Dairy Wastewater as a Potential Feedstock for Valuable Production with Concurrent Wastewater Treatment through Microbial Electrochemical Technologies

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Abstract: A milk-processing plant was drafted as a distinctive staple industry amid the diverse field of industries. Dairy products such as yogurt, cheese, milk powder, etc., consume a huge amount of water not only for product processing, but also for sanitary purposes and for washing dairy-based industrial gear. Henceforth, the wastewater released after the above-mentioned operations comprises a greater concentration of nutrients, chemical oxygen demand, biochemical oxygen demand, total suspended solids, and organic and inorganic contents that can pose severe ecological issues if not managed effectively. The well-known processes such as coagulation–flocculation, membrane technologies, electrocoagulation, and other biological processes such as use of a sequencing batch reactor, upflow sludge anaerobic blanket reactor, etc., that are exploited for the treatment of dairy effluent are extremely energy-exhaustive and acquire huge costs in terms of fabrication and maintenance. In addition, these processes are not competent in totally removing various contaminants that exist in dairy effluent. Accordingly, to decrease the energy need, microbial electrochemical technologies (METs) can be effectively employed, thereby also compensating the purification charges by converting the chemical energy present in impurities into bioelectricity and value-added products. Based on this, the current review article illuminates the application of diverse METs as a suitable substitute for traditional technology for treating dairy wastewater. Additionally, several hindrances on the way to real-world application and techno-economic assessment of revolutionary METs are also deliberated.

Keywords: bioelectrochemical system; dairy wastewater; microbial fuel cell; microbial electrochemical system; wastewater treatment

1. Introduction

Industrial pollution is a gigantic global concern that is triggering environmental deterioration and polluting the air, water, and food around us. With the excessive ingestion of water and the increase in the effluent generation per unit of product manufactured, food-processing industries have created a significant impact from an ecological perspective [1]. Specifically, among the food-processing industries recently, the dairy sector has witnessed massive progress due to the escalating demand for milk and dairy products globally [2]. According to the International Dairy Federation’s World Dairy Situation 2016, 800 MT of milk was produced worldwide, which was 2% higher than the production rate of 2014 [3]. In addition, with the increasing demand, the quantity of effluent released from the dairy sector has also increased; i.e., about 2 to 2.5 L of wastewater is discharged for each 1 L of milk processed [4]. This dairy effluent comprises proteins, fats, milk carbohydrates, nutrients, and other cleaning solutions that contribute to the pollution load. Usually, dairy wastewater is found to have characteristics such as a chemical oxygen demand (COD) that varies from 80,000 to 90,000 mg/L and a biochemical oxygen demand (BOD) of around 50,000 to 45,000 mg/L, high total suspended solids (TSS) of about 25,000 to 45,000 mg/L, and a
varying pH that ranges between 4 and 10 [5–7]. The existing wastewater management machinery is inefficient for eliminating all these contaminants at one time; as a result, partially treated water is discharged into the environment. In addition, due to a lack of proper rules and regulations, a considerable quantity of effluent is discharged into the environment without providing the required treatment, which can further result in adverse environmental impacts such as eutrophication, massive depletion of oxygen, etc. Therefore, dairy wastewater requires appropriate treatment before being disposed into the environment [8,9]. Further, if strategies such as zero-liquid discharge and reuse of treated water are implemented in the dairy industry, it would go a long way toward dealing with the issues associated with water pollution from this industrial sector [10,11].

Dairy effluents are also the basis for numerous emerging pollutants, especially estrogenic compounds containing hormones that end up in the environment with industrial discharges [4]. The destiny of these emerging pollutants is renowned as a matter of concern for civic well-being and ecology. In addition, dairy wastewater is characterized by extensive variations in volume and flow rates that are associated with incoherence in the diverse production cycles in a milk-processing unit. The highly mutable attributes of dairy effluent in terms of the pH and other characteristics such as the TSS make it challenging to select an efficient wastewater-treatment technology and scheme [12]. On the other hand, to align with the new discharge standards and implement the sustainable development goals, dairy plants have implemented an intricate treatment mechanism that has influenced the industry’s total expenses. For this reason, a vital requisite is to perceive a pioneering low-cost and sustainable technology that would aid in the accomplishment of all these objectives.

Treatment of dairy effluents comprises the utilization of physicochemical and biological treatment technologies. Among the physicochemical processes, methods such as membrane technologies, coagulation–flocculation, etc., are adapted [13], whereas the biological processes comprise both aerobic and anaerobic processes such as the activated sludge process, lagoons, sequencing batch reactors (SBRs), upflow anaerobic sludge blankets (UASB), etc. [12,14]. Nevertheless, with the limitation of soluble COD removal through physicochemical methods and higher reagent costs, the preference for biological methods in the dairy industry has risen immensely recently. However, these traditional processes are associated with several drawbacks that include colossal capital costs/energy demands and substantial sludge production. The huge energy demands of these treatment facilities have also furthered the need for alternate wastewater-management techniques that are economical and necessitate limited energy for operation.

In this veneration, microbial electrochemical technologies (METs) have gained attention from scholars due to the opportunity to yield energy and valuables such as bioenergy, hydrogen, etc., from wastewater along with pollution remediation. In 1911, for the first time, an English botanist Potter expressed the capability of microbes to develop energy from their dynamic activities. In his study, he measured the potential of a galvanic cell using *Saccharomyces cerevisiae* and *Escherichia coli*, and ascribed his interpretations to the breakdown of organic matter [15]. Further, in 1931 Cohen established that by using necessary electron acceptors such as potassium ferricyanide, etc., the cell reactions could be sustained, thereby increasing the cell potential [16]. In the early 1960s, a proof of principle for energy production via diverse microbes was established that stated that the enzymatic action of the bacterial culture results in the generation of an overall cell voltage; the term microbial fuel cell (MFC) was coined for this process [17,18]. Conversely, only in the 1990s did the MFC-derived technologies, which are frequently mentioned as microbial electrochemical technologies (METs), attain communal consideration and show increasing signs of progress in publications due to their inherent advantage of the usage of microbes for value-added product recovery from waste [19,20].

METs are an amalgamation of technologies that can transform the chemical energy present in organic matter into electrical energy and valuables such as H₂, acetate, etc. [21]. A typical MET setup consists of two electrodes; namely, the anode and cathode, separated using a cation or anion exchange membrane (AEM). From an application point of view,
METs are categorized as MFCs for the simultaneous wastewater treatment and bioenergy production, as microbial electrolysis cells (MECs) majorly for the production of H₂, as microbial desalination cells (MDCs) for desalination along with bioenergy recovery, as microbial carbon capture cells (MCCs) for carbon sequestration with bioenergy and biofuel recovery, and as microbial electrosynthesis (MES) for recycling carbon dioxide to commodity chemicals [22–24].

Usually, the energy generation of METs is majorly associated with the ability of microbial catalysts to oxidize the organic substrate and discharge electrons. As a result, the substrate composition and characteristics highly impact the evolution of the bacterial community and therefore the performance of METs in terms of efficiency and yield of valuables [25]. Therefore, this state-of-the-art review concisely narrates the practicality of employing METs as a prospective choice for generating valuables from dairy wastewater, thus demonstrating a circular economy. Further, it also discusses the challenges involved, system configurations, and strategies for improving the efficiency of METs to cultivate a better understanding of this innovative technology among budding researchers. In addition, the current review article provides information on all the processes involved in a typical dairy industry as well as the sources and categories of dairy wastewater along with their characteristics. Moreover, the environmental impact and techno-economic assessment of METs and future forecasts are also deliberated in this review. To the best of our knowledge, there is no prior review article that focused on the application of METs for dairy wastewater treatment. The current review article is compared with other review articles that elucidated the treatment of different types of wastewater such as petrochemical wastewater in Table 1. The crystal-clear comparison proves that this review is a comprehensive article that provides detailed information on different aspects of METs in treating dairy wastewater. Therefore, there lies a lacuna in exploiting the use of METs for dairy wastewater management, so the present state-of-the-art review aimed to bridge this by connecting the dots starting from the origin of dairy wastewater to different treatment procedures employed for dairy effluent management, including its treatment through METs with concomitant value-added product recovery. Therefore, this review will serve as a guidebook for researchers and scientists who work in the domain of METs and the dairy industry that will abet them in designing a more efficient MET-based wastewater treatment scheme for the dairy industry.

Table 1. Detailed comparison of information covered in different review articles pertaining to the treatment of different pollutants.

<table>
<thead>
<tr>
<th>Review Article Reference</th>
<th>Type of Pollutant Covered</th>
<th>Prevailing Technologies for Pollutant Treatment</th>
<th>Application of METs for Pollutant Removal</th>
<th>Electrode Modifications</th>
<th>Membrane Modifications</th>
<th>Different Configuration for Pollutant Treatment</th>
<th>Integrated System Approach</th>
<th>Circular Economy in METs</th>
<th>Environmental Impact Assessment of METs</th>
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<tr>
<td>[26]</td>
<td>Heavy metals</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
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<td>[27]</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>[28]</td>
<td>Perchlorate and nitrate</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<tr>
<td>[29]</td>
<td>Nitrogen removal</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
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</tr>
<tr>
<td>[22]</td>
<td>Petrochemical wastewater</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Current review</td>
<td>Dairy wastewater</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

2. Characteristics of Dairy Wastewater and Pollutants Present

Water plays a key role in the unit operations of milk processing, including in cleaning, washing, sterilization, pasteurizing, cooling, heating, and other processes required for the preparation of dairy products [12,30]. As a result, the dairy industry consumes a huge amount of water to manufacture milk-based products, which results in an increase in dairy wastewater generation. Approximately 50–80% of the total water consumed in a dairy
factory is transformed into wastewater, which includes sanitary wastewater, whereas the remaining 20–50% is provisionally clean and can be used for cleaning equipment, watering lawns, etc. [12]. The amount of wastewater produced by the dairy industry is around 2.5 times higher than the amount of milk processed, and the organic compounds present in effluent differ according to the composition of the product and the process used therein [12]. Especially in the process of manufacturing ghee, commonly known as clarified butter, the generated wastewater contains a high amount of carbohydrates and proteins along with the presence of a higher level of lipids. Furthermore, dairy wastewater is also composed of nitrogenous compounds as well as other complex organic matter such as carbohydrates, lipids, and proteins [30]; it also contains soluble and trace organics in addition to suspended solids [31], which increases the BOD and chemical oxygen demand (COD) of the industrial effluent. Dairy effluents are whitish in colour and possess a slightly alkaline pH that ranges from 6.5 to 8.0; however, dairy wastewater can sometimes also be acidic due to the rapid fermentation of sugar-producing lactic acid in milk [31].

Dairy effluent can be characterized based on the temperature, color, pH, dissolved oxygen (DO), BOD, COD, dissolved solids, suspended solids, chlorides, sulfate, oil, and grease. Both the quality and quantity of dairy effluent is largely dependent on the quantity of milk processed and the type of products manufactured [32]. Wastewater effluent from the dairy industry comprises hefty quantities of milk ingredients such as casein and inorganic salts as well as cleansers and sanitisers that are used for washing purposes [31]. As there is a wide variety of products manufactured in the dairy industry, the characteristics and quantity of the wastewater generated by a plant also vary considerably [33]. However, based on the origin and composition of the wastewater, dairy effluent can be divided into three main categories, which are presented in the subsequent section.

2.1. Processing Water

The processing water is polluted water formed from the cooling of milk in coolers and condensers as well as condensates from the milk or whey evaporations [12]. Moreover, while drying milk and whey, vapors are produced. These are among the cleanest dairy effluents; however, milk or whey droplets, along with volatile substances originating from evaporators, might also be present in the effluent [32]. In processing water, pollutants are absent and thus, after negligible pretreatment, it can be discharged with stormwater or reused to augment the water supply for milk processing [31]. The reuse of treated wastewater is conceivable in installations that are not in direct contact with the finished products; it can be applied in hot water and steam production as well as in the cleaning of the membrane used in the clarification of milk and in the separation of the specific valuable components from milk and/or dairy byproducts [34]. Further, the water produced from the cooling of products during pasteurization can be used for the cleaning of rooms, lawn irrigation, etc.

2.2. Cleaning Wastewater

Cleaning wastewater is produced while washing equipment that is directly in contact with milk and/or dairy products [12]. Cleaning wastewater contains spillage products. milk, brine, whey, clean in place (CIP) wastes, and discharges initiated from equipment malfunctions and operational errors [35]. More than 90% of the organic solids present in dairy effluent originate from milk and manufacturing residues such as cheese pieces, cream, whey, water originating from separation and clarification of suspended solids and color, starter cultures, yogurt, fruit concentrates, or stabilizers [12]. Therefore, appropriate treatment is required for this moderately polluted cleaning water prior to its reuse or disposal.

2.3. Sanitary Wastewater

Sanitary wastewater present in dairy wastewater comes from lavatories, shower rooms, etc., used by staff and workers. The composition of sanitary wastewater is like that of
municipal wastewater and is disposed of into the sewerage system directly [12,31]. For unbalanced dairy effluents before secondary aerobic treatment, sanitary wastewater can be used as a source of nitrogen [35]. A more detailed discussion of the various processes involved in the dairy industry with their respective wastewater quantities and characteristics is elucidated in a later section.

3. Environmental Impacts from the Discharge of Dairy Wastewater

Wastewater that originates from dairy industries contains cleaning chemicals such as nitric acid and sodium hydroxide, milk, and other wastes produced during the different operations of the dairy industry [31]. These contaminants increase the organic content of the wastewater and also make it slightly alkaline when fresh and thus are characterized as having a high organic load (COD in the range of 1500 to 3000 mg/L and BOD$_5$ of 1000 to 1900 g/L), nitrogen content (70 to 100 mg/L), and phosphorus content (10 to 60 mg/L) that are much higher than the discharge limits [31]. Therefore, dairy wastewater must be treated efficiently prior to disposal into the environment because it contains a higher load of harmful substances that can adversely affect the natural ecosystem [12,31,36–38].

The major problem with milk production is that it affects the air, water, and biodiversity, which often causes the growth of algae and bacteria that can consume oxygen from water bodies and choke rivers, which leads to the gradual disappearance of fishes [39]. Correspondingly, bacteria and other pathogens present in dairy wastewater can spread harmful diseases such as tuberculosis. Along with these issues, wastewater originating from the dairy industry also imparts turbidity to the receiving water bodies due to its high solid content. Milk waste contains significant quantities of soluble organics, suspended solids, and trace organics that release gases, spread odors, and impart turbidity and color to the discharged effluents [30,31]. However, the dairy waste should be discharged in a fresh condition; otherwise, it may cause the corrosion of sewers because dairy waste becomes acidic via the decomposition of lactose into lactic acid in an anaerobic condition, which causes rapid DO depletion [40]. In addition to the water streams, dairy effluent also affects the land because the application of wastewater on the soil is the most common method of wastewater management followed in the dairy industry. In the process of the disposal of nitrogen-rich wastewater on the soil, nitrate contamination of the groundwater can occur; if the groundwater is subsequently used for water supplies, it might be problematic for humans and can lead to various threatening diseases such as blue baby syndrome, congenital disabilities, an increased risk of colon cancer, etc. [41].

Similarly, during manufacturing operations, numerous toxic gases such as CO$_2$, SOx, NOX, etc., are emitted by the dairy industry into the atmosphere. Emissions of CO$_2$, SOx, and NOx into the atmosphere take place from boiler stacks. Further, the emission of methane can also take place from anaerobic treatment systems and sites irrigated with wastewater, whereas nitrous oxide is emitted from the soil. In this regard, CO$_2$, methane, and nitrous oxide released by the dairy industry are greenhouse gases, which lead to adverse global consequences. Furthermore, boiler stacks and powder driers also emit particulate matter, which results in the formation of a dust coating on the surrounding infrastructures that might be objectionable and corrosive. Smoke and steam plumes from dairy industries may also be observed and can lead to visual pollution [31,40]. Therefore, all these adverse environmental impacts that arise from the dairy industry warrant the employment of appropriate technologies to counter them.

4. Processes from Which Wastewater Is Generated with Characteristics

The dairy industry is a primary food-processing industry that utilizes a large amount of water in each step of its operation. In the dairy industry, a wide variety of products such as pasteurized milk, curd, cheese, butter, etc., are processed [42–44]; as a result, a huge volume of wastewater is generated that is eventually discharged into the environment [3,4]. Therefore, it is important to develop strategies for the treatment of dairy wastewater that will reduce the stress on the environment that arises due to the discharge of this polluted
industrial wastewater. For this reason, it is essential to identify how milk and its products are processed in the dairy industry as well as the sources and characteristics of the wastewater produced at each stage.

Primarily, the processes in the dairy industry are conducted in two major areas: the milk yield from farmhouses or from producers, which includes the guardianship of cattle such as cows, buffaloes, etc.; and the milk-processing unit to extend the marketable life of milk. The processing of milk is the most prominent activity in the production and packaging of milk. Milk processing is attained through: (a) the pasteurization of milk to ensure safety for further applications and to extend the shelf life of milk [45]; and (b) making a wide range of milk foods to store them either in a semi-dried or dried form. In some parts of the dairy industry in which there is a more than adequate milk supply, other products such as butter, ghee, whey, cream, ice cream, milk powder, yogurt, cheese, etc., are also produced [46,47]. Recently, butter and cheese production has been growing throughout the world and as a result, wastewater generation from the dairy industry is also on the rise.

4.1. Operations Involved in Milk Processing

A series of processes containing milk reception and storage, processing of milk into targeted products, packing and storage of finished products, and a set of additional actions such as cooling and cleaning are a few processes that are carried out in the processing of milk [2]. The particulars of processes executed in the dairy industry are discussed below.

4.1.1. Milk Reception and Storage

Regardless of the product targeted, every single unit in the dairy industry has a division in which the milk is transported to the receiving unit and preserved in silos for further processing. The milk containers are delivered from farms to the receiving unit, then the contents are emptied into a reception chamber followed by the immediate testing of the samples. After the milk is delivered, the silos or storage tanks are employed for the storage of milk for further processing. Milk storage aids in harmonizing the diverse volumes amid the milk-receiving and -processing stages and thus functions like the equalization tank frequently employed in a wastewater treatment plant. Typically, stainless steel or fiberglass storage units with capacities that vary from 20 to 200 m$^3$ are set up outdoors in the industry for the storage of milk [48]. At this stage, the wastewater arises from the leakages of tanks and from the washing and disinfection of milk containers, silos, trucks, and pipelines. Most of the effluent at this phase contains milk solids, detergents, and disinfectants.

4.1.2. Processing of Milk into Dairy Products

In both developed and developing countries such as Europe, North America, India, etc., milk is pasteurized and further de-creamed using centrifuge machines to isolate the suspended solids from the milk. Pasteurization is attained by subjecting the milk to a higher temperature of around 60 °C for 30 min and then cooling it to 4 °C [49]. Next, the sterilized milk is either sent to a packaging unit for distribution or for further processing to make dairy products. Butter is another product that is made from churning cream that is separated from milk by means of centrifugation. However, the process of making butter is quite varied in developed and developing countries, which can alter the characteristics of the wastewater generated [50]. During these processes, the wastewater generated by cooling systems and the cleaning of milk containers, storage units, etc., requires an effective treatment if reused or to safely dispose of it into water bodies [51].

Cheese is the other dairy product whose manufacturing processes usually include several steps such as milk coagulation; cutting, cooking, and molding of curd after draining the whey; and then hard mold pressing for perfect shaping and packing. The process of cheese making produces whey, which is the liquid part left in the process; given the environmental concerns, the whey produced during the curd formation is quite important due to its high organic and saline content [52]. The quantity of whey varies for distinct types
of cheese produced; hard cheese produces a higher amount of whey, whereas soft cheeses produce either a lower quantity or no whey. Around the globe, there are 500 varieties of cheese made for different utilization purposes that require different kinds of production methods [52,53]. Therefore, the characteristic of the effluent during each targeted process differs according to the different methods used as well as the kind of milk processed.

Ice cream, one of the most famous milk-based desserts, comprises carbohydrates and fats. In addition, to make ice cream, a few essences or flavorings, sweeteners, and thickeners are blended with de-creamed milk to form a homogenous mixture [54]. Next, the mixture is sterilized and chilled and then sent to the packaging unit. Unsweetened condensed milk is another dairy food that is very thick; to produce unsweetened condensed milk, the receiving milk is evaporated at elevated temperatures and normalized to produce condensed milk without sugars. Furthermore, khoa, a prevalent product used to make a wide variety of sweets on the Indian subcontinent, is typically made via a process of the thermal evaporation of milk to reach at least 60% of its initial volume [55]. Another product of the dairy industry is milk powder; to manufacture it, the milk is subjected to vacuum evaporation followed by spray drying.

As water plays a significant role in all milk-processing operations, the resultant wastewater is huge in quantity and is almost 80% of the total water consumed in the dairy industry. In terms of the volume, the wastewater is approximated to be more than 2.5 times that of the milk processed in a factory [12]. In addition, sudden volumetric variations in effluent are commonly observed in the dairy industry due to the separate network lines for each milk product. The system of separate network lines can alter the wastewater composition with the onset of every new operational cycle. Wastewater from all of the above-mentioned operations is produced during the washing of the units and the cleaning of the tools employed. Wastewater comprising detergents, cleansers, and disinfectants is produced during the cleaning of all the production units, which calls for efficacious treatment of this wastewater prior to its disposal.

4.2. Dairy Effluent Composition

Among the important parameters used in wastewater engineering, dairy wastewater typically demonstrates a high organic load in terms of BOD and chemical oxygen demand (COD) that ranges from 0.1 kg/m$^3$ to 100 kg/m$^3$ with an average BOD$_5$/COD ratio between 0.4 and 0.8. The major contributors to the high organic load in the effluent are carbohydrates and proteins such as lactose, casein, etc., due to the oozing of milk and dairy products into wastewater. Moreover, fats ranging from 0.1 to 10.6 kg/m$^3$ and nutrients such as nitrogen and phosphorus are also prevalent in dairy wastewater [52]. The key factors that influence the composition and concentration of dairy wastewater are the operations performed, the processing of different dairy products, the water-management strategies implemented, and the design of the dairy industry. Typically, the dairy industry uses the CIP scheme for washing equipment and tools by employing caustic soda, sodium hypochlorite solutions, acids such as nitric acid, etc.; all of these chemicals end up in the wastewater [3]. These reagents affect the quantity and pH of the wastewater and also contribute about 10% to the wastewater COD. Further, the inclusion of different operations such as cheese making, butter production, etc., in a factory can result in the production of wastewater with varied characteristics. However, dairy effluent can be majorly divided into three main categories based on its source and contents; these will be described subsequently.

A huge amount of water is employed in chilling warm milk or other dairy products by means of condensers or chillers, which results in the formation of process water. This process water also includes the condensates produced after the evaporation of milk or whey at various stages. These condensates, which are one of the least polluted wastewaters generated in the dairy industry, contain a few dairy drops collected from evaporators along with a few volatile compounds such as decanoic acid, octanoic acid, etc. [42,56]. Broadly speaking, the process water contains negligible organic contaminants and with minimum pretreatment, the effluent can either be reused for chilling or can be safely discharged into
the environment. Classic reuses this water include the production of steam and washing of membranes used in membrane separation processes such as reverse osmosis, nanofiltration, etc. [57]. Further, the liquid used for the chilling of products throughout the sterilization and the condensates produced during thermal evaporation can be reused for irrigation, cleaning of rooms, etc. [58].

Cleaning wastewater commonly originates from scrubbing and cleaning apparatus and tools that are in contact with milk or processed food. Cleaning wastewater consists of CIP discharges; milk and dairy product residues such as cheese, yogurt, etc.; and some byproducts such as whey or whey permeates that are formed during cheese making. More than 90% of the cleaning effluent comprises milk because the loss of milk during operations is 2.5% of the processed milk and sometimes can be as high as 4% [2]. This wastewater is generated in huge volumes and is highly contaminated with organics and nutrients; therefore, it requires an effective treatment before disposal.

Sanitary wastewater in the dairy industry is the wastewater released from sanitary conveniences such as toilets, lavatories, etc. It is pumped out into the sewage-collection system because it has similar characteristics to those of municipal wastewater. Further, sanitary wastewater can be employed as a nitrogen source to balance the nitrogen deficit present in dairy wastewater when it is subjected to aerobic treatment. However, in an investigation by Danalewich and co-workers, a survey of a few milk-processing plants in various places in the USA, such as Minnesota, South Dakota, etc., regarding the mixing of both sanitary and dairy wastewater was conducted [59]. The study proved that the separation of sanitary wastewater from dairy wastewater during treatment assisted in reducing the concern with the disposal of produced sludge that contained pathogenic microbes. Hence, it is advisable to separate sanitary wastewater from dairy wastewater and opt for onsite treatment of the same.

The other option for effective dairy wastewater treatment could be to incorporate a separate collection system for byproducts such as whey and whey infiltrates, as they are the primary pollutants of the industry [60,61]. The critical contaminant in dairy effluent is the whey produced during cheese making, which is remarkably high in both organic and volumetric load. Thus, whey being a nutrient-rich effluent can cause eutrophication and excessive oxygen depletion when released into the environment without appropriate treatment. Typically, whey alone comprises lactose of around 4–5%, proteins and lactic acid together of around 1%, fats of less than 0.5%, and a varied salt content of 1.5 to 3% [12,62]. Since the BOD5/COD ratio for whey is higher than 0.5, whey can be treated using biological processes. However, without a proper control of biological processes employed for whey treatment, the decomposition of proteins can result in a foul odor. Therefore, understanding the characteristics of milk and dairy products can abet a better estimation of the organic load present in dairy wastewater and further guide in designing the required treatment units. Although dairy plants produce wastewater that is equivalent in characteristics to the milk and dairy products manufactured, every single process discharges effluent with unique characteristics and quantity, which calls for a specially designed treatment scheme prior to its disposal (Table 2).

Among the vital parameters, an optimal pH for effective wastewater treatment is imperative. Though most of the operational units in the dairy industry produce neutral pH effluents, the plants with a whey discharge tend to create wastewater with an acidic pH of less than 6, which is due to the acidic coagulation process incorporated in cheese making, from which whey is generated as a byproduct. Further, if a sudden hike in pH up to 10 is observed in the effluent, it can be attributed to the discharge of detergents and disinfectants after cleaning the equipment. Further, a longer retention of dairy effluents in the sewerage system creates an anaerobic environment, which helps in the fermentation of lactic acid, thus resulting in a reduction in pH from basic to acidic.
Table 2. Characteristics of dairy effluent at various stages of milk processing.

<table>
<thead>
<tr>
<th>Stages in the Processing of Milk</th>
<th>Sources of Wastewater</th>
<th>pH</th>
<th>BOD\textsubscript{5} (g/L)</th>
<th>COD (g/L)</th>
<th>TSS (g/L)</th>
<th>TN (g/L)</th>
<th>TP (g/L)</th>
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<tr>
<td>Milk receiving stage</td>
<td>a. Poor drainage facility</td>
<td>7.18</td>
<td>0.8–5</td>
<td>2.54–10</td>
<td>0.65–3</td>
<td>-</td>
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<td>[43,45]</td>
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<td></td>
<td>b. Cleaning of units</td>
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<td>c. Spillage and overflows</td>
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<td>d. Foaming</td>
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<tr>
<td>Butter production process</td>
<td>a. Vacreation process (pasteurisation by vacuum methods)</td>
<td>12.08</td>
<td>0.22–2.65</td>
<td>8.93–10</td>
<td>0.7–5.07</td>
<td>-</td>
<td>-</td>
<td>[45,63]</td>
</tr>
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<td></td>
<td>b. Use of salts increases salinity and ions such as Na\textsuperscript{+} and Cl\textsuperscript{−}</td>
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<td>c. Cleaning and washing operations</td>
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</tr>
<tr>
<td>Cheese making</td>
<td>a. Whey separation</td>
<td>3.38–9.5</td>
<td>0.59–5</td>
<td>1–63.3</td>
<td>0.19–2.5</td>
<td>0.018–0.83</td>
<td>0.005–0.28</td>
<td>[45,50,64]</td>
</tr>
<tr>
<td></td>
<td>b. Cleaning and washing operations</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>c. Usage of salts tends to increase ionic concentration and suspended solids</td>
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<td></td>
<td>d. Spillages and leaks</td>
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<tr>
<td>Ice cream production process</td>
<td>a. Plant and tank clean-up</td>
<td>5.1–6.96</td>
<td>1.8–2.45</td>
<td>4.94–5.2</td>
<td>1.1–3.1</td>
<td>0.014–0.06</td>
<td>-</td>
<td>[43,62,65]</td>
</tr>
<tr>
<td></td>
<td>b. Backflushing water</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>c. Pasteurizer and chiller flush-out</td>
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</table>

BOD\textsubscript{5}: 5-day biochemical oxygen demand, COD: chemical oxygen demand, TSS: total suspended solids, TN: total nitrogen, TP: total phosphorus.

The presence of higher settleable solids, which arises mostly from butter and cheese-making processes in the dairy industry, might also result in the clogging of sewage pipes. In addition, the molecular protein formation and deposition of fats along the walls of the pipes that carry dairy wastewater requires regular cleansing with necessary chemical solutions. This increases the maintenance cost of the conveyance system that is employed for the transportation of dairy effluent. Furthermore, different concentrations of total nitrogen (TN) and total phosphorus (TP) are also observed in distinct types of dairy wastewater due to the existence of amino acids and inorganic phosphates in milk. However, the presence of these levels of TN and TP values are dependent on biological processes; thus, METs can also be employed for the treatment of dairy wastewater with the concomitant recovery of valuables.

5. Current Treatment Approaches for Dairy Wastewater

Dairy wastewater significantly affects the quality of the receiving environment due to the high volume of the effluent, which is loaded with heavy organic loads and has a fluctuating pH. These issues entail effective and economic effluent-management technologies that can safeguard the environment. In this regard, the present section elucidates the application of various chemical, physicochemical, and biological processes for the treatment of dairy effluent.

5.1. Chemical Treatment

Chemical treatment is executed by adding oxidants to dairy effluent and then blending it vigorously using rapid mixers. Chemical treatment employs either oxidation of
the targeted pollutant using reagents or pH alteration to facilitate removal. When FeSO\(_4\) and H\(_2\)O\(_2\) were used as chemical reagents to treat cheese wastewater, an 80% fat-removal efficiency was obtained with an initial fat concentration of 1.93 g/L [66]. An extreme pH of the dairy effluent of under 6.5 or over 10 can accelerate the deterioration of piping tubes and can be highly pernicious to the microbiome employed in biological procedures. Thus, this extreme pH must be adjusted to diminish these repercussions. In the case of using dissolved air flotation, pH regulation is an obligatory stage to attain the optimum results [67]. Nevertheless, coagulants perform outstandingly in lower pH environments, which necessitates a consequent pH tuning to the required level before additional treatment [12]. Due to the use of chemicals for dairy effluent treatment, it is always appropriate to employ self-reliantly utilized CIP effluents and discharge them continuously in an effluent-treatment plant. Although the contaminants are removed efficiently in this mode of treatment, the accumulation of sludge creates a significant problem, and the prerequisite of chemicals also makes the treatment quite expensive [42,68].

5.2. Physicochemical Processes

Physicochemical processes such as coagulation–flocculation, adsorption, membrane technologies, etc., emphasize the removal of colloidal substances from dairy wastewater. Some physicochemical techniques employed for the treatment of dairy wastewater are discussed below.

5.2.1. Coagulation–Flocculation

Coagulation and flocculation are employed to eliminate suspended, colloidal, and dissolved materials from dairy effluent. These processes aid in precipitating inexplicable compounds such as phosphate as a mode of tiny constituent parts, which then bulk into bigger flocs. The bulkier flocs settle in clarifiers as a core sludge, while clear seepage is discharged into other reactors for subsequent treatment. This phase decreases the suspended and colloidal constituents that are accountable for the turbidity of the liquid and aids in decreasing the organic matter, thus diminishing the COD and BOD [69]. Usually, coagulation in dairy effluent can be accomplished via explicit lactic acid microbes. These microbes help to ferment the lactose, thereby converting the lactose into lactic acid and lowering the pH, which concentrates the proteins with the combination of flocculants, causing the denaturation of water-soluble proteins in the dairy effluent. In this regard, different coagulants such as chitosan, carboxymethylcellulose, etc., were employed to enhance the coagulation process. A study reported that the use of chitosan achieved a COD removal efficiency of 82%, whereas the employment of carboxymethylcellulose as a coagulant obtained a COD reduction of around 78% [70]. However, irrespective of the excellent removal efficiencies obtained, the higher sludge generated and the requirement of chemicals for pH adjustment makes the technology of coagulation and flocculation ineffective for treating dairy wastewater.

5.2.2. Adsorption

Amid the various physicochemical approaches, adsorption remains a unique method for eliminating organic matter from dairy effluents. For effective dairy wastewater treatment, activated carbon (AC) is utilized the most compared to other adsorbents due to its high surface area and possession of excellent porosity. However, a few other adsorbents such as fly ash that are economical can also be employed in the treatment of dairy effluent. Rao et al. applied powdered AC (PAC) as an adsorbent for dairy-wastewater treatment and compared it with different low-priced adsorbents such as straw dust, coconut coir, etc., to lower the total solids concentration [71]. Another study reported a maximum COD removal efficiency of 92.5% using rice husk as an adsorbent to treat dairy wastewater with a dose of 5 g/L at an acidic pH of 2 [72]. Moreover, the downside of adsorption processes such as the separation of the adsorbent from the pollutant, a weak selectivity, and an excess...
generation of waste products has led researchers to deeply question the applicability of this technology for dairy-wastewater management.

5.2.3. Electrocoagulation

Electrocoagulation (EC), which can be another practical alternate approach to treating dairy wastewater, has recently gained a great deal of consideration due to its easy installation and functioning and lack of chemical requirements. The technology of EC involved the development of an electrolysis method that aids in the removal of soluble organic matter, turbidity, colloidal matter, and color through the passage of electric current through the dairy wastewater via electrodes. Sengil et al. applied the EC method to remove COD and oil/grease from dairy effluent using mild steel electrodes and obtained COD and oil/grease removal efficiencies of 98% and 99% with a pH and electrolysis time of 7 and 1 min, respectively [73]. Another study outcome specified that EC could effectively attain removal efficiencies of 98.8%, 97.9%, and 97.75% for COD, BOD, and TSS using dairy effluent, respectively, with 60 V of applied cell potential in 60 min of reaction time with aluminium electrodes [74]. Although this method is an effective solution for treating dairy wastewater, this technology has a few significant drawbacks such as higher energy requirements and recurrent restoration of electrodes to minimalize the formation of the passivation layer, which elevates both its operative and maintenance costs.

5.2.4. Membrane Treatment Technologies

Membrane technologies such as microfiltration, nanofiltration, ultrafiltration, reverse osmosis, and electrodialysis have appeared as alternative treatment technologies for managing dairy effluent due to higher pollutant removal efficiencies with no additional chemical requirements. A higher degree of targeted-pollutant removal can be achieved with the operations mentioned above, and the final effluent generated is of an excellent quality that can be used straight in the process, thus exemplifying a zero-liquid discharge. Frappart et al. described that the recovery of lactose and milk proteins and an ion reduction of up to 80% was possible using dynamic nanofiltration equipped with a rotating disc unit [75]. Another study reported the treatment of dairy wastewater by employing RO; a maximum of 90 to 95% water recovery was accomplished with a permeate flux of 11 L/h.m² and a concomitant 99.8% total organic carbon removal [76].

Recently, a study by Kumari et al. was aimed at improving the water recovery rate via the comprehensive elimination of organic matter and total solids from dairy effluent with a membrane bioreactor (MBR) [77]. The study achieved removal efficiencies of 99.8%, 98%, 40%, 80%, and 98.7% for COD, BOD, total dissolved solids, NH₄-N, and PO₄³⁻, respectively, via the integration of MBR with a polyvinylidene membrane [77]. Therefore, the above-mentioned study emphasized the fact that membrane technologies can be operative in removing contaminants from dairy effluent. Nevertheless, despite the effectual management of dairy wastewater with membrane operations, the fouling and scaling of membranes disturbs the enduring steadiness of the membranes and results in a further rise in the maintenance cost of the process.

5.3. Biological Treatment

The consistent treatment approaches for dairy wastewater are microbial methods that can adapt to all dairy wastewater constituents, but they still prevalently use solvable composites and minor colloids as a substrate, hence removing them from the wastewater [36]. Furthermore, due to their wild adaptation abilities, these methods can be conjointly employed with several arrangements for the effective component-degradation needs [42,78]. Biological-treatment processes have two different classifications based on oxygen supplies: aerobic and anaerobic processes, both of which are employed in the treatment of dairy wastewater.

Currently, many dairy-effluent-treatment units are adapting aerobic processes; however, these are not highly effective, mostly due to the filamentous development and
quick acidification triggered by greater lactose values and lower aqua-buffering capabilities \[52,68,79\]. The difficulties usually met in activated sludge processes (ASPs) are the bulking of sludge, sludge foaming, ionic precipitation, extra biomass generation, and inefficient treatment efficiency at colder temperatures. The sharp \(O_2\) exhaustion (greater than 3 kg of oxygen required per kg of \(BOD_5\) consumed) necessitates enormous energy requirements throughout the aerobic treatment of dairy effluent \[42\]. A study reported that when synthetic dairy wastewater with an initial concentration of 4 g/L of COD was treated using an ASP in continuous mode, a COD removal efficiency greater than 96% was obtained, which provided an optimistic response \[80\]. Another study done by Russell revealed that with the use of a milk–butter mixture effluent for an ASP, reliable COD and TN removals of more than 90% and 65% could be achieved \[81\]. However, to improve the removal efficiency of an aerobic system, an appropriate pretreatment or acceptable effluent dilution needs to be provided.

A sequencing batch reactor (SBR) is often chosen to treat dairy wastewater due to its extravagant loading abilities and flexible nature in treating wide varieties of effluents. The management of dairy wastewater was demonstrated by Britz et al., who reported that maximum COD and TN removal efficiencies of 97% and 38%, respectively, could be obtained via an SBR \[42\]. Further, a recent examination demonstrated that the SBR is a notable technology for merging the activated-sludge granulation in the management of milk effluent. Maximum removal efficacies of 90% for COD, 80% for TN, and 67% for TP were obtained in an eight-hour reaction time for soluble dairy effluent \[82\].

Anaerobic approaches are very appropriate for the treatment of complex dairy effluent and are also very economical than aerobic systems. If suitably operated, these processes do not generate any undesirable smells, which increases their applicability in residential areas \[42,68\]. The primary complications of anaerobic processes comprise an extensive start-up time due to the presence of complex matter; the performance and generation of methane are affected by pH variation, sludge floating, etc. \[83,84\]. Nevertheless, the evidence on the industrial-level application of anaerobic processes using whey wastewater revealed a COD removal efficacy of about 75% at around a 10 kg/day.m\(^3\) organic-loading rate.

Dairy wastes are treated in traditional single-phase anaerobic processes such as in an upflow anaerobic sludge blanket (UASB) reactor. Earlier, lab-scale UASB reactors for cheese whey permeate treatment were designed and employed for an effluent with an initial COD ranging between 0.2 and 10.4 g/L of wastewater under a hydraulic retention time (HRT) of 0.4 to 5 days \[85,86\]. A comparative investigation of the prospect of flocculent sludge with granular sludge under diverse HRTs between 6 and 16 h on a UASB was made; approximately 80% of COD and VFA removal for each and an almost 60% fat removal were obtained with the flocculant sludge at an HRT of 12 h \[87\].

The above deliberation exposed that there are critical restrictions for different treatment technologies such as EC, as they need an extremely conductive effluent in order to minimalize the ohmic resistance between the cathode and anode to bring down the energy consumption for an efficient performance. Likewise, membrane scaling, fouling, and maintenance costs are the main disadvantages of membrane-based techniques (Table 3). Therefore, to circumnavigate these bottlenecks, minimal energy-concentrated and effective technologies such as METs are mandatory for generating the self-sustainable energy associated with value-added product retrieval. Like MFCs, METs possess a smaller land footprint when compared to ASPs, and self-sustainable usable energy also can also be yielded with MFCs. Furthermore, compared to EC, in which toxic intermediates can be generated, METs have been proven to be amazingly effective in the overall mineralization of pollutants. Hence, METs can be used as a credible counterfeit of the existing treatment options for the treatment of milk-processing effluent.
Table 3. Treatment of dairy wastewater using different treatment techniques.

<table>
<thead>
<tr>
<th>Treatment Technology</th>
<th>Process Conditions</th>
<th>Treatment Efficiency</th>
<th>Drawbacks</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coagulation and flocculation</td>
<td>Polyacrylamide and polyferric sulfate as coagulants, pH = 7.5, coagulant dose = 20 mg/L</td>
<td>95% turbidity removal 82% COD removal</td>
<td>• Chemical requirement • Sludge management</td>
<td>[88]</td>
</tr>
<tr>
<td>Adsorption</td>
<td>Synthesized copper oxide nanoparticles coupled with Sophora Japonica fruit as adsorbent, contact time = 120 min, temperature = 25°C, pH = 7.5, adsorbent dose = 1 g/L</td>
<td>77 to 95% COD removal</td>
<td>• Weak pollutant selectivity • Separation of pollutants from the adsorbent</td>
<td>[89]</td>
</tr>
<tr>
<td>Electrocoagulation</td>
<td>Six aluminium electrodes in parallel connection, voltage input = 60 V, maximum current = 5 A, HRT = 60 min</td>
<td>98.84% COD removal 97.95% BOD₅ removal 97.75% TSS removal</td>
<td>• Higher energy requirement • Passivation layer on electrodes</td>
<td>[74]</td>
</tr>
<tr>
<td>Reverse osmosis</td>
<td>RO membrane area = 540 m², transmembrane pressure = 20 bar</td>
<td>95% Water recovery 99.8% TOC removal</td>
<td>• Membrane scaling • Fouling of membranes • Higher maintenance costs</td>
<td>[76]</td>
</tr>
<tr>
<td>Membrane bioreactor</td>
<td>MBR with PVDF membrane of 0.2 to 0.3 µm pore size, water flux = 4 to 7 L/h, HRT = 6 h, organic loading = 20 to 22 g/L, pH = 6.5−7</td>
<td>99.8% COD removal 98% BOD₅ removal 40% TDS removal 80% NH₄-N removal 98.7% PO₄⁻⁻ removal</td>
<td>• Higher capital and operational costs • High membrane cleaning and replacement costs</td>
<td>[77]</td>
</tr>
<tr>
<td>Sequencing batch reactor</td>
<td>Initial COD = 20,000 mg/L, HRT = 2 days</td>
<td>80.2% COD removal 63.4% TS removal 66.2% VS removal 75% TKN removal 38.3% TN removal</td>
<td>• Higher oxygen requirement • Sludge bulking • Poor activity at low temperature</td>
<td>[90]</td>
</tr>
<tr>
<td>Upflow anaerobic sludge blanket reactor</td>
<td>Organic loading rate = 6.2 g COD/L/day, reactor volume = 10 L, HRT = 6 day</td>
<td>98% COD removal</td>
<td>• Long start-up period • Extensive pH variations • Improper sludge settling</td>
<td>[85]</td>
</tr>
</tbody>
</table>


The METs are promising innovative technologies that employ microbes to catalyze different electrochemical reactions to produce value-added products from different waste streams [91]. The different variants of METs that are employed to recover valuables from waste are MFCs, MECs, microbial desalinization cells (MDCs), and MCCs. In METs, wastewater that is rich in organics is used as the fuel or substrate by the anaerobic microbes residing on the anode, whereas oxygen is used as the terminal electron acceptor that facilitates the oxygen-reduction reaction in the cathodic chamber [92]. The microbes cultured in METs are electroactive in nature, and those that transfer electrons to the anode are known...
as exoelectrogens; these microbes function as biocatalysts for the conversion of waste to valuables [93]. The inventive METs possess the potential to synthesize several types of valuables such as bioelectricity, hydrogen, methane, biofuels, etc., with concomitant wastewater treatment or brackish-water desalination [94]. As a result, these technologies have drawn considerable attention from researchers due to their inherent demonstration of a circular economy by converting waste into resources. A more detailed explanation and the working principle of diverse types of METs are elucidated subsequently.

6.1. Microbial Fuel Cell

An MFC is a promising technology that exemplifies wastewater treatment with simultaneous bioelectricity production by converting the chemical energy present in the chemical bonds of organic matter present in wastewater directly to bioelectricity with the assistance of the catalytic activities of microorganisms [95]. A typical MFC consists of two chambers, namely the anodic and cathodic chambers, which are partitioned by a proton-exchange membrane (PEM). The electrodes housed in the respective chambers are connected via an external circuit through which reusable electricity can be harvested [92]. The microbes present in the anodic chamber produce electrons and protons from the organic matter present in the wastewater. The electrons are transferred to the cathodic chamber via the external load, thus completing the circuit. On the other hand, the protons produced in the anodic chamber pass through the PEM that separates the chambers and reach the cathode. In the cathodic chamber, the protons and electrons combine with oxygen, which leads to the formation of water through an oxygen reduction reaction (ORR) (Figure 1) [96].

![Figure 1. A schematic diagram of a typical dual-chamber microbial fuel cell.](image)

The anodic microbes in an MFC are strictly anaerobic in nature and as a result, the presence of oxygen in the anodic chamber can inhibit the generation of electricity; however, aerobic conditions must be maintained in the cathodic chamber to facilitate the ORR [97]. The oxygen required for the ORR is provided in either an aqueous form (in the case of aqueous cathode MFC) or can be consumed from the air (such as in an air-breathing MFC or single-chamber MFC) [98]. This emerging technology of the MFC can be employed in the dairy industry for the treatment of dairy effluent in the anodic chamber, which will reduce the organic load that reaches the subsequent treatment unit, thus reducing the operational costs [99]. Further, the energy recovered from the operation of an MFC that employs dairy wastewater can be used to provide electricity to low-power sensors, which are employed in quality controls [100]. The technology of the MFC possesses the advantage of power recovery from waste; however, the amount of power recovered via MFCs is inferior for...
medium/large-scale applications, and the exorbitant fabrication cost of scaled-up MFCs makes this technology infeasible for practical applications [101]. Hence, to commercialize this novel technology, researchers are toiling hard to synthesize low-cost electrode and membrane materials that would not only reduce the capital investment, but would also improve the power generation of a scaled-up MFC.

6.2. Microbial Electrolysis Cell

A MEC is a derivative of the MFC that is employed to produce hydrogen, methane, hydrogen peroxide, etc., from the organic matter present in wastewater, with the application of a minute amount of imposed potential depending upon the targeted product [102]. The operation of the anodic chamber of an MEC is like that of a MFC, in which electrons and protons are produced during the decomposition of the organic matter present in wastewater [102]. The electrons from the anodic chamber are drawn to the cathodic chamber via an externally connected potentiostat; the protons reaching the cathode through the PEM are reduced by these electrons to produce hydrogen (Figure 2).

![Figure 2. A schematic diagram of a microbial electrolysis cell.](image)

If suitable cathode catalysts and catholyte are employed in an MEC, other value-added products such as hydrogen peroxide, acetic acid, etc., can be produced through this innovative technology [103]. A scaled-up MEC can be installed in the dairy industry that could treat the effluent in the anodic chamber with concurrently produced hydrogen or other commodity chemicals [104]. These products can be further used in the dairy industry itself, thus exemplifying a circular economy [105]. However, the technology of the MEC also suffers from similar drawbacks to those of MFCs, which include inferior yields of valuables and higher fabrication costs; hence, researchers are attempting to circumnavigate these drawbacks by integrating other biotechnologies with MECs.

6.3. Microbial Desalinization Cell

An MDC is a type of MET that is primarily employed for the removal of salts from brackish water with concomitant wastewater treatment and bioelectricity recovery [106]. Typically, an MDC consists of three chambers with an additional desalination chamber sandwiched between the cathodic and anodic chambers (Figure 3) [107].
Figure 3. A schematic diagram of a microbial desalination cell.

The working principle of the anodic and cathodic chambers of an MDC is similar to that of an MFC; however, the movement of ions from the additional desalination chamber to the anodic and cathodic chambers is the only difference [108]. The AEM separates the anodic chamber from the desalination chamber, which also facilitates the movement of anions from the brackish water present in the desalination chamber to the anodic chamber [109]. Alternatively, the cation-exchange membrane (CEM) that separates the cathodic chamber from the desalination chamber facilitates the movement of cations from the brackish water present in the desalination chamber to the cathodic chamber, thus demonstrating the successful desalination of the brackish water [110]. Instead of a single desalination chamber, an MDC can have multiple desalination and concentrate chambers to increase the quantity of saline water getting treated; however, in that case, the internal resistance of the system rises, thus considerably affecting the power generation [105]. An upscaled MDC can be employed in the dairy industry to treat saline water before sending it to the RO system, thus increasing the longevity of the RO membranes. However, the build-up of salinity and pH in the concentrate chamber, membrane fouling, and a lower yield of bioelectricity are also some of the major challenges in the use of this technology.

6.4. Microbial Carbon Capture Cell

An MCC is a modified version of an MFC in which carbon capture is accomplished by algae cultured in the cathodic chamber of the MCC [111]. Further, these algae growing in the cathodic chamber can be harvested to produce biodiesel and other valuable products such as carotenoids [112]. The anodic chamber of an MCC functions similarly to that of an MFC; however, in the cathodic chamber, algae provide the oxygen required for the ORR instead of the external aeration used in MFCs (Figure 4) [113]. An MCC can be employed to remove the nutrients present in dairy effluent by using them for the growth of algae, which can produce biodiesel when harvested; this produced biodiesel can be further used to produce in-house power in the dairy industry [114]. An MCC can demonstrate carbon capture and sequestration by capturing CO\textsubscript{2} from the dairy emissions, which also aids in tackling global warming, climate change, and air pollution [115]. However, culturing of algae via industrial effluents, sluggish reduction kinetics, and an inferior yield of byproducts are some of the major challenges of this technology that must be overcome prior to its successful commercialization.
Figure 4. A schematic diagram of a microbial carbon capture cell.

7. Dairy Wastewater Treatment Utilizing METs

Recently, the concurrent dairy wastewater treatment and energy production by METs have fascinated investigators and have massive considerations. METs are an exceptional technology that integrates biotic and electrochemical pathways for simultaneous dairy effluent management with simultaneous energy generation and recovery of valuables such as H₂ [116]. In this context, the subsequent section will elucidate the comprehensive mechanisms and applications of diverse METs for dairy-effluent management. Depending on the configuration, function, and type of valuables produced, METs are further categorized into MFCs, MECs, and MDCs. The term MXC was newly composed for the technologies mentioned earlier, where X denotes the diverse categories of METs and their operations [19]. In recent years, the notion of MES, which is another mode of microbial electrocatalysis, was familiarized for carbon dioxide recycling to valuable commodity products. The process adopted in MES is quite the opposite of MFCs, in which the oxidation of organic matter triggers the microbial transfer of electrons to an anode. Therefore, an MES does not generate electricity but produces valuable chemicals along with the microbial conversion of CO₂ through the electrotrophic microbes cultured in the cathodic chamber of the MES [21]. Numerous operative variations between these METs varieties can be recognized and are deliberated with their features below (Table 4).

7.1. MFCs for Bioelectricity Generation using Dairy Effluent

MFCs typically use microbes as biocatalysts to change the form of the chemical energy to electrical energy through degradation of the organic matter present in the wastewater. As an evolving process, MFCs are getting an incredible amount of attention because their potential contribution to simultaneous power generation and treatment of wastewater such as dairy effluent is comprehended. In this regard, the treatment of dairy industry effluent was perceived in a catalyst-less and mediator-less membrane MFC (CAML-MMFC). A maximum coulombic efficiency and voltage of 37.16% and 0.856 V, respectively, were achieved at a corresponding organic loading rate (OLR) equal to 17.74 kg COD/m³.day and 53.22 kg COD/m³.day with five days of HRT through the CAML-MMFC [117]. During another investigation, real dairy wastewater with 8000 mg/L of initial COD was fed continuously in a single-chamber MFC with a 0.2 L working volume for 15 days. In the investigation, the maximum current density and power density were observed to be 141 mA/m² and 50 mW/m², respectively, with a simultaneous COD removal efficiency of 92.21% [1].
In a fascinating study, a single-chamber MFC inoculated with a mixed culture was fed with real dairy wastewater and operated continuously for 264 h. The system demonstrated outstanding results with a coulombic efficiency of 31.58% and a maximum COD removal efficiency of 95.31%. The peak power density and optimum cell voltage of the MFC were shown to be 62.27 mW/m² and 0.48 V, respectively \[5\]. Similarly, dairy effluent was used as the substrate to understand the long-term performance of an air-cathode single-chamber MFC that was operated for 95 days. The maximum removal efficiencies for COD and nitrate of the MFC were observed to be 93% and 100%, respectively \[118\]. Therefore, these investigations proved that the MFC provides a multifaceted waste-handling opportunity for dairy effluent; nevertheless, additional research needs to be performed that focuses on the advances in affordable and steady electrocatalysts to improve the lethargic oxygen reduction reaction (ORR) kinetics, which would further enhance its energy generation.

### 7.2. MECs for Simultaneous H₂ Evolution and Dairy Wastewater Treatment

The use of MECs is a new-fangled processes that aids in the oxidation of organic compounds with the assistance of exoelectrogenic microorganisms that exist in the anodic compartment to generate H₂, H₂O₂, etc. \[21\]. Nevertheless, the production of H₂ via a reduction process is not spontaneous due to the lower reduction potential; hence, MECs necessitate an external voltage source > 0.2 V of external potential for the reduction reaction to take place \[101\]. Furthermore, CH₄ is frequently found in MECs with H₂ generation due to the reception of electrons by electromethanogenic microbes in the cathode compartment if functioning in biotic environments. Moreover, if suitable metallic catalysts are employed in MECs, chemicals such as H₂O₂ can also be recovered that can be directly used in the industry.

With the increasing global energy demand, the utilization of biofuels can diminish the ingestion of non-renewable fuel sources, thereby lowering greenhouse gas emissions and eventually limiting global warming and the associated climate change \[119\]. Henceforth, the evolution of alternate energy sources is imperative for self-sustainable development and the attainment of sustainable development goals. In a prior investigation, a single-chamber MEC was fed with dairy wastewater with 6000 mg/L of initial COD and operated under optimized conditions such as an HRT of two days and an applied cell voltage of 0.8 V. The findings showed a COD removal efficiency of 95% along with H₂ generation of 32 mL/L.day \[120\]. Likewise, the treatment of dairy effluent combined with landfill leachate was studied in a membrane-less batch-fed MEC operated at an applied cell voltage of 0.8 V with an HRT of 48 h. A sustained functioning of the MEC at an OLR of 24 g COD/m³.day for 10 operation cycles resulted in a maximum COD removal of 73% and H₂ generation of 15 mL/L.day \[121\]. Therefore, the above discussion exposed that an MEC can professionally manage dairy effluent and valuables such as bio-hydrogen can concurrently be retrieved during the treatment process.

The key benefits of MECs comprise the biotransformation of waste into valuable products when linked with dark fermentation that uses complex carbohydrates to produce green hydrogen. In contrast, MECs use various organic substrates for H₂ evolution. Furthermore, H₂ generation in MECs occurs via organic matter oxidation, which necessitates a low redox potential when associated with water oxidation in the usual electrolysis. Irrespective of these advantages, the main limitation of MECs is their lower rate of H₂ production, which restricts their real-life applications. Hence, imminent studies need to be conducted to elucidate the complicated associations amid the diverse working parameters of MECs and their H₂ production rate.

### 7.3. MDCs for Water Desalination and Dairy Wastewater Treatment

The application of MDCs in the desalination process was presented in 2009 by Cao et al. \[122\]. The fundamental basis of MDCs is to exploit the natural electric potential created between the electrodes; i.e., the anode and cathode, to initiate the on-site desalination
process [123]. Contrary to METs, MDCs adopt a tertiary compartment for desalination by installing both an AEM and a CEM across the anodic and cathodic compartments. MDCs often are employed as either a self-standing technology for concurrent organics degradation and desalination with power generation or as a pretreatment process for traditional salt-removal technologies such as reverse osmosis (RO) to decrease the salt load, thereby reducing the scaling and fouling of the RO membrane and minimizing the power ingestion.

**Table 4. Treatment of dairy wastewater using different METs.**

<table>
<thead>
<tr>
<th>Type of MET</th>
<th>Wastewater Used</th>
<th>Power Density (W/m²)</th>
<th>Treatment Efficiency</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air-cathode single-chamber MFC</td>
<td>Real dairy wastewater</td>
<td>0.005</td>
<td>COD removal of 92.21%</td>
<td>[1]</td>
</tr>
<tr>
<td>Catalyst-less and mediator-less membrane MFC</td>
<td>Dairy wastewater</td>
<td>0.062</td>
<td>COD removal of 90.46% BOD₅ removal of 81.72%</td>
<td>[117]</td>
</tr>
<tr>
<td>Membrane-less MEC</td>
<td>Combined leachate and dairy wastewater</td>
<td>800</td>
<td>COD removal of 73%</td>
<td>[121]</td>
</tr>
<tr>
<td>Single-chamber MEC</td>
<td>Dairy wastewater</td>
<td>1520</td>
<td>COD removal of 95%</td>
<td>[120]</td>
</tr>
<tr>
<td>Three-chamber MDC</td>
<td>Dairy effluent</td>
<td>0.0020</td>
<td>Salt removal rate of 0.341 g/L.day</td>
<td>[124]</td>
</tr>
</tbody>
</table>

MFC: microbial fuel cell, MEC: microbial electrolysis cell, MDC: microbial desalination cell, COD: chemical oxygen demand, BOD₅: 5-day biochemical oxygen demand.

In an exciting study, dairy effluent with COD of 1000 mg/L was applied as feedstock in the anodic chamber with a *Chlorella Vulgaris*-inoculated biocathode in an MDC. Continuous experimental trials were executed by consuming a saline solution with a concentration of 15 g/L and 35 g/L in two MDCs while the rate of salt removal and the power density were constantly scrutinized. A maximum salt removal rate of 0.341 g/L.day with a maximum power density of 20.25 mW/m² was noticed in the MDC with a 35 g/L salt content compared to the MDC with a 15 g/L salt concentration [124]. These studies showed that due to the insignificant energy contribution needed for the concurrent treatment of dairy effluent and salt removal by an MDC, it can be foreseen as an energy-competent and reasonably economic process.

The other substantial benefits of MDCs include a low energy consumption, an effective salt removal rate, additional energy generation, and concurrent wastewater treatment. Nevertheless, apart from these extraordinary benefits, the main drawback of MDCs is the scaling and fouling of membranes caused by the existence of different ions such as sodium, calcium, etc., present in the salt solution. Scaling further results in the inhibition of the movement of ions and raises the overall resistance of an MDC, thus diminishing the power generation [107]. Henceforward, supplementary research is needed to explain the inhibition of the movement of ions, which would aid in minimizing the maintenance costs and improve the performance of MDCs.

### 7.4. Valuables Recovered through MES using Dairy Wastewater

The technology of MES is an evolving one in bioelectrochemical research; it utilizes the electrons resulting from the cathode to reduce CO₂ and other compounds into different chemicals [125]. The benefits of MES include not only CO₂ sequestration and chemical production, but also address the harvesting, storing, and circulation difficulties linked
with energy, as the electrons harvested can be from any sustainable source [126]. As this technology is still in its embryonic form, there has been limited research conducted on it and that also employing dairy wastewater. In a recent finding, CO$_2$ was converted to CH$_4$ using membrane-less MES inoculated with anaerobic granular sludge to treat dairy wastewater. The MES experiments were performed for 144 days; i.e., about six cycles, and the CH$_4$ was steadily collected in the serum bottles. A maximum CH$_4$ level of about 46% was observed in the second cycle within 16 days of operation. Bacterial data examination exhibited that the Methanobacterium was the utmost leading group of microbes in every experimental sample [127]. Therefore, as deliberated earlier, the MES conveys boundless potential, but there also are few challenges involved such as a low product yield, separation and purification of the obtained products, etc., which must be resolved before commercializing the technology.

8. Strategies to Improve the Performance of METs

The execution and economics of METs are connected to the employment of appropriate materials for membranes and electrodes and an efficient system architecture. METs characterize a ground-breaking technology for simultaneous dairy wastewater treatment and valuables recovery that can be chosen for numerous environmentally based concerns [128]. Harvesting energy and value-added products through METs is not restricted by the Carnot cycle because it is a rudimentary translation of biochemical energy deprived of limited heat losses [129–131]. Therefore, they can deliver a higher rate of energy alteration in the range of 70%, similar to traditional fuel cell technologies [132]. In addition, the efficacy and operations differ depending on the feedstocks and bacterial catalysts employed. To improve METs’ efficiency and commercialize them, advancements in electrode materials, membranes, the biocatalysts employed, and the architecture of METs are elucidated below [133]. The integrated-system approach to METs for augmenting wastewater-treatment efficacy is also deliberated in detail.

8.1. Electrode Modifications

The constitutional and constructural properties of electrode materials impact MET functionality. For anodes, the influence is on the adhesion of microbes and the potency of the coalescent electron transfer from microorganisms to anodes [134]. These structural abilities are related to the electron-transfer efficiency and can be increased by increasing the specific surface area to enhance biofilm development. Furthermore, the microbe’s metabolism rate can also be amended by anodic constituents that provide an anaerobic terminal electron acceptor for breaking down the organic compounds in dairy wastewater [135]. In a recent investigation, a batch-fed dual-compartment MFC was studied using three diverse anodes (a graphite rod, graphite felt, and carbon cloth) and that employed dairy effluent as feedstock with an initial COD of 1357 mg/L. In this investigation, the maximum open circuit voltage and power density of 0.847 V and 1.36 W/m$^2$, respectively, resulted from the carbon cloth, along with a COD removal efficiency of 91.3% [136].

During another study, an anode adorned with copper-doped iron oxide nanoparticles (Cu-FeO) was utilized to treat proteins and lipids present in dairy effluent through an MFC. The operation of the MFC showed an improved power density of 161.5 mW/m$^2$ for the Cu-FeO anode along with a COD removal of 75% [137]. The Cu-FeO-coated anode exhibited an outstanding performance due to its better hydrophilic nature and reduced resistance, which were confirmed by the wettability and an electrochemical impedance spectroscopy analysis. More recently, in a study by Mahdi Mardanpour et al., a stainless-steel spiral anode coated with graphite was employed in a single-annular-compartment MFC for dairy wastewater treatment. The study’s findings showed a maximum coulombic efficiency and COD removal efficiency of 26.8% and 91%, respectively. Further, a 20.2 W/m$^3$ peak power density was achieved, which demonstrated the effectiveness of using a spiral anode in the MFC due to the better attachment of microbes to the anode [138]. Henceforth, choosing suitable anode materials and their alteration is obligatory to intensify MET performance.
Not only the anode but also the MET efficiency in terms of energy and valuables recovery along with concurrent dairy effluent treatment is affected by cathodic materials as well because they affect the reduction reaction kinetics [139,140]. The typical cathodes employed in METs such as platinum, etc., have limitations comprising cost-intensity, the tendency for bacterial fouling, and intoxication of microorganisms for biotic cathodes [141,142]. Due to these concerns, several low-priced and inert bacterial constituents with higher electrocatalytic capabilities have been discovered to boost the performance of METs. Affordable chemical cathodic modifications help to enhance the adsorptive and electrochemical activities of METs by changing the cathodic exterior to cultivate the inert bacterial features.

In a study by Veeramani et al., the researchers synthesized cobalt oxide (CoO) from cobalt nitrate and sodium hydroxide and exploited it as cathode material in an MFC for energy recovery from dairy effluent by coating CoO on carbon cloth. A maximum open circuit voltage of 630 mV was obtained along with a peak power density of 80 mW/m^2 [143]. Another interesting study was executed by opting for a copper-blended 3D cathode (Cu-blended 3D cathode) in an air-cathode MFC fed with dairy wastewater. The peak power density and COD removal efficiency achieved with these Cu-blended 3D cathodes were 14.4 W/m^3 and 88.1%, respectively [144]. Henceforward, the performance of METs can be significantly improved via the modification of the electrode materials, thereby paving the way toward real-world implementation and commercialization for energy recovery and dairy effluent treatment.

8.2. Membrane Modifications

In a typical MET, membranes aid in transporting the ions and separating the anodic and cathodic compartments. Furthermore, the membrane is vital in the interception of coupling between the anodic and cathodic sides exclusively by dairy wastewater, CO₂, and O₂ [145,146]. For the selection of membranes, aspects such as the resistance, feed uptake, membrane fouling, and O₂ dispersion are considered for justification. Several types of membranes were established for H⁺ transport in METs [147,148]. Characteristically, polymer membranes are categorized as perfluorinated polymer membranes, hydrocarbon polymer membranes, and hybrid membranes. Mostly, DuPont™ Nafion® membranes under perfluorinated polymer membranes are applied as PEMs in METs due to their excellent H⁺ conductivity [146]. However, the downsides of using this type of membrane are the cost intensity and non-biocompatibility.

To counter the cost concerns, numerous polymers and chemical-based additives such as TiO₂, etc., were presented to formulate a competent PEM for MET applications. In a study by Ayyaru et al., the authors employed sulphonated polyether ether ketone (SPEEK) as a PEM in a single-chamber MFC to treat dairy and domestic wastewater; this was further correlated with a Nafion® 117 membrane. The MFC-containing SPEEK membrane generated 55.2% greater power when compared to the Nafion® 117 membrane. In obtaining the oxygen mass transfer coefficients, SPEEK and Nafion® 117 demonstrated 2.4 × 10⁻⁶ cm/s and 1.6 × 10⁻⁵ cm/s, respectively, resulting in lowered oxygen diffusion [149]. During another investigation, TiO₂ nanofillers were added to SPEEK to synthesize the TiO₂-SPEEK membrane for application in an MFC. Different weight percentages of TiO₂ that varied from 2.5 to 10% were studied to understand the membrane performance; a 5% TiO₂–SPEEK membrane generated a peak power density of 1.22 W/m² and a voltage of 0.635 V, which were higher than those of the Nafion [150].

8.3. Different Configurations Employed

A large variability in MET architectures is being fathomed for explicit applications and to enhance METs’ functionality by minimalizing system losses. In this regard, a few noteworthy illustrations comprise single-chamber METs, air-cathode single-chambered METs, upflow tubular METs, etc. [129,133]. Nevertheless, the most frequently described configurations are the dual-chamber METs; despite their lower voltage generation, they have been
the utmost expedient to optimize METs’ performance with component modifications and additional functional circumstances.

Firstly, the air-cathode single-chamber METs are the effectual configuration system for better optimal performance. The purpose of the air cathode is to opt for the freely available oxygen from the environment as a terminal electron acceptor for the reduction reaction [133]. Therefore, the oxygen requirement for aeration is reduced, thereby improving the system’s sustainability. In a study, dairy wastewater with an initial COD in the range of 900 to 1500 mg/L was fed into single-chamber MFCs with an HRT of 2.4 days. A peak power density of 170 mW/m² and a coulombic efficiency of 12.8% were attained with a simultaneous COD removal efficiency of 71.1% [151]. During another investigation, single-chamber MECs were fed with dairy wastewater operated for two days at an applied voltage of 0.8 V. The results demonstrated that a COD removal efficiency of 95% along with a maximum H₂ generation of 32 mL/L.day [120].

Now, the other configuration is the most suitable and simpler version of METs; i.e., dual-chamber METs. These reactors comprise two different compartments separated by the membranes and tightly sealed with the assistance of a gasket. This model is the most appropriate reactor for laboratory trials because it is not affected by cathode fouling due to separation. In an investigation by Cecconet et al., the researchers fabricated a dual-chambered MFC for dairy effluent treatment that was run continuously for 96 days. The average feeding rate for the MFC was 1 L/day and the maximum CE and COD removal efficiency obtained were 30.4% and 80.9%, respectively. Moreover, the average produced power density was 12.21 W/m³ throughout the operational period of 96 days [152]. Apart from the exceptional outcome of dual-chambered reactors, single-chamber reactors are the most preferred ones to fulfil the needs for upscaling of the reactor.

A conventional three-chambered MDC is constructed by placing the additional compartment between the two compartments of a typical dual-chambered MFC and separating the anode with an AEM and the cathode with a CEM. The membrane positions can also be altered by placing an AEM near the cathode and a CEM near the anode. In a fascinating study, dairy effluent was applied as a substrate in the anodic chamber in a biocathode MDC. The middle chambers were filled with salt concentrations of 15 g/L and 35 g/L in two different MDCs, and the rate of salt removal and the power density were noted. An extreme salt removal rate of 0.341 g/L.day with a peak power density of 20.25 mW/m² was found in the MDC with a 35 g/L salt content compared to the MDC with a 15 g/L salt concentration [124].

Tubular air-cathode MFCs are intended to function in a constant mode of operation. Typically, in a tubular MFC, the anode is positioned at the bottom of the tubular reactor, and the cathode is attached to the PEM to form a membrane electrode assembly (MEA). A study recently described the advancement of an upflow tubular air-cathode MFC fed with dairy effluent. Maximum COD and BOD removal efficiencies of 96% and 97%, respectively, were obtained along with a peak power density of 3.5 W/m³ [153]. The above results specified that the different METs built have an outstanding potential in dairy effluent treatment, valuables recovery, and energy recovery.

8.4. MET-Based Integrated Systems

The combination of various treatment processes assists in attaining a greater removal efficacy compared to the stand-alone process and further aids in reaching the levels of the discharge standards, specifically for an intricate effluent such as dairy wastewater. Nevertheless, limited integrated-system approaches have been undertaken to date in dairy wastewater treatment. In a recent fascinating study [154], MFCs were coupled with a dark-fermentation hydrogen-generation reactor to treat complex cheese whey wastewater. A peak power density of 439 mW/m² was achieved from the effluent after the fermentation process, which was almost 1000 times better than that when using cheese whey alone in the MFC. The above results demonstrated that MFCs could be an important part of the process
to obtain additional chemical energy from cheese whey wastewater when they follow the dark-fermentation process.

A study was made by coupling the electro-Fenton process with an MFC, renowned as a bio-electro-Fenton MFC, for dealing with combined dairy and oil wastewater by employing an AEM in the reactor. The authors observed a COD removal of 77% and a maximum power density of 260 mW/m² with voltages up to 2.3 times better than that of the conventional system [155]. During another investigation, integrating an MFC with a microalgal approach such as a photobioreactor system can aid in reducing GHG emissions from dairy wastewater treatment plants, thereby sequestrating CO₂ released from industries. The MFC-PBR configuration used an industrial dairy effluent as the anolyte; the COD removal efficiency was constantly noted and finally shown to be 99% [156].

These research findings exposed that the amalgamation of METs with supplementary technologies such as dark fermentation and PBR (Table 5) improves the removal efficacy, valuables recovery, and bioelectricity generation of METs. Therefore, combining METs with progressive approaches can support overcoming the boundaries of stand-alone approaches and hence can result in clean water for discharging or recycling purposes. In addition, the above discoveries demonstrated that METs can be established as a self-sustainable way to manage dairy effluent and also aid in reducing operational costs by recovering bioenergy and valuables.

Table 5. Strategies for improving the performance of METs.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Modification of Material/System</th>
<th>Type of MET</th>
<th>Power Density</th>
<th>Removal Efficiency</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode modification</td>
<td>Anode decorated with copper-doped iron oxide nanoparticles</td>
<td>Dual-compartment MFC</td>
<td>161.5 mW/m²</td>
<td>COD removal of 75%</td>
<td>[137]</td>
</tr>
<tr>
<td></td>
<td>Copper-blended 3D cathode</td>
<td>Air-cathode MFC</td>
<td>14.4 W/m³</td>
<td>COD removal of 88.1%</td>
<td>[144]</td>
</tr>
<tr>
<td>Membranes</td>
<td>Sulfonated polyether ether ketone</td>
<td>Single-chamber MFC</td>
<td>5.7 W/m³</td>
<td>COD removal of 75%</td>
<td>[149]</td>
</tr>
<tr>
<td></td>
<td>TiO₂-SPEEK membrane</td>
<td>Dual-chamber MFC</td>
<td>1.22 W/m²</td>
<td>COD removal of 90%</td>
<td>[150]</td>
</tr>
<tr>
<td>Configurations</td>
<td>-</td>
<td>Air-cathode-single chamber MFC</td>
<td>170 mW/m³</td>
<td>COD removal of 71.1%</td>
<td>[151]</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>Dual-chamber MFC</td>
<td>12.21 W/m³</td>
<td>COD removal of 80.9%</td>
<td>[152]</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>Conventional-three chamber MDC</td>
<td>20.25 mW/m²</td>
<td>Salt removal rate of 0.341 g/L.day</td>
<td>[124]</td>
</tr>
<tr>
<td>Integrated systems</td>
<td>Integration with dark fermentation</td>
<td>Single-chamber MFC</td>
<td>439 mW/m²</td>
<td>COD removal of 42%</td>
<td>[154]</td>
</tr>
<tr>
<td></td>
<td>Integration with electro-Fenton process</td>
<td>Dual-chamber MFC</td>
<td>260 mW/m²</td>
<td>COD removal of 77%</td>
<td>[155]</td>
</tr>
</tbody>
</table>

MFC: microbial fuel cell, MEC: microbial electrolysis cell, MDC: microbial desalination cell, COD: chemical oxygen demand, MET: microbial electrochemical technology.


Conventionally, a linear economy is being engaged to harvest energy and resources that generate beneficial products by utilizing limited supplies and sending the waste arising from the process to the landfill. This plan, which uses a ‘take-make-disposal’ policy, creates a significant quantity of factory-made and domestic waste. Further, these wastes are inevitable and detrimental to the environment because they are incinerated or dumped in landfills [80,157]. Meanwhile, the rising greenhouse gases (GHGs) produced during several waste disposal/remediation activities are responsible for global warming conditions. Therefore, ecologically beneficial and continual economic models are recommended
for the recycling of waste generated with the potential recovery of resources [158,159]. The circular economy is one such model that aids in the augmentation of salvaging and recycling existing waste materials for harvesting varied materials and power by exploiting environment-friendly methods.

The notion of circularity, which was instigated by industrialized ecosystems, targets the diminishment of resource depletion and discharges/emissions into the environment by completing the circuit of constituents [160]. On the downside of these criteria, material loss needs to be mitigated and can be regenerated either for recycling or reusing. In agreement with the above-stated basis, rallying in the direction of a circular economy infers probing for sustainable practices or technologies. Furthermore, circularity can circumnavigate the issue of limited supplies by boosting the usage of recovering resources and further preventing the escape of native resources such as nutrients in the form of nitrogen (N), phosphorus (P), carbon (C), and water from the ecological system [161]. This idea aids in encouraging the reuse and reclaiming of the loss of specific resources that can complement their significance to the ecosystem. Briefly, for a circular economy, wastes are converted into resources through the implementation of different sustainable technologies and strategies, which is imperative in the conservation of natural resources and in alleviating emerging environmental challenges.

9.1. Circular Economy in METs in the Dairy Industry

Several investigations have scrutinized resource recovery from dairy wastewater effluent via METs, and many encouraging yields were deliberated. Although further comprehensive studies and analyses of the upscaling of METs must be made to demonstrate future opportunities. Innovative METs are highly capable of being part of a circular economy because they function to recover energy and produce valuable commodity chemicals along with simultaneous dairy wastewater treatment [101,162,163]. The wastewater employed as a substrate in METs undergoes biological degradation to generate energy and new materials concurrently. As in a typical MET, aerobic wastewater treatment is not obligatory, and the energy consumption for the process is significantly alleviated. In addition, extensive self-sustainable systems can be attained by pairing METs with other popular energy sources such as solar, tidal, etc. [164].

Both MFCs and MECs are alleged to be self-sustainable podiums for recuperating energy from waste because they can break down the organic matter present in dairy wastewater along with an additional production of electricity or clean fuel such as H\textsubscript{2} [7, 164]. Similarly, MCCs that employ algal cells assist in the recycling of CO\textsubscript{2} into biomass, resulting in the sequestration of CO\textsubscript{2} [165]. Although CO\textsubscript{2} is discharged as one of the byproducts in the above process, due to the biological degradation of organic matter, it can be further utilized for algal growth, which exemplifies METs as carbon-neutral systems. Moreover, salt elimination and water reclamation are critical issues in dairy plants that can be solved by applying MDCs, which are a type of MET. Compared to the traditional treatment technologies, these METs use less energy and instead reasonably yield power under anaerobic conditions, thus accomplishing sustainability.

Among the METs, MESs have captured immense attention in the sequestration of CO\textsubscript{2} with concomitant beneficial biochemical production in which microorganisms exploit CO\textsubscript{2} as the carbon source. A recent study reported the conversion of CO\textsubscript{2} to CH\textsubscript{4} using a membrane-less MES incorporated with carbon-cloth electrodes functionalized with copper nanoparticles for different cycles. A maximum energy efficiency of 46% within 16 days was reported for methane production in the second cycle. However, the system performance declined with the continual process cycles due to the decreased hydrogen production, which resulted in decreased methane generation [147]. Similar valuable substances such as the methane produced above can be utilized either for straightaway uses or as reactants for other chemical processes. This CO\textsubscript{2} closed-loop plan through METs can be envisaged as a potential part of a circular economy by achieving a self-sustainable waste-to-valuable chemical platform, thereby making the system economical.
Recently, a database of the biochemical components of milk foods revealed that numerous organic composites such as nutrients, organic acids, conjugated linoleic acids, volatile fatty acids, etc., originate from milk, cheese, and other dairy products [166]. The retrieval of nutrients such as N and P from dairy effluent will permit the ecological protection of the marine environment and aid in creating biofertilizers through the waste-to-fertilizer platform. Mansoorian et al. reported nutrient recovery from dairy wastewater with higher elimination efficacies of about 69.43% for ammonia nitrogen (NH$_4^+$-N) and 72.45% for phosphorous with an HRT of 6 days [117]. Similarly, lactic acid, an exciting organic acid usually observed in dairy wastewater, can be employed as an effective substrate in METs for energy generation. Lactic acid recovery/removal can be accompanied by utilizing it as a source of electrons in the METs [167]. In addition, retrieving VFAs from dairy effluent is another excellent pathway that is being studied in the domain of METs [168]. Therefore, through the implementation of METs representing the above-mentioned technologies, a circular economy can be demonstrated in the dairy industry.

9.2. Circular Economy in the Dairy Industry via Other Technologies

Many sustainable approaches strive to recover resources from dairy wastewater as part of a circular economic plan. Among them, nutrient recovery through struvite production from dairy wastewater has been studied and can be easily adapted for real-life applications [169,170]. A few other investigations on the production of biogas employing anaerobic digestion from dairy wastewater also were demonstrated recently. According to a recent study, the rate of CH$_4$ generation in anaerobic digestion could be enhanced via the application of various conductive substances such as Fe$_2$O$_3$ [171], nanomagnetites [172], etc. Microalgae harvesting is also one of the alternative methods for producing biofuels with the parallel removal of nutrients from dairy wastewater [173]. In this veneration, Dębowski et al. studied the usage of a dairy wastewater digestate as a growth medium for microalgal cells to produce biofuels that contained a greater content of oleic acid [174]. Nevertheless, this method of producing biofuels is not yet applied in a commercialized way since a detailed examination and preliminary testing still need to be performed extensively.

9.3. Real-life Applications of METs for Dairy Wastewater Treatment

Laboratory and benchtop studies of METs are very prevalent in the literature. However, there are a minimal number of articles on the commercialization and real-life applications of METs for dairy wastewater treatment. For example, a long-term pilot plant functioned for 65 days with an MFC with a capacity of one litre per day for simultaneous organic matter elimination and energy recovery [175]. The above work proved that dairy wastewater could be successfully treated by an MFC and showed an average COD removal of 82% along with the recovery of a maximum power density of 26.5 W/m$^3$ in a field-scale investigation. A maximum CE of 24% was obtained at an OLR of 3.7 kg COD/m$^3$.day; this was further reduced to 5% when the OLR was increased. Likewise, another pilot-scale study of an MFC with a 3 L volume of dairy effluent in an anodic chamber was also demonstrated [176]. The maximum removal efficacies attained by this field-scale MFC under the optimum conditions were about 93.9%, 90.6%, and 72.6% for parameters such as COD, BOD, and TDSs, respectively. As a result, based on the above-cited studies, we concluded that METs are highly proficient in treating dairy wastewater with concomitant real-time energy retrieval.

10. Environmental Impact Assessment and Techno-Economic Assessment of METs

A careful examination to identify savings in energy and emissions from various kinds of dairy wastewater treatment and plausible valuable recovery through METs must be conducted to expedite the commercialization thereof. In this regard, a technoeconomic analysis (TEA) and an environmental impact assessment might prove to be valuable tools in gauging the sustainability of dairy effluent treatment through METs because they would assist in deciding whether METs should be investigated further or possess any feasible
field applicability [177]. The economic assessment of dairy wastewater treatment via METs and other technologies such as aerobic digestion can be compared, whereas a life cycle assessment (LCA) would shed some light on the environmental impacts that could arise from the traditional technologies or METs employed during the treatment of dairy wastewater [178]. However, to the best of our knowledge, there are no previous articles that pertained to the LCA and TEA of METs employed in the treatment of dairy wastewater. However, a few investigations briefly and critically explained the TEA and LCA of METs; these are explained subsequently. An investigation conducted by Trapo et al. (2017) showed that MFCs were economically beneficial (EUR 1700–2300 per year) compared to the conventional activated-sludge process (EUR 8166 per year) when no replacement of the electrode or membrane was required because the capital cost of MFCs is higher than the operating cost due to the use of expensive membranes and electrodes in METs [179]. However, few pilot- and field-scale experiments on METs have been investigated, which restricts a better understanding of the long-term economic feasibility of METs.

Similarly, an LCA aids in the evaluation of the positive and negative effects of products on human health, the environment, and the depletion of sources. An experiment revealed that the environmental benefit of valuables recovered from wastewater was only 0.01–7% of the overall environmental impact of METs [180]. Another investigation revealed that METs, especially MFCs and MDCs, would only become environmentally sustainable if their power density rose to at least 500 W/m$^3$ from the present maximum of 20 W/m$^3$ [181]. Similarly, MECs will become only beneficial if hydrogen production contributes to environmental benefits; this will be possible if the produced hydrogen can be used as a biofuel in vehicles and industries. The TEA and LCA can provide a better understanding of the economic and environmental impact of the METs employed for dairy wastewater treatment [182]. Therefore, investigations pertaining to the TEA and LCA of METs in treating dairy wastewater should be conducted for the better understanding of the applicability of METs for dairy wastewater treatment.

11. Challenges Involved and Future Prospects

METs have a wide opportunity for application in treating dairy wastewater with simultaneous resource recovery. Further, METs are promising technologies that have the competence to resolve the problems of energy requirements and environmental pollution. In this regard, numerous investigations have demonstrated resource recovery from dairy wastewater via METs [183]. However, there are a few challenges that are impeding progress toward the commercialization of these technologies. Still, many unanswered questions remain regarding the implementation of METs at a pilot or field scale for industrial wastewater treatment, such as the cost of installation and operations, energy requirements, and efficacy [8]. The operation of METs is beneficial in the short term; however, research should be directed toward determining their long-term suitability for the generation of valuables from waste.

Understanding the cell microbiome can also be beneficial when suggesting operational strategies for the improvement of the activity of electroactive microbes, which in turn will increase the yield of valuables recovered [184]. In addition, a better understanding of these aspects can be achieved with more field-scale investigations. However, the upscaling of METs from lab to pilot or field scales is still one of the serious challenges, although dairy wastewater has been proven as an ideal substrate in the application of these technologies [185]. Further, design and material issues interfere with the practical application because the increase in the volume or size resulted in a decline in performance and efficiency. Therefore, MET technologies are not fully ready at this moment for real-life application; however, they might become a valid alternative to conventional technologies soon.

In METs, electrode materials and membranes play vital roles and are the major reasons for the high fabrication costs of the said technologies [22]. Usually, the raw materials utilized for electrode fabrication in METs are expected to demonstrate an exceptional stability, superior conductivity, a mass transfer ability, a high porosity, a greater surface
area, biocompatibility, and a capacity to scale up. Nevertheless, materials with the above-mentioned characteristics such as platinum are presently very expensive, which hinders the scalability along with the technical feasibility of METs. Additionally, the application of membranes that serve as a separator between the anodic and cathodic compartments in METs is hindered by several drawbacks such as a decreased proton permeability, substrate loss, and oxygen dispersion into the anodic chamber. Further significant barriers to membrane employment in METs involve membrane fouling and increased resistance. Therefore, the implementation of an appropriate membrane is challenging and poses technological obstacles to the configuration, efficacy, and real-life application of METs.

Furthermore, METs are exceedingly temperature-sensitive, which can further affect the efficacy and power output and may reduce the potential life of METs in field-scale operations. This is majorly due to the inability of METs to operate at minimal temperatures due to the lethargic biological responses in such circumstances. Additionally, overpotential losses at electrode surfaces, architectural design and operations, low efficiency, and poor power output are also factors behind the challenges leading to the upscaling of METs [186]. To navigate these challenges encountered in dairy wastewater treatment via METs, further interdisciplinary research is necessary to determine the complexities and schematic approaches that can be employed to overcome the challenges faced during the upscaling of METs, which would move these novel technologies toward commercial applications.

The prospects of METs are significant in numerous potential functions that extend from power generation to wastewater treatment. The extremely well-studied purpose of METs is the use of microorganisms to produce electrical energy. A few other findings emphasized the possibility of hydrogen evolution from METs. Recent studies emphasized the fact that hydrogen can be competently generated from bacterial reactions using dairy wastewater through a fermentation process with or without expensive membranes. An additional vital function of METs is in dairy wastewater treatment, for which several investigations examined the prospects of METs. Moreover, the investigators revealed that METs can be applied in the field of water treatment involving a desalination process. Further noteworthy uses of METs were seen in different areas such as the lowering of carbon dioxide emissions and greenhouse gas mitigation.

12. Conclusions

The current review article deliberated the worldwide threats regarding the treatment of dairy effluent and highlighted the evolving technologies employed for dairy wastewater treatment. Traditional systems such as coagulation–flocculation, MBR, EC, and aerobic and anaerobic processes are typically utilized for managing dairy effluent. Nevertheless, the earlier processes are energy-consuming and expensive, yield vast quantities of surplus sludge, and create toxic products throughout the treatment process. In recent times, METs have acquired the colossal recognition of researchers due to their effectual effluent-management competence with the contemporaneous generation of valuables and diminished sludge generation. However, the use of METs is affected by diverse working/operational parameters such as membranes, catalysts, the feedstocks exploited, etc., which need to be optimized to improve the production of valuables to encounter marketable anticipation for real-world implementations. Consequently, additional investigations must be undertaken to advance economical electrocatalysts and membranes. Further research in pilot studies and in experimental laboratory trials will aid in the field-scale propagation of METs.

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