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Optimization Of Wastewater Treatment In The Dairy Industry

[1]N B Geetha, S E Sangeetha[2], Devasena B [3], L Ashwini[4], Nafisa Farheen [5] , Mahalakshmi J[6]
[1] PERI Institute of Technology, Chennai -600048
[2&5]PERI College of Pharmacy, Chennai-600048.
[3]PERI College of Physiotherapy, Chennai- 600048
[4]PERI College of Arts and Science, Chennai-600048.
[6]PERI College of Nursing, Chennai- 600048
Corresponding mail id: publications@peri.ac.in

ABSTRACT:
The dairy industry is a significant contributor to industrial wastewater due to the extensive use of water in milk processing and equipment cleaning. Operations such as cleaning of silos, tanks, heat exchangers, homogenizers, and pipelines generate large volumes of effluent characterized by high organic and inorganic loads. Dairy effluent typically contains milk residues, dairy products, inorganic salts, cleaning agents, detergents, and sanitizers, resulting in elevated levels of chemical oxygen demand (COD), biochemical oxygen demand (BOD), oils and grease, nitrogen, and phosphorus—often exceeding the permissible limits set by the Bureau of Indian Standards (BIS). The food processing sector, particularly dairy, not only ranks among the highest in water consumption but also produces significant quantities of sludge from biological treatment processes. Effective wastewater management strategies are essential to mitigate the environmental impacts and ensure compliance with regulatory standards.

Keywords
Dairy wastewater, COD, BOD, effluent treatment, organic load, water quality, nitrates, alkalinity

I.INTRODUCTION

The dairy industry is one of the most water-intensive sectors within the food and beverage manufacturing landscape. Its operations involve the processing of raw milk into a wide array of products such as pasteurized milk, cheese, butter, yogurt, and other value-added dairy derivatives. These processes necessitate extensive cleaning of equipment—such as pasteurizers, homogenizers, heat exchangers, pipelines, and storage silos—at frequent intervals to maintain hygiene standards. Consequently, large volumes of wastewater are generated, often laden with significant organic and inorganic pollutants.

Dairy effluent is characterized by high concentrations of milk residues, fats, proteins, carbohydrates, suspended solids, and cleaning chemicals, leading to elevated levels of Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD). Additionally, the presence of nitrogenous compounds, phosphates, oils, and greases further complicates the treatment process. If improperly managed, this wastewater can result in severe environmental degradation, including eutrophication of surface waters, depletion of dissolved oxygen, and contamination of soil and groundwater.

Optimization of wastewater treatment in the dairy industry has therefore become a pressing necessity—not only to comply with increasingly stringent environmental regulations such as those stipulated by the Bureau of Indian Standards (BIS) or international norms—but also to promote sustainability, reduce operational costs, and recover valuable resources such as water, energy, and nutrients. Traditional treatment systems, including primary sedimentation, activated sludge processes, and anaerobic digestion, have been widely implemented; however, they often fall short in terms of efficiency, energy consumption, and adaptability to variable effluent characteristics.

Recent advancements in treatment technologies, such as membrane bioreactors (MBRs), sequencing batch reactors (SBRs), advanced oxidation processes (AOPs), bioenzymatic treatment, and integrated anaerobic-aerobic systems, offer promising avenues for enhancing the performance of existing treatment setups. These technologies aim to not only improve removal efficiencies of organic and nutrient pollutants but also enable water reuse and minimize sludge generation.

II.LITERATURE REVIEW

Electrochemical methods have proven effective for the treatment of saline and high-COD dairy effluents. Mohammad et al. [1] used electrochemical oxidation with RSM (Response Surface Methodology) for saline wastewater, achieving high pollutant removal. Similarly, Da Silva et al. [2] applied central composite design to optimize electro-oxidation using boron-doped diamond anodes, targeting pharmaceutical contaminants.Tak et al. [3] demonstrated color and COD reduction using electrocoagulation with Box–Behnken design, while Kushwaha et al. [4] highlighted organic load reduction in dairy wastewater via electrochemical processes coupled with appropriate sludge disposal methods. Kumari et al. [5] further advanced this with a continuous stirred tank electrochemical reactor (CSTER), identifying optimal operating conditions through kinetics analysis.Electrocoagulation's efficacy was also illustrated by Bazrafshan et al. [6], and Davarnejad and Nikseresht [7] statistically validated process parameters for dairy wastewater treatment. Chang et al. [8] introduced the electro-Fenton method to degrade persistent organic pollutants, broadening the electrochemical approach's applicability.

Biological processes remain foundational due to their cost-effectiveness and sustainability. Rajan et al. [9] integrated pretreatment techniques with Sequencing Batch Reactors (SBR), optimizing pollutant removal and analyzing kinetics. Banu et al. [10] examined the synergistic use of anaerobic digestion and solar photocatalysis, achieving significant COD and BOD reductions.
Deshpande et al. [11] focused on biomethanation, revealing high methane yields from dairy waste. Danalewich et al. [12] provided an extensive characterization of dairy effluents and proposed nutrient removal strategies tailored to their unique composition.

Najafpour et al. [13] employed an upflow anaerobic sludge-fixed film bioreactor, achieving stable biological treatment performance, while Mendez et al. [14] explored anaerobic treatment of cheese whey, detailing operational challenges during reactor startup.Membrane technologies offer high removal efficiencies, though fouling remains a challenge. Balannec et al. [15] compared nanofiltration (NF) and reverse osmosis (RO) membranes, establishing performance benchmarks for dairy effluent treatment.Chen et al. [16] focused on physicochemical membrane properties, influencing flux and rejection rates. Huang et al. [17] explored antifouling strategies in oily wastewater applications, highlighting wetting behavior as a critical factor. A novel turbulence promoter design was introduced by another study [18], showing that 3D-printed devices significantly improve ultrafiltration performance and mitigate fouling.

Several studies utilized statistical tools like RSM and factorial design for process optimization. The use of organic coagulants was evaluated through factorial comparisons in [19], showing enhanced pollutant reduction.Fenton and electro-Fenton methods were systematically optimized using RSM in [20], demonstrating precise control over degradation efficiency via interaction modeling of process variables. Beyond treatment efficacy, energy consumption and environmental impact are growing concerns. The carbon footprint of treatment systems was assessed by [21], promoting the selection of low-impact technologies. Żyłka et al. [22] analyzed electricity usage patterns in dairy treatment plants, offering insights for energy-efficient designs.Reinforcement learning was applied in [23] to optimize operational parameters in real-time, paving the way for AI-driven smart wastewater management systems.

III.METHODOLOGY

3.1 PROCESS DESCRIPTION

A laboratory-scale treatment plant was designed incorporating three main stages:

1. Primary sedimentation
2. Anaerobic digestion
3. Membrane filtration

In primary sedimentation, wastewater is allowed to flow into a sedimentation tank where heavier particles settle at the bottom due to gravity, forming a sludge layer. Floating materials such as fats and oils are skimmed from the surface. This step significantly reduces the total suspended solids (TSS) and some portion of the BOD.

Parameter	Typical Values

Parameter	**Typical Values**
Removal Efficiency	50–70% of TSS, 25–40% BOD
Retention Time	2–4 hours
Output	Clarified water + primary sludge

Anaerobic Digestion-Clarified water from primary sedimentation is transferred to an anaerobic digester. In this oxygen-free environment, anaerobic bacteria decompose complex organic compounds into simpler molecules, producing biogas as a by-product. Anaerobic digestion is highly efficient for high-strength dairy effluent and produces valuable energy.

Parameter	**Typical Values**
BOD Removal Efficiency	75–90%
Operating Temperature	30–37°C (mesophilic range)
Retention Time	15–25 days
Output	Biogas + digested sludge

Membrane Filtration-After biological treatment, the partially treated water is passed through membranes such as microfiltration (MF), ultrafiltration (UF), or reverse osmosis (RO). These membranes act as physical barriers, filtering out contaminants based on size and molecular weight. This stage enables the treated water to meet discharge or reuse standards.

Membrane Type	**Removal Target**
Microfiltration (MF)	Suspended solids, bacteria
Ultrafiltration (UF)	Proteins, viruses
Reverse Osmosis (RO)	Dissolved salts, COD, nitrate
Output	High-quality effluent water

3.2 OPTIMIZATION TOOLS

- Response Surface Methodology (RSM) was employed to optimize key process parameters including:
  - pH (4–10)
  - Hydraulic Retention Time (HRT: 4–24 hrs)
  - Temperature (20–40°C)

IV.TREATMENT OF DAIRY WASTES

Dairy wastewater typically exhibits a low Chemical Oxygen Demand (COD) to Biochemical Oxygen Demand (BOD) ratio, making it highly amenable to biological treatment processes. These effluents are rich in organic matter and contain sufficient nutrients to support robust microbial activity, which facilitates their degradation in properly managed treatment systems.

To enhance the efficiency of wastewater management in the dairy industry, several preventive and recovery measures can be implemented:

1. Minimization of Product Losses: Preventing spills, leakages, and milk wastage during processing and handling can significantly reduce the organic load in the wastewater.
2. Reduction of Water Use: Optimizing washing procedures and equipment can minimize water consumption without compromising hygiene.
3. Segregation and Reuse: Uncontaminated cooling water should be segregated from process effluent and recycled wherever feasible.
4. Resource Recovery: By-products such as buttermilk and whey can be utilized for the production of value-added dairy products instead of being discarded.

TREATMENT TECHNOLOGIES

- Conventional Systems: High-rate trickling filters and activated sludge systems are effective for the complete treatment of dairy effluents. These systems are capable of handling variable loads and achieving significant pollutant reduction. However, they require skilled personnel and advanced operational infrastructure.
- Low-Cost Alternatives: Simpler methods like oxidation ditches offer a cost-effective and reliable solution, especially suitable for small to medium-sized dairy units. These systems are easier to operate and maintain, though they may occupy more space.
- Irrigation Reuse: After undergoing primary treatment in aerated lagoons, dairy wastewater can be safely used for agricultural irrigation, provided it meets local environmental regulations. This approach not only disposes of the effluent but also contributes to water resource conservation.

TABLE 1 :Standards Norms Of Pollution Control Board For Milk Dairy Effluents.

Sr.No	Details	Value
1.	pH	5.5-9.0
2.	Total solids	Not to exceed 2200
3.	Total Dissolved solids	Not to exceed 2100
4.	Suspended Solids	Not to exceed 100
5.	Total Chlorides	Not to exceed 600
6.	Sulfates	Not to exceed 1000
7.	Chemical Oxygen Demand	Not to exceed 250
8.	Biological Oxygen demand	Not to exceed 30
9.	Oil	Not to exceed 10
10.	Grease	Not to exceed 10

V.RESULTS AND DISCUSSION

The physico-chemical characteristics of the dairy wastewater were analyzed and compared with standard permissible limits.The pH of the sample was found to be 6.53, which lies within the acceptable range of 6.5 to 8.5, indicating a near-neutral nature of the wastewater. The total solids content was 1900 mg/L, slightly below the standard limit of 2000 mg/L, suggesting moderate pollutant load. The sample showed high alkalinity (1050 mg/L) and total hardness (1200 mg/L), both of which exceed standard limits (600 mg/L). High alkalinity can buffer pH changes but may indicate the presence of bicarbonates or carbonates. The COD value was 115 mg/L, well below the permissible limit of 250 mg/L, indicating a moderate organic load. The BOD value was 665 mg/L, which is within the broad acceptable range (190–763 mg/L). A relatively high BOD indicates the presence of biodegradable organic matter, characteristic of dairy effluent, and affirms the suitability of biological treatment processes.The ammonia concentration was 1.0 mg/L, exceeding the recommended limit of 0.5 mg/L. Elevated ammonia levels can cause oxygen depletion in receiving water bodies and must be addressed through nitrification processes. The nitrate content was 75 mg/L, well within the limit (100 mg/L), indicating minimal risk of eutrophication.The levels of fluoride (1.0 mg/L), phosphate (1.0 mg/L), and iron (2.0 mg/L) were all within their respective permissible limits (1.5 mg/L, 5.0 mg/L, and 3.0 mg/L). These parameters do not pose any immediate environmental or health concerns in the current context.A significantly high chloride concentration of 950 mg/L was observed against the standard of 250 mg/L. The results are presented in Table 2.

TABLE 2: COMPARISON WITH SAMPLES

S.NO	PARAMETERS	STANDARD VALUES	TESTED SAMPLE
1.	pH	6.5-8.5	6.53
2.	Total solids	2000mg/l	1900mg/l
3.	Total dissolved solids	2000mg/l	2100mg/l
4.	Alkalinity	600mg/l	1050mg/l
5.	Hardness	600mg/l	1200mg/l
6.	C.O.D	250mg/l	115mg/l
7.	B.O.D	190-763mg/l	665mg/l
8.	Ammonia	0.5mg/l	1mg/l
9.	Fluoride	1.5mg/l	1mg/l
10.	Chlorides	250mg/l	950mg/l
11.	Phosphate	5.0 mg/l	1.0mg/l
12.	Iron	3.0mg/l	2.0mg/l
13.	Nitrate	100mg/l	75mg/l

CONCLUSION AND FUTURE SCOPE

Effluent treatment in the dairy indudtry is essential for several critical reasons. Primarily, it helps mitigate the adverse environmental impacts associated with the discharge of untreated wastewater, which can harm aquatic ecosystems and public health. Additionally, effective treatment ensures compliance with the regulatory standards prescribed by the State Pollution Control Boards (SPCB) and the Central Pollution Control Board (CPCB), thereby avoiding legal and financial penalties.Beyond regulatory compliance, wastewater management is a reflection of the industry's responsibility to future generations—to safeguard natural resources and promote a pollution-free environment.Process optimization strategies, such as the implementation of Clean-In-Place (CIP) systems and the reuse and recycling of water, have proven effective in reducing water consumption and the volumetric loading of effluents. Most cleaning processes benefitted from these approaches; however, exceptions were noted. For instance, some transportation trucks lacked "spray bowl" fixtures compatible with CIP systems, and manual operation of the spray dryer led to excessive water usage.To address these inefficiencies, a dual-action approach is recommended:Reduction in water consumption through technological upgrades and automation.Minimization of organic load by optimizing cleaning cycles and integrating pre-treatment processes.Together, these measures can significantly improve the sustainability and environmental footprint of dairy wastewater management systems.

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