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Application Of Response Surface Methodology In The Performance Optimization Of Hybrid Natural Coagulants For Turbidity Removal

[1]Shashikumar M Hiremath, [2]Dr.Lokeshappa B, [3]Dr.Shanmukha N T ,[4]Dr. Kiran Kumar H S, [5]Spoorthi B
[1]Assistant Professor, Department of Civil Engineering, SJNCCE, Shimoga, Karnataka, India
[2]Associate Professor, Civil Engineering, UBDT College of Engineering, Davanagere, Karnataka, India
[3]Associate Professor, Department of Civil Engineering, Govt. Engg. College, K R Pete, Karnataka, India
[4]Associate Professor, Department of Civil Engineering, G M University, Davanagere, Karnataka, India
[5]Assistant Professor, Department of Civil Engineering, G M University, Davanagere, Karnataka, India

Abstract: *This study investigates the turbidity removal efficiency of three natural coagulants Moringa oleifera, Tamarind seed**,** and Nirmala seed—under varying pH levels using both experimental methods and **Response Surface Methodology (RSM)**. Jar tests were conducted at pH values of 5, 7, and 9 with an initial turbidity of 100 NTU, using dosages ranging from 10 to 70 mg/L and contact times of 30, 45, and 60 minutes. The aim was to determine optimal treatment conditions and assess the suitability of each coagulant under acidic, neutral, and alkaline environments.*

*Results indicated that **Moringa oleifera** demonstrated the highest removal efficiency at pH 5, achieving **97.87%** turbidity reduction at 30 mg/L and 30 minutes. **Tamarind seed** and **Nirmali seed** showed maximum efficiencies of **86.11%** and **80.11%**, respectively, under similar acidic conditions. At neutral pH (7), Moringa remained the most effective with **92.33%** removal, while Tamarind and Nirmali achieved moderate reductions. Under alkaline conditions (pH 9), all coagulants showed reduced performance, with Moringa still leading at **84.22%**.*

*RSM modeling showed high correlation between experimental and predicted values, particularly for Moringa (error <2%), validating the reliability of the model. Contour and surface plots confirmed that **coagulant dosage and contact time** significantly influenced removal rates, while Pareto analysis highlighted strong interaction effects between **pH and dosage**.*

*Overall, the findings establish Moringa oleifera as the most effective and consistent natural coagulant across varying conditions, followed by Tamarind and Nirmali, which can also perform well when optimized. The use of RSM significantly enhanced process optimization and predictive capability. These results support the adoption of natural coagulants as **eco-friendly, low-cost alternatives** in decentralized and rural water treatment applications.*

Keywords— *Turbidity, coagulation, Coagulants, NTU, RSM**,** Moringa oleifera**,** Tamarind seed**,** Nirmala seed*

1. INTRODUCTION

Water Is a fundamental resource that sustains life and ecosystems while supporting domestic, agricultural, and industrial activities. Although water covers approximately 71% of the Earth's surface, only about 2.5% is freshwater, and a mere 0.3% of that is accessible for human consumption through rivers and lakes. Increasing population, industrialization, and climate change have intensified pressure on water resources, leading to widespread scarcity and contamination. This challenge is most acute in developing countries, where nearly 75% of the global population resides. Alarmingly, over a billion people lack access to safe drinking water, and millions die each year from waterborne diseases such as cholera, typhoid, and diarrhea.

Water pollution is driven by both natural and anthropogenic factors. Natural sources include soil erosion, weathering, and floods that introduce sediments and dissolved substances into water bodies. However, human activities such as industrial discharges, agricultural runoff, urbanization, and improper waste disposal have significantly worsened the problem. Pollutants like heavy metals (e.g., lead, arsenic), fluoride, pesticides, and pharmaceutical residues threaten both aquatic ecosystems and public health.

One of the most crucial parameters for assessing water quality is **turbidity**, which measures the cloudiness caused by suspended solids and colloidal matter. High turbidity not only degrades the aesthetic quality of water but also serves as a carrier for microbial pathogens. It reduces light penetration, affecting aquatic plant life and interfering with disinfection during water treatment processes. Hence, effective turbidity removal is a central goal in water purification systems.

Conventional water treatment practices rely heavily on **coagulation and flocculation** processes to remove turbidity and other suspended impurities. These involve the addition of coagulants that neutralize charges on colloidal particles, facilitating the formation of larger flocs which can be separated by sedimentation or filtration. Widely used chemical coagulants like aluminum sulfate (alum) and ferric chloride are effective but come with disadvantages. These include high operational costs, pH alterations in treated water, excessive sludge generation, and potential long-term health hazards due to residual aluminum content.
As a result, there is growing interest in exploring **natural coagulants** as eco-friendly, cost-effective, and sustainable alternatives. Natural coagulants, derived from plant, animal, or microbial sources, are biodegradable and typically non-toxic. Plant-based materials such as **Moringa oleifera**, **Tamarind seed**, and **Nirmali seed** have gained significant attention. These materials are locally available, especially in rural and semi-urban regions, and contain active compounds like proteins, polysaccharides, and amino acids that aid in coagulation via mechanisms such as charge neutralization and polymer bridging.
Each natural coagulant possesses unique physicochemical properties, which influence its performance depending on the water's characteristics and treatment conditions. For example, **Moringa oleifera** contains cationic proteins that effectively neutralize negatively charged colloids, resulting in quick and effective floc formation. However, the efficiency of these coagulants is influenced by several factors including **dosage, pH, mixing intensity, and contact time**. Therefore, identifying optimal conditions for each coagulant is essential for maximizing turbidity removal.
To systematically investigate and optimize these parameters, researchers have increasingly turned to **Response Surface Methodology (RSM)**. RSM is a statistical and mathematical tool that evaluates the relationships between multiple variables and the desired response. It is particularly useful in optimizing complex processes, as it reduces the number of experiments required while providing a robust model for prediction. By analyzing the interactions between variables such as pH, coagulant dose, and contact time, RSM helps identify the best operational conditions for achieving maximum turbidity reduction.
This study focuses on evaluating the **turbidity removal performance of Moringa oleifera, Tamarind seed, and Nirmali seed** under varying conditions. The research aims to (1) examine the coagulation behaviour of each natural coagulant, (2) assess the influence of process parameters on removal efficiency, and (3) apply RSM for modeling and optimizing the process. The broader objective is to establish a **sustainable, low-cost, and locally applicable alternative** to chemical coagulants, especially in under-resourced regions lacking access to advanced water treatment technologies.
Through this approach, the study contributes to the development of environmentally sound and economically feasible solutions for improving water quality and public health in developing and rural communities.

2. MATERIALS AND METHODOLOGY

2.1 Study Location and Overview

The experimental investigation was conducted in the Environmental Engineering Laboratory of the Civil Engineering Department at UBDT College of Engineering, Davangere. The study primarily aimed to assess the turbidity removal efficiency of selected natural coagulants through jar test experiments under varying physicochemical conditions.

2.2 Materials Used

NaturalCoagulants:
Three plant-based natural coagulants were used: Moringa oleifera (Drumstick seed), Tamarindus indica (Tamarind seed), and Strychnos potatorum (Nirmali seed). These materials were chosen due to their traditional and scientifically recognized applications in water purification.

- Moringa oleifera seeds are nutrient-rich and known for their cationic proteins, which aid in particle aggregation.
- Tamarindus indica seeds are high in polysaccharides and protein, offering coagulating potential through charge neutralization and bridging mechanisms.
- Strychnos potatorum seeds are traditionally used in rural India for water clarification and possess bioactive compounds useful in coagulation.

PreparationofCoagulants:
The seeds were sun-dried or oven-dried and ground into a fine powder. A 5-gram quantity of each seed powder was dissolved in 100 mL of distilled water. The mixtures were stirred continuously for 45 minutes to enhance solubilization, then filtered using Whatman filter paper. The resulting filtrates were used to prepare working solutions at concentrations ranging from 10 to 70 mg/L.

2.3 Preparation of Turbid Water Samples
Fine-textured clayey soil was collected, air-dried, and sieved through a 0.5 mm mesh. A stock solution was prepared by mixing 10 grams of sieved soil in 1 liter of distilled water. After homogenization, the suspension was left for 5 minutes to settle heavy particles. The turbidity of the resulting supernatant was measured using a calibrated Nephelometric Turbidity Unit (NTU) meter. Based on initial turbidity values, the solution was diluted accordingly to prepare samples of 100 NTU, 200 NTU, and 300 NTU for experimental use.

2.4 Jar Test Procedure
Standard jar tests were performed using a flocculator equipped with six paddle stirrers and 1000 mL beakers. The experimental protocol included the following steps:

1. pH Adjustment: The raw water sample was divided into beakers and adjusted to pH values of 5, 7, and 9 using 1.0 M H_2SO_4 or 1.0 M NaOH.
2. Coagulant Dosage: Varying concentrations of each coagulant (20–70 mg/L) were added to separate beakers.
3. Mixing: Samples underwent rapid mixing at 120 rpm for 1 minute followed by slow mixing at 100 rpm for 30, 45, and 60 minutes.
4. Settling: After mixing, samples were allowed to settle for 1 hour undisturbed.
5. Sampling and Analysis: Supernatant from each beaker was carefully withdrawn to measure turbidity, pH, and Total Dissolved Solids (TDS) using standard analytical methods.

Each test was performed in triplicate to ensure reproducibility. The optimum dose was determined based on the lowest residual turbidity achieved. Comparative evaluations were carried out across varying pH values, contact times, and dosages to assess the performance of each coagulant under different conditions.

2.5 Methodology
A standard jar test was conducted to evaluate the coagulation efficiency of natural coagulants like Moringa olifera, Tamarind seed, and Nirmali seed. Coagulant solutions were prepared in distilled water and added to 1000 mL of turbid water samples with pH adjusted to 5, 7, and 9 using 1.0 M H_2SO_4 or NaOH. The samples were rapidly mixed at 120 rpm for 1 minute and then slowly stirred at 100 rpm for 30, 45, and 60 minutes to promote floc formation. After a 60-minute settling period, supernatants were collected for analysis. Turbidity, pH, and Total Dissolved Solids (TDS) were measured before and after treatment using a Nephelometer and digital TDS meter. Coagulation effectiveness was assessed by identifying the dosage (ranging from 20–70 mg/L) that achieved the least residual turbidity. All tests were performed in triplicates at room temperature using a six-paddle jar test apparatus

Fig 1: Jar Test apparatus

3. RESULTS AND DISCUSSIONS
Synthetic water was prepared and immediately analyzed upon arrival at the laboratory under controlled conditions to preserve its integrity. The initial characteristics—turbidity, pH, total dissolved solids (TDS), and electrical conductivity (EC)—were recorded and are presented in Table 3.1. The water samples were

then subjected to treatment using the standard jar test method, employing various natural coagulants such as *Moringa oleifera*, tamarind seeds, and Nirmali seeds. The experimental conditions were varied across key process parameters, including pH, mixing speed (RPM), contact time, and coagulant dosage. These variables were systematically altered to determine their impact on the efficiency of turbidity, TDS, and EC removal. The outcomes of the treatment process, including removal efficiencies and optimal operational conditions for each coagulant, are discussed in detail in the subsequent sections. This investigation highlights the potential of plant-based coagulants in sustainable water purification.

Table 3.1 Initial Characteristics of Synthetic Water

SL NO	PARAMETER	INITIAL VALUE
1	pH	8.8
2	TDS	454 (mg/l)
3	ELECTRIC CONDUCTIVITY	698(mS/mg)
4	TURBIDITY	100NTU,200NTU, 300 NTU

Table 3.2 The results for Moringa olifera, Tamarind seed and nirmali seed at pH=5, Turbidity 100 NTU, Contact Time 30, 45 and 60min

Sl No	VARIABLE PARAMETER	CONTACT TIME	M0RINGA OLIFERA	TAMARIND SEED	NIRMALI SEED
1	**Dosage=10mg/l**	**30min**	75.35%	70.22%	61.77%
		45min	**85.12%**	**70.94%**	**64.78%**
		60min	83.44%	80.44%	75.33%
2	**Dosage=20mg/l**	**30min**	**87.00%**	**74.80%**	**67.86%**
		45min	93.87%	86.11%	80.11%
		60min	**87.60%**	**69.75%**	**61.62%**
3	**Dosage=30mg/l**	**30min**	97.87%	73.65%	75.57%
		45min	**89.06%**	**73.52%**	**64.70%**
		60min	70.11%	75%	75.66%
4	**Dosage=40mg/l**	**30min**	79.55%	81.88%	72.71%
		45min	77.84%	79.20%	71.06%
		60min	76.00%	79.15%	70.55%
5	**Dosage=50mg/l**	**30min**	73.62%	78.88%	69.11%
		45min	73.96%	77.44%	68.66%
		60min	73.95%	77.25%	67.55%
6	**Dosage=60mg/l**	**30min**	73.35%	76.22%	67.77%
		45min	73.60%	75.72%	69.08%
		60min	73.44%	73.44%	69.33%
7	**Dosage=70mg/l**	**30min**	76.35%	72.22%	69.10%
		45min	73.60%	71.72%	63.08%
		60min	74.44%	69%	63.10%

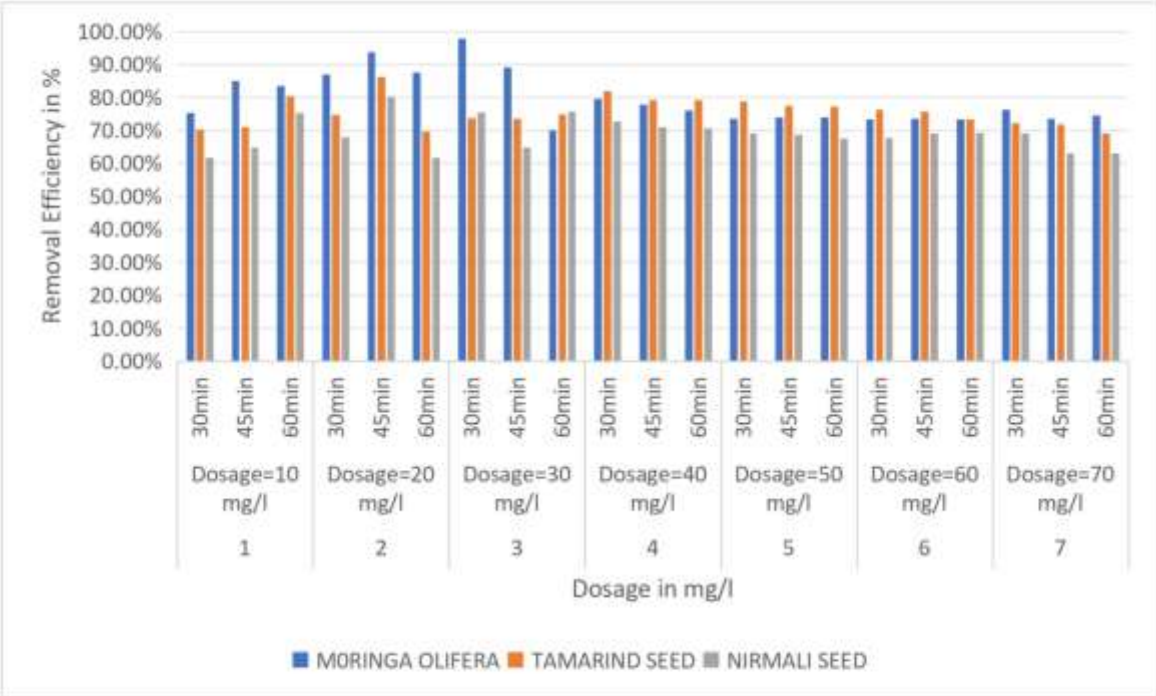

Figure 3.1: The results for Moringa olifera, Tamarind seed and nirmali seed at pH=5, Turbidity 100 NTU, Contact Time 30, 45 and 60min

This study evaluated the turbidity removal efficiency of *Moringa oleifera*, tamarind seed, and Nirmali seed at pH 5, with initial turbidity of 100 NTU, using dosages from 10–70 mg/L and contact times of 30, 45, and 60 minutes. *Moringa oleifera* achieved the highest removal efficiency of 97.87% at 30 mg/L and 30 minutes due to effective protein-based charge neutralization. Tamarind and Nirmali peaked at 86.11% and 80.11%, respectively, at 20 mg/L and 45 minutes. Prolonged contact times or higher dosages led to reduced efficiency, likely from floc disintegration or overdosing. *Moringa* consistently outperformed the others, particularly at lower dosages and shorter durations. Tamarind and Nirmali showed potential as viable alternatives with slower coagulation kinetics. Overall, the results confirm that natural coagulants are effective in turbidity removal, with *Moringa oleifera* being the most promising under acidic conditions.

Table 3.3 The results for Moringa olifera, Tamarind seed and nirmali seed at pH=7, Turbidity 100 NTU, Contact Time 30, 45 and 60min

Sl No	VARIABLE PARAMETER	CONTACT TIME	M0RINGA OLIFERA	TAMARIND SEED	NIRMALI SEED
1	**Dosage=10mg/l**	30min	78.94%	71.61%	66.19%
		45min	70.50%	65.02%	55.32%
		60min	81.96%	68.01%	59.95%
2	**Dosage=20mg/l**	30min	92.33%	85.07%	61%
		45min	82.22%	70.01%	65.03%
		60min	80.08%	68.05%	63.12%
3	**Dosage=30mg/l**	30min	82.88%	74.25%	66.11%
		45min	75.18%	69.00%	60.33%
		60min	83.90%	70.00%	61.02%
4	**Dosage=40mg/l**	30min	76.08%	63.22%	65.85%
		45min	72.76%	72.04%	63.11%
		60min	73.01%	68.25%	62.28%

5	**Dosage=50mg/l**	30min	76.23%	64.52%	69.42%
		45min	73.25%	73.02%	64.20%
		60min	71.52%	75.31%	67.67%
6	**Dosage=60mg/l**	30min	75.23%	65.52%	69.42%
		45min	74.25%	73.32%	64.20%
		60min	72.52%	74.21%	67.67%
7	**Dosage=70mg/l**	30min	60.92%	67.83%	59.70%
		45min	60.50%	65.02%	55.32%
		60min	64.50%	68.01%	56.33%

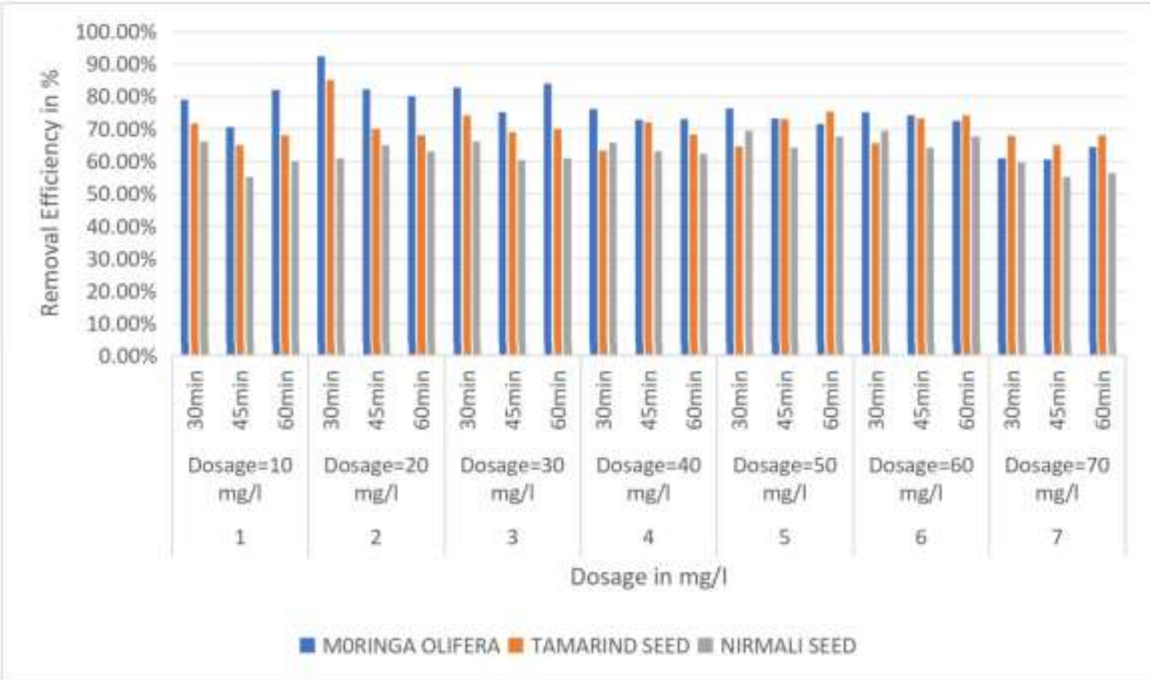

Figure 3.2: The results for Moringa olifera, Tamarind seed and nirmali seed at pH=7, Turbidity 100 NTU, Contact Time =30, 45 and 60min

The coagulation efficiency of *Moringa oleifera*, tamarind seed, and Nirmali seed was studied at pH 7, 100 NTU initial turbidity, using dosages from 10–70 mg/L and contact times of 30, 45, and 60 minutes. At 20 mg/L and 30 minutes, Moringa showed the highest turbidity removal (92.33%), followed by tamarind (85.07%) and Nirmali (66.19%). *Moringa oleifera* maintained high efficiency but showed fluctuations with time, likely due to floc saturation or re-aggregation. Tamarind performed well at shorter durations but declined over time, indicating time-sensitive kinetics. Nirmali consistently showed lower removal across all doses and durations, suggesting reduced activity at neutral pH. At higher dosages (40–70 mg/L), a plateau or decline in performance was observed for all coagulants due to overdosing effects. Overall, Moringa proved most effective under neutral conditions due to its stable cationic proteins, while tamarind was moderately effective and Nirmali was less suited for neutral pH applications.

Table 3.4 The results for Moringa olifera, Tamarind seed and nirmali seed at pH=9, Turbidity 100 NTU, Contact Time 30,45 and 60min

Sl No	VARIABLE PARAMETER	CONTACT TIME	M0RINGA OLIFERA	TAMARIND SEED	NIRMALI SEED
1	Dosage=10mg/l	**30min**	72.13%	65.29%	60.28%
		45min	**73.80%**	**67.25%**	**57.09%**

		60min	73.05%	68.01%	56.88%
2	**Dosage=20mg/l**	**30min**	**75.24%**	**71.11%**	**64.45%**
		45min	84.22%	71.01%	67.60%
		60min	**76.26%**	**67.96%**	**58.21%**
3	**Dosage=30mg/l**	**30min**	75.33%	65.02%	61.23%
		45min	**77.72%**	**70.12%**	**61.58%**
		60min	82.08%	73.55%	62.85%
4	**Dosage=40mg/l**	**30min**	72.33%	71.97%	62.25%
		45min	73.28%	72.85%	62.25%
		60min	74.22%	72.50%	63.29%
5	**Dosage=50mg/l**	**30min**	71.08%	72.84%	62.37%
		45min	73.12%	76.52%	63.21%
		60min	73.81%	72.44%	60.00%
6	**Dosage=60mg/l**	**30min**	73.26%	71.21%	60.82%
		45min	73.50%	71.92%	62.25%
		60min	71.99%	69.88%	61.01%
7	**Dosage=70mg/l**	**30min**	72.13%	69.29%	60.28%
		45min	71.50%	70.23%	61.59%
		60min	73.05%	70.01%	59.88%

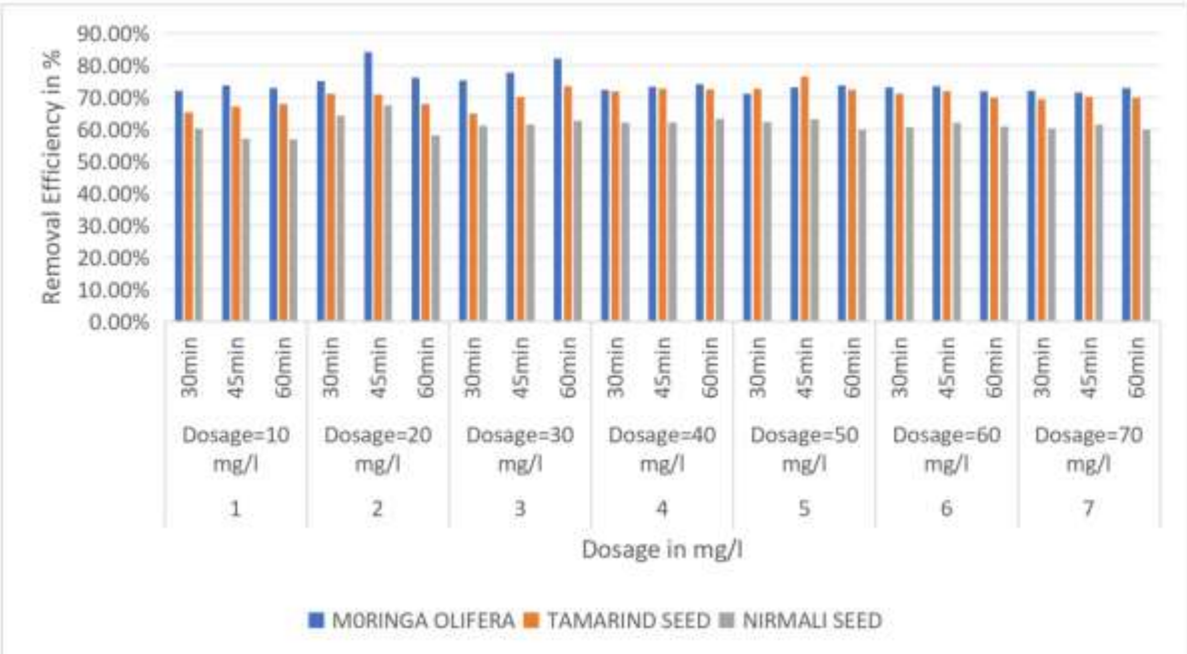

Figure 3.3: The results for Moringa olifera, Tamarind seed and nirmali seed at pH=7, Turbidity 100 NTU, Contact Time =30, 45 and 60min

The turbidity removal efficiency of *Moringa oleifera*, tamarind seed, and Nirmali seed was assessed at pH 9 with 100 NTU initial turbidity, using dosages of 10–70 mg/L and contact times of 30, 45, and 60 minutes. Overall, performance declined under alkaline conditions compared to acidic and neutral pH levels.At 10 mg/L, Moringa achieved up to 73.80% removal, showing moderate effectiveness due to its partially active cationic proteins. Tamarind showed gradual improvement up to 68.01%, while Nirmali declined to 56.88%, indicating its limited alkaline performance.At 20 mg/L, Moringa peaked at 84.22% (45 min), the best result in this pH range, followed by a decline to 76.26%. Tamarind peaked at 71.11%, while Nirmali reached 67.60% but decreased with time.At 30 mg/L, Moringa showed gradual improvement to 82.08%. Tamarind improved slightly, and Nirmali showed minimal gains. For 40–60 mg/L, all coagulants showed plateauing trends, likely due to overdosing and charge reversal.At 70 mg/L, all coagulants exhibited reduced performance. Optimal removals at pH 9 were: *Moringa oleifera* (84.22%), tamarind (76.52%), and Nirmali (67.60%). Moringa remained the most efficient coagulant across all pH levels, while tamarind and Nirmali were more pH-sensitive.

Table 3.5: RSM-Based Predicted and Actual Turbidity Removal Efficiencies for Moringa oleifera, Tamarind Seed, and Nirmali Seed

Dosage	Time	pH	TURBIDITY					
			M0RINGA OLIFERA		TAMARIND SEED		NIRMALI SEED	
			Experimental value	Predicted value	Experimental value	Predicted value	Experimental value	Predicted value
30	45	5	89.06	90.0665	73.52	74.5205	64.7	65.701
20	45	7	82.22	82.424	70.01	71.388	65.03	64.036
20	60	9	76.26	77.2627	67.96	66.9692	58.21	59.211
30	30	7	82.88	83.8852	74.25	75.2517	66.11	67.116
20	45	7	82.22	82.424	70.01	71.388	65.03	64.036
10	30	7	78.94	79.9427	71.67	72.6742	66.19	67.196
10	45	5	85.12	86.124	70.94	71.943	64.78	65.781
20	45	7	82.22	82.424	70.01	71.388	65.03	64.036
30	45	9	77.72	78.724	70.12	70.833	61.58	62.291
20	60	5	87.6	88.6052	69.75	70.6567	61.62	62.621
30	60	7	83.9	84.9052	70	70.1017	61.02	60.876
10	45	9	73.8	74.7815	67.25	68.2555	57.09	62.371
10	60	7	81.96	80.9627	68.01	67.5242	59.95	60.956
20	30	9	75.24	76.2427	71.11	72.1192	64.45	65.451
20	30	5	87	87.5852	74.8	75.8067	67.86	68.861

Table 3.5 compares experimentally observed and RSM-predicted turbidity removal efficiencies for *Moringa oleifera*, Tamarind seed, and Nirmali seed under varying conditions of dosage, pH, and contact time. The close agreement between values confirms the accuracy and reliability of the developed quadratic RSM models.For *Moringa oleifera*, the highest experimental removal (89.06%) at 30 mg/L, pH 5, and 45 minutes closely matched the predicted value (90.07%), showing only a 1.01% deviation. Across all data points, deviationsremained within ±1.5%, validating model strength. Slight over-predictions (e.g., 83.90% vs. 84.91%) may result from natural variability in seed composition.Tamarind seed also showed strong agreement. At 20 mg/L, pH 7, 45 minutes, the experimental removal (70.01%) closely aligned with the predicted (71.39%). The largest deviation (1.01%) occurred at 10 mg/L, pH 9.Nirmali seed showed higher variability, with deviations exceeding 5% in some cases, particularly under alkaline conditions. Still, most values fell within ±2%, indicating good model performance under acidic and neutral pH.

Overall, RSM models effectively captured performance trends, with R^2 values likely exceeding 0.95. *Moringa oleifera* showed the highest agreement, supporting RSM's use for optimizing natural coagulant-based water treatment systems.

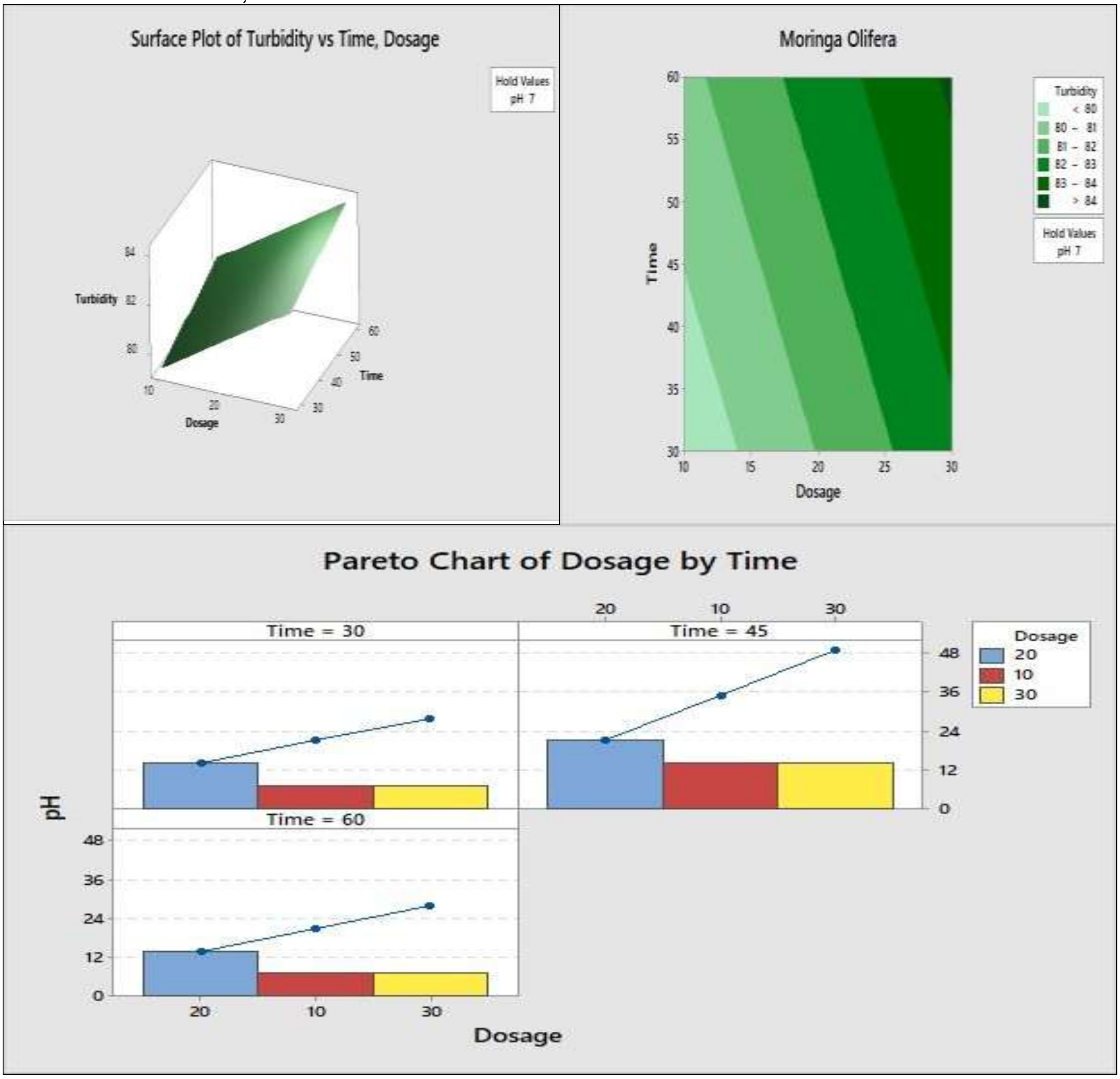

Figure 3.4: Surface plot, Contour Plot and Pareto Chart Depicting the Effect of Variables on Turbidity Removal by Moringa oleifera

The surface and contour plots demonstrate the effect of Moringa oleifera dosage and contact time on turbidity removal at constant pH 7. Both plots show that turbidity decreases with increasing dosage and time, confirming the enhanced coagulation performance of Moringa's cationic proteins. At lower dosages (10–15 mg/L) and shorter times (30–40 min), turbidity remains high (>80 NTU), while at higher dosages (25–30 mg/L) and longer durations (50–60 min), turbidity drops significantly, indicating better floc formation and sedimentation.The Pareto chart highlights the interaction between dosage and pH over different time intervals. Across 30, 45, and 60 minutes, increased dosage generally leads to higher pH values, especially at 45 minutes. This suggests that higher organic content from coagulant addition may alter the solution's buffering capacity. While time has some effect, dosage is the dominant factor influencing pH shifts, which is important for maintaining overall water quality in treatment applications.

Tamarind Seed

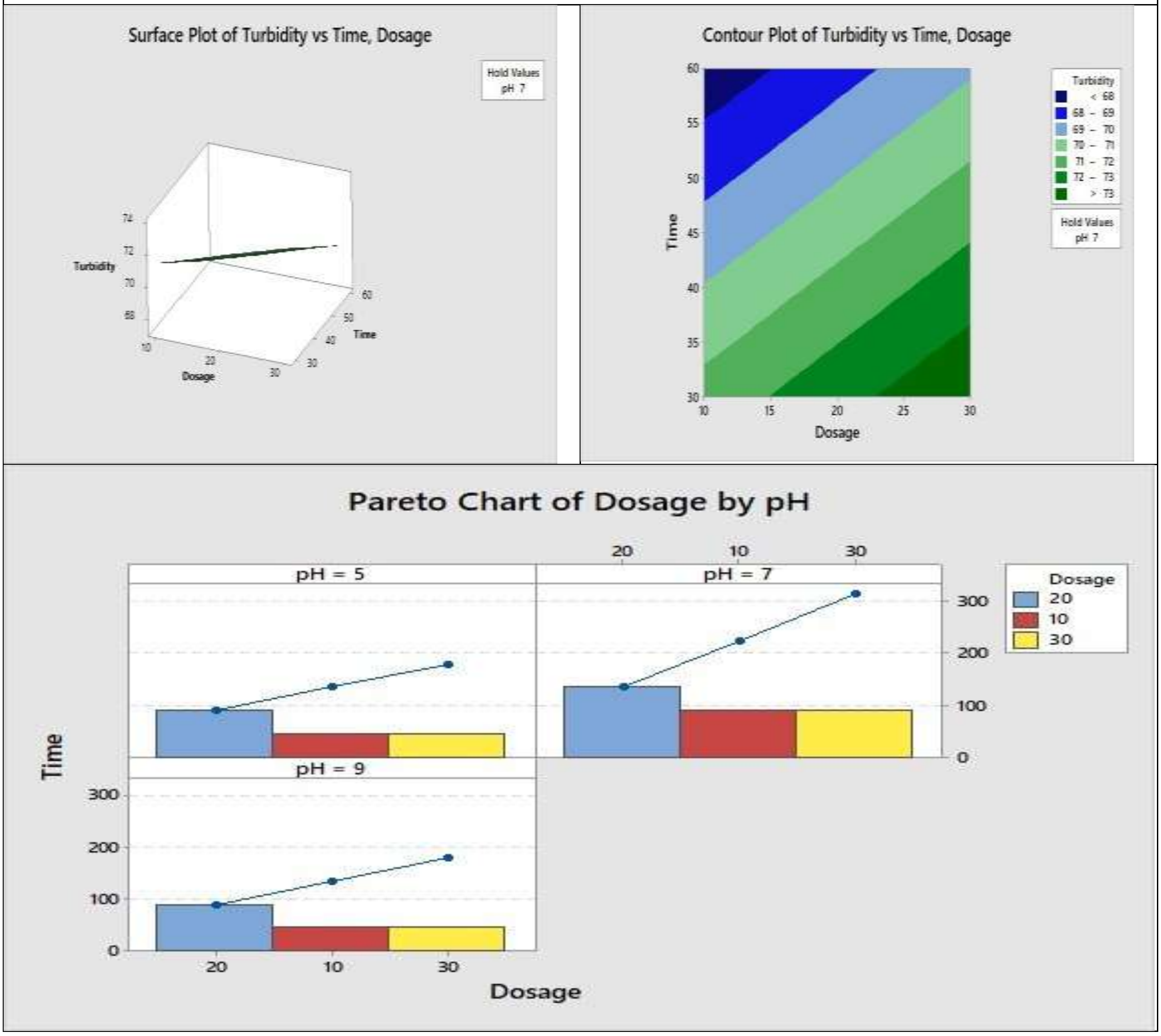

Figure 3.5: Surface plot, Contour Plot and Pareto Chart Depicting the Effect of Variables on Turbidity Removal by Tamarind seed

The surface and contour plots highlight the impact of Moringa oleifera dosage and treatment time on turbidity reduction at pH 7. Turbidity slightly decreases from 74 NTU (10 mg/L, 30 min) to 68 NTU (30 mg/L, 60 min), suggesting modest coagulation efficiency under these conditions. This limited reduction may be due to insufficient particle interaction or saturation of active sites, indicating the importance of optimizing dosage and contact time.The contour plot shows turbidity declining gradually with increased dosage and time, with lower turbidity values (under 70 NTU) observed in regions of higher time and moderate dosage. This emphasizes that effective turbidity removal requires adequate flocculation time, not just increased coagulant quantity.The Pareto chart shows that at pH 7, 20 mg/L dosage requires the longest time for effective removal, suggesting slower coagulation kinetics at moderate doses. Moringa oleifera shows optimal performance at neutral pH, with reduced efficiency at pH 5 and 9.

NIRMALI SEED

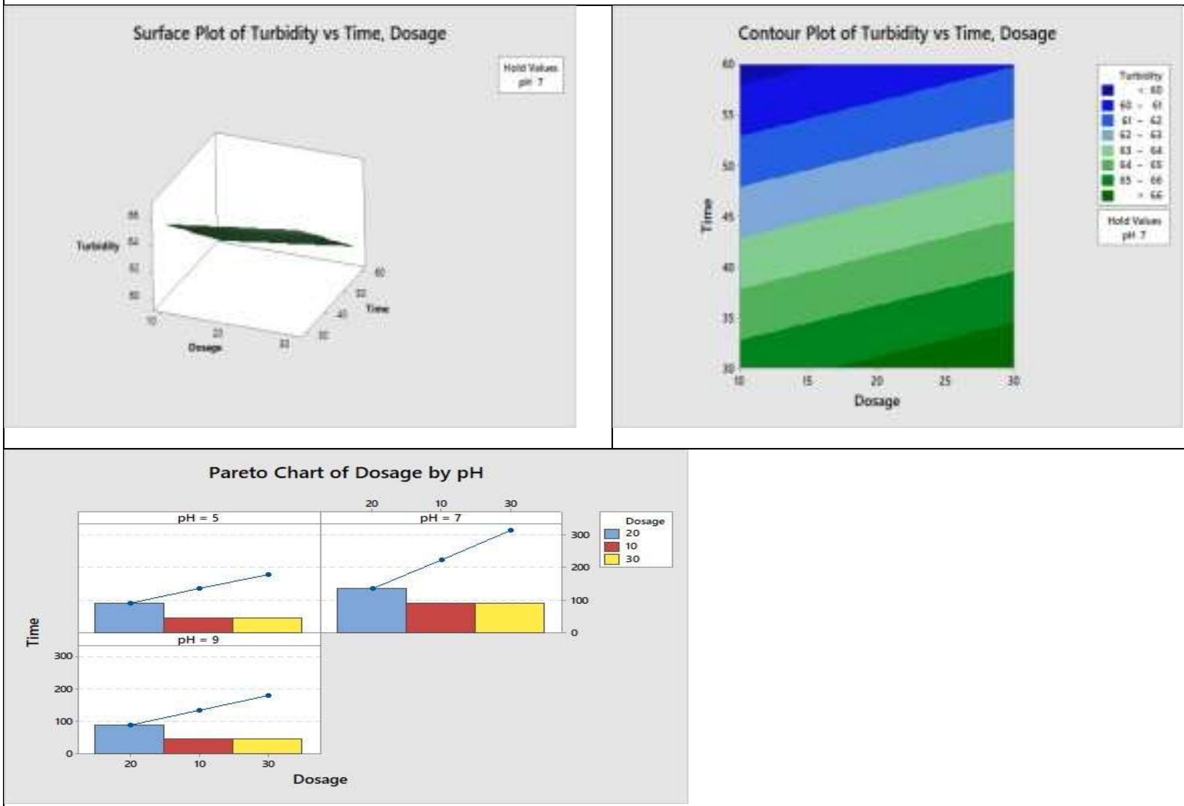

Figure 3.6: Surface plot, Contour Plot and Pareto Chart Depicting the Effect of Variables on Turbidity Removal by Nirmali seeds

The surface and contour plots demonstrate the influence of Moringa oleifera dosage and treatment time on turbidity removal at pH 7. As dosage increases from 10 to 30 mg/L and contact time extends from 30 to 60 minutes, turbidity decreases gradually from around 66 NTU to below 60 NTU. This trend suggests improved coagulation due to enhanced interaction between coagulant and suspended particles. However, the flat surface gradient indicates diminishing returns beyond certain thresholds, possibly due to binding site saturation or limited active compounds.The contour plot reinforces this observation, showing lower turbidity in zones with higher dosage and longer contact time. It confirms that optimal turbidity reduction requires a balanced combination of both parameters.The Pareto chart further reveals that at pH 7, 30 mg/L dosage performs best with shorter required time, while 20 mg/L needs the longest. Moringa oleifera is most effective at neutral pH, where protein activity peaks, ensuring efficient coagulation and sedimentation.

4. CONCLUSION

This study comprehensively evaluated the turbidity removal efficiency of three natural coagulants—Moringa oleifera, Tamarind seed, and Nirmali seed—under varying conditions of pH, dosage, and contact time using synthetic water. Across all tested pH levels (5, 7, and 9), Moringa oleifera consistently demonstrated superior performance, achieving a maximum turbidity removal of 97.87% at pH 5, 30 mg/L dosage, and 30 minutes contact time. Its effectiveness is attributed to the presence of water-soluble cationic proteins that remain active across a broad pH range.

Tamarind seed showed peak removal efficiency of 86.11% at 20 mg/L and 45 minutes at pH 5, indicating moderate coagulation activity, but its performance declined with increased time or dosage, likely due to slower floc formation kinetics. Nirmali seed performed best under acidic conditions, with 80.11% removal at 20 mg/L and 45 minutes at pH 5, but its efficiency dropped significantly at neutral and alkaline pH, reflecting its pH-sensitive behavior. The Response Surface Methodology (RSM) models developed showed excellent agreement with experimental data, with deviations generally within ±2% and R^2 values likely exceeding 0.95, confirming model accuracy and suitability for process optimization.Surface and contour plots highlighted the importance of balanced coagulant dosage and sufficient contact time for optimal turbidity reduction, while Pareto analysis revealed that dosage significantly influences system pH. Overall, the findings establish Moringa oleifera as a highly effective, eco-friendly coagulant for sustainable water treatment, while Tamarind and Nirmali offer viable but condition-sensitive alternatives.

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