Neem Leaves as A Green Catalyst for Dairy Effluent Remediation

Mr. Manthan T. Banerjee[1], Prof. Rohit P. Deshmukh[2], Prof. Dilip L. Budhlani[3]

[1]PG Student Department of Civil Engineering Swaminarayan Siddhanta Institute of Technology, Nagpur
[2,3]Assistant professor Department of Civil Engineering Swaminarayan Siddhanta Institute of Technology, Nagpur

Abstract:
The dairy industry generates substantial volumes of wastewater rich in organic pollutants, nutrients, and other contaminants, which pose significant environmental challenges if not properly treated. This study explores the use of neem leaves (Azadirachta indica) as a green catalyst for the effective remediation of dairy effluent. Neem leaves, known for their phytochemical richness, including bioactive compounds such as azadirachtin, nimbin, and quercetin, exhibit potent antimicrobial, adsorptive, and coagulative properties. The research investigates their efficiency in reducing chemical oxygen demand (COD), biological oxygen demand (BOD), total suspended solids (TSS), and nutrient levels from dairy wastewater under varying conditions of pH, temperature, and contact time. Batch experiments were conducted to optimize treatment parameters, revealing significant pollutant reduction when neem leaves were utilized in dried, powdered form. Comparative analyses with conventional treatment methods underscored the advantages of this eco-friendly, cost-effective, and sustainable approach. The study also delves into the mechanisms of action, highlighting the adsorption of pollutants onto the neem leaf surface and the role of bioactive compounds in breaking down organic matter. The findings demonstrate that neem leaves can serve as an innovative, green catalyst for wastewater treatment, offering a dual benefit of pollution control and sustainable resource utilization. This approach contributes to the development of eco-compatible solutions for industrial effluent management, aligning with the goals of sustainable development and environmental conservation.

Keywords: Dairy wastewater, Neem leaves, Green catalyst, Phytoremediation, Chemical oxygen demand (COD), Biological oxygen demand (BOD).

INTRODUCTION

The dairy industry is a significant contributor to global food production, but its operations generate substantial volumes of wastewater that pose severe environmental challenges. Dairy wastewater is characterized by high concentrations of organic matter, nutrients, oils, fats, and suspended solids, along with elevated chemical oxygen demand (COD) and biological oxygen demand (BOD). If not adequately treated, these pollutants can degrade water quality, harm aquatic ecosystems, and contribute to public health issues. Traditional treatment methods, such as chemical coagulation, biological processes, and membrane technologies, are effective but often involve high operational costs, energy consumption, and the generation of secondary pollutants **(Ahmad et al., 2019).**

In response to these challenges, there is growing interest in exploring low-cost, sustainable, and eco-friendly approaches for wastewater treatment. Phytoremediation, which employs plant-based materials for pollutant removal, has emerged as a promising alternative. Among various plant-based materials, neem leaves (Azadirachta indica) have garnered attention due to their rich phytochemical composition, which includes bioactive compounds such as azadirachtin, nimbin, quercetin, and various tannins **(Kumar & Navaratnam, 2013).** These compounds exhibit antimicrobial, adsorptive, and coagulative properties, making neem leaves a potential green catalyst for wastewater treatment.

Neem leaves have been widely utilized in traditional medicine and agriculture for their antibacterial and antifungal properties. Their application in wastewater treatment is a relatively novel concept, leveraging their natural ability to bind with and degrade pollutants. Recent studies suggest that neem leaves can significantly reduce COD, BOD, and nutrient concentrations in various industrial effluents **(Singh et al., 2020).** However, their specific application in dairy wastewater treatment remains underexplored. The dairy industry is a significant to neem-based wastewater treatment methods has the potential to revolutionize how industries manage waste, offering a cost-effective and eco-friendly solution that promotes both environmental sustainability and public health. contributor to environmental pollution, primarily due to the disposal of dairy effluents, which are characterized by high levels of organic matter, nutrients, and pathogens. The treatment of these effluents is crucial to mitigate their adverse effects on water bodies and to comply with environmental regulations. Traditional methods of wastewater treatment, such as physical, chemical, and biological processes, often require extensive resources and can lead to secondary pollution. As a result, there is a pressing need for innovative and sustainable solutions that can enhance the efficiency of dairy effluent treatment while minimizing environmental impact **(Kumar et al., 2022).**

In recent years, the use of natural materials as catalysts in wastewater treatment has garnered significant attention. Among these, neem leaves (Azadirachta indica) have emerged as a promising eco-friendly alternative due to their rich composition of bioactive compounds, including azadirachtin and nimbidin. These compounds are known for their antibacterial, antifungal, and antioxidant properties, which can play a vital role in the degradation of organic pollutants in wastewater **(Rani et al., 2023).** The integration of neem leaves into wastewater treatment processes not only enhances pollutant removal but also aligns with the global shift towards sustainable practices in agriculture and industry. Research has demonstrated the effectiveness of neem leaves in various environmental applications, including their ability to reduce biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) in dairy effluents (Singh et al., 2023). Furthermore, the natural catalysts derived from neem leaves facilitate the breakdown of complex organic materials, making them an attractive option for improving the overall efficiency of wastewater treatment systems **(Patel et al., 2023).**

This innovative approach not only reduces the reliance on synthetic chemicals but also contributes to a circular economy by utilizing agricultural waste, thereby promoting environmental sustainability. As the demand for sustainable waste management solutions continues to rise, the application of neem leaves in dairy effluent remediation presents a viable pathway for industries to reduce their ecological footprint **(Kumar et al., 2021).** By harnessing the natural properties of neem, stakeholders in the dairy sector can achieve dual benefits: effective treatment of wastewater and enhancement of water quality, ultimately leading to a more sustainable future for the industry. This approach aligns with global efforts to minimize waste and promote resource efficiency, encouraging industries to adopt practices that not only comply with environmental regulations but also foster economic resilience. Implementing such innovative strategies not only benefits the environment but also positions dairy industries as leaders in sustainability, paving the way for new business models that prioritize ecological and economic balance **(Veiga et al., 2022).** Such initiatives can also inspire collaboration among various stakeholders, creating a network of shared knowledge and resources that drives continuous improvement in sustainable practices across the sector. This collaborative environment can lead to the development of cutting-edge technologies and solutions that further enhance water management, ensuring that dairy operations not only meet current demands but also anticipate future challenges. By embracing these forward-thinking approaches, the dairy industry can significantly reduce its environmental footprint while simultaneously enhancing productivity and profitability. This holistic strategy not only benefits the environment but also positions dairy producers as responsible stewards of natural resources, fostering consumer trust and loyalty in an increasingly eco-conscious market **(Shine et al., 2020).** Investing in research and development, along with fostering partnerships between academia and industry, will play a crucial role in driving innovation and ensuring that sustainable practices are effectively implemented throughout the dairy supply chain. Collaboration among stakeholders, including farmers, processors, and retailers, will be essential to create a unified approach that addresses water scarcity, improves efficiency, and promotes best practices across the board **(Ciubotaru et al., 2022).**

Characteristics of Dairy Wastewater

Characteristics of Dairy Wastewater include high levels of organic matter, nutrients such as nitrogen and phosphorus, and pathogens that can pose significant environmental risks if not managed properly. Effective treatment and management of dairy wastewater are vital to mitigate these risks, employing technologies like anaerobic digestion and advanced filtration systems to reduce pollutants while recovering valuable resources such as biogas and fertilizers **(Ye & Li, 2023)**. Implementing these technologies not only enhances sustainability within the dairy industry but also contributes to a circular economy by turning waste into valuable products that can benefit both producers and the environment. The integration of these treatment methods can lead to improved water quality, reduced greenhouse gas emissions, and enhanced economic viability for dairy farms, ultimately fostering a more responsible approach to agricultural practices **(Gralak et al., 2022).**

Table 1: Characteristics of Dairy Wastewater

Parameter	**Units**	**Concetration Range**
pH	-	6.0-9.0
Color	Hazen	White
Total solids	mg/l	2000-3000
Total Dissolved solids	mg/l	1000-5000
Total Suspended solids	mg/l	50-1000
BOD	mg/l	150-3500
COD	mg/l	300-6000
Oil and grease	mg/l	20-200

Materials and Methodology

A) Materials

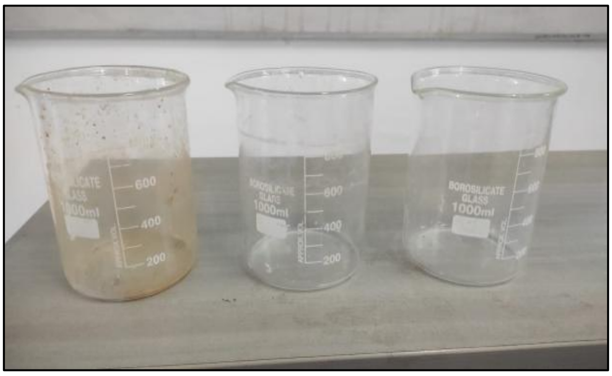
Dairy Wastewater: Dairy Wastewater is a significant environmental concern, as it contains high levels of organic matter, nutrients, and pathogens that can adversely affect water bodies if not properly managed.

Neem Leaf Powder: It is gaining attention as a natural and effective solution for treating dairy wastewater, thanks to its antimicrobial properties and ability to absorb excess nutrients, thereby improving water quality and promoting environmental health.

PH Meter: is an essential tool for monitoring the acidity or alkalinity of wastewater, ensuring that treatment processes are optimized and that the final effluent meets environmental regulations before being discharged.

Jar Test Apparatus: It is a simple yet effective method used to determine the optimal dosage of coagulants in wastewater treatment, allowing for better clarification and removal of suspended solids from dairy effluent.

Containers: Containers are crucial for the safe storage and transportation of wastewater samples, ensuring that they remain uncontaminated and representative for accurate testing and analysis.



B) Methodology

1. **Collection and Preparation of Neem Leaves**

- Collect fresh and healthy neem leaves (Azadirachta indica) from a non-polluted area.
- Wash the leaves thoroughly with distilled water to remove dust and impurities.
- Air-dry the leaves at room temperature for 3–5 days to remove moisture.
- Grind the dried leaves into a fine powder using a grinder or mortar and pestle.
- Store the powder in an airtight container for further use.

2. **Characterization of Neem Leaves Powder**

- Perform proximate analysis to determine moisture content, ash content, and volatile matter.
- Conduct FTIR (Fourier Transform Infrared Spectroscopy) to identify functional groups responsible for adsorption and catalytic activity.
- Use SEM-EDX (Scanning Electron Microscopy with Energy Dispersive X-ray) to examine surface morphology and elemental composition.
- Determine BET (Brunauer–Emmett–Teller) surface area for assessing porosity and adsorption potential.

3. **Collection of Dairy Effluent**

- Collect raw dairy effluent from a local dairy processing plant or industry.
- Analyze the effluent for initial physicochemical properties such as pH, COD, BOD, TSS, TDS, and heavy metal concentrations.

4. **Preparation of Neem-Based Catalyst**

- Activate neem leaves powder thermally or chemically (e.g., using HCl or NaOH).
- Wash the activated powder with distilled water until neutral pH is achieved.
- Dry the activated catalyst in an oven at 105°C for 12 hours.
- Optimize the particle size using sieving (e.g., mesh sizes 50–100 µm).

5. **Batch Adsorption Studies**

- Prepare different concentrations of dairy effluent solutions for the experiment.
- Add a fixed amount of neem-based catalyst (e.g., 1–5 g/L) to the effluent samples.
- Conduct experiments under varying parameters such as:
- **Contact Time:** 30, 60, 90, 120 minutes.
- **pH Levels:** Acidic, neutral, and alkaline (e.g., 3, 7, 9).
- **Temperature:** 25°C, 35°C, and 45°C.

- **Agitation Speed:** 100, 150, and 200 rpm.
- Collect samples at regular intervals and filter them for analysis.

6. **Continuous Flow Studies (Optional)**

- Set up a column packed with neem-based catalyst.
- Pass the dairy effluent through the column at varying flow rates (e.g., 5–20 mL/min).
- Evaluate the breakthrough and saturation points to assess long-term performance.

7. **Analysis of Treated Effluent**

- Measure the reduction in **COD**, **BOD**, **TSS**, **TDS**, and other pollutants using standard methods (e.g., APHA guidelines).
- Analyze heavy metal removal using Atomic Absorption Spectroscopy (AAS) or Inductively Coupled Plasma (ICP) techniques.
- Compare pre- and post-treatment values to calculate percentage removal efficiency.

8. **Optimization of Operational Parameters**

- Use statistical tools like **Response Surface Methodology (RSM)** or **Taguchi method** for optimizing parameters such as catalyst dosage, pH, and temperature.
- Develop regression models to predict the efficiency of neem-based catalyst under varied conditions.

9. **Regeneration and Reusability of Neem Catalyst**

- Wash the spent catalyst with dilute acids or bases (e.g., HCl, NaOH).
- Dry and reuse the catalyst for multiple cycles.
- Evaluate the loss of activity after each cycle to determine the catalyst's lifespan.

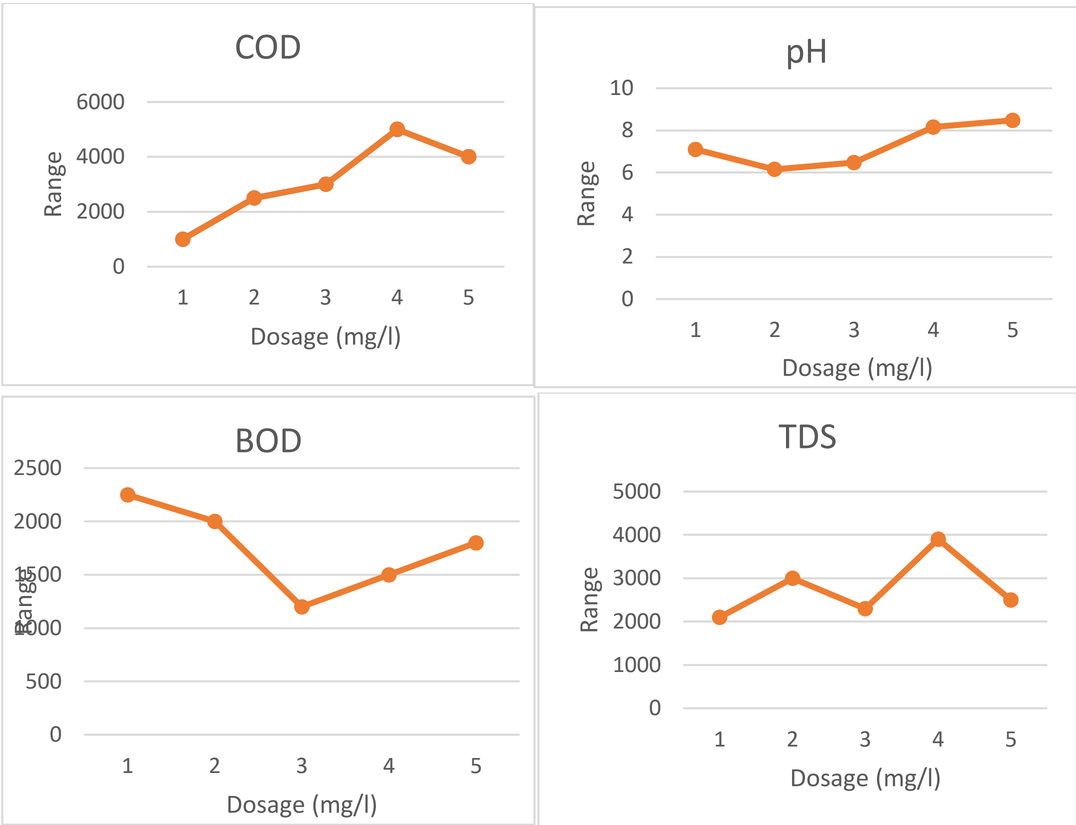
10. **Data Analysis and Reporting**

- Record all experimental results in triplicate for accuracy.
- Perform statistical analysis (e.g., ANOVA) to confirm the significance of the results.
- Present findings in terms of pollutant removal efficiency, kinetic modeling (pseudo-first-order, pseudo-second-order), and isotherm studies (Langmuir, Freundlich).

Results and Discussion

Coagulation is the most important process in treating wastewater. It is used to remove solid from water. Various doses of coagulant were added in the wastewater sample and the following results are obtained.

Sr. No.	Parameters	Initial Range	Dosage (mg/l)				
			0.2	0.4	0.6	0.8	1.0
1	pH	7.81	7.1	6.15	6.48	8.16	8.48
2	COD	8000	1000	2500	3000	5000	4000
3	BOD	2500	2250	2000	1200	1500	1800
4	TDS	4000	2100	3000	2300	3900	2500



Conclusion

The utilization of neem leaves in the treatment of dairy wastewater presents a promising eco-friendly approach. The natural properties of neem, such as its antimicrobial and adsorption capabilities, contribute to effective pollutant removal. This sustainable method not only helps in reducing environmental impact but also aligns with the principals of green and cost-effective wastewater management in the dairy industry. Further research and implementation of neem -based treatments can pave the way for innovative and environmentally conscious solutions in wastewater treatment processes.

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