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Physicochemical Assessment of Dairy Effluent Characteristics and Sustainable Waste Management Strategies

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ABSTRACT: The dairy sector, a fundamental component of the global food ecosystem, has witnessed notable expansion due to technological innovations and shifting consumer preferences. Nonetheless, the management of dairy waste poses a significant challenge, with inadequate treatment resulting in severe environmental repercussions, including aquatic pollution, eutrophication, and ecological deterioration. This research examines the physicochemical characteristics of effluents from two dairies in Varanasi—Parag Industrial Dairy and Ganga Local Dairy. Parameters such as pH, dissolved oxygen, biological oxygen demand (BOD), chemical oxygen demand (COD), hardness, and nutrient concentrations were evaluated using standardized methodologies. The results indicated substantial deviations from prescribed standards, particularly for ammoniacal nitrogen, COD, BOD, as well as oil and grease concentrations, highlighting deficiencies in existing treatment protocols. The findings accentuate the necessity for enhanced effluent management strategies to ensure compliance with environmental regulations and promote sustainability. Additionally, this research underscores the potential applicability of treated effluent for agricultural use, warranting further investigation into optimal dilution ratios and microbial interactions to maintain ecological equilibrium and sustained productivity.

Keywords: Physicochemical; waste management; sustainable; dairy

1. Introduction

The dairy industry is an essential part of the global food system, providing a wide range of products such as milk, cheese, butter, and yogurt [1]. The industry had existed for centuries and evolved significantly in recent years, with modern farming and advanced technology enhancing productivity and efficiency [2]. Dairy waste management was a critical issue worldwide due to the substantial environmental impact caused by improper handling and disposal of dairy industry by-products [3]. Accurate characterization of dairy waste was required for designing effective management strategies [4]. Efficient resource recovery from dairy waste could help transform dairy effluent into valuable products [5]. Dairy waste management had to prioritize environmental protection and sustainability. There was also a need to outline the key challenges faced in dairy waste management, including regulatory barriers, technological limitations, and economic feasibility [6]. Its potential was explored as a solution in fields such as integrated waste management systems, decentralized approaches, and policy interventions.

Global development in the dairy industry for the processing and production of milk and dairy products, as valuable agricultural products, was needed to meet development goals. Global milk production was projected to increase by 177 million tons by 2025, representing a compound growth rate of 1.8% per annum over the next decade [4]. Over the same period, per capita dairy consumption was projected to increase by 0.8–1.7% per year in developing countries and 0.5–1.1% in developed countries [7]. Due to the sheer scale of the dairy industry, such growth rates could have significant developmental benefits for livelihoods, the environment, and public health. At that time, the global dairy industry was valued at over $750 billion and was expected to continue growing in the coming years [8]. The Asia-Pacific region led as the largest consumer of dairy products, accounting for more than 40% of global demand. Milk was considered a highly nutritious food material for humans [9]. The average composition of milk consisted of 87.20% water and 12.80% dry matter [10].

India was the world's largest milk producer, contributing nearly 20% of the world's total milk production [11]. Milk was mostly consumed domestically, and an estimated 8 million rural households across India were involved in milk production, with rural markets consuming more than half of all milk production [12]. Due to the traditional diet of Indian households, approximately 60% of the milk produced was consumed in liquid form, while the remainder was processed into butter, clarified butter (desi ghee), cheese, curd, paneer, ice cream, and milk creamer, or consumed in the form of traditional sweets [13].

The dairy industry produced a wide range of value-added products such as puddings, desserts, custards, sauces, mousses, stirred yogurts, and nectar [14]. A growing population with higher disposable incomes and increasing health consciousness was expected to drive tremendous demand for processed and packaged dairy products in urban centers. Andhra Pradesh, Bihar, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh, and West Bengal were the 14 major dairy-producing states in India, accounting for more than 90% of the country's milk production [15]. The dairy sector accounted for 98% of the feedstock, representing a substantial proportion of the cattle and buffalo population [16]. According to recent research, milk demand in India was expected to grow at an average annual growth rate of around 4% over the following few years [17].

Over the past 30 years, the dairy industry in India had grown tremendously, producing millions of tons of milk and dairy products. Milk production in the country was reported at 123 million tons in 2010–2011 and increased to 127.9 million tons in 2011–2012 [18]. Dairy production in India grew at 4% per year, compared with 2.1% in the rest of the world. India's production was estimated at approximately 116 million tons [19]. Organized retail sales of value-added dairy products and the management of catering services contributed to the growth of this sector. The growth of grocery and coffee chains such as Cafe Coffee Day, Pizza Hut, Domino's, KFC, and McDonald's was expected to drive the consumption of value-added dairy products. In the short term, the Indian dairy sector was well-positioned to cope with the rapid increase in dairy consumption. As the population became more urbanized and incomes rose, demand was also expected to rise.

However, the dairy industry faced various challenges, one of which involved dealing with dairy effluents. The United States Environmental Protection Agency (EPA) determined that dairy wastewater problems caused by inadequate wastewater management posed serious health and environmental hazards because wastewater flowed into streams before reaching treatment facilities [20]. The dairy industry included a variety of processing operations such as pasteurization, bottling, and the preparation of butter, cheese, and milk powder. Wastewater from the dairy industry consisted mainly of milk residues, and dairy effluent exhibited very high BOD values, in some cases reaching 100 mg/L [21]. Wastewater could also contain detergents, disinfectants, and other chemicals. Milk waste was organic in nature and slightly alkaline. Untreated discharge into rivers could lead to rapid depletion of dissolved oxygen (DO) and promote the growth of sewage fungi that covered the river bed [22].

The main effects were associated with microbial contamination and reduced oxygen levels. A particular problem in the treatment of milk waste was that even relatively small amounts in natural water could cause turbidity, which became noticeable when the milk was diluted into a larger volume [23]. Excessive use of surfactants on dairy farms could render the waste unsuitable for biological treatment [25]. Dairy effluent was defined as the liquid waste generated by dairy farms during milk processing and other farm activities. It consisted of a mixture of cow manure, urine, water, milk residues, cleaning agents, and fertilizers [26]. If not properly managed and treated, it could result in significant environmental and health issues, including contamination of waterways and groundwater, nutrient leaching, and odor problems [27].

Dairy effluent was also generated during various stages of milk production, including cleaning, sanitizing, and cooling processes [25]. The wastewater contained organic matter, nutrients, and chemicals that tended to contaminate waterways [20]. To avoid adverse impacts on humans and the environment, proper planning and management practices were required, as high levels of organic matter, total suspended solids, fats, salinity, and nutrients such as nitrogen and phosphorus in wastewater could lead to eutrophication, algal blooms, oxygen depletion, and fish mortality [28]. The wastewater could also contain pathogens such as bacteria, viruses, and parasites. Direct discharge of dairy wastewater caused several negative environmental impacts [29]. In the field of wastewater management, various treatment processes were implemented. Due to increasing water scarcity issues, the reuse of treated wastewater could help conserve water resources and promote a circular economy, where the waste from one industry became a raw material or valuable resource for another production process [30].

2. Materials and Methods

The major objective of the study was to collect dairy effluent from the dairy industry, compare it with untreated local dairy effluent, and determine its physicochemical parameters.

2.1. Study area and sampling sites.

The study was conducted at two dairy facilities in Varanasi, Uttar Pradesh, India: Parag Industrial Dairy (Dugadh Utpadak Sahakari Sangh Limited) and Ganga Local Dairy. Parag Industrial Dairy represented treated industrial dairy effluent (PD) collected from an organized processing facility, whereas Ganga Local Dairy represented untreated local dairy wastewater

(LD) generated from small-scale dairy handling and washing activities. This distinction was maintained throughout the manuscript to clarify differences in pollution sources and treatment efficiency. Parag Industrial Dairy was located at 63V7 + 8FF, Ram Nagar Industrial Area, Ram Nagar, Varanasi, Uttar Pradesh (25°14′29″ N, 83°03′45″ E). Ganga Local Dairy was located at 32A, Laxmi Bhuvan, Orderly Bazar, Tagore Town, Bhubaneshwar Nagar, Varanasi, Uttar Pradesh (25°20′56″ N, 82°58′36″ E).

Varanasi experienced a humid subtropical climate, with summer extending from April to June and the monsoon period from July to October. The annual mean temperature was approximately 25.7 °C, and the average annual rainfall was about 982 mm. Sampling was conducted during the summer season; therefore, ambient temperature and microbial activity may have influenced short-term changes in effluent characteristics during storage. Proper sampling methodology was imperative to ensure precise outcomes, as the constituents of water could fluctuate markedly over time. Compliance with standardized protocols ensured that the collected sample accurately reflected the source while maintaining a manageable volume for transportation and handling. This methodological rigor ensured that the sample arrived at the laboratory in an optimal condition for subsequent characterization and investigation.

In the context of this research, Parag Industrial Dairy, situated 12 kilometres from the Banaras Hindu University Institute of Environmental and Sustainable Development (IESD), was selected as a focal point. The selection of Parag was based on its substantial contribution to supplying dairy products to a significant portion of Varanasi's population. Furthermore, Ganga Dairy, located 3 kilometres from the department, was included based on a survey indicating that many local sweet shops and hotel vendors sourced milk and dairy products from this establishment. This selection highlighted the varied and representative characteristics of dairy suppliers within the region, thereby facilitating a comprehensive analysis.

2.2. Sampling container and sample collection procedure.

Effluent samples were collected using clean 5 L plastic containers fitted with tightly sealed plastic caps. Before sampling, each container was washed, rinsed with distilled water, and subsequently rinsed two to three times with the respective effluent at the sampling site to minimize contamination and matrix effects. Samples were collected from approximately 20 cm below the wastewater surface after avoiding visible non-homogeneous floating materials. Each container was labelled immediately with the sampling location, sampling date, collector's name, and sample identification code. The labelled containers were placed in an ice box and transported to the laboratory at approximately 4 °C to minimize physicochemical alterations before analysis.

2.3. Physicochemical analysis.

The physicochemical parameters were analyzed using standard methods recommended by APHA and the Water and Wastewater Analysis protocol of Maiti. The parameters included dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD), electrical conductivity (EC), pH, temperature, colour, total dissolved solids (TDS), salinity, total hardness, magnesium hardness, calcium hardness, nitrate, phosphate, sulphate, ammoniacal nitrogen, sodium, potassium, calcium, chloride, and oil and grease.

2.4. Statistical analysis.

All physicochemical measurements were summarized as mean ± standard deviation (SD). Differences between treated industrial effluent (PD) and untreated local dairy wastewater (LD) were evaluated using independent-sample t-tests at $p < 0.05$. Statistical reporting was included to strengthen reliability; however, the authors were advised to verify the SD and p-values against the original replicate worksheets before final resubmission.

2.5. Treatment and reuse context.

Modern treatment approaches could convert dairy effluent from an environmental liability into a potential resource. Biological treatment, membrane filtration, reverse osmosis, electrocoagulation, bioremediation, and precision fertigation were reported as feasible options for reducing organic load, recovering nutrients, and improving water reuse potential. These technologies provided the basis for interpreting whether the tested effluents were suitable for discharge, further treatment, or controlled agricultural reuse.

3. Results and Discussion

3.1. Comparative physicochemical characteristics of treated industrial effluent and untreated local dairy wastewater.

The Results and Discussion sections were integrated so that each result was immediately followed by interpretation and comparison with previous studies. Table 1 were cited explicitly before interpretation.

Table 1. Comparative assessment of water quality parameters in dairy effluents.

No.	Parameters (Unit)	Standards	Parag Dairy (PD)	Local Dairy (LD)	Instrument/Method
1	Temperature (°C)	<5°C	27.3	28.9	Thermometer & Systronics Water Analyser 371
2	pH	5.5–9.0	8.4	3.22	pH meter
3	Electrical Conductivity (mS/cm)	–	84.6	45.1	Systronics Water Analyser 371
4	Colour	–	Pale yellow	Whitish yellow	Visual observation
5	Salinity (ppm)	–	31.4	12.89	Systronics Water Analyser 371
6	Total Dissolved Solids (mg/L)	2100	146.358	78.023	Gravimetric method
7	Dissolved Oxygen (mg/L)	5	3.7	8.1	Winkler's method
8	BOD (mg/L)	350	170	335	Winkler's method
9	COD (mg/L)	250	810.65	1321.9	Colorimetric method
10	Total Hardness (mg/L)	180	393.43	168.86	EDTA titrimetric method
11	Calcium Hardness (mg/L)	–	127.26	160.86	EDTA titrimetric method
12	Magnesium Hardness (mg/L)	–	266.08	8.86	EDTA titrimetric method
13	Chloride (mg/L)	1000	541.36	347.97	Mohr's method
14	Nitrate (mg/L)	10	13.53	2.99	Spectrochemical analysis
15	Sulphate (mg/L)	100	10.615	77.123	Turbidimetric method
16	Total Phosphate (mg/L)	5	1.834	0.969	Spectrophotometry
17	Ammoniacal Nitrogen (mg/L)	50	214.77	39.501	Nesslerization (Colorimetric method)
18	Sodium (mg/L)	–	104.506	130.031	Flame photometry
19	Potassium (mg/L)	75.6	50.3407	244.991	Flame photometry
20	Calcium (mg/L)	–	132.46	157.486	Flame photometry
21	Oil and Grease (mg/L)	10	0	26.26	Partition gravimetric method

The revised discussion differentiated treated industrial dairy effluent (PD) from untreated local dairy wastewater (LD), compared the measured values with CPCB-related standards, and interpreted the environmental significance of COD, BOD, ammoniacal nitrogen, oil and grease, nutrients, and ionic load. In the present study, two dairies in Varanasi were selected, namely Parag Industrial Dairy (PD) and Ganga Local Dairy (LD). The study was conducted during the summer season from April to mid-June, and various physicochemical parameters were analyzed. As shown in Figure 1A, the initial temperatures of LD and PD were 28.9 ± 1.20 °C and 27.3 ± 1.10 °C, respectively. During storage, the temperature of LD increased from 27.8 °C to 38.3 °C within five days, whereas PD increased from 27.3 °C to 33.2 °C. The subsequent decline toward initial values after 15 days suggested gradual stabilization of the wastewater matrix. This trend indicates active microbial degradation of organic matter during early storage, followed by reduced metabolic activity as substrates became limited.

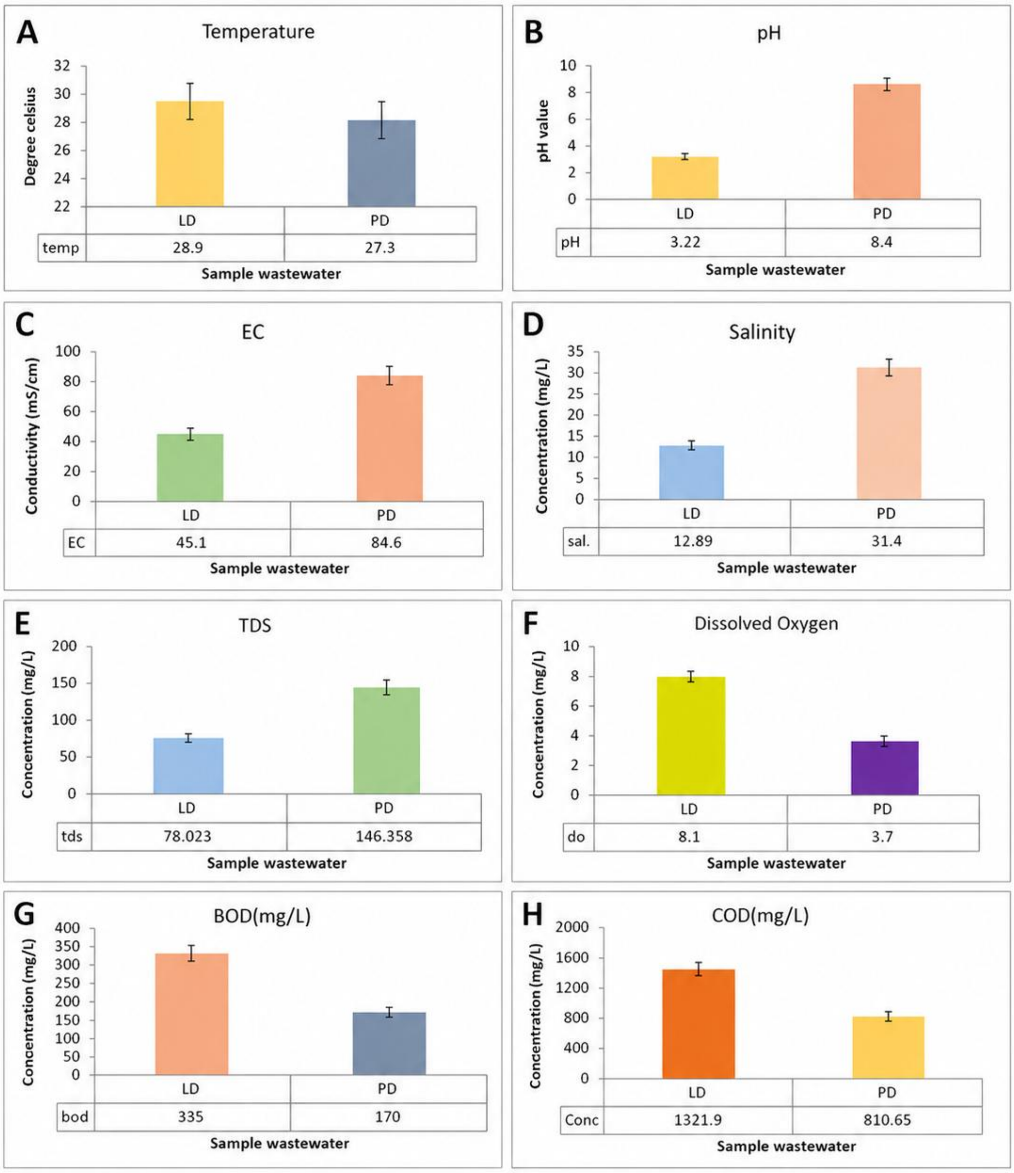

Figure 1. Physicochemical characteristics of sample wastewater under light/dark (LD) and pale/dark (PD) conditions. (A) Temperature (°C), (B) pH, (C) Electrical conductivity (EC, mS/cm), (D) Salinity (mg/L), (E) Total dissolved solids (TDS, mg/L), (F) Dissolved oxygen (DO, mg/L), (G) Biochemical oxygen demand (BOD, mg/L), and (H) Chemical oxygen demand (COD, mg/L). Bars represent mean values, and error bars indicate standard deviation (n = 3).

The local dairy wastewater exhibited a strong pungent odour, a yellowish-white colour, and a high amount of coagulated suspended solids. In contrast, the treated industrial effluent appeared brownish and lacked any obnoxious odour. As shown in Figure 1B, LD was strongly acidic, with a pH of 3.22 ± 0.08, whereas PD was alkaline, with a pH of 8.4 ± 0.12, which remained within the CPCB permissible range. During storage, the pH of LD increased slightly from 7.5 to 7.69, whereas PD showed no substantial variation. The acidic condition of LD reflects fermentation of lactose and protein degradation products, while the alkaline nature of PD suggests partial neutralization during industrial treatment processes.

As illustrated in Figures 1C–1E, PD exhibited higher electrical conductivity (EC), salinity, and total dissolved solids (TDS) than LD, indicating that the treated industrial effluent retained a higher dissolved ionic load. EC in PD increased substantially during the first five days of storage, while TDS also increased from 3.86 to 27.5. Similar patterns were reported in previous studies, where dairy wastewater composition was strongly influenced by milk residues, detergents, dissolved salts, and cleaning agents generated during dairy processing operations [20, 25, 26].

As shown in Figure 1F, dissolved oxygen (DO) was lower in PD (3.7 ± 0.20 mg/L) than in LD (8.1 ± 0.35 mg/L), indicating reduced oxygen availability in the treated effluent due to residual organic and inorganic load. As illustrated in Figure 1G–1H, biochemical oxygen demand (BOD) and chemical oxygen demand (COD) were significantly higher in LD (335 ± 12.5 mg/L and 1321.9 ± 54.6 mg/L) than in PD (170 ± 8.4 mg/L and 810.65 ± 31.8 mg/L). Although PD showed partial treatment efficiency through reduced BOD, COD values in both effluents exceeded CPCB benchmark limits, indicating that discharge without further treatment may impose substantial oxygen demand on receiving water bodies. This can lead to dissolved oxygen depletion, ecological imbalance, and aquatic stress, as also reported in previous studies on dairy wastewater pollution [21, 28, 29].

As shown in Figure 1F, DO levels were lower in PD (3.7 ± 0.20 mg/L) compared with LD (8.1 ± 0.35 mg/L). This indicates that, despite undergoing treatment, the industrial effluent still contained residual oxygen-consuming substances that reduced oxygen availability in the water matrix. The comparatively higher DO in LD may be attributed to rapid oxygen diffusion and reduced stabilization time of reduced compounds at the sampling moment; however, this does not necessarily indicate better environmental quality, as DO alone does not reflect overall organic pollution load. Instead, it should be interpreted alongside oxygen demand parameters such as BOD and COD.

As illustrated in Figures 1G and 1H, BOD and COD were substantially higher in LD (335 ± 12.5 mg/L and 1321.9 ± 54.6 mg/L, respectively) than in PD (170 ± 8.4 mg/L and 810.65 ± 31.8 mg/L). The elevated BOD in LD reflects a higher concentration of readily biodegradable organic matter such as lactose, proteins, and fats from unprocessed dairy residues. Similarly, the extremely high COD values in both LD and PD indicate the presence of both biodegradable and non-biodegradable organic compounds, including detergents, surfactants, and complex organic residues from cleaning and processing activities. Although PD showed a reduction in both BOD and COD relative to LD, the COD values in both effluents still exceeded the CPCB permissible limit of 250 mg/L. This suggests that the existing treatment system was only partially effective in removing total oxidizable organic load. Consequently, if discharged without further treatment, both effluents could exert a high oxygen demand on receiving aquatic systems, leading to rapid DO depletion, disruption of aerobic microbial communities, and increased risk of hypoxic conditions, which are known to negatively affect aquatic biodiversity [21, 28, 29].

As shown in Figure 2A, chloride concentrations were higher in PD (541.36 ± 21.7 mg/L) than in LD (347.97 ± 14.1 mg/L). This elevation in PD suggests accumulation of soluble inorganic salts during industrial processing and cleaning operations, where repeated use of disinfectants and water softening agents may contribute to chloride enrichment. Elevated chloride levels can increase water salinity stress and affect freshwater organism osmoregulation when discharged into natural systems.

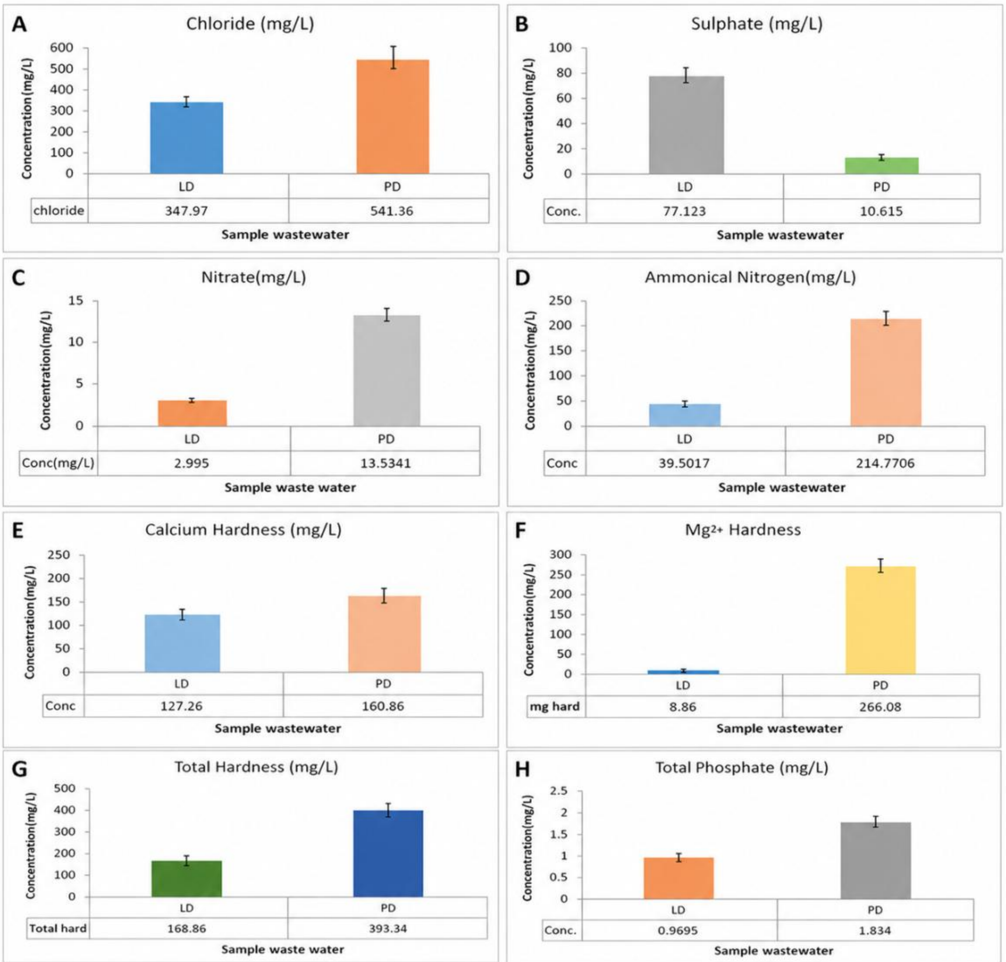

Figure 2. Concentrations of major chemical constituents in sample wastewater under light/dark (LD) and pale/dark (PD) conditions. (A) Chloride (mg/L), (B) Sulphate (mg/L), (C) Nitrate (mg/L), (D) Ammoniacal nitrogen (mg/L), (E) Calcium hardness (mg/L), (F) Mg^{2+} hardness (mg/L), (G) Total hardness (mg/L), and (H) Total phosphate (mg/L). Bars represent mean values, and error bars indicate standard deviation (n = 3).

Furthermore, Figures 2B–2H demonstrate distinct differences in inorganic nutrient and hardness profiles between LD and PD. Sulphate and calcium hardness were higher in LD, indicating stronger influence from raw milk residues and natural mineral content of untreated wastewater. In contrast, PD exhibited higher nitrate, ammoniacal nitrogen, magnesium hardness, total hardness, and total phosphate, suggesting that industrial treatment reduced organic load but did not effectively remove dissolved nitrogenous compounds and mineral ions. In particular, ammoniacal nitrogen in PD reached 214.77 ± 9.84 mg/L, exceeding the CPCB standard of 50 mg/L by more than four times, while nitrate in PD also exceeded the 10 mg/L threshold.

These elevated nitrogen species are environmentally significant because they contribute directly to eutrophication processes in receiving water bodies. Ammoniacal nitrogen is especially problematic due to its toxicity to aquatic organisms and its role in oxygen-consuming nitrification reactions, which further reduce dissolved oxygen levels. The simultaneous presence of elevated nitrate and ammoniacal nitrogen suggests incomplete nitrification–denitrification processes in the treatment system. Together with elevated phosphate, these nutrients increase the risk of algal blooms, subsequent biomass decay, and secondary oxygen depletion under stagnant or low-flow conditions [3, 4, 22]. These results confirmed that treatment performance was parameter-specific: PD reduced readily biodegradable and hydrophobic fractions, whereas additional polishing treatment remained necessary for COD, ammoniacal nitrogen, nitrate, hardness, and dissolved ions [4–6].

As shown in Figure 3, oil and grease and major cations (Na^+, K^+, and Ca^{2+}) exhibited clear differences between LD and PD, reflecting variations in wastewater source characteristics and treatment efficiency. Oil and grease were detected only in LD (26.26 ± 1.32 mg/L) and were absent in PD (Figure 3A), indicating effective removal of fats and lipids through industrial treatment processes such as skimming and physicochemical separation, while their presence in LD reflects direct discharge of milk residues and washing effluents that can form surface films and reduce oxygen transfer in aquatic systems.

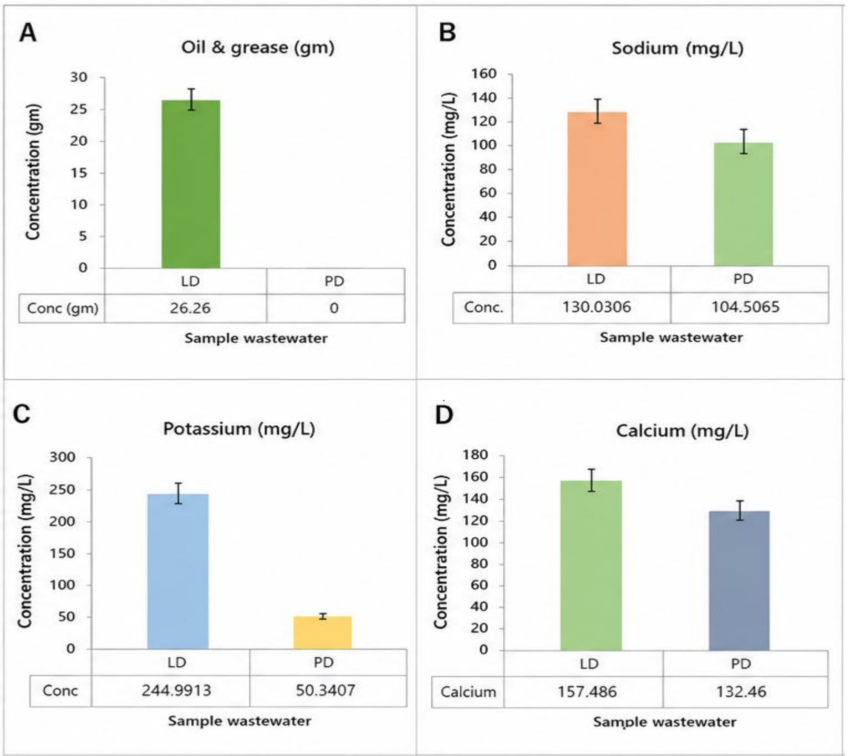

Figure 3. Concentrations of major chemical constituents in sample wastewater under light/dark (LD) and pale/dark (PD) conditions. (A) Oil and grease (gm), (B) Sodium (mg/L), (C) Potassium (mg/L), (D) Calcium (mg/L). Bars represent mean values, and error bars indicate standard deviation (n = 3).

In contrast, sodium concentrations were higher in PD (130.031 mg/L) than in LD (104.506 mg/L) (Figure 3B), likely due to the use of detergents and disinfectants during industrial cleaning operations. Potassium showed the opposite trend, being substantially higher in LD (244.991 mg/L) than in PD (50.3407 mg/L) (Figure 3C), which can be attributed to its release from raw milk residues and organic matter degradation in untreated wastewater. Similarly, calcium levels were slightly elevated in PD (157.486 mg/L) compared with LD (132.46 mg/L) (Figure 3D), suggesting ion concentration or release during treatment processes and contributing to increased hardness in the treated effluent. Overall, Figure 3A–3D demonstrates that while treatment was effective in removing oil and grease, it was less efficient in reducing dissolved inorganic ions, highlighting the need for additional polishing treatment prior to safe discharge or reuse.

Rationale for Comparison: The juxtaposition of Parag Dairy and the Local Dairy is imperative for the comprehensive evaluation of the quality and safety of dairy products, which is determined by an array of physico-chemical and biological parameters. Through meticulous examination of temperature regulation, pH values, microbial dynamics, and chemical composition, one can ascertain which dairy entity complies more stringently with established standards and guarantees enhanced product quality. The underlying rationale for this comparative analysis is to evaluate the potential implications for consumer health, environmental sustainability, and the overall integrity of the products.

The comparative investigation elucidates notable disparities between Parag Dairy and the Local Dairy concerning temperature regulation, pH equilibrium, mineral content, and contamination levels. While Parag Dairy aligns more closely with acceptable industry standards, the local dairy reveals alarming levels of acidity, pollutants, and temperature anomalies, which may adversely affect product quality and consumer health. This study accentuates the necessity for enhanced dairy management practices and rigorous regulatory oversight to ensure safer dairy consumption.

3.2 Integrated environmental interpretation and treatment implications.

The revised discussion differentiates the two wastewater streams more clearly. LD represents untreated local dairy wastewater, where milk residues, curdling products, manual washing water, suspended coagulated solids, and oil-grease residues enter the drain with little or no treatment. In contrast, PD represents treated industrial effluent discharged from a more organized dairy facility; therefore, lower BOD and the absence of detectable oil and grease in PD indicate partial treatment efficiency. However, the persistence of high COD, ammoniacal nitrogen, EC, salinity, hardness, and nitrate in PD suggests that the treatment process was not sufficient to remove dissolved organic compounds, nitrogenous residues, and ionic contaminants. This interpretation is consistent with previous studies reporting that dairy wastewater contains carbohydrates, proteins, fats, detergents, and nutrient-rich residues that can maintain high oxygen demand even after partial treatment [25, 20, 26, 21].

The temporal fluctuations observed during storage can be explained by microbial and biochemical transformations. The initial rise in temperature, EC, salinity, pH, and TDS during the first five days likely reflects rapid microbial degradation of lactose, proteins, and fats, leading to the release of soluble ions, organic acids, ammonia, and other metabolites. Subsequent declines toward the initial values may have resulted from volatilization of ammonia, sedimentation or coagulation of suspended solids, microbial assimilation of soluble nutrients, and partial stabilization of biodegradable organic matter. These processes are biologically plausible because dairy effluents contain readily degradable substrates that stimulate microbial respiration and biochemical conversion soon after storage [22, 3].

The exceedance of CPCB-related benchmarks has important environmental implications. COD values of 1321.9 mg/L in LD and 810.65 mg/L in PD exceeded the 250 mg/L benchmark, indicating that discharge without adequate treatment could impose a high oxygen demand on receiving waters. This can reduce dissolved oxygen, alter microbial community structure, and impair aquatic life. The BOD value of LD approached the regulatory threshold and, together with high oil and grease, suggests a stronger risk of surface film formation, odour generation, and localized anaerobic zones. Similar ecological concerns have been reported in dairy wastewater studies where untreated discharge promoted oxygen depletion, turbidity, eutrophication, and deterioration of aquatic habitats [28, 29].

Nitrogen and phosphorus results also require environmental interpretation rather than simple reporting. Ammoniacal nitrogen in PD (214.77 mg/L) exceeded the 50 mg/L standard by more than four times, whereas nitrate in PD (13.53 mg/L) exceeded the 10 mg/L benchmark. These values indicate incomplete nitrogen removal and may contribute to nutrient enrichment, algal growth, nitrification-related oxygen consumption, and ammonia toxicity under unfavorable pH and temperature conditions. Although total phosphate remained below the standard, its presence together with nitrogen may still contribute to eutrophication if effluent is discharged repeatedly into low-flow water bodies. Therefore, PD should not be considered environmentally safe solely because some parameters are within standards; residual nitrogen and COD loads remain critical treatment gaps.

The comparison also shows that treatment efficiency is parameter-specific. PD performed better for BOD reduction and oil-grease removal, indicating effective removal of readily biodegradable and hydrophobic fractions. Conversely, PD showed higher EC, salinity, hardness, nitrate, ammoniacal nitrogen, chloride, and phosphate than LD, suggesting that dissolved ions and nitrogenous compounds were not adequately removed by the existing treatment process. This pattern supports previous evidence that dairy effluent treatment requires combined biological, physicochemical, and nutrient-removal stages to reduce both organic load and dissolved nutrient fractions [4, 5, 6].

Overall, the findings demonstrate that untreated local dairy wastewater poses immediate risks due to high COD, BOD, oil and grease, acidity, and suspended organic matter, whereas treated industrial effluent still requires polishing treatment for COD, ammoniacal nitrogen, nitrate, salinity, and hardness. Future work should include replicated seasonal sampling, microbial profiling, and treatment performance evaluation across anaerobic, aerobic, coagulation-flocculation, membrane, or constructed wetland systems. These additions would provide stronger evidence for sustainable effluent reuse in agriculture and safer discharge management.

4. Conclusion

The study demonstrates that the two dairy effluent streams differed not only in their measured physicochemical values but also in pollution sources and treatment performance. The untreated LD exhibited stronger indicators of organic pollution, including high COD, BOD, oil and grease, low pH, and visible suspended milk residues, reflecting direct discharge of dairy processing and washing wastes with minimal treatment. In contrast, the treated PD showed effective removal of oil and grease and reduced BOD, indicating partial treatment efficiency; however, it still exceeded critical regulatory benchmarks for COD, ammoniacal nitrogen, nitrate, hardness, and exhibited low dissolved oxygen, suggesting incomplete removal of both organic and inorganic contaminants. The temporal variations observed during storage further indicated active microbial degradation of milk-derived organic matter, coupled with biochemical transformation processes such as ion release, ammonia formation and oxidation, and partial stabilization of the wastewater matrix. From an environmental perspective, the persistent exceedances of COD, nitrogen species, oil and grease, and oxygen-demand parameters imply a high risk of oxygen depletion, eutrophication, odour generation, and ecological stress in receiving water bodies, thereby limiting direct discharge or reuse potential. Therefore, dairy effluents require enhanced treatment strategies and post-treatment monitoring before agricultural reuse or environmental release. Future studies should incorporate seasonal sampling, increased replication, microbial community analysis, and detailed evaluation of treatment technologies to strengthen regulatory relevance and support sustainable wastewater management.

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

S.S: Conceptualization, investigation, data collection, laboratory analysis, writing—original draft preparation; J.S: Methodology, physicochemical analysis, validation, data curation; K.S: Statistical analysis, visualization, interpretation of results; R.S: Literature review, writing—review and editing; R.P.S: Supervision, project administration, conceptual guidance, manuscript review and final approval.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request. All relevant data generated or analyzed during this study are included in the published article.

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