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Comparative Analysis of Plant-Based Natural Coagulants for Wastewater Treatment

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Abstract

Wastewater containing elevated turbidity levels can pose a significant risk if discharged directly into the environment. Conventional treatment involves chemical coagulants, presenting drawbacks like high cost, excessive sludge generation, and health risks To enhance sustainability in the treatment, it is essential to explore alternative methods that minimize environmental impact. Implementing natural coagulants, such as plant-based materials, can reduce reliance on costly inorganic salts and decrease sludge production. To reduce these drawbacks, alternative coagulants derived from natural sources are being explored for their potential to enhance sustainability while minimizing environmental impact. This research evaluates sustainable alternatives using natural coagulants—papaya seed powder, tamarind seeds, orange peels, and neem leaves—to treat municipal wastewater with an initial turbidity of 364 NTU. The effectiveness of these coagulants at different dosages was evaluated by jar tests, and the ideal dosage for each was identified. Along with turbidity reduction, the study also looked at the elimination of chemical and biochemical oxygen demands (BOD and COD). According to the findings, papaya seeds were able to remove up to 91.7% of the turbidity, 52% of the BOD, and 68% of the COD. 89.1% turbidity, 67% BOD, and 78% COD were eliminated by tamarind seeds. Neem leaves performed the best, removing 99.89% of the turbidity, 75% of the BOD, and 82% of the COD. Orange peels showed 66.89% turbidity reduction, 79% BOD removal, and 80% COD removal. The FTIR analysis showed functional group presence such as tannins and flavonoids in neem leaves, which likely contributed to their superior coagulation performance. Orange peels, being abundant and

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cost-effective, also demonstrated significant practical utility. These findings highlight the potential of natural coagulants as sustainable alternatives to conventional chemical treatments. The implications of this study suggest that plant-based coagulants, especially neem leaves and tamarind seeds, offer a viable, cost-effective solution for improving wastewater treatment while reducing environmental impact

Introduction

Water pollution generated from various sources poses a significant threat globally, indicating the urgent need for effective wastewater treatment. Turbidity, indicating suspended particles in water, demands attention due to its impact on water quality for various purposes. Wastewater treatment typically offer coagulation to remove suspended solids consciously improve water quality. The traditional method involves chemical coagulants like alum, which have several drawbacks like high cost, sludge disposal issues and raising concerns for environmental & human health. This issue has led to the exploration of alternative, eco-friendly solutions. Natural waste derived from plant materials such as papaya seed powder and tamarind seed powder provide a sustainable and eco-friendly alternative. These materials, along with orange peels and neem leaves, serve as effective bio-coagulants for wastewater treatment due to their inherent natural properties.

Papaya seeds function as a natural coagulant due to the presence of positively charged proteins. These proteins bind negatively charged particles such as silt, clay, bacteria, and toxins found in wastewater. This interaction enhances the formation and settling of flocs, leading to clearer water through processes of adsorption and charge neutralization. Additionally, papaya seed powder has the ability to combine with solids in water, facilitating their sedimentation at the bottom. This property further aids in the clarification of water by removing suspended particles.[1]

Tamarind seeds serve as natural coagulants (bio coagulants) due to their protein content, which functions as polyelectrolytes. The dissolved protein possesses the -NH_3^+ group, allowing it to bind to negatively charged particles. This interaction destabilises the particles, leading to the formation of larger aggregates that can ultimately be precipitated.[2]

Neem leaves, rich in tannins, flavonoids, and fatty acids, have been traditionally used for their medicinal properties, including potential effects on coagulation. Tannins in neem leaves can modulate the coagulation system.[3]

Orange peel pectin is a natural coagulant and adsorbent that successfully lowers turbidity and eliminates contaminants from water. Orange peels are a rich source of this polysaccharide, which has several uses, most notably in wastewater treatment. Pectin present in orange peels acts as a flocculant, facilitating the aggregation of suspended particles in water, which aids in turbidity reduction[4] Orange peels contain bioactive compounds such as ascorbic acid and phenolics, which contribute to their ability to reduce turbidity and adsorb pollutants[5] The functional groups present in orange peels, such as –OH and –COOH, enable effective adsorption of various pollutants, including heavy metals and dyes.[6] Studies have shown that orange peels can remove contaminants like methyl orange from water, demonstrating their potential as low-cost adsorbents.[7]

Papaya seeds, tamarind seeds, orange peels, and neem leaves are widely available as agricultural byproducts. Orange peels come from fruit markets and juice industries, while papaya and tamarind seeds are sourced from food processing waste. Neem leaves are abundant in tropical regions, making all these materials easily accessible and sustainable for wastewater treatment.

This paper investigates the effectiveness of papaya seed, Tamarind seed powder, orange peels and neem leaves powder as a coagulant for turbidity removal in wastewater treatment. Through systematic experimentation, we assess its performance under different dosages. We aim to provide insights into a sustainable approach to addressing turbidity issues in wastewater. By harnessing the natural properties of papaya seeds, tamarind seeds, orange peels, and neem leaves, we aim to contribute to greener and more efficient water treatment solutions. This research highlights the significance of exploring natural alternatives in the pursuit of cleaner and safer water resources, ultimately achieving Sustainable Development Goal [6] i.e. Clean Water and Sanitation.

A significant number of academic studies have assessed the performance of different natural coagulants in relation to water treatment. Natural coagulants are classified into two distinct categories: those derived from plant sources and those that are not derived from plant sources. Plant-derived coagulants can be derived from various sources such as leaves, seeds, fruit waste, tree bark and more. These plant-derived coagulants have been studied more extensively than non-plant-derived ones, mainly due to their cost-effectiveness.8 Various natural coagulants, including moringa seeds, banana peel, cassava peel, starch, beans, nirmali seeds, jatropha curcas, watermelon, and okra, have been explored in previous studies.[9] For instance, Kishor and Singh highlighted that natural coagulants like Moringa oleifera, Cicer arietinum, tamarind seed, papaya seeds and neem leaves can effectively remove turbidity and total dissolved solids (TDS) from water.[10] These organic coagulants offer a viable and sustainable alternative to their chemical counterparts, as they are considered safe, environmentally friendly, cost-effective. In contrast to chemical coagulants, they do not augment the metal load or generate large volumes of sludge during water treatment. Furthermore, natural coagulants can be used alone or in combination with chemicals like aluminium sulfate to enhance water treatment.[11] In another study, Dollah found that the optimum pH for using orange peels as a natural coagulant is 5.0, with an optimal dosage of 60 mg/L, achieving up to 88.40% turbidity removal from synthetic water samples.[12] Similarly, Al-Aubadi and Hashim reported that orange peel coagulants could achieve 94% turbidity removal at a pH of 5.2. They also noted that plant coagulants could be used as coagulant aids with alum to increase coagulation efficiency and reduce the amount of alum needed.[13]

Several researchers have explored the use of citrus fruit peels for water treatment.[14] shown that a mix of citrus microcarpa peels and citrus aurantiifolia peels with an 80:20 ratio had the highest turbidity removal efficiency of 77.6%, with optimal mixing conditions being 120 rpm rapid mixing for 3 min, 50 rpm slow mixing for 20 min, and 60 min of sedimentation time. Additionally, Hamzah found that lemon peels could remove up to 89% of turbidity in water at an optimal dosage of 60 mg/L and pH of 4.0, making lemon peels a feasible and environmentally friendly alternative to synthetic chemical coagulants.[15]

Jamila El Gaayda *et al*. experimented on moringa seeds, and the results demonstrated removal efficiencies of 98.5% for turbidity and 92.2% for dye from synthetic wastewater.[16]

Moreover, Khan *et al* proposed that powdered neem seeds can be used as an effective coagulant to remove up to 86% of turbidity from water when used at an optimal dose of 3 g/L, pH of 13.2 and mixing conditions of 60 minutes at 80 rpm. This indicates that powdered neem seeds may serve as a viable alternative to traditional chemical coagulants in the treatment of drinking water.[17]

Additionally, tamarind seed extract has been shown to act as a bio coagulant in reducing wastewater pollutants, with effective concentrations at 80 mg/L and 120 mg/L. Pujiastuti reported that tamarind seed powder achieved an 85% reduction in turbidity at a dosage of 30 mg/L, resulting in a final turbidity of 15 NTU. Furthermore, winged bean powder was found to achieve an 80% reduction in turbidity, emphasising the efficacy of these natural coagulants in water treatment.[18]

Yimer found that Papaya seed extract proved to be an effective coagulant for water treatment.

achieving 96.32% total coliform removal and reducing turbidity to 4.25 NTU, meeting WHO drinking water standards.[19]

Another research compares the efficiency of neem leaves and orange peels with textile waste and found neem leaf powered as a coagulant is more effective. The turbidity was reduced to approximately 4 NTU using neem, while orange peel powder reduced the turbidity to about 8 NTU. The pH remained alkaline with the use of neem, but it slightly decreased with the application of orange peel powder.[20]

Farah Amira Binti Mohammad Lanan utilised fenugreek (Trigonella foenum-graecum) as a coagulant and okra (Abelmoschus esculentus) as a flocculant in the treatment of palm oil mill effluent (POME). The treatment accomplished removal efficiencies of 94.97% for turbidity, 92.70% for total suspended solids, and 63.11% for chemical oxygen demand.[21]

Many other natural coagulant like Petai belalang (*Leucaena leucocephala*),[22] Prickly Pear Peel Waste[23] Almond Hull,[24] some of the researchers explored combined effects blend of plant based natural and synthetic coagulants like Moringa Oleifera-Cactus Opuntia-alum blend,[25] alum and neem leaves.[26]

While various studies have explored the effectiveness of natural coagulants, there is a lack of comprehensive comparative analyses that evaluate the performance of multiple natural coagulants against each other under identical experimental conditions. This gap hinders the ability to identify the most effective coagulant for specific wastewater treatment scenarios.

Most studies on natural coagulants have been conducted at a laboratory scale, leaving a significant gap regarding their scalability for industrial applications. Research is needed to assess the practical challenges of implementing these coagulants in wastewater.

Table 1: Comparison of natural coagulant and traditional coagulant

Aspect	Natural Coagulants	Traditional Coagulants
Eco-friendliness	High (biodegradable)	Moderate to Low
Toxicity	Non-toxic	Potentially toxic (e.g., aluminum-based)
Cost	Lower, especially in rural areas	Higher
Sludge Volume	Low	High
Byproducts	Minimal	Possible harmful residues

Materials and Methods

Raw Water Quality

Wastewater samples were collected from a sewer manhole in Chandkheda, Ahmedabad, during September 2024. The pH of the water was measured at 6.9. Turbidity was recorded at 364 NTU. The Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were 307 mg/L and 496 mg/L, respectively. These parameters represent the initial characteristics of the water used in the study.

Coagulant Preparation

Papaya Seeds

The preparation of papaya seed coagulant for wastewater treatment involves several methodical steps to harness the natural coagulating properties of the seeds. First, fresh papaya seeds are extracted from the fruit and thoroughly washed to remove any residual pulp. These seeds are then dried by spreading them out under the sun for several days until fully dehydrated. Once dried, the seeds are reduced to a fine powder utilizing a high-performance blender. or grinder. To prepare the coagulant solution, 10gm of the papaya seed powder is dissolved in 500 ml distilled water, although this ratio can be adjusted based on the wastewater's characteristics. The solution is stirred thoroughly to ensure even dispersion of the powder. Lastly filter the solution to remove any remaining seed solids & collect the clear supernatant (liquid extract) and store it in a clean, airtight bottle.[27]

Tamarind Seeds

The tamarind seeds were gathered from kitchen refuse within the municipal jurisdiction. They were thoroughly cleansed and subsequently desiccated under sunlight for an extended duration until completely dehydrated. The desiccated seeds were thereafter processed into a fine powder utilizing a commercial mixer. Following the grinding process, the resultant material was subjected to sieving through a 750 µm mesh, with the fraction exhibiting particle sizes smaller than 750 µm designated for the experimental procedures. Fifty grams of the resultant powder was amalgamated with 1 L of distilled water and 1.0 M NaCl. The resultant mixture was agitated using a magnetic stirrer for a duration of 10 minutes to facilitate the extraction of the coagulation-active constituents. These constituents were subsequently filtered through filter paper, yielding a solution designated as crude extracts, which were prepared and preserved in a sterile container.

Neem Leaves

Neem leaves were collected and washed with distilled water, then dried naturally in sunlight for several days until fully dried. The dried leaves were crushed using a mixer and powdered, passing through a 75-micron sieve. To prepare a stock solution of the coagulant, 10 grams of the prepared powder was mixed with 1 litre of distilled water. The mixture was filtered through a muslin cloth. The resulting filtered solution, crude extract, was stored in a clean bottle for future use.

Orange Peel

Fresh orange peels were collected from a local market and thoroughly washed to remove dirt to prepare orange peel coagulant. Peels were dried naturally in sunlight until fully dried. After drying, the peels were manually cut into small pieces and finely crushed into a powder. Once dried, the powder was sieved through a mesh size of 600 μm to achieve uniform particle size. The resulting powdered orange peel was stored in an airtight container. To create the stock solution, 10 grams of the powdered peel were mixed with 1000 ml of distilled water, ensuring thorough dissolution by stirring. The solution was then left to stand to allow extraction of active compounds from the orange peel. The stock solution is filtered to remove any residual particles before storage in a clean, labelled container.[28]

Jar Test Procedure

To determine the optimal dosages of the four coagulants mentioned, a systematic approach known as the jar test is employed. This process begins by filling six 1-liter beakers with raw wastewater samples, which are then labelled from 1 to 6 for easy identification.

Next, varying amounts of prepared stock solutions of each coagulant are added to the corresponding beakers. The mixtures are initially stirred vigorously at a rate of 100-150 revolutions per minute (rpm) for a duration of one minute. This rapid mixing phase is crucial as it ensures that the coagulants are evenly distributed throughout the wastewater, promoting effective interaction between the coagulants and the suspended particles.

Following the rapid mixing, the beakers are stirred at a slower rate of 20 rpm for a period 20 minutes. This slower stirring facilitates the formation of flocs, which are aggregates of particles that settle out of the water column. After the flocculation phase, the mixtures are allowed to settle undisturbed for 20 minutes. This settling period is essential for the flocs to grow larger and to separate from the treated water effectively.[29]

Once the settling time has elapsed, the turbidity of the supernatant in each beaker is measured using a turbidity meter. Turbidity is an important indicator of water quality, as it reflects the concentration of suspended particles remaining in the water after treatment. The objective is to identify the optimum dosage of each coagulant, which is defined as the dosage that results in the lowest turbidity level. A lower turbidity indicates a more efficient coagulation process, leading to cleaner water.

To ensure accuracy and reliability of the results, multiple experiments are conducted with each coagulant. This comprehensive testing approach allows for the identification of the most effective dosage for coagulation, ultimately aiding in the treatment of wastewater and improving overall water quality.

Table 2: Raw Water Quality

Parameter	Unit	Value
Ph		6.9
Turbidity	NTU	364
BOD	mg/lit	307
COD	mg/lit	496

Fourier Transformed Infrared Analysis (FTIR):

The Bruker Alpha FTIR equipped with ZnSe optics was utilised for Fourier Transform Infrared Analysis (FTIR) to identify the organic functional groups. The FTIR spectrum was recorded in the mid-IR range of 400–4000 cm^{-1} utilising the attenuated total reflectance (ATR) method in ATR scanning mode.

For FTIR analysis, a small amount of the fine powdered sample is placed directly on the ZnSe ATR crystal. The powder was lightly pressed onto the crystal to ensure good contact and optimal penetration of infrared radiation. The sample was then analyzed using the ATR technique to obtain the FTIR spectrum.

Results & Discussion

The research project evaluated the performance of naturally obtained coagulants, including orange peels, papaya seeds, tamarind seeds, and neem leaves, for turbidity reduction. The findings revealed that neem leaves, when applied at an optimal concentration of 400 mg/L, accomplished a maximum removal of turbidity with an efficiency of 99.86%. Conversely, papaya seeds and orange peels exhibited comparable efficiencies, approximately 91% at significantly lower concentrations of 200 mg/L, final turbidity of 30 NTU and 30.9 NTU, respectively. Although tamarind seeds proved to be effective with an efficiency of 89.14%, they necessitated a considerably higher dosage of 1250 mg/L, leading to a final turbidity value of 39.5 NTU. These results represent the differential efficiency of natural coagulants. Table 3 and Figure 2 refers to the optimum dosage and corresponding turbidity removal and efficiency for each coagulant.

Table 3: Optimum dose of different coagulant

No	Dosage (ml)	Dosage (mg)	Turbidity (NTU)	% Turbidity Removal
		Coagulant: Papaya Seed		
1	5	100	38.7	89.36
2	**10**	**200**	**30**	**91.75**
3	15	300	32.8	90.9
4	20	400	52.2	85.65
5	25	500	187.2	48.57
6	30	600	250	31.31
		Coagulant: Tamarind Seed		
1	5	250	49.3	86.45
2	10	500	44.6	87.74
3	15	750	44	87.91
4	20	1000	43	88.18
5	**25**	**1250**	**39.5**	**89.14**
6	30	1500	41.2	88.68
		Coagulant: Orange Peel		
1	1	100	33.4	90.82
2	**2**	**200**	**30.9**	**91.51**
3	3	300	39.3	89.17
4	4	400	65.1	82.11
5	5	500	69.1	81.01
6	6	600	120.5	66.89
		Coagulant: Neem Leaves		
1	10	100	41.8	88.51
2	20	200	21.5	94.09
3	30	300	2.2	99.39
4	**40**	**400**	**0.5**	**99.86**
5	50	500	1.4	99.61
6	60	600	3.2	99.12

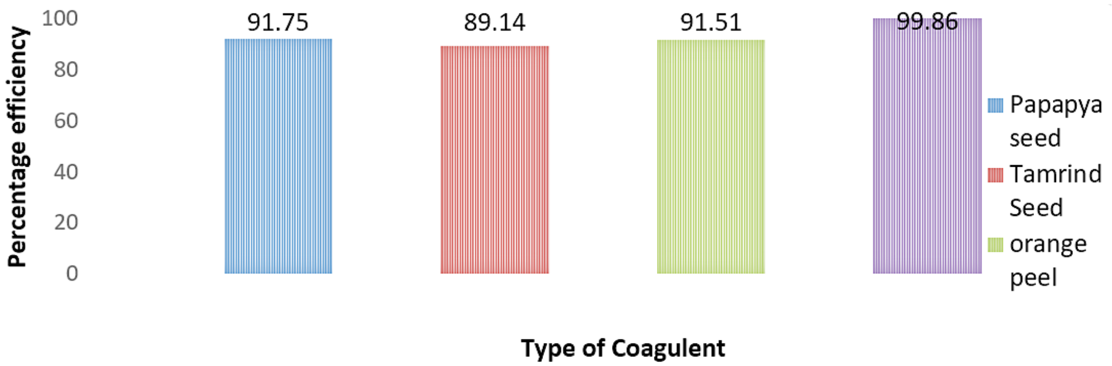

Fig. 2: Graph showing Efficiency of different coagulants

Neem leaves performed the best among the natural coagulants tested, likely due at neem leaves are rich in secondary metabolites, also having flavonoids and tannins, which are responsible for bioactive properties.[30] Tannins are known for their ability to bind and destabilize suspended particles in wastewater, which helps in the formation of flocs that settle effectively.[31] The FTIR analysis (Figure 3) and Table 4 revealed key The significant wavelengths for neem leaves encompass 3340, 2915, 1724, 1600, and 1441 cm^{-1}, which are associated with functional groups such as O-H stretching, C-H stretching, C=O, C=C, and C-H bending. The presence of these groups suggests that neem leaves can effectively interact with organic contaminants in the wastewater,[32] contributing to their superior coagulation performance. However, neem leaves impart a slight color to the treated water, which suggests that additional treatment, such as adsorption or filtration, may be necessary to achieve colour removal.

Table 4: FTIR Spectral Profile of Natural Coagulants for Turbidity Removal

Coagulant	Wavelength cm^{-1}	Functional Group
NEEM LEAFS	3340.58	O-H Stretch (Alcohol)
NEEM LEAFS	2915.75	C-H Stretch (Alkane)
NEEM LEAFS	1724.33	C=O Stretch (Carbonyl)
NEEM LEAFS	1600.82	C=C Stretch (Aromatic)
NEEM LEAFS	1441.53	C-H Bending (Alkane)
NEEM LEAFS	1314.48	C-H Bending (Alkyl)
NEEM LEAFS	1232.62	C-O Stretch (Alcohol/Ether)
NEEM LEAFS	1147.08	C-N Stretch (Amines)
NEEM LEAFS	1034.82	C-O Stretch (Alcohol/Ether)
NEEM LEAFS	895.35	C-H Out-of-plane Bend (Aromatic)
NEEM LEAFS	774.06	C-H Out-of-plane Bend (Aromatic)
NEEM LEAFS	717.04	Aromatic C-H Bend
ORANGE PEELS	3275.08	O-H Stretch (Alcohol)
ORANGE PEELS	2873.48	C-H Stretch (Alkane)
ORANGE PEELS	1737.07	C=O Stretch (Carbonyl)
ORANGE PEELS	1641.85	C=C Stretch (Aromatic)
ORANGE PEELS	1516.60	C-H Bend (Alkanes/Aromatics)
ORANGE PEELS	1403.46	C-H Bending (Alkyl)
ORANGE PEELS	1014.07	C-H Bending (Alkyl)
ORANGE PEELS	916.67	C-H Bending (Aromatic)
ORANGE PEELS	721.84	C-H Stretch (Alkane)

ORANGE PEELS	2922.17	C-H Stretch (Alkane)
ORANGE PEELS	2853.37	C=O Stretch (Carbonyl)
PAPAYA SEEDS	1744.61	C=O Stretch (Carbonyl)
PAPAYA SEEDS	1709.90	C=C Stretch (Aromatic)
PAPAYA SEEDS	1649.86	C-N Stretch (Amines)
PAPAYA SEEDS	1540.1	C=C Stretch (Aromatic)
PAPAYA SEEDS	1510.92	C-O Stretch (Alcohol/Ether)
PAPAYA SEEDS	1232.15	C-O Stretch (Alcohol/Ether)
PAPAYA SEEDS	1030.49	O-H Stretch (Alcohol)
TAMARIND SEEDS	3267.67	C-H Stretch (Alkane)
TAMARIND SEEDS	2920.56	C=O Stretch (Carbonyl)
TAMARIND SEEDS	1742.83	C-O Stretch (Alcohol/Ether)
TAMARIND SEEDS	1032.96	C-H Bending (Alkyl)
TAMARIND SEEDS	990.49	C-H Bending (Alkyl)
TAMARIND SEEDS	773.83	C-H Bending (Aromatic)
TAMARIND SEEDS	713.47	O-H Stretch (Alcohol)

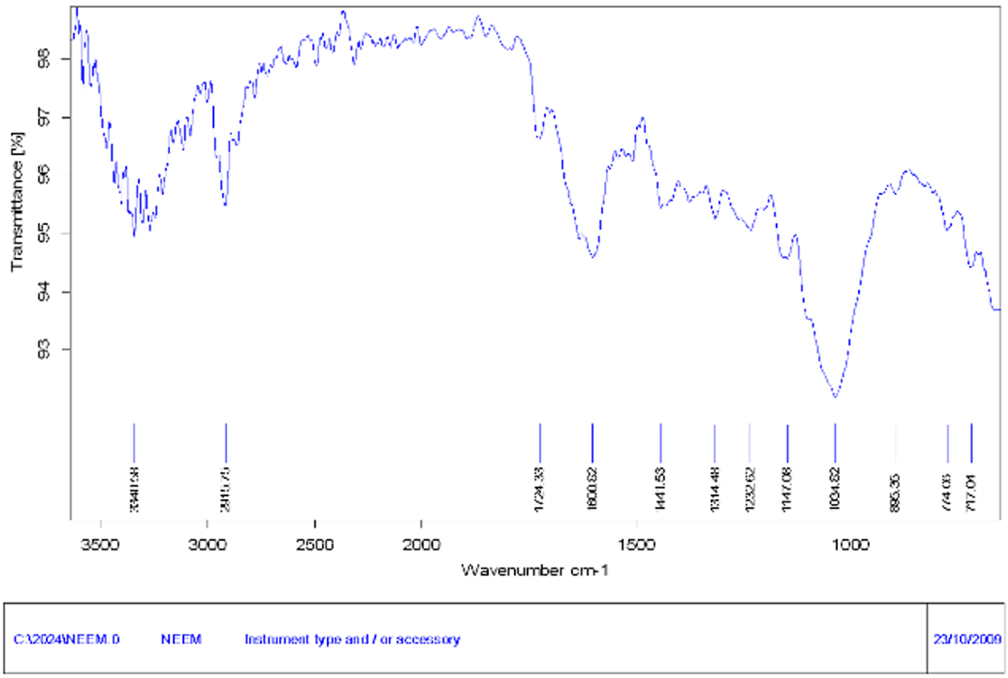

Fig. 3: FTIR Spectrum for Neem leaves

Similarly, the use of papaya seeds aligns with findings by Yimer,[33] who determined that papaya seed extract could effectively eliminate up to 96.32% of turbidity in aqueous solutions. Our investigation revealed a marginally reduced turbidity removal efficacy (91.75%); however, this was achieved at a significantly lower concentration (200 mg/L), which may imply a more economically viable methodology. The lower dosage requirements in our study can be linked to the preparation method, where fine grinding and proper dispersion likely led to better coagulation efficiency. The FTIR analysis (Figure 4) showed peaks at 1744 cm^{-1}, 1709 cm^{-1}, and 1649 cm^{-1}, which correspond to carbonyl (C=O), aromatic (C=C), and C-N stretches, respectively. These identified functional groups from proteins imply that papaya seed powder possesses a considerable propensity for adsorption with organic pollutants,[33] thereby reducing the turbidity. Papaya seeds showed a significant reduction in BOD (52%) and COD

(68%), but the performance is slightly lower than neem leaves in these metrics. Table 5 shows the final water quality, including BOD and COD reduction, for each coagulant.

Table 5: Final water Quality with different coagulant

Coagulant	Optimum Dosage (mg)	Turbidity (NTU)		BOD (mg/lit)		COD (mg/lit)	
		Final turbidity	% Removal	Final BOD	% Removal	Final COD	% Removal
Papaya Seed	200	30	91.75	147.36	52	158	68
Tamarind Seed	1250	39.5	89.14	101.31	67	110	78
Orange Peel	200	30.9	91.51	64.47	79	74	80
Neem Leaves	400	0.5	99.86	76.75	75	89	82

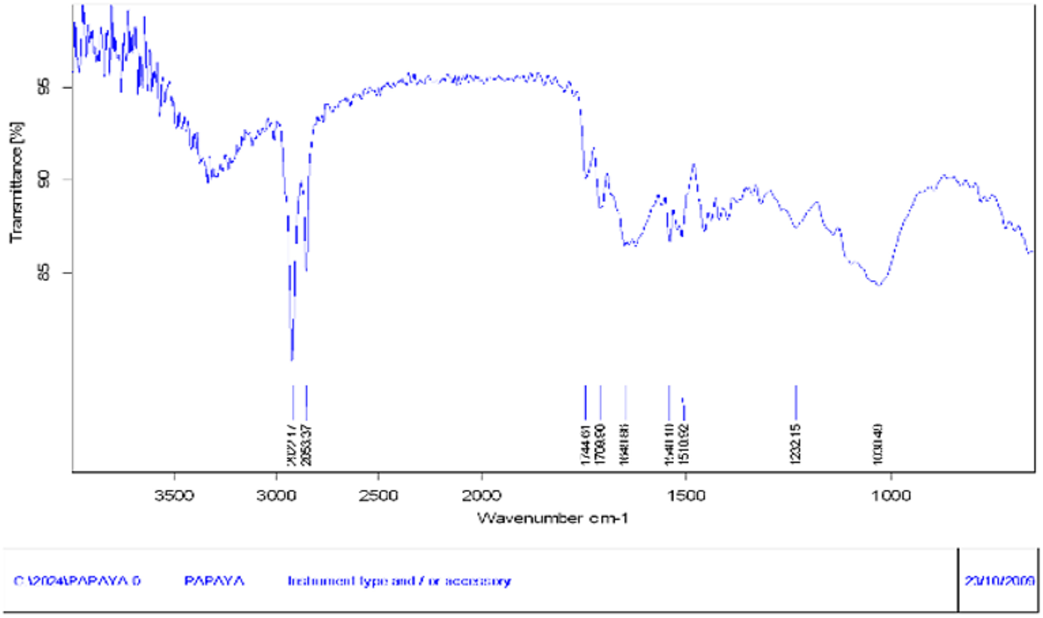

Fig. 4: FTIR Spectrum for Papaya Seeds

Orange peels, which are often overlooked in studies on wastewater treatment, have been shown to be an affordable substitute. They are a very viable choice for communities because to their low cost and free procurement from waste streams, especially in regions with a lot of citrus output. According to similar studies, orange peels and biochar can remove up to 91.92% of the turbidity[34] and orange peel alone can remove up to 79.4% in wastewater.[35] Our results (91.51%) are in line with similar findings. Orange peels coagulating qualities are probably caused by important functional groups including O-H, C-H, C=O, and C-H bending, which were identified by the FTIR study (Figure 5). These functional groups, together with pectin and phenolic chemicals, help to remove turbidity by promoting the adsorption of suspended particles.[36] But compared to neem leaves, the overall efficiency is lower. The noteworthy decrease in BOD (79%) and COD (80%) is consistent with previous research,[35] underscoring their capacity to remove organic compounds.

In contrast, tamarind seeds need larger dosages to effectively remove turbidity, which is consistent with research that showed tamarind seed extract reduced turbidity by up to 85% at a dosage of 30 mg/L.[37]

However, our research used tamarind seeds instead tamarind seed extract of needed a much greater dosage of 1250 mg/L to remove 89.14% of the turbidity. This suggests that tamarind seeds would not be as effective as orange peels or neem leaves for large-scale applications. Peaks at 3267, 2920, 1742, and 990 cm^{-1} were found in the FTIR study (Figure 6), which corresponded to C-H bending, carbonyl (C=O), and alcohol/ether (C-O) stretches. When compared to other coagulants, tamarind seeds may not be as cost-effective due to the large dosage that is necessary. In spite of this, tamarind seeds showed significant drops in BOD (67%) and COD (78%), which makes them appropriate for use in wastewater in areas where their waste byproduct is easily accessible, like in food processing facilities.

Fig. 5: FTIR Spectrum for Orange peels

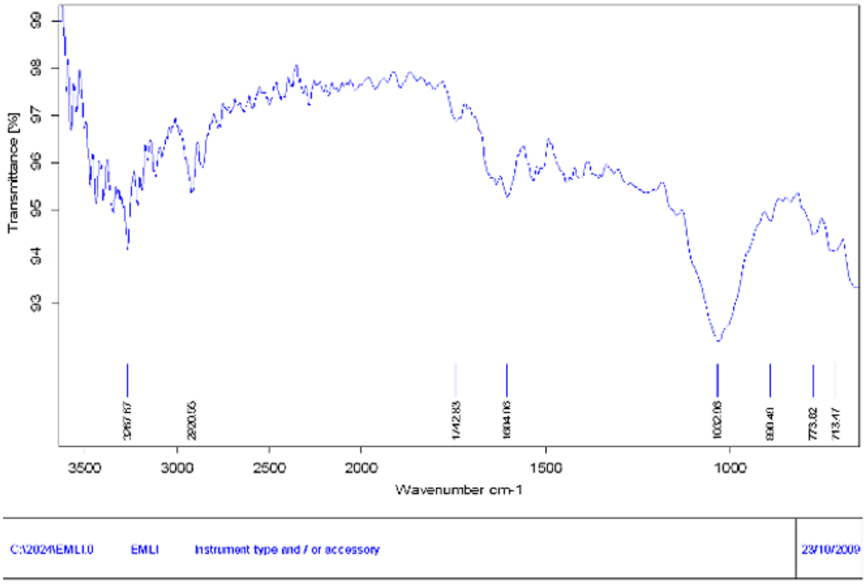

Fig. 6: FTIR Spectrum for Tamarind Seeds

Although orange peels are readily available and offer a cost-effective alternative, their turbidity reduction efficacy (66.89%) was marginally lower than that of papaya seeds and neem leaves. Nonetheless, orange peels' effectiveness in removing BOD and COD (79% and 80%, respectively) shows that they can be a good choice for wastewater organic matter removal. When it comes to practical application, orange peels are the most economical choice because they don't require any processing fees.

On the other hand, although they work well, papaya and tamarind seeds might need to be specifically sourced from nearby food processing businesses, which could affect how cost-effective they are overall. While tamarind seeds may be neglected in regions that do not process tamarind in big amounts, papaya seeds, despite their effectiveness, are frequently limited in availability, particularly in countries without a substantial papaya manufacturing industry. Both seeds, however, performed rather well in terms of reducing BOD and COD.

Regarding the FTIR study, spectral analysis indicated the the availability of functional groups like hydroxyl (-OH) and carboxylic acid (-COOH),[38] and amines (-NH2) in these natural coagulants, confirming their potential to interact with suspended particles and organic pollutants in wastewater. These functional groups facilitate adsorption, bridging, and charge neutralization mechanisms, essential for the coagulation-flocculation process, thus validating their effectiveness.

According to this study, neem leaves are the best natural coagulant, removing 99.86% of turbidity; nevertheless, color removal requires an extra step. Because they are readily available and inexpensive to treat, orange peels are the most economical coagulant. They remove 91.51% of turbidity and significantly lower BOD and COD. Though their cost-effectiveness is dependent on local availability and processing needs, papaya and tamarind seeds also exhibit promise. Given the cost, accessibility, and viability of these materials in actual wastewater treatment systems, this study offers a thorough comparison of natural coagulants and emphasizes the need for additional research to maximize their industrial-scale utilization.

To better understand the efficiency differences among the coagulants tested and enhance their use in wastewater treatment, more research into the mechanisms underlying coagulation is required. This includes examining the role of particular functional groups found in the FTIR analysis.

Conclusion

The study demonstrated that neem leaves emerged as the most effective natural coagulant, achieving an impressive 99.86% turbidity removal. However, it is important to note that neem leaves impart a slight color to the treated water, necessitating additional treatment for complete acceptability in water usage. In terms of cost-effectiveness, neem leaves remain a viable option due to their natural abundance and minimal processing costs. They also showed significant effectiveness in BOD and COD reduction, with reductions of 75% in BOD and 89% in COD, further enhancing their appeal as an affordable and efficient coagulant.

When considering alternatives, orange peels exhibited a comparable efficiency of around 91% turbidity removal, making them a highly cost-effective choice due to their zero-cost availability as a waste material. This coagulant also achieved substantial reductions in BOD (79%) and COD (80%), reinforcing its potential as an economical and sustainable solution.

Papaya seeds, while demonstrating a turbidity removal efficiency of 91.75%, required a lower dosage (200 mg/L) compared to tamarind seeds. However, their availability may depend on food processing waste sources, impacting their overall cost efficiency. Despite this, their significant reduction of BOD (52%) and COD (68%) makes them a promising option where availability is not a constraint.On the other hand, tamarind seeds required a higher dosage (1250 mg/L) to achieve 89.14% turbidity removal, which may affect their cost-effectiveness when compared to other natural coagulants. Nevertheless, they demonstrated strong reductions in BOD (67%) and COD (78%), making them suitable for applications where their waste byproduct is readily available, such as in food processing industries.

Regarding the FTIR study, spectral analysis indicated the presence of functional groups such as hydroxyl (-OH), carboxylic acid (-COOH), and amines (-NH2) in these natural coagulants, confirming their potential to interact with suspended particles and organic pollutants in wastewater. These functional groups facilitate adsorption, bridging, and charge neutralization mechanisms, essential for the coagulation-flocculation process, thus validating their effectiveness.

This research was conducted only at laboratory scale, without considering long-term stability, toxicity, or industrial-scale variability, potentially limiting real-world applicability.

In conclusion, while neem leaves offer the highest efficiency, their cost-effectiveness must be weighed against the need for additional color removal treatment. Orange peels stand out as the most practical and economical coagulant, given their wide availability, zero procurement cost, and strong turbidity and organic matter removal efficiency. Papaya seeds and tamarind seeds remain viable options, but their cost-effectiveness depends on sourcing feasibility and processing requirements.

This study emphasizes the importance of balancing removal efficiency, availability, and overall cost-effectiveness when selecting natural coagulants. Future research should focus on optimizing the industrial-scale application of these coagulants, including exploring cost-efficient methods for mitigating secondary drawbacks such as coloration and enhancing overall feasibility.

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Conflict of Interest

The authors do not have any conflict of interest.

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This statement does not apply to this article.

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This research did not involve human participants, animal subjects, or any material that requires ethical approval.

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This study did not involve human participants, and therefore, informed consent was not required.

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Not Applicable.

Author Contributions

- **Dhriti Ramdas Rawat:** Conceptualization of the study, methodology development, and supervision of research work. Contributed to the analysis and interpretation of results and manuscript review.
- **Khushboo Mahendra Parmar:** Conducted data collection, assisted in data analysis, and contributed to the literature review. Assisted in manuscript writing and formatting.
- **Shraddha Shriram Thorat:** Performed the experimental work, contributed to data analysis and interpretation, and drafted the initial manuscript. Assisted in manuscript editing and final proofreading

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