

Dairy Industry Wastewater Treatment in India: Processes, Challenges, and Emerging Technologies

G. Kamatchi¹, S. Karthikeyan¹, V. Ramamoorthi¹, R. Santhya¹, R. Vignesh²

¹Undergraduate Student, Department of Civil Engineering

²Associate Professor, Department of Civil Engineering

Akshaya College of Engineering and Technology (Autonomous), Coimbatore, Tamil Nadu

Abstract: *The dairy industry is a vital component of the global agro-based economy, with India emerging as the largest producer of milk, contributing over one-fifth of global production. The rapid growth of the sector, driven by initiatives such as the Operation Flood, has significantly enhanced rural livelihoods, food security, and economic development. However, this expansion has also led to substantial environmental challenges, particularly due to the generation of large volumes of high-strength wastewater. Dairy processing is highly water-intensive, producing 2 - 10 liters of wastewater per liter of milk processed, characterized by elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), nutrients, and fats, oils, and grease. The discharge of untreated or inadequately treated effluents can result in severe environmental impacts, including oxygen depletion, eutrophication, and ecological degradation.*

This study presents a comprehensive review of the Indian dairy industry with a focus on wastewater generation, characteristics, environmental implications, and treatment technologies. Conventional treatment methods, including physico-chemical and biological processes such as activated sludge systems and anaerobic digestion, are critically evaluated for their effectiveness and limitations. In addition, emerging and advanced treatment technologies, including membrane filtration, membrane bioreactors, advanced oxidation processes, electrochemical methods, constructed wetlands, and zero liquid discharge systems, are discussed in detail. The paper also highlights key challenges such as variability in wastewater composition, high operational costs, and limited infrastructure in small-scale dairies. Furthermore, the study emphasizes the growing importance of sustainable wastewater management approaches, including resource recovery, water reuse, and integration of digital technologies such as artificial intelligence for process optimization.

Keywords: Dairy wastewater, India, anaerobic digestion, membrane bioreactor, advanced oxidation processes, zero liquid discharge

I. INTRODUCTION

The dairy industry constitutes one of the most important agro-based sectors in the global economy, with a particularly dominant presence in India. Over the past few decades, India has emerged as the largest producer of milk in the world, contributing more than one-fifth of global milk production. This remarkable growth has been largely attributed to systematic agricultural policies, cooperative movements, and technological advancements initiated during the Operation Flood, which transformed India from a milk-deficient nation into a leading dairy producer. The sector plays a vital role in ensuring food security, enhancing rural incomes, and generating employment for millions of smallholder farmers (FAO, 2019).

The rapid expansion of dairy processing industries has, however, brought significant environmental challenges, particularly in terms of water consumption and wastewater generation. Dairy processing is inherently water-intensive, requiring large volumes of water for activities such as equipment cleaning, pasteurization, cooling, and sanitation. It is estimated that approximately 2 to 10 liters of water are consumed per liter of milk processed, resulting in the generation



of substantial quantities of wastewater with high pollution potential (Kushwaha et al., 2011). The wastewater generated from dairy industries is characterized by high concentrations of biodegradable organic matter, including lactose, casein, fats, and residual milk solids, along with cleaning agents such as alkalis and acids used in cleaning-in-place systems.

From an environmental perspective, dairy wastewater is considered a high-strength effluent due to its elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which typically range between 1000–3000 mg/L and 2000–5000 mg/L, respectively (Slavov, 2017). The presence of nutrients such as nitrogen and phosphorus further exacerbates its environmental impact by promoting eutrophication in receiving water bodies. If discharged untreated or inadequately treated, dairy effluents can lead to severe ecological consequences, including oxygen depletion, disruption of aquatic ecosystems, and degradation of soil quality. These impacts are particularly pronounced in developing countries, where a significant portion of dairy operations falls under the unorganized sector with limited access to wastewater treatment infrastructure.

Traditionally, dairy wastewater treatment has relied on conventional methods such as physico-chemical processes and biological treatment systems. Aerobic processes like the activated sludge system are widely used due to their effectiveness in reducing organic load; however, they are energy-intensive and produce significant quantities of sludge (Tchobanoglous et al., 2014). On the other hand, anaerobic treatment technologies, such as upflow anaerobic sludge blanket reactors, offer advantages including lower energy consumption and the generation of biogas, which can be utilized as a renewable energy source (Bella and Rao, 2021). While these conventional systems are effective to a certain extent, they often fail to meet stringent discharge standards, particularly in terms of nutrient removal and residual organic compounds. Technologies such as membrane filtration, membrane bioreactors, advanced oxidation processes, and electrochemical methods have demonstrated significant potential in treating dairy wastewater to higher standards (Al-Tayawi et al., 2023).

Furthermore, the adoption of digital technologies, including artificial intelligence and real-time monitoring systems, is expected to play a significant role in optimizing treatment processes and improving operational efficiency in the near future. In this context, the present study provides a comprehensive review of dairy industry wastewater in India, focusing on its generation, characteristics, treatment technologies, and emerging trends. The objective is to critically analyze existing practices and highlight sustainable approaches for effective wastewater management in the dairy sector.

Overview of the Dairy Industry in India

The dairy industry in India represents one of the most significant components of the agricultural economy, contributing substantially to national income, rural employment, and nutritional security. India has consistently maintained its position as the largest producer of milk globally, accounting for more than 22% of total world milk production (FAO, 2019). The sector plays a crucial role in sustaining the livelihoods of millions of small and marginal farmers, with dairy farming often serving as a primary or supplementary source of income in rural areas. Unlike many other agricultural sectors, the dairy industry in India is characterized by its inclusivity, involving a large number of landless laborers and women, thereby contributing to social and economic equity.

The structural framework of the Indian dairy sector is broadly categorized into organized and unorganized segments. The organized sector includes cooperative institutions, private dairy companies, and government-supported enterprises that operate with relatively advanced processing infrastructure and supply chain systems. Prominent cooperative organizations such as Amul have played a transformative role in streamlining milk procurement, processing, and distribution networks. Similarly, private sector companies like Hatsun Agro Product Ltd and other regional players have significantly expanded processing capacities and introduced value-added dairy products to meet growing urban demand. In contrast, the unorganized sector comprises small-scale dairy farmers, local vendors, and informal milk distribution systems, which collectively handle a substantial portion of milk production but often lack access to modern processing and wastewater treatment facilities (Kushwaha et al., 2011).



Another notable aspect of the Indian dairy industry is its shift toward sustainability and resource efficiency. Increasing awareness of environmental issues, coupled with regulatory pressures, has encouraged dairy industries to adopt cleaner production techniques, water recycling practices, and energy-efficient technologies. Many large dairy plants are now integrating wastewater treatment with resource recovery systems, such as biogas generation from anaerobic digestion, which not only reduces environmental impact but also contributes to energy self-sufficiency (Slavov, 2017). Furthermore, initiatives aligned with circular economy principles are gaining traction, focusing on minimizing waste generation and maximizing the reuse of water and by-products.

Despite these advancements, several challenges persist in the sector, including inadequate infrastructure in rural areas, high capital investment requirements for advanced treatment technologies, and variability in milk supply and quality. Climate change and water scarcity are emerging as additional concerns, necessitating the adoption of sustainable water management practices across the dairy value chain. Addressing these challenges requires a coordinated effort involving government agencies, industry stakeholders, and research institutions to promote innovation, capacity building, and policy implementation.

Dairy Processing and Water Consumption

Dairy processing involves a sequence of operations, including milk collection, storage, pasteurization, homogenization, separation, product manufacturing, and packaging. Water plays a critical role throughout these processes, particularly in cleaning-in-place systems, cooling operations, and equipment washing. It is estimated that dairy plants consume between 2 and 10 liters of water per liter of milk processed, depending on the scale and efficiency of operations.

A significant portion of wastewater is generated during cleaning processes, where detergents and sanitizers are used to maintain hygiene standards. Additionally, product losses during processing contribute to the organic load of wastewater. The variability in production processes leads to fluctuations in both the quantity and quality of effluent generated.

Wastewater Generation and Characteristics

The dairy processing industry is widely recognized as a water-intensive sector, generating substantial quantities of wastewater with high organic load and variable composition. In India, the rapid expansion of dairy processing facilities, driven by increasing demand for milk and value-added products, has led to a corresponding rise in wastewater generation. The volume and characteristics of dairy effluent depend on several factors, including plant capacity, type of dairy products manufactured, level of process automation, and efficiency of water management practices (Kushwaha et al., 2011).

Wastewater in dairy industries originates from multiple operational activities, with cleaning processes being the dominant source. Cleaning-in-place (CIP) systems, which are essential for maintaining hygienic conditions in processing equipment, contribute significantly to wastewater generation through the use of detergents, sanitizers, acids, and alkalis. Additional sources include milk spillage during handling and processing, leakage from pipelines and storage tanks, whey disposal from cheese and paneer production, and floor washing operations. Among these, whey is particularly noteworthy due to its high organic content, contributing significantly to the overall pollution load if not properly managed (Slavov, 2017).

In addition to organic pollutants, dairy wastewater contains nutrients such as nitrogen and phosphorus, originating from milk constituents and cleaning chemicals. These nutrients, while essential for microbial growth during biological treatment, can lead to eutrophication if discharged into natural water bodies without adequate removal. The pH of dairy effluent typically ranges from 6.5 to 8.5; however, fluctuations are common due to the intermittent discharge of acidic and alkaline cleaning solutions used in CIP operations. Suspended solids (TSS) in dairy wastewater, usually ranging between 200 and 1000 mg/L, consist of coagulated milk particles, curd residues, and other organic matter. These solids contribute to turbidity and can settle in receiving water bodies, affecting aquatic habitats. Additionally, temperature



variations in the effluent, resulting from thermal processing operations, can influence biological treatment efficiency and must be considered in treatment system design.

Another important characteristic of dairy wastewater is its temporal variability. The composition and flow rate of effluent can vary significantly throughout the day, depending on production schedules, cleaning cycles, and product types. This variability necessitates the use of equalization tanks in treatment systems to ensure consistent influent quality and prevent shock loading in biological reactors (Tchobanoglous et al., 2014).

Environmental Impacts of Dairy Wastewater

The discharge of untreated or inadequately treated dairy wastewater can have severe environmental consequences. High organic loads lead to rapid depletion of dissolved oxygen in receiving water bodies, adversely affecting aquatic life. Nutrient enrichment results in eutrophication, causing excessive algal growth and deterioration of water quality. Additionally, the accumulation of fats and solids can alter soil properties when wastewater is used for irrigation. Odor generation due to the decomposition of organic matter further contributes to environmental and social concerns.

Conventional Wastewater Treatment Technologies

Conventional treatment of dairy wastewater typically involves a combination of physical, chemical, and biological processes. Preliminary treatment includes screening and grit removal to eliminate large solids and debris. Primary treatment methods such as oil and grease traps and equalization tanks are employed to stabilize flow and remove suspended solids.

Physico-chemical treatment processes, including coagulation-flocculation and dissolved air flotation, are widely used to remove fats, oils, and colloidal particles. These processes involve the addition of coagulants that destabilize suspended particles, forming flocs that can be easily separated.

Biological treatment forms the core of dairy wastewater management. Aerobic processes such as the activated sludge system are effective in reducing BOD and COD through microbial oxidation of organic matter. However, these systems require significant energy input for aeration and generate large quantities of sludge. Anaerobic treatment processes, particularly upflow anaerobic sludge blanket reactors, offer advantages such as lower energy consumption and the production of biogas, which can be utilized as a renewable energy source. Combined anaerobic-aerobic systems are often employed to achieve higher treatment efficiencies and operational stability.

Advanced and Emerging Treatment Technologies

In response to increasingly stringent environmental regulations and the need for water reuse, advanced treatment technologies are gaining prominence in the dairy industry. Membrane-based processes, including ultrafiltration, nanofiltration, and reverse osmosis, are capable of producing high-quality effluent suitable for reuse. However, membrane fouling and high operational costs remain significant challenges.

Membrane bioreactors represent a hybrid technology that integrates biological treatment with membrane filtration, offering superior effluent quality and reduced footprint. Advanced oxidation processes, such as ozonation and Fenton oxidation, are effective in degrading recalcitrant organic compounds that are resistant to biological treatment. Electrochemical methods, including electrocoagulation and electrooxidation, provide an alternative approach for removing pollutants through electrochemical reactions.

Constructed wetlands have emerged as a sustainable and low-cost option for treating dairy wastewater, particularly in rural areas. These systems utilize natural processes involving vegetation, soil, and microbial activity to remove contaminants. Zero liquid discharge systems, which combine membrane filtration and evaporation technologies, enable complete recovery of water and elimination of liquid waste, aligning with the principles of circular economy.



Challenges and Future Perspectives

Despite advancements in treatment technologies, several challenges persist in the management of dairy wastewater. The variability in wastewater composition, high fat content, and seasonal fluctuations pose operational difficulties. Small-scale dairies often lack the financial and technical capacity to implement advanced treatment systems. Furthermore, sludge management and disposal remain critical issues.

Future research should focus on the development of hybrid treatment systems that combine the advantages of different technologies. The integration of artificial intelligence and automation in wastewater treatment processes can enhance efficiency and reduce operational costs. Emphasis on resource recovery, including biogas production and nutrient recycling, will play a crucial role in achieving sustainable wastewater management.

II. CONCLUSION

The dairy industry in India is a vital component of the national economy but poses significant environmental challenges due to wastewater generation. Conventional treatment methods, while effective, are increasingly being supplemented by advanced technologies to meet stringent discharge standards and enable water reuse. The adoption of sustainable practices, including resource recovery and circular economy approaches, is essential for minimizing environmental impact and ensuring long-term viability of the dairy sector.

REFERENCES

- [1]. Al-Tayawi, A.N., et al. (2023). Wastewater treatment in dairy industry: Classical to promising technologies. *Processes*, 11, 2133.
- [2]. Bella, K., Rao, P.V. (2021). Anaerobic digestion of dairy wastewater: Effect of parameters and co-digestion options. *Biomass Conversion and Biorefinery*.
- [3]. Food and Agriculture Organization (FAO). (2019). Dairy production and processing.
- [4]. Kushwaha, J.P., Srivastava, V.C., Mall, I.D. (2011). An overview of various technologies for the treatment of dairy wastewater. *Critical Reviews in Food Science and Nutrition*, 51, 442–452.
- [5]. Slavov, A.K. (2017). General characteristics and treatment possibilities of dairy wastewater. *Food Technology and Biotechnology*, 55(1), 14–28.
- [6]. Tchobanoglous, G., Burton, F.L., Stensel, H.D. (2014). *Wastewater Engineering: Treatment and Resource Recovery*. McGraw-Hill.

