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Integrated photo-assisted electrochemical oxidation and biodegradation for enhanced treatment and detoxification of dairy effluent

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Abstract

The dairy industry effluents constitute a significant environmental burden due to their elevated organic load, salinity, suspended solids, and complex mixture of protein and lipid rich compounds. Their uncontrolled discharge can induce oxygen depletion, eutrophication, ecological disturbances, and the accumulation of potentially hazardous constituents in aquatic and terrestrial ecosystems, and human health. The present study investigated a sustainable hybrid treatment approach integrating photo-assisted electrochemical oxidation with biodegradation (PEO-BIO) for dairy effluent remediation. The dairy wastewater was characterized in terms of chemical oxygen demand (COD), total organic carbon (TOC), and recalcitrant organic compounds. The photo-assisted electrochemical oxidation (PEO) process effectively transformed complex, non-biodegradable pollutants into simpler, more biodegradable intermediates, improving the effluent's overall biodegradability. COD removal using PEO was 89%, whereas electrooxidation achieved COD removal of 78%. Subsequent biological treatment using *Enterobacter hormaechei* facilitated further mineralization of the oxidized compounds, resulting in substantial reductions in COD (92%) and TOC (88%). Fourier transform infrared spectroscopy and gas chromatography–mass spectrometry confirmed the progressive degradation of aromatic, nitrogenous, and halogenated compounds into low-molecular-weight acids, aldehydes, and ketones, which were readily assimilated by the microorganisms. The integrated PEO-BIO system demonstrated higher efficiency than individual treatment processes, highlighting its effectiveness in enhancing pollutant removal efficiency and reducing toxicity. Overall, the findings indicate that the integrated PEO-BIO process is a promising, environmentally sustainable, and efficient strategy for treating dairy industrial wastewater.

Keywords: Dairy effluent; Photo-assisted electrochemical oxidation; Biodegradation; *Enterobacter hormaechei*

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1. Introduction

The global expansion of the dairy sector serves as a pivotal driver of economic stability and growth across numerous nations.[1,2] Rapid global industrialization has created a significant need for freshwater, concomitantly generating large-scale industrial wastewater.[3,4] Liquid milk processing is widely recognized as the most water- and resource-intensive segment in food processing industries. Approximately 2–10 L of effluent may be generated for every liter of milk processed through operations including pasteurization, homogenization, neutralization, and equipment cleaning. The quantity of effluent depends on the frequency of clean-in-place cycles and the type of product line. India, being the world's largest milk producer, handles an average of around 200 million metric tons of milk annually, with a compound annual growth rate exceeding 5%.[5-7] While the Central Pollution Control Board warns of a critical decline in surface water quality across India, the expanding water footprint of the burgeoning dairy industry further intensifies this pressure on national water security and sustainability.[8-11] Dairy processing is among the most water-intensive segments of the food industry, generating large volumes of effluents rich in organic matter, nutrients, suspended solids, fats, and pathogens.[12,13] Effluent production remains disproportionately high within the dairy industry. Typically, dairy wastewater exhibits high chemical oxygen demand (COD), biochemical oxygen demand (BOD), nutrient content, variable pH (4–10), and substantial loads of colloidal and dissolved organics. Consequently, discharging this effluent without adequate treatment causes eutrophication, oxygen depletion, and ecological imbalance.[14-16] Furthermore, the discharge of untreated effluent introduces recalcitrant organics, suspended solids, and pathogens, leading to soil degradation and deterioration of groundwater quality. Nutrient enrichment, specifically nitrogen and phosphorus, further drives eutrophication and harmful algal blooms. From a human health perspective, exposure to untreated or partially treated dairy effluent poses risks due to microbial contamination and the potential presence of toxic intermediates formed during degradation processes.[17] Conventional physicochemical and biological technologies such as coagulation, flocculation, membrane processes, and anaerobic and aerobic reactors are used in common effluent treatment plants.[18,19] However, they are energy-intensive and inadequate for complete removal of emerging contaminants. In various regions, the failure to enforce discharge standards causes wastewater to be released untreated, creating environmental pollution.[20] In this study, electrochemical oxidation and microbial degradation were investigated as complementary approaches for dairy-effluent treatment.

A major drawback of conventional treatment techniques is their inability to effectively remove halogenated organics, residual surfactants, and nitrogenous compounds. These fractions are also resistant to microbial oxidation, allowing them to persist in conventional biological systems. The limitations of conventional biological treatment have led to the development of advanced electrochemical oxidation processes as versatile processes that can be used either as pretreatment steps or as standalone treatment technologies.[21-23] Anodic electrooxidation (EO) generates reactive species in situ through the electrochemical discharge of water without external chemical catalysts, utilizing active metal-oxide anodes such as Ti/IrO_2 and Ti/RuO_2–IrO_2.[24] Recent reports have illustrated the ability of EO to remove COD and color, which substantially improves biodegradability. However, its efficiency is highly influenced by the electrode material, electrolyte type, current density, and treatment time. Effective COD removal has been observed in similar high-strength mixed industrial effluents and agro-food effluents such as coffee or slaughterhouse wastewater, where EO effectively breaks down persistent organics into less toxic compounds. However, complete mineralization with EO as a standalone process is highly energy-consuming and results in undesirable oxyhalogenated byproducts. [25]

The need for complete detoxification has motivated the integration of EO with biological treatment schemes. In this hybrid approach, electro- or photoelectrochemical pre-oxidation breaks complex recalcitrant structures, reduces toxicity, and increases the BOD/COD ratio, thereby allowing subsequent biological steps to achieve large-scale mineralization at a minimal operational cost. Many studies have reported combined approaches as the most promising, outperforming individual treatment techniques with advantages including BOD/COD removal and biodegradability of a wide range of effluents such as pharmaceuticals, pesticide wastewaters, textile effluents, and landfill leachates.[21,23]

The diversity of dairy effluents, compared with other effluents, limits the systemic evidence of available reports on combined approaches of EO with biological schemes for treating effluents. The high lipid–protein content tends to form stable emulsions, and the varying salinity of dairy effluents further complicates the effort to tailor a specific hybrid approach for their treatment. The comparative evidence of the merits of EO versus photoassisted electrochemical oxidation (PEO) as pretreatments, particularly in terms of effluent transformation pathways, enhancement of biodegradability, and overall energy–treatment tradeoffs, is less studied and needs to be quantified for dairy effluents.

This study addresses these limitations using a unique hybrid approach of photoelectrochemical oxidation and aerobic biodegradation to treat dairy effluents. The present study highlights the mechanisms of EO and PEO treatment by comparing their organic matter removal efficiencies, detailing spectral and functional group transformations, and evaluating the enhancement of biodegradability. The primary objective of this study is to assess how these pre-oxidation pathways influence subsequent biological COD and TOC removal and toxicity mitigation, and to evaluate their energy and operating requirements relative to conventional biological treatment. By situating dairy effluent treatment within the broader framework of advanced photoelectrooxidation and biological hybridization demonstrated for other complex wastewaters, this study aims to provide mechanistic and performancebased evidence for deploying a robust, energyefficient, and scalable treatment strategy for the dairy sector.

2. Materials and methods

2.1. Chemicals and reagents

Sodium chloride (NaCl) and sodium sulfate (Na_2SO_4) with 99% purity were procured from Himedia (Mumbai, India) for physicochemical analysis of the control and treated samples. Standard solutions (99.9% purity) for COD, BOD, and TOC were sourced from Sigma-Aldrich, Germany. Analytical-grade chemicals were used for the study without further purification. Deionized water (resistivity ≥ 18 MΩ·cm) was used for standard preparation and sample dilution.

2.2. Dairy effluent collection and characterization

Raw dairy effluent was collected from the equalization tank of a liquid milk processing unit at the Thejes Dairy Products plant, Chittoor, Andhra Pradesh, India (latitude: 13.373654 and longitude: 79.090927). Composite samples were sourced from the discharge line immediately after production in clean polyethylene containers and stored at 4 °C until use. Samples were allowed to equilibrate to room temperature and further processed for analysis within 24 hours to minimize any compositional changes.[26] Coarse suspended solids were removed by filtration through a 1–2-mm sieve. The filtered effluent was characterized for its physicochemical properties, including pH, total dissolved solids (TDS), total suspended solids (TSS), COD, BOD, and total organic carbon (TOC) following standard methods recommended by American Public Health Association. Calibrated meters were also used to monitor pH and electrical conductivity.[27]

2.3. Fabrication of electrochemical and photoelectrochemical reactors

A single-compartment tubular-flow-cell batch electrochemical reactor with an effective working volume of 250 mL was employed for EO and PEO experiments. The reactor was configured with a dimensionally stable Ti/RuO_2–IrO_2–TiO_2-coated titanium plate (100 × 50 × 1.5 mm) as the anode and a titanium mesh (100 × 50 × 1.5 mm) as the cathode. The electrodes were placed vertically and facing parallel to each other, with an interelectrode distance of 8 cm, consistent with previous EO and PEO designs for wastewater treatment. The electrodes were connected to a DC power supply operated at a constant voltage of 12.26 V, resulting in a current density of 30 mA/cm^2.[28,29] In both the EO and PEO experiments, effluent entered the reactor from the bottom, flowed to the anode and cathode, and exited from the top of the reactor. The reactor working volume was 250 mL, with 2,000 mL of the reservoir used to collect the circulation solution, and the flow rate was maintained at 150 mL/min.

A supporting electrolyte, NaCl at 0.1 M, was employed to enhance solution conductivity and to promote in situ generation of active chlorine, albeit with the potential for indirect oxidation. Several studies have suggested that Na_2SO_4 (0.1 M) could be used to contrast sulfate radical-dominated oxidation pathways, as conventionally described for industrial effluents.[30-32]

For PEO, a lowpressure mercury UV lamp (6 W, λ = 254 nm, with 20 mm diameter and 350 mm length) was used externally through the reactor wall, as conventionally used in a tubular flow configuration for effluents. The lamp was housed in a quartz sleeve and positioned centrally between the electrodes, ensuring uniform irradiation of the reaction volume, and was operated continuously during electrolysis to provide simultaneous photolysis and photoassistance of electrochemical reactions.[33]

2.4. Electrooxidation and photoassisted electrochemical oxidation

Pre-screened effluents were subjected to EO and PEO experiments in batch mode, with an operational volume of 1 L and an ambient temperature of 28 ± 2 °C. The effluent was stirred or recirculated to minimize mass transfer, and an appropriate concentration of supporting electrolyte (NaCl or Na_2SO_4) was added and adjusted to the required pH. The current flow was optimized to an appropriate density; for PEO batches, the UV lamp was turned on simultaneously. Aliquots were withdrawn at predetermined time intervals (0, 30, 60, 90, 120, 150, 180,

210, 240, and 270 min) for analysis of COD, TOC, and UV–visible (UV–Vis) spectra, following the sampling strategy used in an earlier EO/PEO study.[33] Samples under identical conditions without applied electrical current served as blanks to evaluate photolytic effects, and samples treated without UV irradiation were used to distinguish between EO and PEO. All test and blank samples were filtered before analysis to remove residual suspended solids.[33-35]

2.5. Isolation and identification of the bacteria

In this study, the indigenous rod-shaped, motile, and Gram-negative bacterial strain *Enterobacter hormaechei* was isolated from coastal soil sediment and identified through biochemical analysis and 16S rRNA sequencing. Further details of the strain were reported in the previous study.[36] The sequence was deposited in NCBI GenBank (accession number: OR978624). Stock cultures were maintained at −20 °C and revived in replacement lysogeny broth to reach the logarithmic growth phase before use in treatment processes.

2.6. Biodegradation of treated and untreated effluents

The integrated effect of EO and PEO with biodegradation was assessed with an aerobic biodegradation assay with three discrete samples: (i) raw dairy effluent, (ii) EOtreated effluent, and (iii) PEOtreated effluent. The optimum treatment time for the biodegradation of EO- and PEO-treated samples was determined through COD and TOC removal profiles.[34] The biodegradation experiment was carried out using an indigenous *Enterobacter hormaechei* strain isolated from coastal sediment. The bacterial culture was revived in lysogeny broth to the exponential growth phase and subsequently used as the bacterial inoculum. For the biodegradation experiment, 250 mL of the raw effluent was placed in a 500 mL flask and inoculated with the bacterial culture at an initial concentration of 10^6 CFU/mL. The inoculated flasks were incubated at 30 °C–35 °C under continuous agitation at 120 rpm to evaluate biodegradation efficiency. The samples were collected at regular intervals and monitored for biodegradation efficiency. Control flasks without inoculum were also evaluated to account for any abiotic changes. All experiments were carried out in triplicate following approaches reported for integrating advanced oxidation and biological treatment for effluent treatment.[33-35]

2.7. Analytical methods

The dichromate closed-reflux method with commercially available digestion vials was used to determine COD and spectrophotometric detection, in accordance with the standard methods recommended by American Public Health Association.[27,33] The standard 5-day incubation method at 20 °C was used for BOD determination. Shimadzu TOC-VCPN analyzer (Shimadzu Corporation, Japan) was used to quantify TOC, as reported in previous studies on effluent treatment. Chromogenic changes before and after treatment were recorded using a doublebeam UV–Vis spectrophotometer, Shimadzu UV-1800 (Shimadzu Corporation, Japan), with a scan range of 200–800 nm with appropriate dilutions.[33] Functional groups in the raw effluents and the occurrence of new functional groups in treated effluents were investigated using Fourier transform infrared (FTIR) spectra (LS45, PerkinElmer Inc., USA). Sample residues were dried, homogenized, and pressed into pellets with spectroscopic-grade potassium bromide and analyzed in attenuated transmission mode.[37] All experiments were carried out in triplicate, and the results are reported as mean values. Where relevant, standard deviations were calculated to indicate experimental variability.

2.8. Toxicity assessment

The ecological risks of intermediate products generated during the sequential PEO with biodegradation (PEO-BIO) process were evaluated using the Ecological Structure-Activity Relationship (ECOSAR) predictive model. Both acute and chronic toxicity endpoints were assessed across three aquatic trophic levels: fish, daphnid, and green algae. These toxicities were quantified via lethal concentration, 50% (LC_{50}) and effect concentration, 50% (EC_{50}) values, representing the concentrations required for 50% mortality in fish (96 hours) and daphnids (48 hours), and 50% growth inhibition in green algae (96 hours). To ensure a conservative risk assessment, the lowest concentration eliciting a biological response was adopted for the toxicity profile.[33]

2.9. Toxicity effect

The phytotoxicity of both untreated and PEO-BIO-treated dairy effluents was assessed using *Vicia faba* germination assays. Seeds were sourced from a local market in Vellore, Tamil Nadu, India, and were surface-sterilized with 0.2% mercury(II) chloride for 2 to 3 minutes before being rinsed thoroughly with distilled water. Germination tests were conducted in sterile soil using untreated effluent, PEO-BIO-treated effluent, and distilled water (control). All samples were maintained in a growth chamber at 30 °C, and germination rates were recorded after a 5-day incubation period.[33]

2.10. Statistical analysis

All experiments were performed in triplicate ($n = 3$), and the results are expressed as mean ± standard deviation.

Statistical comparisons among groups were performed using one-way analysis of variance, followed by Dunnett's multiple-comparisons test, using GraphPad Prism version 10 (GraphPad Software, USA). Differences were considered statistically significant at $p < 0.05$.

3. Results and discussion

3.1. Physicochemical characterization

The raw dairy effluent exhibited typical characteristics of dairy and cheese-processing wastewaters, with a light grey color and a slightly acidic pH of 6.23. Additionally, the effluents contained high TSS and moderate TDS levels, at 698 mg/L and 550 mg/L, respectively. These observations align with the broad ranges reported for dairy effluents, in which TSS and TDS levels typically fall in the range of 500–700 mg/L and 900–3,500 mg/L, respectively, depending on operational cycles and cleaning practices. The effluents contained a substantial organic load, exhibiting high concentrations of COD, BOD, and TOC at 880 mg/L, 612 mg/L, and 736 mg/L, respectively. The observed concentrations align with previous reports on dairy and cheese-processing wastewaters, with COD and BOD concentrations of 1,900–90,000 mg/L and about 19,900 mg/L, respectively. The raw dairy effluent indicated a good inherent biodegradability, which was evidenced by the BOD/COD (612 mg/L/880 mg/L) ratio of 0.695.[38] The observed BOD/COD ratio lies in the general range of 0.4–0.8 reported for dairy wastewater. Previous reports cite a ratio of 0.55–0.60 as fairly to readily biodegradable; however, the associated toxicity and oxygen-depleting potential warrant biological treatment.[39] This relatively high BOD/COD ratio indicates that a considerable fraction of the organic matter in the raw dairy effluent is biologically degradable, although the remaining non-biodegradable or slowly biodegradable fraction necessitates proper treatment. In conventional biological treatment, proteins, fats, and cleaning chemicals complicate the process by increasing COD, whereas anaerobic digestion is highly hindered by the formation of long-chain fatty acids from lipid hydrolysis.[40,41] High organic loading, foaming, sludge bulking, pipe blocking, and odor are the results of high organic load and solids, and potentially recalcitrant constituents may limit the efficiency of biological treatment alone. Therefore, electrochemical and photoelectrochemical pretreatment can be adopted to transform complex organic compounds into more biodegradable intermediates, facilitating the subsequent microbial degradation.

The biological degradability is highly limited by COD and TOC levels, as well as a significant load of suspended solids in the dairy industrial effluents. In the present study, the COD and TOC ratio of 1.196 clearly indicates that partial biological degradation occurred following EO/PEO pre-oxidation, enabling subsequent efficient degradation. Souli *et al.*[42] were able to reduce highly toxic effluents to less toxic levels by treating cheese whey wastewater through electrochemical oxidation using a boron-doped diamond (BDD) long wire with titanium as an anode. Several other studies also demonstrated that advanced electrochemical oxidation processes effectively reduce COD and transform complex, partly inhibitory organics into smaller intermediates that are more amenable to biological treatments, thereby enhancing downstream performance.[43,44] A combined electrochemical and biological treatment approach offers immense potential in meeting stringent discharge or reuse requirements for dairy effluents.[45]

3.2. UV–visible spectral changes during electrooxidation and photo-assisted electrochemical oxidation

A progressive decrease in absorbance was recorded in the UV–Vis spectra of the effluent treated by electrochemical oxidation, with the most notable attenuation occurring between 200 and 300 nm, as shown in Figure 1. This spectral window typically corresponds to chromogenic organics originating from milk-derived aromatic amino acids, proteins, and fatty acid residues.[46,47] The attenuation primarily signifies the disruption of conjugated and aromatic moieties, electrochemically generating active chlorine species and hydroxyl radicals (•OH) through partial degradation of these complex organics (**Equations 1** and **2**).[48]

$$Cl^- \rightarrow Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^- \quad (1)$$

$$H2O \rightarrow \bullet OH + H^+ + e^- \quad (2)$$

UV irradiation enhanced the generation of •OH and other reactive species at the electrode–solution interface, which was evidenced by the decline in absorbance in the PEO shown in Figure 1b. This synergistic effect accelerated the oxidation of both chromogenic and non-chromogenic organics. Pasindu *et al.*[49] also observed rapid decolorization (200–300 nm) and near-complete oxidation of aromatic and carboxylic pollutants in cheese-whey wastewater after sequential electrocoagulation/photoelectro-Fenton (PEF) or EO with UVA irradiation. Similarly, electrochemical oxidation coupled with UV for treating landfill-derived dissolved organic matter and concentrated leachates exhibited a blue shift and flattening of UV spectra, confirming the breakdown of humic substances and protein fractions into low-molecular-weight metabolites.[48]

In the present study, the nearflattening of the spectra after PEO suggests a deeper destruction of conjugated systems than in EO alone. This is consistent with the

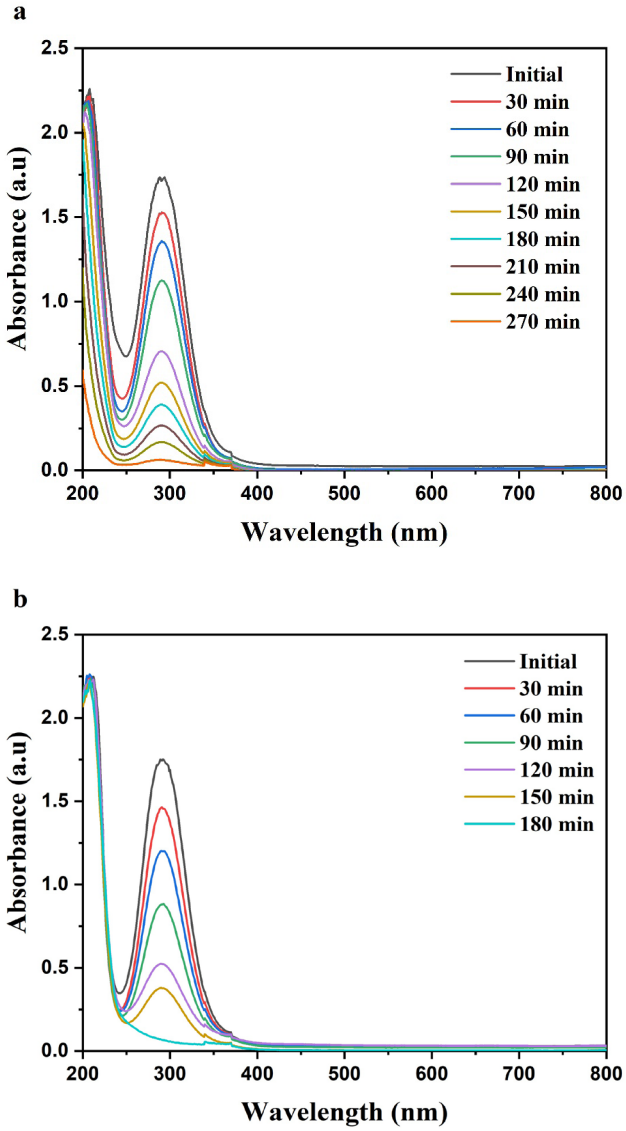


Figure 1. UV–Vis spectra of the pretreatment processes of dairy effluent. (a) EO, (b) PEO.
Abbreviations: EO: Electrooxidation; PEO: Photo-assisted electrochemical oxidation; UV–Vis: UV–visible.

higher mineralization and improved biodegradability as indicated by subsequent COD and TOC measurements. The findings align with recent works showing that PEF and other photoassisted electrochemical advanced oxidation processes achieve faster decolorization, greater loss of UVabsorbing species, and higher TOC removal than dark electrochemical oxidation for dairy effluents and other complex wastewaters.

3.3. Biodegradation

The biodegradation process exhibited a gradual increase in COD and TOC removal over 15 days, as shown in Figure 2. Initial COD and TOC removal were lower; during the first 3 days, COD removal was 5% (836 mg/L), and TOC removal was 7% (684.48 mg/L). Subsequently, removal efficiencies improved steadily; by day 9, COD and TOC removal achieved 29% and 21%, respectively, as shown in Figure 2a. The maximum removal was achieved on day 15, with 42% (510.40 mg/L) and 32% (500.48 mg/L) removal recorded for COD and TOC, respectively. The values confirm the progressive degradation of organic matter, as evident in Figure 2b. Throughout the treatment

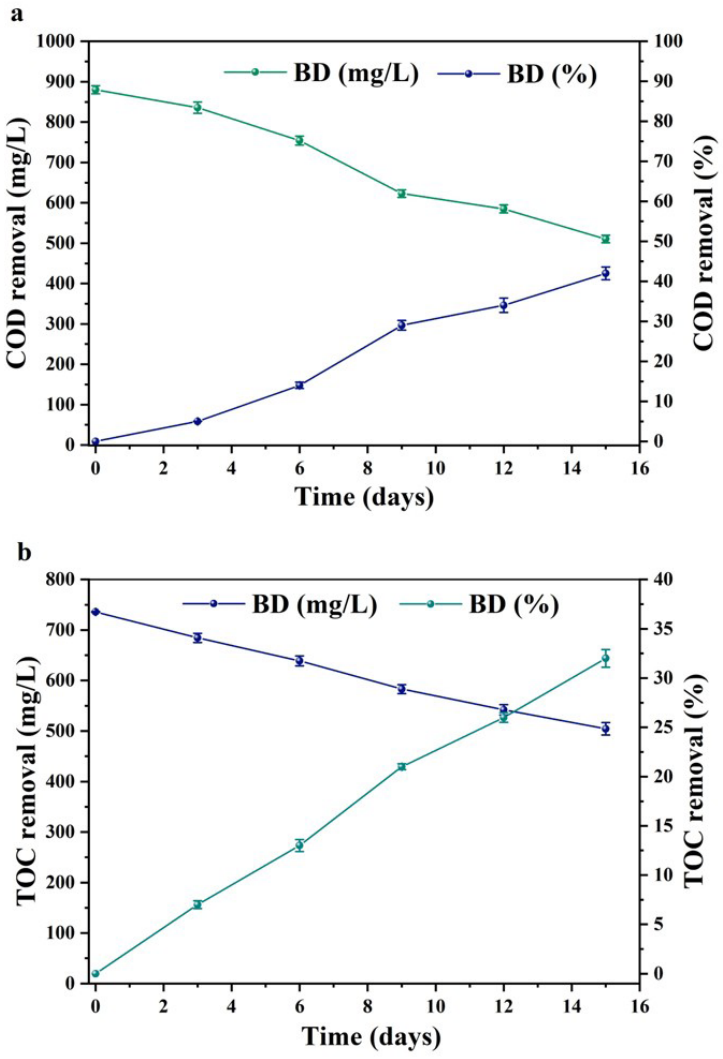


Figure 2. COD and TOC analysis for biodegradation of dairy effluent. (a) COD, (b) TOC.
Abbreviations: BD: Biodegradation; COD: Chemical oxygen demand; TOC: Total organic carbon.

period, TOC removal remained consistently lower than COD removal. This indicates that biodegradation primarily led to partial oxidation of organic compounds, forming intermediate products rather than complete mineralization.[33,42] The persistence of TOC suggests the presence of slowly biodegradable and recalcitrant organic fractions in the dairy effluent.[50] The moderate removal efficiencies observed highlight the limitations of standalone biological treatment for high-strength dairy wastewater. Incomplete mineralization and intermediate accumulation emphasize the need for pretreatment processes. Integration with electrochemical or photoelectrochemical oxidation was therefore essential to enhance biodegradability and achieve higher overall pollutant removal.[45,51]

3.4. Electrochemical studies

Electrochemical oxidation of dairy effluent in existing systems occurs via direct anodic oxidation and indirect oxidation mediated by electro-generated reactive species. In this study, the Ti/RuO_2–IrO_2–TiO_2 electrode surface generates adsorbed •OH, which are rapidly transformed into higher oxide species.[48] These oxidants predominantly lead to partial oxidation products rather than complete mineralization. Consequently, complex organic constituents such as proteins, lipids, and lactose present in dairy effluent are initially broken down into smaller intermediates including aldehydes, ketones, and short-chain carboxylic acids.[43,48,50] In the presence of chloride ions, indirect oxidation through active chlorine species becomes

the dominant degradation pathway. Chloride ions are electrochemically oxidized at the anode to chlorine (Cl_2), which subsequently hydrolyzes to form hypochlorous acid (HOCl) and hypochlorite ions (ClO^-).[52,53] These species act as strong oxidants and react with organic matter, thereby enhancing pollutant degradation efficiency. Additionally, oxygen evolution and formation of higher-oxidation-state chlorine species can reduce current efficiency and raise concerns regarding secondary pollution. Integrating UV irradiation in the PEO process significantly enhances degradation performance by promoting photolysis of electro-generated chlorine species. Under UV irradiation, HOCl and ClO^- decompose to generate highly reactive radicals such as •OH and chlorine radicals (Cl•/ClO•), which exhibit varied but generally higher standard oxidation potentials than their parent compounds.[52-55] These radicals accelerate the breakdown of conjugated and aromatic structures, improving decolorization, increasing TOC removal, and enhancing mineralization compared to electrochemical oxidation. Although these reactive transformations drive the degradation of complex organic compounds, their distinct contributions depend on the chloride concentration, pH, electrode surface, irradiation conditions, and reaction matrix.[56,57]

$$H_2O \rightarrow M\text{–}OH^{\bullet} + H^+ + e^- \quad (3)$$

$$2Cl^- \rightarrow Cl_2 + 2e^- \quad (4)$$

$$Cl_2 + H_2O \leftrightarrow HOCl + H^+ + Cl^- \quad (5)$$

$$HOCl \leftrightarrow H^+ + ClO^- \quad (6)$$

$$R + HOCl/ClO^- \rightarrow Intermediates + Cl^- \quad (7)$$

$$HOCl + h\nu \rightarrow \bullet OH + \bullet Cl \quad (8)$$

$$ClO^- + h\nu \rightarrow \bullet Cl + \bullet O^- \quad (9)$$

$$R + \bullet OH/\bullet Cl \rightarrow Degraded\ products \quad (10)$$

$$Intermediates \rightarrow CO_2 + H_2O \quad (11)$$

Equations 3–11 describe the proposed mechanism of electrochemical and photo-assisted oxidation of organic pollutants in dairy effluent. The mechanism involves the generation of surface-bound hydroxyl radicals (M–OH•) at the anode, electrochemical oxidation of chloride ions (Cl^-) to chlorine (Cl_2), and subsequent formation of hypochlorous acid (HOCl) and hypochlorite ions (ClO^-). These active chlorine species oxidize organic pollutants, represented by R, into intermediate compounds. Under UV irradiation, denoted by hν (photon energy), HOCl and ClO^- may undergo photolysis to generate reactive radical species, including hydroxyl radicals (•OH) and chlorine radicals (Cl•), which further promote pollutant degradation. The resulting intermediates may undergo subsequent oxidation and biodegradation, ultimately contributing to mineralization into carbon dioxide (CO_2) and water (H_2O).

Symbols used in **Equations 3–11**:

- hν: Energy of incident photons (UV irradiation; 254 nm in this study).
- R: Organic pollutants present in dairy effluent, including proteins, lipids, fatty acids, and other organic contaminants.
- M: Anode surface or electrode metal-oxide active site.
- M–OH•: Surface-bound hydroxyl radical or adsorbed hydroxyl species formed at the anode.
- HOCl: Hypochlorous acid.
- ClO^-: Hypochlorite ion.
- Cl•: Chlorine radical.
- •OH: Hydroxyl radical.

Removal efficiencies of COD and TOC during EO and PEO of dairy effluent are presented in Figure 3. A significant enhancement in treatment performance was observed under PEO conditions compared with EO alone. Specifically, a sharp decline from the initial COD level of 880 mg/L was recorded. The highest COD removal efficiencies of EO and PEO were 78% (193.6 mg/L) and 89% (96.8 mg/L), respectively. TOC removal efficiencies achieved by EO and PEO were 56% (323.84 mg/L) and 73% (198.72 mg/L), respectively. At longer reaction times, both COD and TOC removals further increased, with PEO consistently outperforming EO. The improved efficiency under PEO conditions can be attributed to the synergistic effect of electrochemical oxidation and UV irradiation, which promotes the generation of highly reactive species such as •OH and Cl•.[58,59] These radicals exhibit strong, non-selective oxidation potential, enabling the rapid breakdown of complex organic molecules in dairy effluent. A pre-pilot study by Tirado *et al.*[60] recorded 49% TOC removal in cheese whey effluents using EO coupled with BDD and UVA, exhibiting a greater removal efficiency than using EO alone. The results clearly demonstrate that EO alone offers limited oxidation efficiency, primarily resulting in partial degradation of organic matter. PEO significantly enhances both degradation and mineralization. The better performance of PEO highlights its potential to increase biodegradability and reduce the load on subsequent biological treatment processes.

3.5. Integrating biodegradation with electrooxidation and photo-assisted electrochemical oxidation treatment

Effluents pretreated with EO exhibited greater COD reduction during subsequent aerobic biodegradation than raw effluent, demonstrating the ability of EO to degrade complex organic loads to readily biodegradable

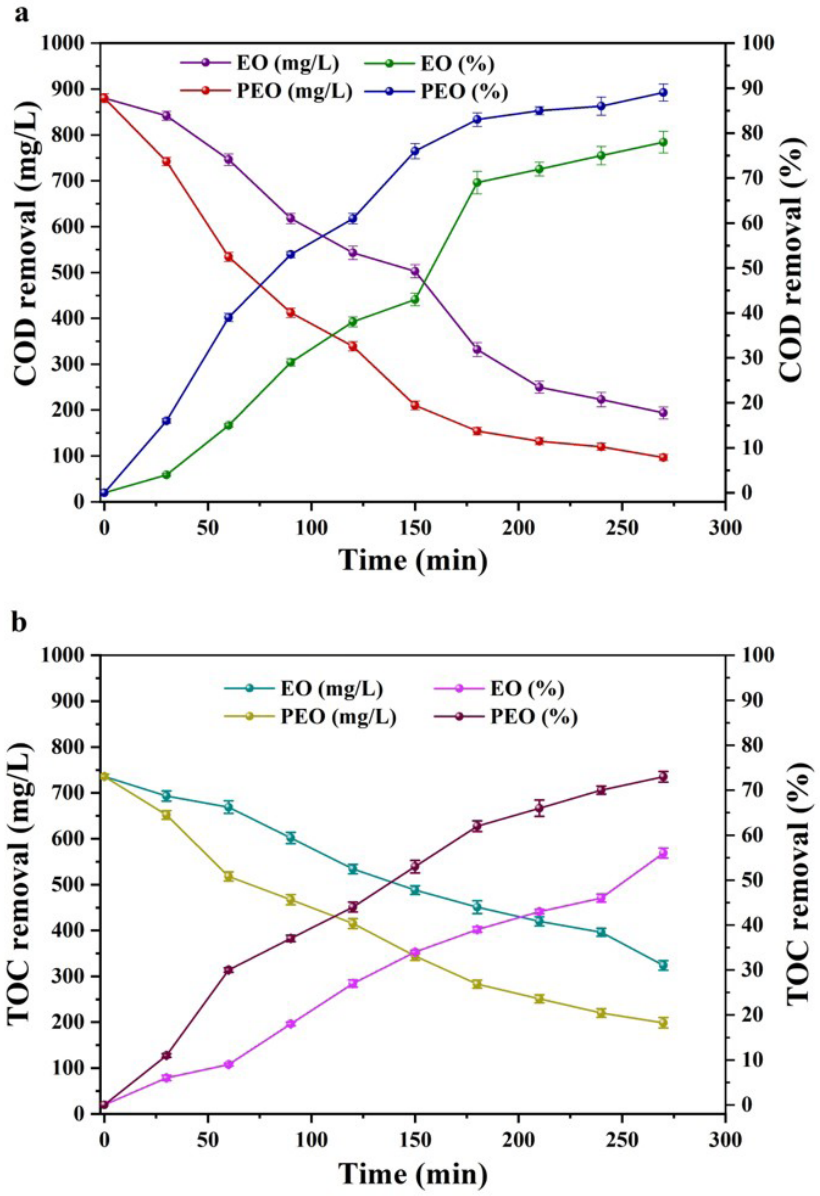


Figure 3. COD and TOC analysis during EO and PEO of dairy effluent. (a) COD, (b) TOC.
Abbreviations: COD: Chemical oxygen demand; EO: Electrooxidation; PEO: Photo-assisted electrochemical oxidation; TOC: Total organic carbon.

intermediates, as shown in Figure 4a. A further enhanced biodegradability index (BOD_5/COD) from 0.55 to 0.81 was reported by Souli *et al.*[42] when EO is coupled with BDD. The report also highlights that anodic oxidation and electro-Fenton treatment significantly increase the BOD_5/COD index and facilitate the biodegradability of dairy wastewaters.

The greatest reduction in COD was observed in PEO-BIO treatment, where the lowest COD was observed in the PEO effluent during biological treatment. This pattern mirrors several reports on combined electrochemical advanced oxidation process-bio systems in complex effluent treatment.[32] For instance, maximum COD removals of 90–97% were achieved through the integrated application of electrochemical advanced oxidation processes and anaerobic digestion or activated sludge for the treatment of dairy and mixed industrial streams.[45] These reports demonstrated that pretreated effluent from

photoassisted processes generally outperforms dark EO in terms of efficiency and per-unit operational cost.

A similar oxidation pattern was observed in TOC removal, where EO facilitated moderate TOC removal, as shown in Figure 4b. EO primarily transforms complex molecules but does not favor complete mineralization. Notably, active anodes only induce indirect oxidation by active chlorine, which favors partial oxidation. Conversely, PEO exhibited notably higher TOC removal (Figure 4b), which aligns with several pre-pilot scale studies[5,33] where 40–50% TOC removal was achieved using PEF and hybrid EO/UVA for the treatment of cheese whey and dairy effluents, clearly outperforming dark EO with similar operational conditions. Overall mineralization was enhanced by PEO-BIO, where high TOC removal was observed in samples pretreated with EO and PEO (Figure 4b). EO and PEO play a pivotal role as biodegradability enhancers, resulting in higher TOC removal in pre-oxidized effluents. They act by generating low-molecular-weight carboxylic acids and carbonyl compounds that can be mineralized by activated sludge. Table 1 compares these findings with previously reported treatment techniques. However, individual approaches have inherent limitations. Although biological treatments can achieve substantial COD and BOD removal, they require microbial acclimation, longer treatment periods, and controlled operating conditions. Additionally, they may exhibit limited effectiveness toward refractory organic compounds.

3.6. Fourier transform infrared spectroscopy

The evolution of diverse functional groups in pre-oxidized and biodegraded samples was investigated using FTIR spectroscopy. The raw effluents were characterized by aromatic, nitrogen-containing, and halogenated organics, as evidenced by the presence of bands assigned to nitro N–O (1,533 cm^{-1}), aldehydic C–H (872 cm^{-1}), amine C–N (1,038–1,123 cm^{-1}), alkene C=C (839 cm^{-1}), and C–Cl (553 cm^{-1}) (Figure 5a). To contextualize the primary organic load, the spectral profiles of the characteristic protein and lipid fractions typical of dairy and cheese-whey wastewater were cross-referenced with standard FTIR correlation

Table 1. Efficacy of the proposed method against recent wastewater treatment methods

No.	Treatment process	Wastewater	Treatment condition	Removal efficiency (%)	References
1	Biological activated sludge	Dairy wastewater	Aerobic biological treatment	BOD, 95%	14
2	Flat-plate photobioreactor	Raw dairy wastewater	*Ascochloris* sp. ADW007	COD, 94% Nitrate removal, 72%	61
3	Microphoto bioreactor	Simulated dairy wastewater	*Chlorella vulgaris*	COD, 42.5%	62
4	Biodegradation–microbial consortium	Real dairy effluent, Madurai, India	Effective microorganism consortium; recycling prototype, aerobic biological treatment	COD, 82%; BOD, 78%	38
5	EO	Anaerobically digested dairy wastewater	Ti/PbO_2 anode and stainless-steel cathode; 90 mA/cm^2; 0.08% electrolyte	COD, 78.36%	25
6	Photoelectrochemical/PEF oxidation	Real dairy wastewater	UV/Fe^{2+}/H_2O_2, 14,000 mg/L H_2O_2, 198 mg/L Fe^{2+}, pH 3.5	COD, 60%; TOC, 73%	63
7	PEF + electrocoagulation	Real dairy-industry wastewater	UV/Fe^{2+}/H_2O_2 pretreatment followed by Al electrocoagulation, optimized at 85.71 A/m^2, 35 min, pH 2.95	COD, 90%	64
8	Integrated photoelectrochemical oxidation + biodegradation	Dairy effluent	Ti with triple coated plate and non-coated (Ti/RuO_2–IrO_2–TiO_2), 12.26 V (30 mA)	COD, 92%, TOC, 88%	Current study

Abbreviations: Al: Aluminum; BOD: Biochemical oxygen demand; COD: Chemical oxygen demand; EO: Electrooxidation; PEF: Photoelectro-Fenton; TOC: Total organic carbon.

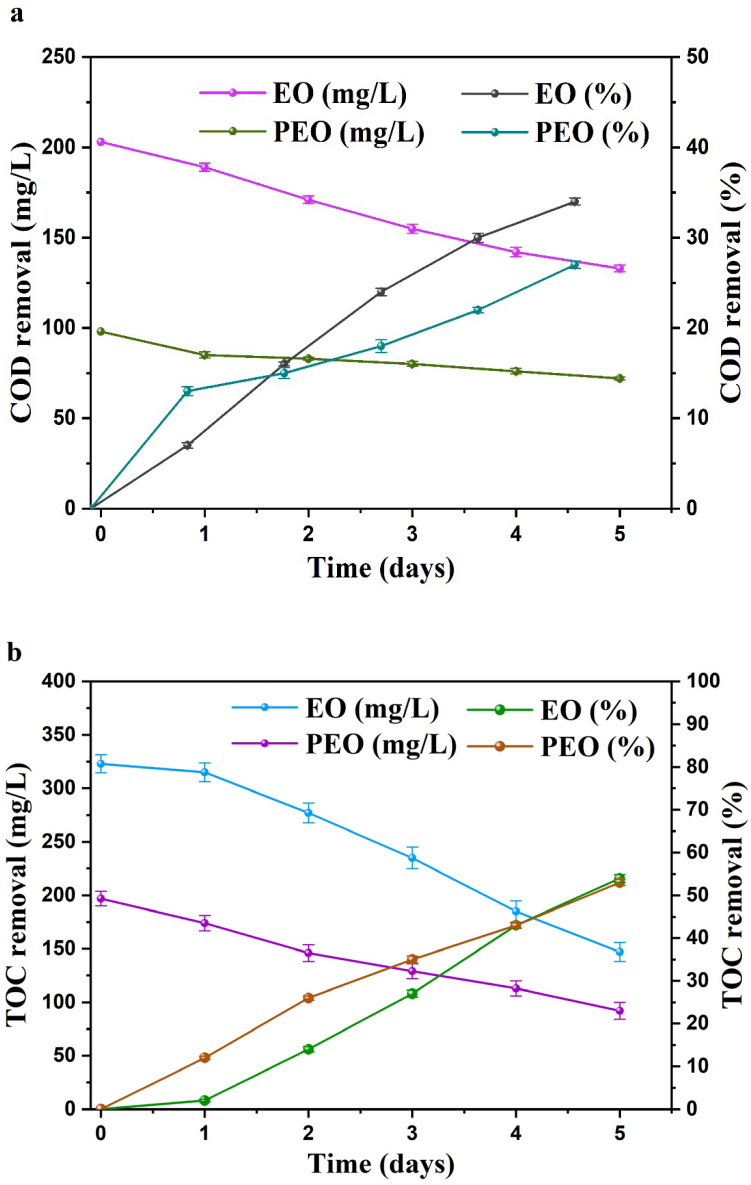


Figure 4. COD and TOC analysis of biodegradation of pretreated dairy effluent. (a) COD, (b) TOC.
Abbreviations: COD: Chemical oxygen demand; EO: Electrooxidation; PEO: Photo-assisted electrochemical oxidation; TOC: Total organic carbon.

tables.

The potential for biodegradation was evaluated with raw effluent, which revealed the presence of aldehydic, halogenated (C–Cl, C–F), and aromatic compounds (Figure 5b). This evidently demonstrates that conventional biological treatment is more effective for organic contaminants but is not effective in eliminating recalcitrant halogenated and nitrogen-containing compounds. Previous studies have reported that dairy and leachate effluents rich in halogenated and nitrogen-rich compounds are resistant to biological or coagulation-based treatments, which aligns with current observations.[63]

Figure 5c revealed a substantial reduction in aromatic and nitro components after EO, whereas aldehydic C–H (1,384 cm^{-1}), residual alkene, and trisubstituted aromatic C–H (873 cm^{-1}) bands showed no changes. This signifies the partial breakdown of complex aromatics and N-bearing groups into simpler, more oxidized intermediates. This

phenomenon has been widely reported: EO preferentially acts on conjugated and aromatic compounds, but does not facilitate complete mineralization on active metal-oxide anodes. As shown in Figure 5d, PEO further narrowed the spectroscopic profile, resulting in weak aldehyde bands (1,385 cm^{-1}) and more pronounced halogen-related bands such as C–F, a 1,2,4-trisubstituted C–H bending, and C–Cl at 1,003 cm^{-1}, 879 cm^{-1}, and 624 cm^{-1}, respectively. Electrochemical oxidation in chloride-rich environments generates halogenated byproducts, leading to the formation of organochlorines as a result of partial organic oxidation. Similar phenomena have been evidenced in various reports on cheese whey and other highsalinity wastewaters rich in chlorine.[33,42,60]

The comparative analysis of FTIR spectra for EO and PEO effluents after biodegradation reveals distinct patterns. As shown in Figure 5e, EO-treated effluent upon microbial transformation resumed strong aliphatic C–H (1,450 cm^{-1}), ethertype C–O bands (1,271 cm^{-1}), and aldehydes (1,384 cm^{-1}), indicating that biodegradation

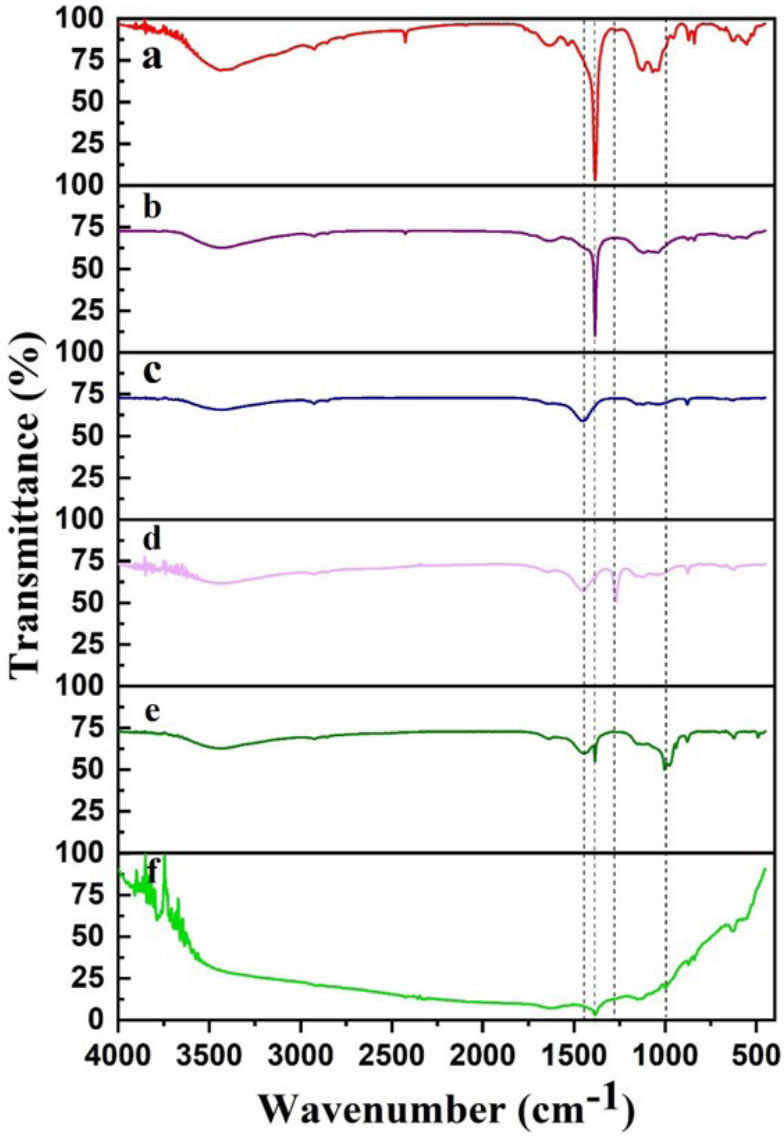


Figure 5. FTIR spectra of untreated and treated dairy effluent. (a) Untreated dairy effluent, (b) Biodegradation of dairy effluent, (c) EO of dairy effluent, (d) PEO of dairy effluent, (e) EO with biodegradation of dairy effluent, (f) PEO-BIO of dairy effluent.
Abbreviations: EO: Electrooxidation; FTIR: Fourier transform infrared spectroscopy; PEO-BIO: Photo-assisted electrochemical oxidation with biodegradation; PEO: Photo-assisted electrochemical oxidation.

has facilitated the conversion of EO metabolites into more reduced, aliphatic compounds, yet chlorine compounds remain persistent. A higher biodegradation efficiency was observed for the PEO-treated effluent, which revealed only aliphatic C–H and weak aromatic C–H bands, while C–Cl, nitro, and C–F bands were absent (Figure 5f). A similar degradation mechanism has been reported by Duraimurugan *et al.*,[33] where EO pretreatment and nanofiltration concentrates effectively transformed humiclike organics into lowmolecularweight acids, facilitating complete mineralization in landfill leachate. Overall, FTIR revealed the efficient oxidation capabilities of PEO compared with conventional EO. The current study highlights the effectiveness of the integrated PEO and biodegradation approach in eliminating persistent molecular functionalities, including aromatic, nitro, and halogenated structures.

3.7. Gas chromatography–mass spectrometry

Gas chromatography–mass spectrometry chromatograms of dairy effluent before and after treatment are provided in Figure 6. To identify the intermediate metabolites produced during effluent treatment, the chromatograms of the control, biodegradation, PEO, and PEO-BIO were compared. The initial dominant compounds in the control system were identified as hexadecanoic acid, octadecanoic acid, and oleic acid, along with phenolic compounds and phthalate derivatives. However, the abundance decreased significantly after PEO-BIO treatment. As shown in Figure 6d, PEO-BIO significantly affected intermediate metabolite fragmentation. The primary intermediates found in PEO include cyclohexane (isopropylcyclohexane), naphthalene (trans-decahydronaphthalene), phenol (3,5-di-tert-butylphenol), 1H-indene (trans-2,2,4,4,7,7-hexamethyloctahydro-1H-indene), toluene (butylated hydroxytoluene), carbonate esters (dodecyl vinyl carbonate), and oxalate esters (ethyl [6-ethyloctan-3-yl] oxalate). After PEO-BIO, the complex, high-molecular-weight compounds were transformed into simpler, lower-molecular-weight intermediates including aldehydes (nonanal, decanal), ketones (2-butanone), and short-chain fatty acids. Figure 6b shows that biological treatment alone resulted in partial degradation with accumulation of volatile fatty acids such as acetic, propionic, and butyric acids. The findings indicate that dairy effluent underwent various stages of PEO and biodegradation with bacterial strains, as shown by aromatic ring cleavage and the addition of hydroxide and acid groups to the intermediate products.

3.8. Degradation pathway

The proposed degradation pathway elucidates the transformation of complex organic constituents in dairy effluent through the integrated PEO-BIO process, demonstrating a sequential breakdown from high-molecular-weight recalcitrant compounds to complete mineralization, as evidenced by the GC–MS profiles (Figure 7 and Table 2). Initially, the raw effluent contains long-chain fatty acids such as palmitic acid (also known as hexadecanoic acid, with a molecular weight of 256.43 g/mol) and aromatic contaminants including phthalates, which are resistant to direct biological degradation.[65] During the PEO stage, generation of highly reactive •OH induces non-selective oxidative cleavage of C–C, C–H, and unsaturated bonds, leading to the fragmentation of these complex molecules into smaller intermediates.[66,67] Palmitic acid undergoes oxidative cleavage to form intermediate aldehydes such as decanal (molecular weight: 156.27 g/mol) and nonanal (molecular weight: 142.24 g/mol). Concurrently, aromatic compounds are hydroxylated to yield phenolic intermediates, which are further converted into catechol (molecular weight: 110.11 g/mol), a significant compound in microbial aromatic degradation pathways. In the subsequent biological treatment stage, these oxidized intermediates become readily biodegradable substrates; nonanal and decanal are enzymatically oxidized by aldehyde dehydrogenase in the presence of oxidized nicotinamide adenine dinucleotide to form their corresponding carboxylic acids, including nonanoic acid (molecular weight: 158.24 g/mol), thereby reducing toxicity and enhancing metabolic accessibility.[68] Simultaneously, ketonic intermediates such as 2-butanone (also known as methyl ethyl ketone, with a molecular weight of 72.11 g/mol), formed during oxidative fragmentation are metabolized through ketone monooxygenase and dehydrogenase enzymes into central metabolic intermediates such as acetyl-CoA and propionyl-CoA, which are funneled into the tricarboxylic acid cycle.[69] Residual fatty acids and newly formed carboxylic acids undergo β-oxidation, a cyclic process that progressively removes carbon units as acetyl-CoA.[70,71] In parallel, aromatic compounds such as dibutyl phthalate (molecular weight: 278.35 g/mol) are subjected to microbial degradation through hydroxylation and subsequent catechol formation, followed by enzymatic ring cleavage by ortho- or meta-cleavage pathways.[72] As the degradation progresses, intermediate metabolites are converted into short-chain fatty acids such as acetic acid (molecular weight: 60.05 g/mol) and butyric acid (molecular weight: 88.11 g/mol).[73] Eventually, all intermediates converge into central metabolic pathways, leading to complete mineralization. Santhosh *et al.*[36] demonstrated that the *Enterobacter hormaechei* enzymatic action resulted in structural disruption and chain scission,

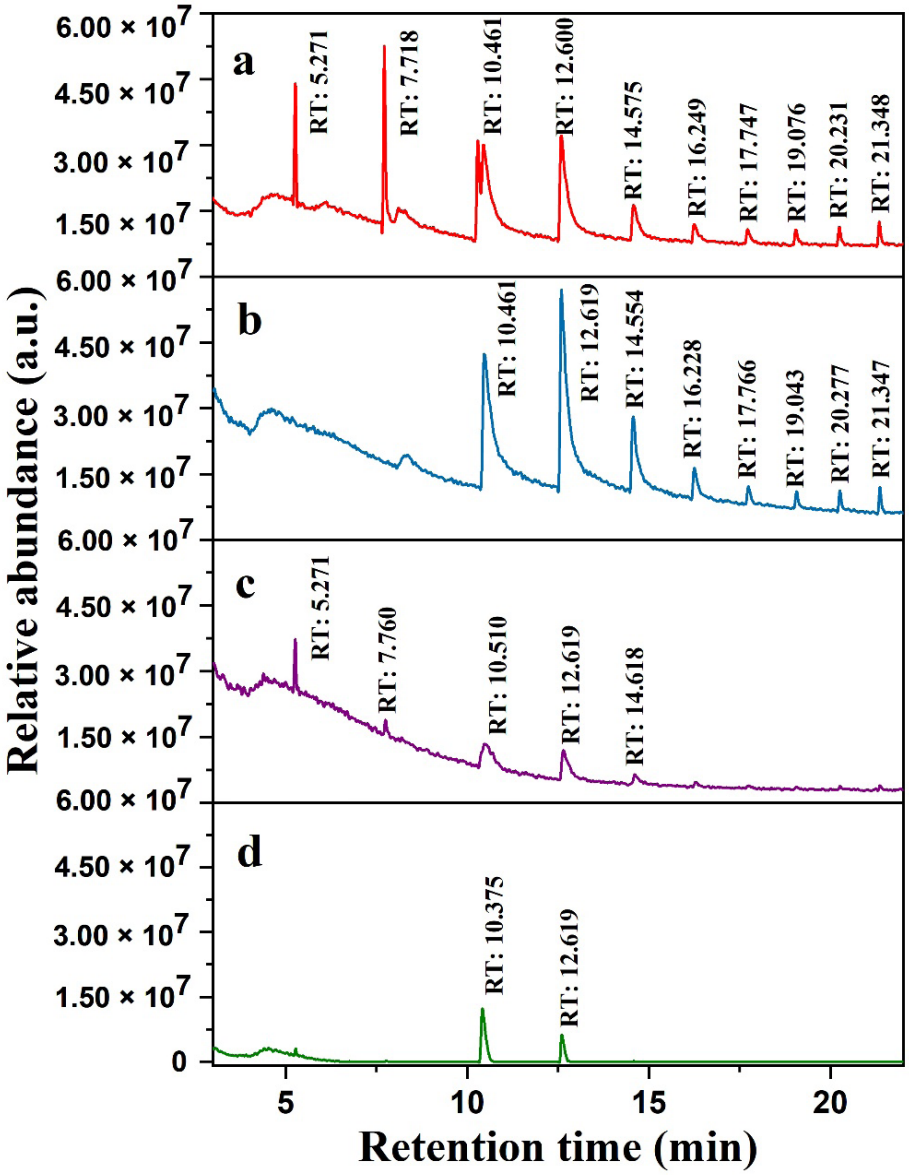


Figure 6. GC–MS spectra of untreated and treated dairy effluent. (a) Untreated dairy effluent, (b) Biodegradation of dairy effluent, (c) PEO of dairy effluent, (d) PEO-BIO.
Abbreviations: GC–MS: Gas chromatography–mass spectrometry; PEO-BIO: Photo-assisted electrochemical oxidation with biodegradation; PEO: Photo-assisted electrochemical oxidation; RT: Retention time.

which were accompanied by changes in carbonyl, carboxyl, hydroxyl, and ether-related functional groups. Although the substrate investigated in that study differs from the organic constituents of dairy effluent, these observations support the general microbial transformation of complex high-molecular-weight organic structures into more oxidized and structurally modified products. A direct mechanistic similarity was observed by Duraimurugan *et al.*[74,75] during the biodegradation of oxygenated aromatic intermediates, including phthalic acid. They proposed that subsequent aromatic-ring cleavage leads to the formation of central metabolic precursors that may enter the tricarboxylic acid cycle. Similarly, the present study observed a decrease in high-molecular-weight fatty acids and phthalate derivatives along with the formation of lower-molecular-weight compounds.

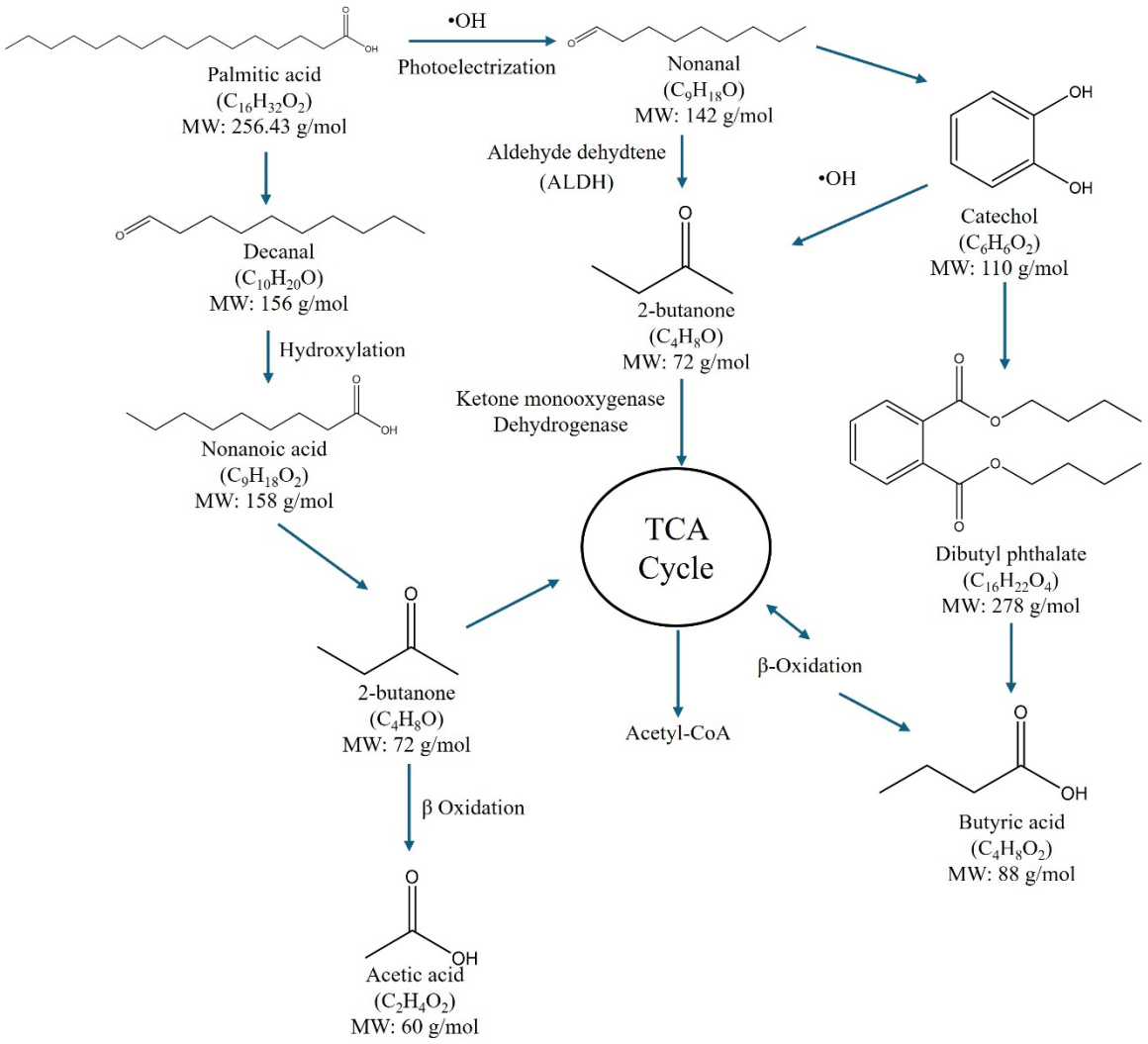


Figure 7. Proposed degradation pathway of dairy effluent
Abbreviations: MW: Molecular weight; TCA: Tricarboxylic acid.

3.9. Cost analysis

The present study employed a sequential PEO-BIO process to effectively remove contaminants from dairy effluent. An energy consumption and treatment cost analysis was performed to evaluate the economic feasibility of the integrated process. The specific energy consumption was estimated to be approximately 37.22 kWh/m^3 of treated effluent. The cost of treatment was INR 0.284 (approximately USD 0.00294) per liter. Thus, the total energy-related cost for treating 1,000 L of dairy effluent was INR 284.00 (approximately USD 2.94). The energy consumption and treatment cost analysis is summarized as follows:

Electrochemical treatment,

$$\text{Energy consumption, E (kWh/m}^3) = \frac{1}{V_s}\int_0^t VIdt \quad (12)$$

where V represents average voltage (V), I represents applied current (A), t represents total time (h), and V_s represents volume of sample treated (L).

The volume of working solution = 1 L

E = 37.22 kWh/m^3 (30 mA/cm^2)

Cost of one unit = INR 7.65 (industrial rate)

Treatment cost = INR 0.284 per liter

3.10. Toxicity assessment

The ECOSAR predictions revealed significant variability in toxicity among the identified compounds, as shown

Table 2. Gas chromatography–mass spectrometry analysis of treated and untreated effluent

No.	Retention time (min)	Compound	Chemical formula	Molecular weight (g/mol)
Control				
1	7.718	Palmitic acid	($C_{16}H_{32}O_2$)	256.43
2	12.586	Dibutyl phthalate	($C_{16}H_{22}O_4$)	278.35
Biodegradation				
3	12.619	Butyric acid	($C_4H_8O_2$)	88.11
PEO				
4	10.510	Nonanoic acid	($C_9H_{18}O_2$)	158.24
5	14.618	Decanal	($C_{10}H_{20}O$)	156.27
6	12.619	Nonanal	($C_9H_{18}O$)	142.24
7	5.271	Catechol	($C_6H_6O_2$)	110.11
PEO-BIO				
8	7.760	2-butanone	(C_4H_8O)	72.11
9	4.114	Acetic acid	($C_2H_4O_2$)	60.05

Abbreviations: PEO-BIO: Photo-assisted electrochemical oxidation with biodegradation; PEO: Photo-assisted electrochemical oxidation.

in Table 3. Acute toxicity values showed that long-chain fatty acids such as hexadecanoic acid (LC_{50} for fish = 0.074 mg/L; LC_{50} for daphnid = 0.066 mg/L), octadecanoic acid (LC_{50} for fish = 0.011; LC_{50} for daphnid = 0.011 mg/L), and oleic acid (LC_{50} for fish = 0.017; LC_{50} for daphnid = 0.016 mg/L) exhibited high toxicity, particularly toward daphnids and fish. Similarly, hydrophobic compounds such as 1H-indene (trans-2,2,4,4,7,7-hexamethyloctahydro-1H-indene) (LC50 = 0.019–0.023 mg/L; EC_{50} = 0.0074 mg/L) and phenol (3,5-di-tert-butylphenol) compound (LC_{50} = 0.144–0.281 mg/L; EC_{50} = 0.206 mg/L) also showed significant toxicity. In contrast, low-molecular-weight acids such as acetic acid ($LC_{50} = 1.23 \times 10^4$–$2.58 \times 10^4$ mg/L; $EC_{50} = 4.40 \times 10^3$ mg/L), propionic acid ($LC_{50} = 5.74 \times 10^3$–$1.15 \times 10^4$ mg/L; $EC_{50} = 2.48 \times 10^3$ mg/L), butyric acid ($LC_{50} = 2.59 \times 10^3$–$4.96 \times 10^3$ mg/L; $EC_{50} = 1.35 \times 10^3$ mg/L), and oxalic acid ($LC_{50} = 6.75 \times 10^4$–$1.68 \times 10^5$ mg/L; $EC_{50} = 1.21 \times 10^4$ mg/L) exhibited negligible toxicity due to their high solubility and biodegradability.

Chronic toxicity values further highlight the ecological risks at lower concentrations. Octadecanoic acid (LC_{50} for fish = 0.0020 mg/L; LC_{50} for daphnids = 0.0047 mg/L) and oleic acid (LC_{50} for fish = 0.0030; LC_{50} for daphnids = 0.0068 mg/L) showed high chronic toxicity. Hexadecanoic acid also showed notable chronic effects (LC_{50} = 0.012–0.023 mg/L). A moderate degree of chronic toxicity was observed for compounds such as butylated hydroxytoluene (LC_{50} = 0.033–0.078 mg/L) and phenolic derivatives (LC_{50} = 0.020–0.055 mg/L). In contrast, simple acids showed high LC_{50} values (acetic acid: $LC_{50} = 2.05 \times 10^3$ mg/L), indicating minimal long-term risk. Overall, the results indicate that hydrophobic and long-chain compounds exhibit high acute and chronic toxicity, whereas simple organic acids are relatively non-toxic. Daphnids were consistently the most sensitive organisms, confirming their importance as bioindicators. These findings emphasize that certain metabolites can pose significant ecological risks despite degradation, highlighting the need to include toxicity evaluation in environmental assessments.

3.11. Toxicity effects

The morphological and physiological plant growth metrics

Table 3. Toxicity assessment for intermediates from the dairy effluent

Intermediate	Acute toxicity (mg/L)			Chronic toxicity (mg/L)		
	Fish (LC_{50})	Daphnid (LC_{50})	Green algae (EC_{50})	Fish (LC_{50})	Daphnid (LC_{50})	Green algae (EC_{50})
Hexadecanoic acid	0.074	0.066	0.327	0.012	0.023	0.238
Octadecanoic acid	0.011	0.011	0.076	0.0020	0.0047	0.067
Oleic acid	0.017	0.016	0.106	0.0030	0.0068	0.090
Cyclohexane (1-methyl ethyl)	0.587	0.420	0.813	0.075	0.078	0.356
Naphthalene, decahydro-, trans-	1.210	0.841	1.450	0.150	0.144	0.596
Phenol, 3,5-bis(1,1-dimethylethyl)	0.144	0.281	0.206	0.020	0.055	0.067
1H-indene, octahydro-2,2,4,4,7,7-hexamethyl-, trans-	0.023	0.019	0.0074	0.0035	0.0057	0.047
Butylated hydroxytoluene	0.248	0.422	0.352	0.033	0.078	0.107
Carbonic acid, dodecyl vinyl ester	0.121	0.212	0.050	0.013	0.059	0.022
Oxalic acid	1.680×10^5	6.750×10^4	1.210×10^4	1.090×10^4	2.520×10^3	1.470×10^3
6-ethyloct-3-yl ethyl ester	2.310	1.600	2.750	0.286	0.274	1.130
Nonanal	8.420	5.380	6.510	0.946	0.727	2.210
Decanal	0.140	0.107	0.277	0.020	0.024	0.142
2-butanone	2.180×10^3	1.050×10^3	404.000	176.000	65.700	73.900
Acetic acid	2.580×10^4	1.230×10^4	4.400×10^3	2.050×10^3	732.000	778.000
Propionic acid	1.150×10^4	5.740×10^3	2.480×10^3	965.000	388.000	485.000
Butyric acid	4.960×10^3	2.590×10^3	1.350×10^3	438.000	199.000	292.000

Abbreviations: EC_{50}: Effect concentration, 50%; LC_{50}: Lethal concentration, 50%.

of untreated and treated dairy effluent are shown in Tables 4–6. Untreated dairy effluent significantly inhibited plant growth, with markedly lower plant height (2.3 cm), relative growth rate (0.028 g g^{-1} d^{-1}), and net assimilation rate (2.6 g m^{-2} d^{-1}) than the control (5.9 cm, 0.066 g g^{-1} d^{-1}, and 6.2 g m^{-2} d^{-1}, respectively). This indicates severe phytotoxic effects, likely due to high organic load and toxic compounds. In contrast, treated effluent substantially improved growth performance, with plant height (5.0 cm), relative growth rate (0.058 g g^{-1} d^{-1}), and net assimilation rate (5.6 g m^{-2} d^{-1}) approaching control values, demonstrating effective reduction of toxicity. Similarly, leaf area index and leaf weight ratio were significantly reduced in the untreated system but recovered in the treated system, indicating restoration of photosynthetic efficiency and biomass allocation. Overall, the results confirm that dairy effluent treatment effectively mitigates phytotoxicity and enhances effluent suitability for plant growth, despite slight deviations from the control suggesting residual stress.

Table 4. Morphological and physiological plant growth metrics for the control system

Day	Plant growth (cm)	Stem length (cm)	Leaf length (cm)	Number of leaves	Relative growth rate (g g^{-1} d^{-1})	Net assimilation rate (g m^{-2} d^{-1})	Crop growth rate (g m^{-2} d^{-1})	Average growth rate (cm d^{-1})	Leaf area index	Leaf weight ratio (g g^{-1})
2	1.3 ± 0.2	1.0 ± 0.1	0.40 ± 0.05	2	0.048 ± 0.005	3.5 ± 0.3	2.3 ± 0.2	0.08 ± 0.01	0.18 ± 0.02	0.60 ± 0.04
4	2.4 ± 0.3	2.0 ± 0.2	0.80 ± 0.10	3	0.054 ± 0.005	4.2 ± 0.4	2.9 ± 0.3	0.12 ± 0.02	0.32 ± 0.03	0.58 ± 0.05
6	3.5 ± 0.4	3.0 ± 0.3	1.20 ± 0.10	4	0.059 ± 0.006	4.9 ± 0.5	3.5 ± 0.4	0.16 ± 0.02	0.48 ± 0.05	0.56 ± 0.04
8	4.8 ± 0.5	3.9 ± 0.3	1.50 ± 0.20	5	0.063 ± 0.006	5.6 ± 0.6	4.2 ± 0.4	0.20 ± 0.03	0.64 ± 0.06	0.54 ± 0.04
10	5.9 ± 0.6	4.7 ± 0.4	1.80 ± 0.20	6	0.066 ± 0.007	6.2 ± 0.6	4.8 ± 0.5	0.23 ± 0.03	0.80 ± 0.07	0.52 ± 0.03

Table 5. Morphological and physiological plant growth metrics for the untreated dairy effluent

Day	Plant growth (cm)	Stem length (cm)	Leaf length (cm)	Number of leaves	Relative growth rate (g g^{-1} d^{-1})	Net assimilation rate (g m^{-2} d^{-1})	Crop growth rate (g m^{-2} d^{-1})	Average growth rate (cm d^{-1})	Leaf area index	Leaf weight ratio (g g^{-1})
2	0.5 ± 0.1	0.4 ± 0.1	0.20 ± 0.05	1	0.020 ± 0.002	1.4 ± 0.2	1.0 ± 0.1	0.04 ± 0.01	0.07 ± 0.01	0.46 ± 0.03
4	1.0 ± 0.2	0.7 ± 0.1	0.40 ± 0.05	2	0.023 ± 0.003	1.7 ± 0.2	1.3 ± 0.2	0.06 ± 0.01	0.13 ± 0.02	0.45 ± 0.03
6	1.5 ± 0.3	1.0 ± 0.2	0.60 ± 0.10	2	0.025 ± 0.003	2.0 ± 0.3	1.6 ± 0.2	0.07 ± 0.01	0.18 ± 0.02	0.44 ± 0.04
8	1.9 ± 0.4	1.2 ± 0.2	0.70 ± 0.10	3	0.027 ± 0.004	2.3 ± 0.3	1.8 ± 0.3	0.08 ± 0.01	0.22 ± 0.03	0.43 ± 0.04
10	2.3 ± 0.5	1.3 ± 0.2	0.80 ± 0.10	3	0.028 ± 0.004	2.6 ± 0.4	2.0 ± 0.3	0.09 ± 0.01	0.25 ± 0.03	0.42 ± 0.03

Table 6. Morphological and physiological plant growth metrics for the treated dairy effluent

Day	Plant growth (cm)	Stem length (cm)	Leaf length (cm)	Number of leaves	Relative growth rate (g g^{-1} d^{-1})	Net assimilation rate (g m^{-2} d^{-1})	Crop growth rate (g m^{-2} d^{-1})	Average growth rate (cm d^{-1})	Leaf area index	Leaf weight ratio (g g^{-1})
2	1.0 ± 0.1	0.8 ± 0.1	0.30 ± 0.05	2	0.040 ± 0.004	2.9 ± 0.3	2.0 ± 0.2	0.07 ± 0.01	0.15 ± 0.02	0.54 ± 0.04
4	2.0 ± 0.2	1.6 ± 0.2	0.70 ± 0.10	3	0.046 ± 0.005	3.7 ± 0.4	2.7 ± 0.3	0.11 ± 0.02	0.30 ± 0.03	0.53 ± 0.04
6	3.0 ± 0.3	2.5 ± 0.3	1.00 ± 0.10	4	0.051 ± 0.005	4.4 ± 0.5	3.3 ± 0.4	0.15 ± 0.02	0.45 ± 0.04	0.52 ± 0.03
8	4.1 ± 0.4	3.3 ± 0.3	1.30 ± 0.20	5	0.055 ± 0.006	5.0 ± 0.5	3.9 ± 0.4	0.18 ± 0.03	0.60 ± 0.06	0.51 ± 0.03
10	5.0 ± 0.5	4.0 ± 0.4	1.60 ± 0.20	6	0.058 ± 0.006	5.6 ± 0.6	4.4 ± 0.5	0.21 ± 0.03	0.75 ± 0.07	0.50 ± 0.03

4. Conclusion

The sequential PEO-BIO process demonstrated its effectiveness and potential as a sustainable treatment of dairy effluent. The electrochemical pretreatment significantly enhanced the degradability of high-strength organic pollutants by generating reactive oxidizing species. This facilitated the breakdown of complex and recalcitrant compounds into simpler intermediates. Compared with conventional electrochemical oxidation, the PEO process performed better due to the synergistic action of UV irradiation and active radical species (•OH, Cl•, ClO•). Subsequent biodegradation using the indigenous bacterial strain *Enterobacter hormaechei* effectively mineralized the oxidized intermediates, leading to substantial reductions in COD and TOC levels. The integrated PEO-BIO achieved 92% COD (from 880 mg/L to 70.40 mg/L) and 88% TOC (from 736 mg/L to 88.32 mg/L) removal efficiency compared with individual processes. FTIR spectra and GC–MS analysis revealed the progressive elimination of aromatic, nitro, and halogenated functional groups, and the subsequent transformation of high-molecular-weight compounds such as fatty acids and phthalates into low-molecular-weight intermediates including aldehydes, ketones, and short-chain fatty acids. The intermediates were further metabolized during biological treatment. The ECOSAR and phytotoxicity analysis using *Vicia faba* demonstrated decreased ecotoxicity and growth-inhibitory toxicity in the transformation byproducts. The study concludes that the sequential PEO-BIO process is a promising, sustainable solution for treating dairy wastewater, with potential applicability in large-scale industrial systems. Further studies on process optimization, energy efficiency, and pilot-scale validation are recommended to evaluate its techno-economic feasibility for real-world applications.

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Conflict of interest

The authors declare they have no competing interests.

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Methodology: Elangovan Janani, Rajasekar Aruliah
Writing–original draft: Elangovan Janani
Writing–review & editing: Elangovan Janani, Rajasekar Aruliah

Availability of data

Data are available from the corresponding author upon reasonable request.

References

1. Douphrate DI, Hagevoort GR, Nonnenmann MW, *et al*. The dairy industry: a brief description of production practices, trends, and farm characteristics around the world. *J Agromedicine*. 2013;18(3):187-197.

   doi: 10.1080/1059924X.2013.796901

2. Fiorillo V, Amico BM. Milk quality and economic sustainability in dairy farming: a systematic review of performance indicators. *Dairy*. 2024;5(3):384-402.

   doi: 10.3390/dairy5030031

3. Tong T, Elimelech M. The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. *Environ Sci Technol*. 2016;50(13):6846-6855.

   doi: 10.1021/acs.est.6b01000

4. Tripathy S, Kar OP, Pradhan A. Challenges and innovations in industrial wastewater treatment: safeguarding water resources and promoting sustainable practices. *Water Air Soil Pollut*. 2025;236:92.

   doi: 10.1007/s11270-025-07742-4

5. Stasinakis AS, Charalambous P, Vyrides I. Dairy wastewater management in EU: produced amounts, existing legislation, applied treatment processes and future challenges. *J Environ Manage*. 2022;303:114152.

   doi: 10.1016/j.jenvman.2021.114152

6. Ye M, Li YY. Methanogenic treatment of dairy wastewater: a review of current obstacles and new technological perspectives. *Sci Total Environ*. 2023;866:161447.

   doi: 10.1016/j.scitotenv.2023.161447

7. Das PP, Paul KK. A review on different treatment possibilities of dairy wastewater. *Theor Found Chem Eng*. 2023;57(4):563-580.

   doi: 10.1134/S0040579523040346

8. Chand P. Environmental protection and regulations in India: role of the Central Pollution Control Board. *Indian J Public Adm*. 2018;64(4):645-663.

   doi: 10.1177/0019556118785427

9. Arif Z, Sethy NK, Swati, Mishra PK, Verma B. Grossly polluting industries and their effect on water resources in

India. In: Singh P, Singh R, Singh VK, Bhadouria R, eds. *Pollutants and Water Management: Resources, Strategies and Scarcity*. John Wiley & Sons; 2021:47-65.

doi: 10.1002/9781119693635.ch3

10. Mwirigi D, Fekete-Farkas M, Borbély C. From cow to climate—tracing the path of dairy sustainability: unveiling the impact on sustainable development goals through bibliometric and literature analyses. *Animals (Basel)*. 2025;15(7):931.

doi: 10.3390/ani15070931

11. Bosire C. *The Water and Land Footprints of Meat and Milk Production and Consumption in Kenya: Implications for Sustainability and Food Security*. Doctoral thesis. Enschede, Netherlands: University of Twente; 2016.

doi: 10.3990/1.9789036542463

12. Ahmad T, Aadil RM, Ahmed H, *et al*. Treatment and utilization of dairy industrial waste: a review. *Trends Food Sci Technol*. 2019;88:361-372.

doi: 10.1016/j.tifs.2019.04.003

13. Asgharnejad H, Khorshidi Nazloo E, Madani Larijani M, Hajinajaf N, Rashidi H. Comprehensive review of water management and wastewater treatment in food processing industries in the framework of water-food-environment nexus. *Compr Rev Food Sci Food Saf*. 2021;20(5):4779-4815.

doi: 10.1111/1541-4337.12782

14. Ramsuroop J, Gutu L, Ayinde WB, Basitere M, Manono MS. A review of biological processes for dairy wastewater treatment and the effect of physical parameters which affect their efficiency. *Water (Basel)*. 2024;16(4):537.

doi: 10.3390/w16040537

15. Al Jobair A, Kwoshik MMK, Ahmed T, *et al*. Comparative performance evaluation of chemical coagulants in dairy wastewater treatment: a multi-criteria decision-making approach. *Sci Rep*. 2026;16(1):13097.

doi: 10.1038/s41598-026-42339-9

16. Singh P, Mohanty SS, Mohanty K. Comprehensive assessment of microalgal-based treatment processes for dairy wastewater. *Front Bioeng Biotechnol*. 2024;12:1425933.

doi: 10.3389/fbioe.2024.1425933

17. Wu X, Nawaz S, Li Y, Zhang H. Environmental health hazards of untreated livestock wastewater: potential risks and future perspectives. *Environ Sci Pollut Res Int*. 2024;31:24745-24767.

doi: 10.1007/s11356-024-32853-6

18. Flayyih AI, Ali SK. Evaluation of the physical and chemical treatment of wastewater for the dairy industry. *J Eng*. 2022;28(10):1-12.

doi: 10.31026/j.eng.2022.10.01

19. Goli A, Shamiri A, Khosroyar S, Talaiekhozani A, Sanaye R, Azizi K. A review on different aerobic and anaerobic treatment methods in dairy industry wastewater. *J Environ Treat Tech*. 2019;7(1):113-141.

20. Kumar R, Goyal MK, Surampalli RY, Zhang TC. River pollution in India: exploring regulatory and remedial paths. *Clean Technol Environ Policy*. 2024;26(9):2777-2799.

doi: 10.1007/s10098-024-02763-9

21. Sravan JS, Matsakas L, Sarkar O. Advances in biological wastewater treatment processes: focus on low-carbon energy and resource recovery in biorefinery context. *Bioengineering (Basel)*. 2024;11(3):281.

doi: 10.3390/bioengineering11030281

22. Najafinejad MS, Chianese S, Fenti A, Iovino P, Musmarra D. Application of electrochemical oxidation for water and wastewater treatment: an overview. *Molecules*. 2023;28(10):4208.

doi: 10.3390/molecules28104208

23. Brillas E, Garcia-Segura S. Electrochemical advanced oxidation processes for real wastewater remediation: systems, performance, and generated oxidants. *ACS Electrochem*. 2025;1(11):2292-2316.

doi: 10.1021/acselectrochem.5c00311

24. Yaşar Çırak S, Öztürk D, Akyol A. Electrocatalytic oxidation of toxic wastewater using electrodes based on transition d-metal oxides. *Water Air Soil Pollut*. 2025;236(2):91.

doi: 10.1007/s11270-024-07727-9

25. Das AK, Reza A, Chen L. Optimization of pollutants removal from anaerobically digested dairy wastewater by electro-oxidation process: a response surface methodology modeling and validation. *J Appl Electrochem*. 2024;54(11):2415-2436.

doi: 10.1007/s10800-024-02113-z

26. Narenkumar J, Das B, Abilaji S, *et al*. Biosurfactant-assisted bio-electrokinetic enhanced remediation of heavy metal-contaminated soil. *Front Microbiol*. 2024;15:1458369.

doi: 10.3389/fmicb.2024.1458369

27. Velmurugan L, Pandian KD. Enhancing physico-chemical water quality in recycled dairy effluent through microbial consortium treatment. *Heliyon*. 2024;10(21):e39501.

doi: 10.1016/j.heliyon.2024.e39501

28. Satheeshkumar A, Duraimurugan R, Parthipan P, *et al*. Integrated electrochemical oxidation and biodegradation for remediation of a neonicotinoid insecticide pollutant. *ACS Omega*. 2024;9(13):15239-15250.

doi: 10.1021/acsomega.3c09749

29. Abilaji S, Narenkumar J, Das B, *et al*. Electrochemical oxidation of azo dyes degradation by RuO2-IrO2-TiO2 electrode with biodegradation *Aeromonas hydrophila* AR1

and its degradation pathway: an integrated approach. *Chemosphere*. 2023;345:140516.

doi: 10.1016/j.chemosphere.2023.140516

30. Wei W, Xu J, Chen W, Mi L, Zhang J. A review of sodium chloride-based electrolytes and materials for electrochemical energy technology. *J Mater Chem A*. 2022;10(6):2637-2671.

doi: 10.1039/D1TA09371A

31. Kumaraguru S, Pandiyan R, Narenkumar J, Vadakkan K, Rajasekar A. Electrochemical oxidation and biological degradation of azo dyes: mechanistic insights and efficacy in contaminant removal from industrial effluents. *J Indian Chem Soc*. 2025;102(12):102239.

doi: 10.1016/j.jics.2025.102239

32. Prakash AA, Sathishkumar K, AlSalhi MS, *et al*. Integrated approach of photo-assisted electrochemical oxidation and sequential biodegradation of textile effluent. *Environ Pollut*. 2022;307:119412.

doi: 10.1016/j.envpol.2022.119412

33. Duraimurugan R, Dhandapani P, Velu P, *et al*. Sequential approach of photoelectrochemical oxidation and biodegradation of reverse osmosis reject water from the tannery industry. *J Environ Chem Eng*. 2025;13(1):115078.

doi: 10.1016/j.jece.2024.115078

34. Chandrasekaran K, Selvaraj H, Sundaram M. Electrochemical oxidation with the aerobic pretreatment process for sulfate-rich tannery effluent. *Environ Sci Pollut Res Int*. 2019;26(12):12194-12204.

doi: 10.1007/s11356-019-04614-3

35. Martínez-Huitle CA, Rodrigo MA, Sirés I, Scialdone O. A critical review on latest innovations and future challenges of electrochemical technology for the abatement of organics in water. *Appl Catal B Environ*. 2023;328:122430.

doi: 10.1016/j.apcatb.2023.122430

36. Santhosh S, Narenkumar J, Vadakkan K, Nandini MS, Rajasekar A, Rajamohan R. *Enterobacter hormaechei* mediated biodegradation of PET: a sustainable approach to plastic waste. *Biodegradation*. 2025;36(5):88.

doi: 10.1007/s10532-025-10183-9

37. Kumar AS, Dhandapani P, Sivakumar L, *et al*. Mitigation of sulphate-reducing bacterial consortium induced corrosion on API 5LX carbon steel using bioactive compounds from *Capsicum annuum* fruit derivatives. *J Environ Chem Eng*. 2026;14(1):120483.

doi: 10.1016/j.jece.2025.120483

38. Barresi S, Marzo AC, Milani M. Constructed wetlands for dairy and livestock wastewater treatment: a review. *Water (Basel)*. 2025;17(24):3492.

doi: 10.3390/w17243492

39. Barbera M, Gurnari G. Water reuse in the food industry: quality of original wastewater before treatments. In: Barbera M, Gurnari G. *Wastewater Treatment and Reuse in the Food Industry*. Springer International Publishing; 2018:1-16.

doi: 10.1007/978-3-319-68442-0_1

40. Holohan BC, Duarte MS, Szabo-Corbacho MA, *et al*. Principles, advances, and perspectives of anaerobic digestion of lipids. *Environ Sci Technol*. 2022;56(8):4749-4775.

doi: 10.1021/acs.est.1c08722

41. Diamantis V, Eftaxias A, Stamatelatou K, Noutsopoulos C, Vlachokostas C, Aivasidis A. Bioenergy in the era of circular economy: anaerobic digestion technological solutions to produce biogas from lipid-rich wastes. *Renew Energy*. 2021;168:438-447.

doi: 10.1016/j.renene.2020.12.034

42. Souli I, Fernandes A, Lopes A, *et al*. Treatment of cheese whey wastewater by electrochemical oxidation using BDD, Ti/RuO2-TiO2, and Ti/RuO2-IrO2-Pt anodes: ecotoxicological and energetic evaluation. *Environ Sci Pollut Res Int*. 2025;32(11):7058-7069.

doi: 10.1007/s11356-025-36174-0

43. Bashir Y, Raj R, Ghangrekar MM, Nema AK, Das S. Critical assessment of advanced oxidation processes and bio-electrochemical integrated systems for removing emerging contaminants from wastewater. *RSC Sustain*. 2023;1(8):1912-1931.

doi: 10.1039/D3SU00112A

44. Nidheesh PV, Couras C, Karim AV, Nadais H. A review of integrated advanced oxidation processes and biological processes for organic pollutant removal. *Chem Eng Commun*. 2022;209(3):390-432.

doi: 10.1080/00986445.2020.1864626

45. Ibrahim AA, Oladipo AA, Gazi M. Electrochemical-based and hybrid technologies: remediation strategies and resource recovery from dairy wastewater. *ACS ES&T Water*. 2025;5(5):2041-2069.

doi: 10.1021/acsestwater.5c00031

46. Imperiale S, Morozova K, Ferrentino G, Scampicchio M. Analysis of milk with liquid chromatography–mass spectrometry: a review. *Eur Food Res Technol*. 2023;249(4):861-902.

doi: 10.1007/s00217-022-04197-3

47. Acquavia MA, Villone A, Rubino R, Bianco G. A comprehensive review of milk components: recent developments on extraction and analysis methods. *Molecules*. 2025;30(9):1994.

doi: 10.3390/molecules30091994

48. Bravo-Yumi N, Oller I, Ruiz-Delgado A, Pacheco-Álvarez MOA, Peralta-Hernández JM. Electrolyte-driven oxidant

generation on Ti/IrO2–SnO2–Sb2O5 electrodes for the efficient removal of alachlor and isoproturon from water. *Water (Basel)*. 2025;17(24):3472.

doi: 10.3390/w17243472

49. Pasindu V, Yapa P, Dabare S, Munaweera I. Multifunctional transition metal oxide/graphene oxide nanocomposites for catalytic dye degradation, renewable energy, and energy storage applications. *RSC Adv*. 2025;15(40):33162-33186.

doi: 10.1039/d5ra04806k

50. Struk-Sokołowska J, Rodziewicz J, Mielcarek A. Effect of dairy wastewater on changes in COD fractions in technical-scale SBR type reactors. *Water Sci Technol*. 2018;77(1):156-169.

doi: 10.2166/wst.2018.099

51. Das AK, Chen L. A review on electrochemical advanced oxidation treatment of dairy wastewater. *Environments*. 2024;11(6):124.

doi: 10.3390/environments11060124

52. Guo K, Wu Z, Chen C, Fang J. UV/chlorine process: an efficient advanced oxidation process with multiple radicals and functions in water treatment. *Acc Chem Res*. 2022;55(3):286-297.

doi: 10.1021/acs.accounts.1c00269

53. de Sousa DDP, Pinto CF, Tonhela MA, *et al*. Treatment of real dairy wastewater by electrolysis and photo-assisted electrolysis in presence of chlorides. *Water Sci Technol*. 2019;80(5):961-969.

doi: 10.2166/wst.2019.339

54. Pei L, Wang S, Tian Y, Zhu X, Ye Z, Huang X. Kinetics modeling for degradation of geosmin and 2-methylisoborneol by photo-electrogenerated radicals. *Water (Basel)*. 2025;17(1):57.

doi: 10.3390/w17010057

55. Kishimoto N. State of the art of UV/chlorine advanced oxidation processes: their mechanism, byproducts formation, process variation, and applications. *J Water Environ Technol*. 2019;17(5):302-335.

doi: 10.2965/jwet.19-021

56. Kumaraguru S, Pandiyan R, Narenkumar J, Ravi A. Chemically synthesized bimetallic Al-Ni nanoparticles as catalysts for photocatalytic degradation of organic pollutants in wastewater. *Environ Geochem Health*. 2026;48(1):19.

doi: 10.1007/s10653-025-02867-1

57. Singaravel V, Murali Y, Sekaran PT, *et al*. *Sesamum indicum* leaf mucilage-derived biogenic ZnO nanoparticles: synergistic antimicrobial activity and photocatalytic degradation of organic pollutants in wastewater. *Water Air Soil Pollut*. 2026;237(18):1036.

doi: 10.1007/s11270-026-09712-w

58. García-Espinoza JD, Zolfaghari M, Mijaylova Nacheva P. Synergistic effect between ultraviolet irradiation and electrochemical oxidation for removal of humic acids and pharmaceuticals. *Water Environ J*. 2019;34(2):232-246.

doi: 10.1111/wej.12456

59. Rim T, Xing Y, Kang M, *et al*. Microplastic pollution remediation: a comprehensive review on electrochemical advanced oxidation processes (EAOPs) for degradation in wastewater. *Environ Sci Water Res Technol*. 2025;11(12):2881-2905.

doi: 10.1039/D5EW00691K

60. Tirado L, Gökkuş Ö, Brillas E, Sirés I. Treatment of cheese whey wastewater by combined electrochemical processes. *J Appl Electrochem*. 2018;48(12):1307-1319.

doi: 10.1007/s10800-018-1218-y

61. Kumar AK, Sharma S, Patel A, Dixit G, Shah E. Comprehensive evaluation of microalgal based dairy effluent treatment process for clean water generation and other value added products. *Int J Phytoremediation*. 2019;21(6):519-530.

doi: 10.1080/15226514.2018.1537248

62. Valizadeh K, Davarpanah A. Design and construction of a micro-photo bioreactor in order to dairy wastewater treatment by micro-algae: parametric study. *Energy Sources Part A Recovery Util Environ Eff*. 2020;42(5):611-624.

doi: 10.1080/15567036.2019.1588425

63. Mostafapour FK, Tahsini MJ, Naseri M. Enhancing dairy wastewater treatment: evaluating the efficacy of chemical coagulation and photo-Fenton oxidation processes. *Appl Water Sci*. 2026;16(5):151.

doi: 10.1007/s13201-026-02811-3

64. Mahdaviarab A, Pahlavanyali K, Cheng R, *et al*. Emergency mass disposal of milk: options and considerations. *J Environ Manage*. 2025;376:124420.

doi: 10.1016/j.jenvman.2025.124420

65. Puri M, Gandhi K, Kumar MS. The occurrence, fate, toxicity, and biodegradation of phthalate esters: an overview. *Water Environ Res*. 2023;95(1):e10832.

doi: 10.1002/wer.10832

66. Fazli A, Athanassiou A, Fragouli D. Current approaches and challenges in advanced oxidation processes for nanoplastic degradation. *Adv Sci (Weinh)*. 2025;12(30):e04352.

doi: 10.1002/advs.202504352

67. Paiu M, Favier L, Gavrilescu M. Assessing the ecotoxicological effects of emerging drug and dye pollutants on plant-soil systems pre- and post-photocatalytic wastewater treatment. *Plants (Basel)*. 2025;14(24):3835.

doi: 10.3390/plants14243835

68. Dong J, Fernández-Fueyo E, Hollmann F, *et al*. Biocatalytic oxidation reactions: a chemist's perspective. *Angew Chem Int Ed Engl*. 2018;57(30):9228-9261.

doi: 10.1002/anie.201800343

69. Frey J. *Activation of Acetone by Sulfate-Reducing Bacteria: Pathway Elucidation and Enzyme Identification in Desulfococcus biacutus*. Doctoral thesis. Konstanz, Germany: University of Konstanz; 2017. Accessed October 13, 2026. https://kops.uni-konstanz.de/server/api/core/bitstreams/7e5fbeb1-7191-4149-9d1d-68f13cb17c6a/content

70. Panov AV, Mayorov VI, Dikalov SI. Role of fatty acids β-oxidation in the metabolic interactions between organs. *Int J Mol Sci*. 2024;25(23):12740.

doi: 10.3390/ijms252312740

71. Liu Y. *Sustainable Waste Management for Lipid-Rich Dairy Wastewater by Anaerobic Digestion*. Doctoral thesis. Galway, Ireland: University of Galway; 2023.

doi: 10.13025/16310

72. Ningthoujam R. *Degradation of Di (2-Ethylhexyl) Phthalate by Marine Sediment Bacteria and Identification of Key Degraders and Degradative Genes*. Doctoral thesis. Bangkok, Thailand: Chulalongkorn University; 2022. Accessed October 13, 2026. https://digital.car.chula.ac.th/chulaetd/9967

73. Markowiak-Kopeć P, Śliżewska K. The effect of probiotics on the production of short-chain fatty acids by human intestinal microbiome. *Nutrients*. 2020;12(4):1107.

doi: 10.3390/nu12041107

74. Duraimurugan R, Vignesh K, Sahasra C, Parthipan P, Narenkumar J, Rajasekar A. Characterization of halophilic bacteria *Vreelandella piezotolerant* DM1 on biodegradation of polyaromatic hydrocarbons and its pathway. *Water Air Soil Pollut*. 2025;236:807.

doi: 10.1007/s11270-025-08449-2

75. Duraimurugan R, Santhosh S, Mohamed Hanifa SH, *et al*. Elucidating the mechanisms of anthracene and phenanthrene degradation by the halophile *Vreelandella piezotolerant* DM1. *Extremophiles*. 2026;30(1):1.

doi: 10.1007/s00792-025-01414-1