH), surface roughness, and the degree of amorphous structure, all of which were confirmed in FTIR and XRD characterizations [20]. The enhanced turbidity removal efficiency of *Tamarindus indica* -derived AC supports earlier findings in studies involving other Fabaceae family materials. For instance, *Albizia lebbeck* seed-based carbon also demonstrated efficient turbidity removal, attributed to its porous structure and high surface reactivity [21]. These findings reinforce the viability of *Tamarindus indica* as a sustainable coagulant/adsorbent for decentralized and low-cost water treatment systems.

Moreover, the direct correlation between heating duration, pore development, and turbidity reduction confirms the importance of thermal activation parameters in tailoring adsorbents for specific environmental applications [3]. The 2 mm AC, with its moderate particle size and optimal thermal history, strikes a balance between surface area, pore volume, and mass transfer efficiency—making it a promising candidate for field-scale implementation.

4. Conclusion and future perspectives

This study successfully established *Tamarindus indica* seed-derived activated carbon (AC) as a viable and sustainable adsorbent for turbidity removal in wastewater treatment. Through comprehensive characterization and performance analysis, the research has demonstrated that *Tamarindus indica* seeds, an agro-waste material, can be effectively transformed into porous, functionalized activated carbon using phosphoric acid activation and thermal treatment.

XRD analysis confirmed the amorphous carbon structure of the synthesized AC, a trait known to enhance adsorption due to increased surface disorder and active sites [3]. FTIR spectroscopy revealed the presence of surface oxygenated functional groups such as hydroxyl, carboxylic, and ester groups, which are essential for pollutant binding. SEM imaging provided visual confirmation of surface modification and pore formation, with the 2 mm AC sample showing the most favorable morphology for adsorption. Performance evaluation through turbidity testing in synthetic wastewater showed that the 2 mm AC achieved a maximum turbidity removal percentage (TRP) of 84.66%, confirming its adsorptive potential. Though slightly outperformed by commercial activated carbon (CAC), *Tamarindus indica* AC presents a cost-effective, biodegradable, and renewable alternative suitable for applications in resource-limited settings. These findings support the broader trend of utilizing plant-derived precursors from the Fabaceae family—including *Albizia lebbeck, Acacia nilotica*, and *Prosopis juliflora*—for developing low-cost adsorbents in water purification [22]; [23].

To further enhance the application of *Tamarindus indica* derived activated carbon in environmental remediation, several specific research directions are proposed. First, a comprehensive adsorption isotherm and kinetics study, including models such as Langmuir, Freundlich, and pseudo-second-order kinetics, should be conducted to better understand the adsorption behavior under varying pH, temperature, and ionic strength conditions. This will offer quantitative insights into surface coverage and interaction mechanisms between the adsorbent and target pollutants [24]; [25]. Second, evaluation of performance in real wastewater matrices, such as domestic sewage or textile effluents, is crucial to assess the material's robustness in complex and competitive adsorption environments. Real wastewater often contains surfactants, metals, organic compounds, and high salinity—all of which can interfere with turbidity removal. Testing in such conditions would strengthen the case for field-scale application [26]; [27]. Third, investigating the regeneration and reusability of *Tamarindus indica* AC through physical or chemical methods is essential to assess its economic viability and environmental impact. Efficient regeneration would reduce waste and operational costs, making the solution more sustainable in long-term applications [7]; [28].

Taken together, these targeted research efforts will provide the mechanistic, practical, and economic foundation needed to upscale the use of *Tamarindus indica* seed-derived activated carbon in real-world water treatment systems.

This study demonstrates that *Tamarindus indica* seed-derived activated carbon is a cost-effective, eco-friendly, and efficient adsorbent for turbidity removal, achieving up to 84.66% efficiency in kaolin-based synthetic wastewater. The material exhibited enriched oxygen-containing functional groups, an amorphous carbon structure, and mesoporous morphology that collectively contributed to its adsorption performance. Importantly, the valorization of *Tamarindus indica* seeds aligns with circular bioeconomy principles by transforming agricultural residues into high-value products for water purification.

The promising results presented here resonate with recent advances in fruit-seed–derived adsorbents, such as *Nephelium lappaceum* (rambutan) seed-based activated carbon, which has also shown excellent turbidity removal and surface functionality [29]. Together, these findings highlight the untapped potential of tropical agro-wastes as sustainable precursors for activated carbons. Future research should focus on optimizing activation protocols, regeneration strategies, and scaling up production to advance these bio-based adsorbents toward real-world water treatment applications.

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