Electrocoagulation Technology for Wastewater Treatment: Mechanism and Applications

Chapter · May 2022

DOI: 10.1007/978-981-19-0987-0_13


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Abstract Electrocoagulation (EC) is an excellent and promising technology in wastewater treatment, as it combines the benefits of coagulation, flotation, and electrochemistry. EC is an efficient process to remove both organic and inorganic pollutants from wastewater. During the last decade, extensive research has focused on the treatment of several types of industrial wastewater using electrocoagulation. EC is a popular technique, which is being applied for the treatment of varieties of wastewater, because of its several advantages like compact, cost-effective, efficient, low sludge production, it's automation conveniences, high efficiency, and eco-friendliness. This chapter highlights the EC working principle, mechanism, factors

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S. S. Muthu and A. Khadir (eds.), *Advanced Oxidation Processes in Dye-Containing Wastewater*, Sustainable Textiles: Production, Processing, Manufacturing & Chemistry,
https://doi.org/10.1007/978-981-19-0987-0_13

affecting EC process, design aspects, and its application in various industrial effluents. The studies on treatment of various industrial wastewater by global researchers are critically reviewed. The capability of employing this technology in combined systems with other conventional methods to eliminate contaminants from wastewater is reviewed also. The core findings proved the capability of this technique in wastewater treatment whether it is performed alone or combined with other technologies providing many pros, such as the decrement of the operation cost and the sludge formation.

Keywords Electrocoagulation refractory contaminants · Industrial wastewater · Combined systems

1 Introduction

Water is one of the most important resources on earth; water plays a vital role for all human beings, animals, and plants to thrive. Water is an equally important resource for the manufacturing sector and social development. Therefore, there is an urgent need to preserve and protect our ecosystems from all types of pollution [38, 42, 49]. In India, water is used in the industrial sector is about 34 billion m^3 per year, which is estimated to increase four times by 2050. Rapid industrialization has tremendously increased the volume of wastewater to be disposed-off, while the capacity of receiving water to accept the increasing inorganic and organic loads remains the same [16, 52]. This has resulted in the rapid deterioration of the quality of surface water and forcing the concerned more stringent legislation [24, 57, 58]. Accordingly, industries are looking for low-cost solutions to reduce the excess pollutant load. The situation is further aggravated by the threat posed by constant discharge of pollutants by industries such as sugar, paper, steel manufacturing, pharmaceutical, oil refineries, mining, chemical paints, petrochemical, textile, slaughterhouse, distilleries, electroplating, etc. These industries discharge untreated or partially treated wastewater into nearby drains, rivers, stagnant ponds, lagoons, or lakes [1, 28, 64, 66].

The wastewater generated from leather, distillery, cement manufacturing, food and beverages, textile, pharmaceutical, and dairy industries contains various toxic organics, metals, phenolic contaminants that are complex, in nature, and discharge of such wastewater has many negative effects on the receiving water bodies such as low dissolved oxygen (DO), scum formation, thermal impact, and slime growth [14, 29, 62]. Thus continuous discharge of untreated wastewater may harm the aesthetic and scenic beauty of water environment finally leading to totally disturbed ecosystem [31, 40]. In developing countries, huge quantity of effluents are generated by different industries, out of these, only few industries reuse the treated effluent. The potential use of the treated wastewater varies significantly depending upon the degree of treatment and on public acceptance [22, 39, 51]. Nevertheless, this practice is being carried out in many countries with the potential use of treated water for various purposes, which includes irrigation, recreational areas, and landscapes.

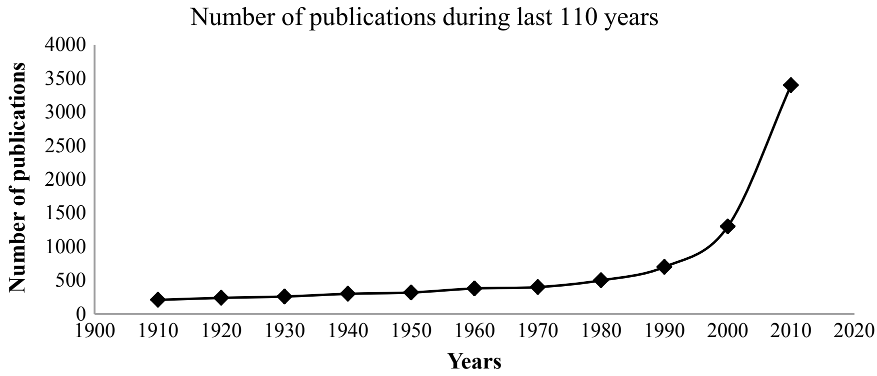

Fig. 1 Number of SCI publications on electrochemical treatment of water and wastewater treatment [70]

In order to trace global research trends in industrial wastewater, the bibliometric analysis is carried out of 110 years as shown in Fig. 1. This figure revealed that many of environmental researchers attracted EC technology due to its inherent advantages—high removal efficiency, environmental compatibility, and clean technology that could be applied in various industrial domains including water and wastewater treatment [70].

Degradation of toxic, refractory contaminants by biological treatment are found to be difficult. Therefore, more effective low-cost wastewater technologies are necessary to fulfill human requirements. Electrochemical treatment technologies have attracted and given attention to their environmental compatibility, high removal efficiency.

Almost all of the electrochemical principles involve the movement of electrons in the conduction media (maybe water or wastewater) and the concept of oxidation and reduction. In recent years, various studies have been focused on the electrocoagulation process, which is an efficient method used to destabilize and remove finely dispersed particles from water and wastewater [43, 47]. Electrocoagulation is a method of treating wastewater containing significant concentrations of organic and inorganic pollutants. Industrial electrochemistry has helped to develop optimal processes and better environmental efficiency.

The EC reactor design cannot be made in isolation as design, flow pattern and operational parameters are dependent on three foundation technologies as shown in Fig. 2. The Venn diagram consists of three lobes, which include electrochemistry, flotation, and coagulation. The intersection of each lobe is highlighted by working principle, characterization method, and tools. In the overall understanding of electrocoagulation, contact pattern kinetics play a key role. The removal path of floatation and settling are represented by vertical arrow. The double-headed arrow (current density) shown in Fig. 2 determines coagulant dosage and bubble production rates. There is a complex interaction between electrochemistry, flotation, and coagulation.

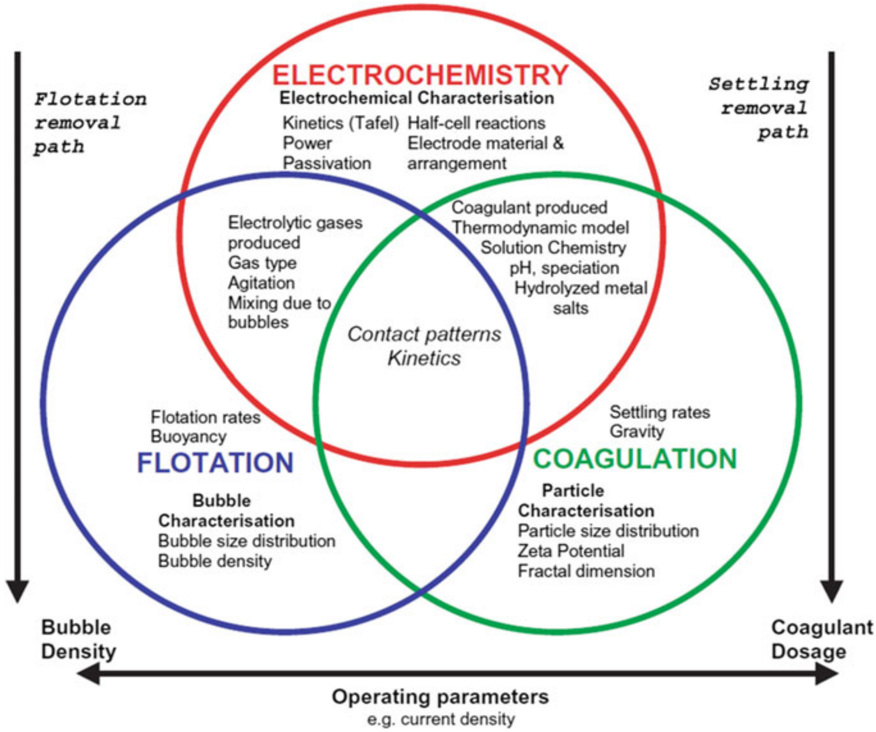

Fig. 2 Conceptual frameworks for electrocoagulation

1.1 Mechanism of Electrocoagulation

EC is a complex separation technique involving a combination of physical and chemical mechanisms. The EC process is a simple and effective method for the treatment of various water and wastewaters. Many investigations in recent years have focused, in particular, on the use of EC due to its advantages such as:

1. A lower amount of coagulant ions is required.
2. A higher rate of pollutant reduction with low treatment time.
3. Simple operation and maintenance, no need for addition of chemicals.
4. The quantity of generated sludge is less and disposal of sludge is simple.
5. Flocs formed settle easily and are readily dewaterable.

Electrocoagulation method has been tested successfully to treat domestic wastewater, dairy, steel manufacturing plant, poultry, olive oil mill, pickle, distillery, textile, dye, pharmaceutical, automobile, photograph processing, electroplating industry wastewater, biodiesel wastewater, petroleum refinery wastewater, paint manufacturing wastewater, tannery wastewater, etc. [3, 5, 64].

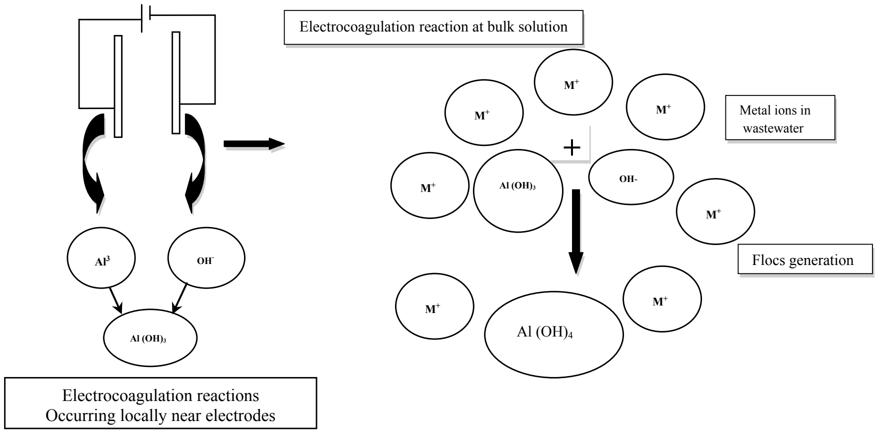

Fig. 3 Electrocoagulation reaction in bulk solution

The simplest EC cell includes a sacrificial anode and a cathode made up of several materials (such as Fe or Al) immersed (partially or fully) in the water or wastewater [60, 67]. An EC system may consist of one or multiple anode–cathode pairs connected either in monopolar or bipolar mode [4, 6]. Three successive stages involved in the EC process are: (i) formation of coagulants by electrolytic oxidation sacrificial anode, (ii) destabilization of pollutants, particulate suspension and breaking of emulsion, and (iii) aggregation of the destabilized phase to form flocs (Fig. 3).

Aluminum is cheap and readily available metal and has an ability to form multivalent ions and various hydrolysis products [44]. Hence, aluminum is the most commonly used anode material. During EC process in a reactor with aluminum electrodes, the important electrochemical reactions that take place are given in Eqs. (1) and (2):

$$\text{At the Anode:} \quad Al_s \rightarrow Al^{3+}_{aq} + 3e^- \tag{1}$$

$$\text{At the Cathode:} \quad 3H_2O^+_{aq} + 3e^- \rightarrow 3/2\,H_2(g) + 3OH^- \tag{2}$$

The Al^{3+} ions generated by the anode and OH^- ions generated by the cathode form various monomeric and polymeric species such as $Al(OH)^{2+}$, $Al_2(OH)^{4-}$, $Al_6(OH)_{15}{}^{9+}$, $Al_8(OH)_{20}{}^{4+}$, $Al_{13}O_4(OH)_{24}{}^{7+}$, and $Al_{13}(OH)_{34}{}^{5+}$ that transform initially into $Al(OH)_{3(s)}$ and finally polymerize to $Al_n(OH)_{3n}$ according to Eqs. (3) and (4) in solution medium:

$$nAl(OH)_3^- \rightarrow Al_n(OH)_{3n} \tag{3}$$

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_{3(s)} + 3H^+ \tag{4}$$

The amphoteric nature of $Al(OH)_{3(s)}$ flocs usually has more surface area that facilitates quick adsorption of soluble matter along with entrapping of colloids. The microbubbles of H_2 and O_2 released at the electrode surface adhere to the agglomerates and carry them to the water surface by electrofloatation [7, 45, 46, 62].

2 Elimination of Contaminants Using Electrocoagulation Technology in Combined Systems

Electrocoagulation technology is also widely performed in integrated systems with other technologies to eliminate numerous pollutants effectively. The hybrid systems could provide several pros, such as low down the sludge generation, minimize the operation cost and consumption of the performed electrodes. The use of this technology in integrated systems has received wide attention from scientists in the last decades. Bilińska et al. [15] combined an electrocoagulation technology and ozonation (O_3) to treat high salinity dye wastewater. They proved the treatability of this hybrid system to obtain 95% dye removal efficacy within 18 min treatment time in comparison with that of 60 min contact time when the ozonation technology was employed alone.

Another study done by Ashraf et al. [10] combined the reverse osmosis process with electrocoagulation to remediate the highly concentrated brine water. They reported 98.9% silica removal within a significant short contact time using iron and/or aluminum electrodes. However, the performance of this system was influenced by generating a thick coating on the used electrodes, for that reason, they performed polarity change to solve this problem. Sharma and Simsek [61] compared the capability of using an integrated system containing of electrocoagulation and electro-oxidation from one side and an electro-peroxidation process on the other side for the remediation of canola oil refinery wastewater. This study found that the integrated system achieved 99% and 95% of COD and dissolved organic carbon (DOC) removal efficiencies, respectively, compared to that obtained using the electro-peroxidation only which removed 77% and 86% only of these pollutants. Hasani et al. [32] investigated the performance of four integrated processes of electrocoagulation flotation system when it was performed for eliminating humic acid from drinking water. The impacts of several technological variables were investigated. They proved that the pulse current-perforated electrode configuration was the most cost-effective in electrode and energy consumption and provided higher contaminants removal efficiency compared to other processes. Tavangar et al. [65] employed an integration system consisting of electrocoagulation and nano-filtration processes to remediate COD and color from real dye wastewater. The cons of each technology were vanished when these technologies were integrated. Another work proposed a combined system containing electrocoagulation and reverse osmosis (RO) technologies. It was documented by Azerrad et al. [11] to enhance the desalination of saline water where higher removal efficiency of carbonate, phosphate, and dissolved organic matter of 98%,

>99%, and (50%), respectively, were achieved using aluminum electrodes, which were larger than in case of iron electrodes. They also concluded that the oxidation of micropollutants was improved by fourfold when this hybrid system was integrated with an advanced oxidation process (AOP), either UVA/TiO_2 or UVC/H_2O_2.

Khani et al. [36] treated wastewater containing olive mill using a hybrid system of electrocoagulation and catalytic sonoperox one processes where the sonoperoxone process consists of the integration of electrooxidation and ozonation addition as well as the ultrasonic process. The impacts of the contact time, current density, and type of electrodes were studied. The (BOD_5/TOC) index was enhanced by 32% in comparison to raw wastewater. Another combination system involved electrocoagulation, membrane distillation, and forward osmosis documented by Sardari et al. [54] for water reuse from high brine wastewater discharged from shale gas extraction process. The findings observed revealed significant removal efficiencies of 78% and 96% of TOC and TSS, respectively, under the selected operational variables. Lalwani et al. [41] performed electrocoagulation and photocatalytic oxidation technologies in an integrated configuration to eliminate TOC from drug wastewater. They found that the elimination of TOC was (33%) using UV-photocatalytic oxidation part compared to 30% of TOC removal in case of natural sunlight-photocatalytic oxidation. Bashir et al. [13] studied the efficiency of a hybrid process containing electrocoagulation and peroxidation technologies to treat wastewater released from the palm oil mill under the impacts of specific operational variables. They concluded that higher removal efficiencies of 100%, 96.8%, and 71.3% were obtained for TSS, color, and COD pollutants, respectively, after 45 min of contact time.

Electrocoagulation and electro-oxidation–reduction steps were investigated individually and together in a combination system by Ghazouani et al. [26] to remediate real wastewater discharged from food processing factories. They found that higher elimination of COD, nitrates, ammonium/ammonia, and phosphates were obtained depending on the configuration set-up employing these two treatment technologies. Shamaei et al. [59] performed a hybrid system of electrochemical coagulation and chemical coagulation to remediate steam-assisted drainage wastewater. A significant removal of 39.8% TOC was achieved after 90 min of contact time using electrodes made of aluminum and connected to the power source in a bipolar mode. Dia et al. [23] studied the ability of an integrated electrocoagulation-biofiltration process to eliminate contaminants from landfill leachates. They obtained 99% and 42% of NH_4 and COD removal. They revealed that the efficient employment of this integration of technologies could remediate different types of wastewater containing numerous kinds of pollutants.

Sardari et al. [53] performed electrocoagulation and ultrafiltration to treat poultry wastewater. They achieved more than 85% removal of pollutants compared to that obtained using the individual methods. The study of the capability of electrocoagulation and membrane distillation was done by Sardari et al. [55] to treat the hydraulic fracturing saline water. A 85% of TSS and organic content removal was achieved and a stable water flux with low fouling had been attained over 434 h experimental period. Al-Malack and Al-Nowaiser [8] tested a hybrid electrocoagulation-membrane bioreactor to eliminate oil and COD and grease from saline oilfield wastewater. They had proved that the removal of these pollutants was decayed with an increment in the concentration of the influent oil. An invented design of the combined system was documented by Sun et al. [63] to remediate humic acid from wastewater, where this cell contains electrocoagulation and electrooxidation integrated with a membrane placed between the electrodes. They had found that this integrated system could be used in wastewater treatment with higher efficacy. Kong et al. [37] documented the ease using of a combined system containing electrocoagulation and electro-peroxone methods, used to remove COD pollutant from shale gas flow-back wastewater. They obtained 35.4% COD removal using 50 mA/cm^2 of current density. Nariyan et al. [50] investigated a hybrid system involving electrocoagulation and chemical precipitation using lime to eliminate sulfate from real wastewater. The obtained findings proved that the hybridization system is useful for eliminating 90% of sulfate pollutants at 25 mA/cm^2 of current density. Zazou et al. [69] had performed hybrid systems consisting of electrocoagulation method and other types of advanced oxidation technologies, involving peroxi-coagulation, anodic oxidation, and the electro-Fenton method to treat wastewater released from textile industries. They had revealed that the integration system of electrocoagulation and electro-Fenton provided the reuse of the treated wastewater belong to WHO specifications.

Barzegar et al. [12] combined electrocoagulation with ozonation methods to improve grey water remediation under the impact of the operational variables of contact time, current density, pH, and the ozone dose was investigated using iron electrodes. They conducted 70% and 85% of TOC and COD removal efficiencies, respectively, after 60 min, 15 mA/cm^2, pH = 7, and 47.4 mg/L of the studied variables. Then the integrated system was combined with UV irradiation where 87% and 95% TOC and COD removal efficiencies were obtained. Jose et al. [34] investigated a hybridization system involving the electrocoagulation and filtration remediation of TDS, TOC, COD, and color from wastewater to attain higher removal. They concluded that the combined system was cost-effective compared to the traditional method. Moradi and Moussavi [48] integrated electrocoagulation technology with UVC/VUV photoreactor to eliminate COD, Cr (III), Cr(VI)) and sulfide from tannery polluted water. They attained higher removal of these pollutants at pH 7 and less and proved the usability of this combined system to treat wastewater released from tannery industries.

A hybrid system containing electrocoagulation and electrooxidation was documented by Costa et al. [21] to remove COD from cashew-nut wastewater discharged from the washing of raw cashew nuts. More than 80% of COD removal efficiency was achieved compared to 51% in the case of using electrocoagulation process alone. GilPavas et al. [27] concluded that the combined system of electrocoagulation-photo-Fenton and electrocoagulation-Fenton followed by adsorption using activated carbon was more valuable to eliminate 76%, 78%, 90%, and 100% TOC, COD, toxicity, and color, respectively, in contrast to that attained using electrocoagulation alone. An integration system of electrocoagulation and sedimentation processes was investigated by Chen et al. [20] to treat polymer containing wastewater under the effects of the operational parameters of current density, flow rate, and tilt angle of electrodes using response surface methodology (RSM) based Box-Behnken method as an experimental design. They achieved higher removal (97%) of oil content at 18.9 mA/cm^2, 5.5 L/h, and (80°) of the applied current density, flow rate, and the tilt angle of electrodes. Keramati and Ayati [35] studied the hybrid system of electrocoagulation and photo-catalytic technologies with ZnO nanoparticles to remediate COD from real oily wastewater. The observed results showed 85% of COD removal under the optimal operating variables. Jiang et al. [33] investigated a hybridization system of electrocoagulation and separation methods to remove oil content and turbidity from a polymer containing wastewater under the impacts of the operating variables of contact time, flow rate, current density, and the tilt angles of electrodes. They attained 96% and 97% of removal efficiencies, respectively, but they minimized with the increase of the tilt angle.

An et al. [9] invented a combined system of electrocoagulation and electro-Fenton for eliminating cyanotoxins and cyanobacteria from wastewater. This efficient system increased the removal of TOC by 30% and minimized the consumption of energy by 92%. Ye et al. [68] performed electrocoagulation and UVA photoelectro-Fenton processes in a hybrid system to eliminate benzophenone-3 from municipal wastewater using aluminum electrodes and boron-doped diamond electrode to achieve total mineralization under the studied conditions. Guan et al. [30] documented an integrated system containing electrocoagulation and electro-Fenton methods to eliminate Cu-EDTA and copper contaminants from wastewater. A higher removal efficacy was observed at pH <7, 72.92 A/m^2 of current density, and 49.4 mM of H_2O_2 concentration, respectively. Bruguera-Casamada et al. [18] constructed a system containing electrocoagulation reactor connected to electro-Fenton or UVA-photoelectro-Fenton cells to treat wastewater discharged from dairy industrial. They attained a 28% TOC removal at pH 3 using UVA-photoelectro-Fenton process and electrocoagulation methods due to the enhancement of the bacterial inactivation by UVA radiation. Another hybrid system consisting of electrocoagulation and forward osmosis methods was proposed by Sardari et al. [56] to eliminate TSS and organic compounds from hydraulic fracturing wastewater. They concluded the treatability of this system for water reuse.

A combined system of photoperoxi-electrocoagulation was performed by Borba et al. [17] to eliminate COD and chromium from tannery wastewater under the influence of the reaction time, pH, the dosage of peroxide, and the current density. They obtained a complete removal of pollutants after 2 h. Adjeroud et al. [2] employed an integrated system containing electrocoagulation and electroflotation processes to remove copper from synthetic wastewater performing aluminum electrodes and opuntia ficus indica (OFI) plant. They achieved a complete removal of copper after 5 min aiding 30 mg OFI/L at pH 7.8 value. Another hybrid system consisting of electrocoagulation and microfiltration was investigated by Changmai et al. [19] for the de-fluorination of contaminated drinking water. This system was applicable to remove 92% of fluoride at pH 7.9 and 15 A/m^2 of current density. Ghanbari et al. [25] tested a combined system involving electrocoagulation, peroxymonosulfate, and electrooxidation to attain higher removal efficiencies of COD, TOC, BOD, and ammonia from landfill leachates.

This summary reveals that effective removal of different pollutants can be attained in the case of combined systems is significantly higher compared to that achieved using individual treatment methods.

3 Conclusion

The electrocoagulation technique is one of the promising technologies to treat different industrial wastewaters. The electrocoagulation process is chosen as an effective method for the treatment of various industrial wastewater, instead of the conventional methods, which have many practical drawbacks. Electrocoagulation cell design is one of the pivotal issues to maintain high mass transfer rates as main reactions take place in electrocoagulation reactor. The selection of appropriate electrode material is also important when designing electrocoagulation cell for maximum removal efficiency. Currently, many of industries use commercially available electrodes made up of BDD, $TiPbO_2$, Ti-SiO_2, graphite, and Zn etc. The cost of these electrodes is high, and they generate toxic elements. This review finds the key achievements and highlights that the major shortcomings in the process are summarized. The fact that EC is a novel technology for water and wastewater treatment that cannot be denied, as it has a number of advantages over traditional methods. However, the technology is still being fine-tuned and refined, and further studies are necessary, to make this technology available all around the world. Due to the overall environmental sustainability, developing membrane technology stands out as the best process to be merged with EC among numerous hybrid EC techniques that have been explored. There must be more research into the optimization of parameters, system design, and economic feasibility to explore the potential of the EC-combined systems.

Acknowledgements This study is a part of research project funded by Science and Engineering Research Board (SERB), Department of Science and Technology (DST) under Teachers Associateship for Research Excellence (TARE) scheme (TAR/2019/000383). The first author sincerely acknowledges and thanks SERB for providing financial support to undertake this study.

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