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Unravelling the emerging carcinogenic contaminants from industrial waste water for prospective remediation by electrocoagulation – A review

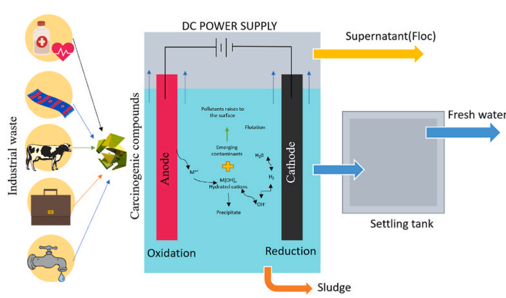
Madhavan Yasasve [a,1], Muralidharan Manjusha [b,1], Dhinakaran Manojj [a], N.M. Hariharan [a,*], P. Sai Preethi [a], Perumal Asaithambi [c], Natchimuthu Karmegam [d], Muthupandian Saravanan [e,**]

[a] Department of Biotechnology, Sree Sastha Institute of Engineering and Technology (Affiliated to Anna University), Chembarambakkam, Chennai, 600123, Tamil Nadu, India
[b] Department of Genetic Engineering, School of Bioengineering, SRM University, Kattankulathur, 603203, Tamil Nadu, India
[c] Faculty of Civil and Environmental Engineering, Jimma Institute of Technology, Jimma University, Jimma, Po Box - 378, Ethiopia
[d] Department of Botany, Government Arts College (Autonomous), Salem, 636007, Tamil Nadu, India
[e] AMR and Nanomedicine Laboratory, Department of Pharmacology, Saveetha Dental College, Saveetha Institute of Medical and Technical Sciences (SIMATS), Chennai, 600077, Tamil Nadu, India

HIGHLIGHTS

- Types & categories of water pollution are clearly discussed.
- Effects of organic wastes and industries producing wastes are highlighted.
- Harmful carcinogens present in the industrial waste water are listed.
- Application of electrocoagulation in different process industries are investigated.
- Removal of metals from waste water using electrocoagulation are discoursed.

GRAPHICAL ABSTRACT



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ABSTRACT

The need of the hour relies on finding new but sustainable ways to curb rising pollution levels. The accelerated levels of urbanization and increase in population deplete the finite resources essential for human sustenance. In this aspect, water is one of the non-renewable sources that is running out very fast and is polluted drastically day by day. One way of tackling the problem is to reduce the pollution levels by decreasing the usage of chemicals in the process, and the other is to find ways to reuse or reduce the contaminants in the effluent by treatment methods. Most of the available water recycling or treatment methods are not sustainable. Some of them even use toxic chemicals in the processing steps. Treatment of organic wastes from industries is a challenging task as they are hard to remove. Electrocoagulation is one of the emerging water treatment technologies that is highly sustainable and has a comparatively cheaper operating cost. Being a broad-spectrum treatment process, it is suitable for treating the most common water pollutants ranging from oils, bacteria, heavy metals, and others. The process is also straightforward, where electrical current is used to coagulate the contaminates. The presence of

* Corresponding author.
** Corresponding author.
E-mail addresses: nmhariharan@gmail.com (N.M. Hariharan), bioinfosaran@gmail.com (M. Saravanan).
[1] These authors have equally contributed to this work.

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carcinogens in these waste water increases the need for its treatment towards further use. The present investigation is made as an extensive analysis of the emerging carcinogens and their various sources from process industries, especially in the form of organic waste and their removal by electrocoagulation and its coupled techniques. The paper also aims to ascertain why the electrocoagulation technique may be a better alternative compared with other methods for the removal of carcinogens in organic wastewater, an analysis which has not been explored before.

1. Introduction

Water pollution is one of the most significant concerns of the modern world, being a finite source essential for human sustenance and well-being of humans. As a resource, water and water bodies are used for many purposes ranging from domestic to industrial use (Törnqvist et al., 2011). The problem is that a lot of emerging contaminants and other unwanted materials are discharged into these water sources reducing the quality of water and the ecological niche (Andrady, 2011; Lata and Samadder, 2016). By definition, water pollution is the degradation of water sources, largely a consequence of human activity that is not legal. The administration of pollutants through any means leads to a lot of health problems depending on the nature of the pollutants present. Despite its long-term existence, the seriousness of its consequences was not known or studied in detail until the 19th century (Manisalidis et al., 2020).

According to UNEP, over 80% of the water waste generated globally goes into the water resources untreated. Approximately 2 million tonnes of sewage, and industrial, and agricultural waste are released every day into the global water (Weerasekara, 2017). The amount of wastewater thus discharged is about six times more than that of the freshwater available through the rivers of the world. The main contributors to the global problem come from releasing toxic industrial discharges. Mainly, the pollution regarding organic sources has led to severe detrimental issues with nearly one-seventh of freshwater resources across Latin America, Africa, and Asia (Ebele et al., 2017; Ferronato and Torretta, 2019). Regarding the Indian scenario, the main contributors to pollution are agricultural wastes and small-scale industries directed its wastes into the water bodies without any pre-treatment, including many agents such as trace metals, inorganic salts, organic matter, and others. Both globally and within India, this causes severe damage to the environment, and it affects both wild and marine life that mainly dependent on the water source (Nivetha and Sangeetha, 2020).

Water pollution is one of the major sources of disease progression in many developing countries. Water-related illnesses kill around 3,574,000 people globally each year, according to the World Counts rganisation report. Around 2.2 million of those are children. With regards to India, every day, around 580 persons die due to water-related pollution (Mudur, 2003; Saravanan et al., 2021). Thus, pollution is one of the most significant threats to society, both in underdeveloped and developed countries. Recent studies shows that the water is contaminated with several carcinogenic material discharged from various industrial effluents such as dairy, cosmetic, leather and textile industries to name a few. The carcinogens in wastewater slowly seep into the drinking water and it becomes an even greater concern to the society (Evans et al., 2019; Ghaffar et al., 2018; Lellis et al., 2019; Tchounwou et al., 2012). Apart from organic and inorganic toxins, recent research has found that carcinogenic substances such as arsenic, azo dyes, chromium, cadmium, uranium, and others have polluted the groundwater in certain parts of India (Kim et al., 2015; Malyan et al., 2019). Moreover, the US carcinogen global report 2021, propounds haloacetic acids as major carcinogens formed as a by-product in water treatment plants.

Identification and removal of these carcinogenic wastes have been a long-discussed topic over the years (Capoor and Bhowmik, 2017; Fu et al., 2021). Electrocoagulation (EC) is one of the modern wastewater treatment methods that combine the benefits of aggregation, floatation, and electrochemistry. Coagulants are created insitu in electrocoagulation by electrolytic oxidation of a suitable anode material (Moussa et al., 2017). Recently, there has been a growing interest in employing electrocoagulation to remove harmful chemicals from wastewater. EC has several advantages, like the use of basic facilities, ease of operation, shorter treatment times, the use of fewer or no chemicals, and discharge of a lower amount of sludge (Jing et al., 2021; Kabdaşlı et al., 2012). It will become vital to give a greater understanding of such electrocoagulation treatment employed in pollutants removal as a prospective treatment technique, a more sustainable and cost-efficient method of waste removal. There are multiple studies connected to the prevention of water pollution caused due to industrial waste discharge in India, however to the best of our awareness, there is a paucity of studies analyzing the carcinogens present in the wastewater. As a result, based on the data accessible from the literature, the present investigation gives an overview of the various carcinogens present in process industrial wastewater discharges and their removal using electrocoagulation and other amalgamated techniques, which have been not explored before at this scale. Thus, the objectives of this research work include, understanding the various categories of water pollution and its sources, types of carcinogens present in the organic waste discharges. Finally, to ascertain the superiority of electrocoagulation with other treatment methods and their efficacy.

2. Types and categories of water pollution

There are a lot of factors that deteriorate the quality and the censurability of the water. Despite the large list of elements, they can be classified into the following major types (Fig. 1).

2.1. Point pollution sources

When the known polluting agents enter a water source from a single point of origin, which can be identified as the true causative agent of the pollution, which is classified as a point source (Poel et al., 2007). This can include a sewer, a drainpipe, or others from a single point from which all the pollutants emerge. For example, wastewater from a tannery established in a specific location entering into the local water resource can be classified as a point source. One of the most important factors of this type of pollution is that it can be estimated quantitatively (Sany et al., 2019).

2.2. Non-point pollution sources

When the source of pollution can't be traced back to a single point of origin or when the polluting agents have multiple sources of origin, this can be classified as non-point sources. This is one of the most complicated forms of pollution that is very hard to manage (Moss, 2008). Moreover, this type of pollution cannot be easily quantitated. The reason is the pollutants from different sources are accumulated into a larger source. For example, pollutants from agricultural water runoff include pesticides, fertilizers, and others (Liu et al., 2015).

2.3. Transboundary pollution

By definition, this type of pollution originates from one country. It spreads to neighbouring countries by numerous forms of border crossing, such as pollution transferred from one country's river flowing through the other. The phrase also applies to pollutants when one form of pollution (for example, land pollution) can seep into another type of pollution distant from its source, particularly water pollution. (Chen and Taylor, 2018).

2.4. Groundwater pollution

The contamination of underwater sources, like water tables, rivers, and others due to the percolation of contaminated water makes them unfit for consumption. One of the major problems with this category is that the pollution is not visible, and by the time it is identified, it would have been too late. Another problem with groundwater pollution is that it is very difficult to clean as it is not accessible and can spread to other resources easily as well (He et al., 2022).

2.5. Surface water pollution

Surface water includes rivers, lakes, oceans and other water bodies. Waster waters from industries, agricultural lands, and other sources can cause degradation in the surface water quality of these water resources, making them unsuitable for use or consumption (Quesada et al., 2019).

2.6. Pathogens

There are usually a lot of microbes presesnt in water sources, but some can cause diseases which leads tofatal. The growth of bacteria like Coliform bacteria is considered a major sign of water pollution. Other microbial species like *Cryptosporidium parvum*, *Burkholderiapseudomallei*, *Giardia lamblia*, Norovirus, *Salmonella* and worms like *Schistosoma* are also a few examples of pathogens that cause water pollution (Ashbolt, 2004; Feng et al., 2020).

2.7. Chemical wastes

These can be from domestic and industrial settings where the wastewater is a by-product of the process or its use. These include agricultural runoffs, industrial discharges, domestic sewers and others. These contain both organic and inorganic matter that is either completely dissolved or partially dissolved. Organic compounds such as detergents, organo-halides, faecal matter, petroleum oils, and other carbon-related matter. Inorganic compounds like ammonia, sulphur, nitrogen etc. These products are highly toxic and can cause serious damage to human health (Atangana, 2018). This also includes other pollution types like suspended materials such as plastic bottles, bags, oxygen-depleting algal blooms, and others (Thushari and Senevirathna, 2020).

2.8. Thermal wastes

The rising or decline in the temperature of a natural body of water induced by human intervention is known as thermal pollution. This is primarily seen in the case of using water as a coolant in industries. Unlike chemical pollution, thermal pollution also causes an effective change in the physical characteristics of water. As a result, the water kills the marine biodiversity that depends on natural resources (Blum et al., 2021).

2.9. Radioactive Wastes

Radioactive Wastes are generated as a product of nuclear material mining, effluents from nuclear power plants, underground storage plants, etc. As they have a long shelf life, the toxic waste continues to cause severe health effects in humans. For instance, Exposure to carcinogenic materials like uranium, and radon causes lung, liver and bone cancer (Hepler et al., 2021; Kalin et al., 2005).

3. Organic waste water pollution

Like all forms of water pollution, the main source of organic waste primarily comes from human intervention. Wastewater from agricultural lands, industries, urban cities, and wastewater treatment plants are some of the notable contributors (Wuana and Okieimen, 2011). However, the mixing of organic wastes in water sources is normal. The discharge of these organic elements that are excessively discharged is a problem. The natural bacteria present in the water start to degrade this organic matter by decomposing them using the oxygen present in the

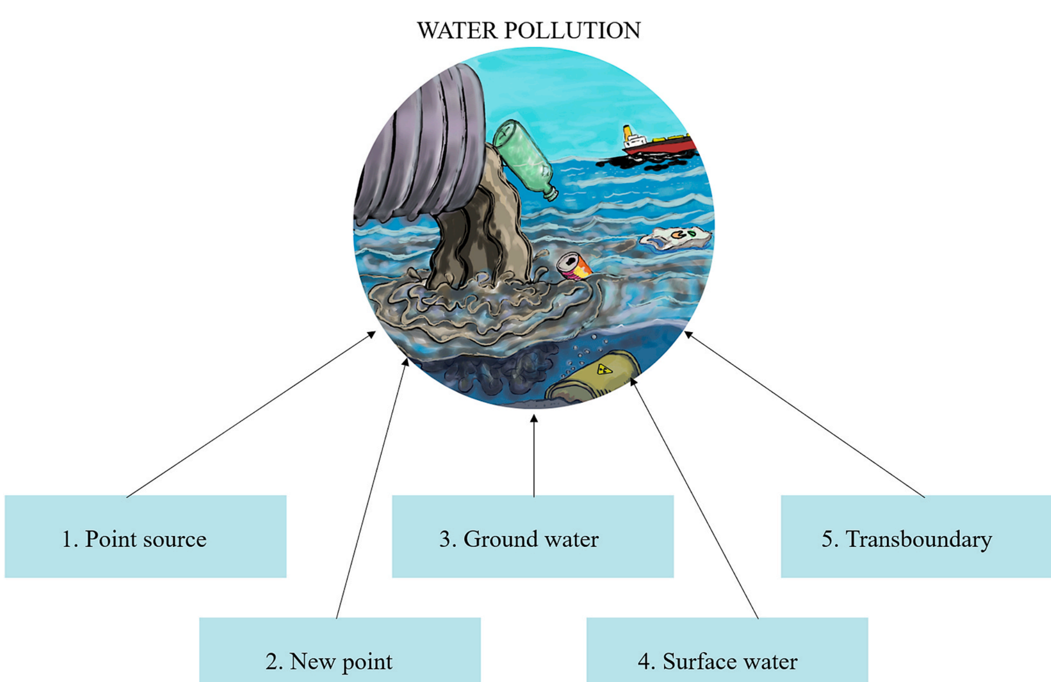

Fig. 1. Classification of water pollution.

water. This leads to two problems, the first being the depletion of oxygen present in the water, which is essential for marine organisms. The second is, that once the oxygen depletes, the process is carried out by anaerobic microorganisms that start continuing the process producing a toxic environment unsuitable for ecosystem sustenance or consumption. One of the major products of this is hydrogen sulphide gas which creates a bad odour (Azubuike et al., 2016).

Emerging Organic Contaminants (EOCs) are recently observed chemical additives that threaten water bodies (Karpińska and Kotowska, 2019). These are relatively diverse set of chemicals that includes molecules from various chemical groups without a single source of their origin but have multiple ones. Consumption of water with these elements has also proven to have severe health effects (Peteffi et al., 2019) like organ failure and cancer. Some of the major chemical compounds found as a part of these EOCs include medicinal compounds, antimicrobials, carcinogens, plasticizers, hormones, etc. There are a few common ways to determine the presence of organic pollution in water. These include Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and Total Organic Carbon (TOC) tests. BOD is the measure of dissolved oxygen required by aerobic microbes to break down organic matter into simpler compounds over time. A BOD of more than 8 mg/L in a water source is considered to be highly polluted (Rani Devi and Dahiya, 2008). COD is similar in principle to that of BOD, but the difference is that instead of measuring the organic matter, this takes into account of oxygen required to chemically oxidize chemical compounds such as organic and inorganic chemicals (Beyan et al., 2021; Hu and Grasso, 2005). A COD greater than 20 mg/L is considered polluted in surface water resources. The acceptable amount of BOD in wastewater discharge is 30 mg/L and for COD is 250 mg/L. TOC is the measure of carbon found in waterwhich is an indirect measure of water quality. The accepted level of TOC in drinking water is less than 2 mg/L. The COD level is usually higher than that of BOD and TOC (Urbansky, 2001).

4. Industries producing organic waste

Industrialization is one of the most important factors that play a vital role in developing a country. Industrial production of consumables, irrespective of their nature, produces waste as a by-product. Industrial wastes produced can be broadly classified into bio-degradable and non-biodegradable based on degradability. Further, they are classified into liquid, solid, chemical, hazardous, toxic and radioactive based on type. Proper treatment of these wastes based on their nature is paramount, as the methods differ and even depend on the chemical composition of the waste being generated (Englande et al., 2015).

Food and beverage, leather and textile, cosmetic, dairy, and pharmaceutical industries produces the most organic waste as by-products that leads to pollution (Fig. 2). The food and beverage industry, including agriculture, meat, and poultry industries, pose a threat by the overuse of nutrients, hormones, and other biological agents to improve the quality of each of their products. The major issue associated with this is that these compounds are neither natural nor in the right proportion required for the body which induces various diseases (Ferronato and Torretta, 2019; Kumar et al., 2017; Zota and Shamasunder, 2017).

In recent years, one of the most significant rising concerns is the emergence of chemical contaminants in food and their waste called Persistent Organic Pollutants (POP). This group of chemicals is bioaccumulative and persistent as they are tough to remove. These are further classified into three main categories: pesticides that include dichlorodiphenyltrichloroethane, Industrial chemicals & preservatives, and by-products of industrial processes, including polychlorinated dibenzo-p-dioxins (PCDDs) (Guo et al., 2019). The textile and leather industry also produces organic waste products. In the dying process, both the textile and leather industry lose 2–20% of the dye as a part of the process, the effluent discharged as such contains organic compounds like naphthalene, benzamide and other aromatic compounds (Adane et al., 2021). Organic compounds like formaldehyde, ethylene oxide, chromium and cadmium are some of the carcinogens used in the cosmetic industry (Siemiatycki et al., 2004). Their use and their disposal

Fig. 2. Industries producing organic waste products.

pose a threat on all fronts. The dairy and the pharmaceutical industries may also use carcinogenic compounds to extend the shelf-life of their products, but invariably either due to biological processes associated with their use or improper disposal leads to many problems (Abnet, 2007).

5. Carcinogens in industrial wastewater

According to World Health Organization (WHO) 2018 report, over 80% of the diseases and deaths observed in developing countries are traced back to water-related pollution. One of the top conditions on this list is cancer. It is defined as a condition in which malignant cells divide out of control and infiltrate surrounding tissues. Cancer cells can potentially move through the blood and lymph systems to other regions of the body. The factors that induce these diseases are called "carcinogens". These can range anything from radioactive elements to heavy metal compounds (Malyan et al., 2019).

The sources of carcinogens can either be organic or inorganic. The majority of risk is posed by arsenic, disinfection by-products, chemical dyes, cosmetics, and radioactive contaminants that can upset the delicate balance of the bodily systems or cause mutations at a genetic level to induce cancer in the body. A study conducted by researchers in the USA identified 22 carcinogens in drinking water. These carcinogens can cause disease in the pancreas, lungs, and skin. The discharge of carcinogens into water resources without proper treatment leads to environmental and health-related problems. Thus, removing these compounds is highly essential in reducing the risk of cancer (Evans et al., 2019).

5.1. *Water treatment plants*

5.1.1. *Haloacetic acids*

Haloacetic acids are produced as by-products from disinfected water systems and their continuous exposure to humans leads to carcinogenic risks. To cite, the dominating haloacetic acids are bromochloroacetic acid, bromodichloroacetic acid, chlorodibromo acetic caid, dibromoacetic acid, dichloroacetic acid and tribromoacetic acid (Global report, 2021) and trihalomethanes (Sinha et al., 2021).

5.2. *Cosmeceutical and leather industry*

A person's appearance is factored by the process of ageing and is externally seen by the texture of the skin. Due to ageing, the natural function and glow of the skin are lost. Hence the cosmetic companies takes this factor into consideration and developing their products (Pimentel et al., 2018). However, extensive use of such chemicals can result in an aggressive reaction that can be carcinogenic. The major carcinogens present in wastewater discharged from cosmetic industries are enlisted in Table 1.

Table 1
List of carcinogens present in cosmetic industry wastewater.

Compound	Product	Cancer caused	Reference
Formaldehyde	keratin hair straighteners, nail polish eyeshadow	skin	Attia et al. (2016)
Phenacetin	facial hair bleach	skin, renal mammary malignancy	Xu et al. (2018)
Coal Tar	hair dyes, shampoos, dandruff/scalp treatment and redness/rosacea treatment.	lung, bladder, kidney, and digestive tract.	Washam (2006)
Benzene	hair conditioner	mammary tumours endocrine disruptor	Lovreglio et al. (2010)
Mineral oils	wide array of personal care products, including eye shadow, moisturizer, lip gloss, lipstick, conditioner, hair colour and bleaching, facial treatment, styling gel/lotion, blush and concealer	lung cancer	Tolbert (1997)
Ethylene oxide	sterilize medical instruments	lymphatic and hematopoietic cancers	Vašková and Kolomazník (2016)
chromium	eye shadow	wide range of cancer	Anna L. Rowbotham (2000)
cadmium	eye shadow	lung cancer liver cancer, kidney cancer, pulmonary cancer and prostrate cancer	Waalkes (2000)

5.2.1. *Formaldehyde*

The compound formaldehyde has a wide range of usage when it comes to the cosmetic industry. It also has antimicrobial properties (especially bacterial contamination) that helps to prolong the shelf life of beauty product (US EPA, 2014). Formaldehyde can decrease the mitochondrial membrane potential thereby inhibiting mitochondrial respiration. Mutagenesis of p53 was encouraged in the presence of formaldehyde (Ji et al., 1998). Industrial workers are exposed to formaldehyde along with leather dust in the region of nasal cavities, sinuses and rhino pharynx and have a higher risk of developing cancer (Olsen et al., 1984). The aggressiveness of the exposure to formaldehyde is increased with the presence of wood dust leading to the formation of adenocarcinoma (Luce et al., 1993). In the presence of coal dust, there is a higher chance of laryngeal cancer (Laforest et al., 2000).

5.2.2. *Phenacetin*

Phenacetin is a pharmaceutical compound that was extensively used for relieving pain and decreasing temperature. Even though phenacetin is currently not considered a drug to treat the aforementioned disease, it is used in developing personal care products (Matsuda et al., 2010). However, when phenacetin is administered orally to produce an analgesic effect, the compound is considered carcinogenic and the expression causes renal damage, anaemia and malignant mammary tumour (Xu et al., 2018).

5.2.3. *Coal tar*

Although considered a carcinogen, it is an important compound that is added in preparing anti-dandruff shampoos and anti-itching creams (Naveed, 2014). Polycyclic aromatic hydrocarbons (PAHs) can react and damage the structural integrity of DNA leading to the formation of tumours in the lungs, bladder and the skin (Washam, 2006) (Brown et al., 2012).

5.2.4. *Benzene*

Benzene is a compound that is derived from coal tar. Cancer induced by Benzene was first reported in 1920s in the form of leukemia in humans and neoplasia in animals (Huff, 2007). The exposure of this compound occurs through inhalation and digestion (Lovreglio et al., 2010). A study conducted in 6 nail salons in Colorado, reported that 70% of workers experienced issues regarding their health as decreased lymphocyte count, distortion of the central nervous system and motor function caused by the solvent (Lamplugh et al., 2019). Occupational exposure is also linked to a wide range of problems including mammary tumours, endocrine disruption, and damaged central nervous system and bone marrow (Regev et al., 2012).

5.2.5. *Mineral oils*

Mineral oils in the cosmetic industry are used in creams and lotions to give a plump to the skin. It is also used in Cosmetic products such as lipsticks and eye shadow (Mackerer et al., 2003). Mineral oils are also considered as polycyclic aromatic hydrocarbon compounds. Currently, the compound is mixed with nitrosamine to eradicate carcinogenicity (Tolbert, 1997).

5.2.6. Chromium

Though chromium is not considered a carcinogenic compound, its hexavalent structure displays carcinogenic characteristics. The route through which it enters is either through inhalation or digestion (Anna L. Rowbotham, 2000). In the Cosmetic industry chromium is used as a colour additive agent for products which is used to enhance the complexion in cheeks and eyes. It has been identified that when chromium comes in contact with the skin, it can cause skin ulcers and dermatitis. The amount of chromium present in the product must not exceed 5 ppm (Parts per million) and is considered dangerous by the Environmental Protection Unit (EPA) (Khalid et al., 2013). Continuous exposure to chromium can lead to cancerous growth associated with the lung, nasal cavity and digestive tract (Vašková and Kolomazník, 2016).

Chromium is inhaled more than it is being digested and plays an essential role in oxidative damage of macromolecules, lipid membrane and nucleic acid (Fryzek et al., 2001). Exposure to high levels of chromium can also result in nasal cancer (Battista et al., 1995). Interestingly chromium heavy metals are highly used in leather industries for tanning leather products.

5.2.7. Cadmium

Cadmium, heavy metal was identified as a human carcinogen in the year 1993. Cadmium is a carcinogenic agent that causes lung cancer, liver cancer, kidney cancer, pulmonary cancer, prostate cancer and its action is poorly mutagenic (Waalkes, 2000). Cadmium induces carcinogenesis if injected and it causes toxic lesions. Cadmium salts also induces mesenchymal tumours (Waalkes, 2003).

5.2.8. Arsenicals

Arsenic trioxide or arsenic is used as paint to keep wood and leather intact (Izdebska et al., 2008). This compound causes acute promyelocytic leukemia in the prostate, breast, stomach, liver, and ovarian cancer. Occupation hazard in the leather industry is in the form of leather dust creating a problematic breathing capacity and leading to Sino-nasal cancer (d'Errico et al., 2009), (Mikoczy et al., 1996).

5.3. Drinking-water industry

There is a large variety of chemicals that are found in drinking water (Table 2). Based on their origin, contaminants can be categorized as:

Table 2
List of carcinogens present in drinking water industry.

Compound	Origin	Cancer caused	Reference
Carbon Tetrachloride	Source water	Hepatocarcinoma	Brennan and Schiestl (1998b)
Trichloroethylene	Source water	Hepatocarcinoma lung and kidney cancer	Wartenberg et al. (2000)
Tetrachloroethylene	Source water and Distribution system leakage	Breast cancer, Lung cancer, Bladder cancer	(Aschengrau et al., 1993), Aschengrau et al., 1998)
Chloroform	Treatment byproducts	Hepatocarcinoma, Kidney cancer	(Brennan and Schiestl, 1998b),
Chlorinated phenols, Chlorinated aldehyde and ketone derivatives	Distribution system leakage	Bladder cancer	Diana et al. (2019)

i. *Source water contaminants*: These are contaminants that are obtained from lakes, rivers and streams such as Carbon tetrachloride, trichloroethylene and tetrachloroethylene.
ii. *Leaking at the distribution site:* During the distribution of drinking water, the water can be subjected to exposure towards contaminants.

5.3.1. Carbon tetrachloride

Carbon tetrachloride is a volatile compound, used for degreasing (Rood et al., 2001). During the process of chlorination, a wide variety of chlorinated hydrocarbons are generated that display carcinogenicity. It also induces intrachromosomal deletions causing genotoxic recombination (Brennan and Schiestl, 1998a). In a study, it was observed that mice under the influence of carbon tetrachloride showed hepatic injury, fibrosis and carcinogenesis because of the up regulation of the Wnt/β-catenin signalling pathway (Preziosi et al., 2018).

5.3.2. Trichloroethylene

Trichloroethylene is a non-flammable organic compound that has displayed liver and kidney cancer in humans (Wartenberg et al., 2000). It is formed naturally but in recent times its presence is increasing in drinking water because of the altered food chain (Lock and Reed, 2006). The compound reacts with a DNA metabolite resulting in mistranscription and cross-species target tissue resulting in the formation of rare tumours with an increase in cell proliferation and up regulated receptor interaction or cytotoxicity in tumours (Clewell et al., 1995).

5.3.3. Tetrachloroethylene

Tetrachloroethylene is present in the interior lining of asbestos cement in the water pipes that are used for the distribution of drinking water. Initially, it was believed that the compound Tetrachloroethylene or perchloroethylene would evaporate because of its volatile nature but the reminisces of the compound remained in the tube. It was estimated that there were 1600–7750 μg/L for low-flow pipes and 1.5–80 μg/L for medium and high-flow pipes (Gallagher et al., 2011). The toxicity of the compound is contributed by factors such as the residential duration of the water in the pipes, occupants that it serves, distribution of water, and the dimensions and age of the pipe (Aschengrau et al., 1993). Tetrachloroethylene causes a wide variety of cancer ranging from breast, lung kidney and colon-rectum cancer (Paulu et al., 1999).

5.3.4. Chlorinated phenols, chlorinated aldehyde and ketone derivatives

Disinfection of drinking water is to inactivate the bacterial contamination and the process of chlorination is considered as an effective method. However, in the light of killing harmful bacteria, the consumption of harmful by-products through chlorination is an event that is prevalent in today's world (Mazhar et al., 2020). Epidemiological studies have consistently provided evidence of a high risk of cancer in chlorinated drinking water accounting for 76 known bladder carcinogens (Diana et al., 2019). During chlorination, the first step is to clarify water from the source and is followed by a passage through a channel in which micropollutants are removed. Finally, chlorine disinfection is done to remove microbial contaminants. The disinfectant by-products can include amines, aromatics, halocyclopentenoic acids, haloquinones, nitrosamines, aromatic amines, halofuranones, haloamides and aromatic amines. In a study conducted in Norway, it was identified that consumption of chlorinated water resulted in carcinogenic effects on the digestive tract and a few incidents of colon cancer (FLATEN, 1992).

5.4. Dairy industry

The use of constructed wastewater treatment systems (CWs) to treat animal wastewater has been acknowledged as a promising technology in recent years; however, data on systems treating dairy effluent, particularly in temperate areas, is sparse. While CWs are typically successful in removing organic matter and total suspended solids (TSS), however because of eutrophication leads to enhancing parts of natural water bodies with minerals and nutrients. Wetlands offer lower start-up costs and fewer maintenance needs than other forms of wastewater treatment systems, making them appealing to small and medium-sized farms (Johnson et al., 2004). There are various carcinogenic materials present in dairy wastewater which causes adenoma in humans (Table 3).

5.4.1. Calcium

The source of calcium is obtained through milk, cheese, curd and untreated drinking water. However high intakes of cancer that are not absorbed by the gut lumen results in harmful effects in the digestion process and encourage colon cancer promotors (Heaney, 2013).

5.5. Textiles and tanneries

Thousands of people are working in the textile business across the world. The textile business employs a variety of dyes, some of which are known to be carcinogenic. The textile and tannery sectors use a wide range of textile dyes, heavy metals and solvents, many of which are carcinogenic as listed in Table 4. As a result, employees in the textile business are constantly exposed to these dyes, solvents, fibre dust, and other harmful compounds (Singh and Chadha, 2016).

5.5.1. Aniline

Aniline is a compound that is present in the dyeing sector (Veyalkin and Gerein, 2006). Aniline largely affects women in the tanning industry. The affected women have a thicker layer of corpus and cervical uteri, melanoma and kidney cancer. The mortality rate of people with pancreatic cancer is competitively higher (Veyalkin and Milyutin, 2003). Table 5 enlists the broad range of carcinogens from distinct industrial sectors.

6. Treatment strategies for organic wastewater

Different organic compounds that are present in wastewater require different water treatment strategies due to the complexity and nature of the strategy itself (Fig. 3). Biological treatment, adsorption, chemical coagulation, and physicochemical approaches are currently used to treat organic wastewater (Fan et al., 2021). The biological treatment approach, which has been employed in large wastewater treatment facilities and it is the most cost-efficient and successful method. However, it is time-consuming and requires a lot of space. Here, microorganisms like bacteria, fungi and other organisms are used to degrade the organic compounds present in the water. Nevertheless, this is not effective for highly concentrated waste as they affect the organisms' activities. This technique cannot address complicated and multiple treatment requirements (Sun et al., 2019). In the adsorption approach, the organic waste is concentrated from liquid waste to solid waste. Though this is a simple and effective process, it does not address any degradation process for the organic compounds (Awad et al., 2019). Adsorption is widely used in treating industrial effluents of coloured and non-coloured organic compounds. Here in the process, the organic compound attaches itself to a solid adsorbent by removing it either through physical or chemical bonds (Englande et al., 2015).

In chemical oxidation technologies, the organic compounds are mostly reduced into simpler, less toxic and manageable compounds. To increase the degrading quality than that of the regular oxidation processes, the emergence of advanced oxidation processes (AOPs) that uses hydroxyl radicals (OH) are used in water treatment (Glaze et al., 1987). Unfortunately, it is not cost-effective. Physiochemical methods include Electro plasma, a newly developed process that includes reactive species molecules, oxidizing species, reduction species, and other processes to eliminate or mineralize the organic compound. This is highly known for its efficacy, cost-effectiveness, and wide application range (Zeghioud et al., 2020). Coagulation techniques only address the pollution from a surface point, i.e., only remove the suspended particles and do not address the dissolved elements to the fullest (Ashraf et al., 2015). Other methods include solvent extraction, where organic solvents are used to extract compounds and electrocoagulation.

Table 3
List of carcinogens present in dairy industry wastewater.

Compound	Product	Cancer caused	Reference
Phosphorus	Milk processing	Adenoma	Vidya et al. (2021)
Calcium	Milk processing	Adenoma	Adeoye (2009)
Non-Dairy Calcium	Milk processing	Adenoma	Lee et al. (2016)
Dairy calcium	Milk processing	Adenoma	Zhang et al. (2009)

Table 4
List of carcinogens present in tannery-textile wastewater.

Compound	Product	Cancer caused	Reference
Chromium and chromium III	Tannery, dyes and pigments	lung cancer, pancreatic nasal cancer	Battista et al. (1995)
Arsenic	tannery	lung cancer	Hayes et al. (1986)
Formaldehyde	leather dust, dyes and pigments	pancreatic	Hayes et al. (1986)
Aniline	leather dust	pancreatic	Veyalkin and Milyutin (2003)
Leather dyes	synthetic fats used under leather stuffing, leather dust, dyes and pigments	skin, kidney, Pancreatic cancer	Decouple (1979)
Dimethylformamide	tannery	Testicular cancer	Mikoczy et al. (1996)
Chlorophenols	pretanning	Soft tissue sarcoma	Saracci et al. (1991)

6.1. Overview of electrocoagulation

Electrocoagulation is an emergent technology, a part of the physicochemical process that is comparatively better than others due to its cost-effectiveness and stability. It is a process in which the coagulation of organic compounds happens without the use of chemical coagulants. The process produces hydroxide complexes causing the particles to agglomerate. This can be later removed by a simple filtration process (Butler et al., 2011). Electrocoagulation is a process consisting of creating metallic hydroxide flocks within the wastewater by electrode solution of soluble anodes, usually made of iron or aluminium. The generation of metallic cations takes place at the anode, due to the electrochemical oxidation of the iron or aluminium, whereas at the cathode, the production of H_2 typically occurs which is illustrated in Fig. 4 (Arroyo et al., 2009). The electrocoagulation process involves many chemical and physical phenomena, such as discharge, anodic oxidation, cathodic reduction, coagulation, electrophoretic migration, and adsorption (Cheng, 2006). Likewise, during an electrocoagulation process, the liquid is not enriched with anions and salts content does not increase, compared with chemical metal precipitation. This contributes to the production of metallic sludges which are compact using electrocoagulation compared with those generated by chemical precipitation. Moreover, electrocoagulation requires simple equipment, a small retention time and is easy to operate. These characteristics contribute to the reduction of operating costs for industrial applications (Meunier et al., 2006).

As most of the conventional water treatment methods are not satisfactory enough to remove the pollutants, sustainable, green technology is required for its maximum removal. Interest in the EC technique among the scientific community has been escalating recently as it eliminates the pollutants which are complicated to remove through primary treatment and other chemical means. Electrocoagulation is comparatively superior

Table 5
List of carcinogens present in industrial effluents from diverse industries.

S. No.	Compound	Industry	Cancer	Reference
1	Asbestos	Mining and milling;	Lung carcinogens	
2	Beryllium	aircraft and aerospace	Lung carcinogens	Sanderson et al. (2001)
3	Diesel exhaust	Railroad work	Lung carcinogens	("Diesel Exhaust Exposure and Lung Cancer on JSTOR," n.d.)
4	Nickel	Nickel refining and smelting; welding	Lung carcinogens	Shen and Zhang (1994)
5	Silica	Mining	Lung carcinogens	McDonald (1989)
6	Benzene	Chemical industry, Pharmaceutical, and rubber industries	Leukaemogens	Bahadar et al. (2014)
7	Ionizing radiation	cosmetics, medicinal and pharmaceutical preparations	Leukaemogens	("Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know | PNAS," n.d.)
8	Ethylene oxide	sterilizing agent	Leukaemogens	Hogstedt et al. (1986)
9	Erionite	Waste treatment	Mesothelioma	("Relation of environmental exposure to erionite fibres to risk of respiratory cancer. - Abstract - Europe PMC," n.d.)
10	Silica, crystalline	Granite and stone industries	Lung	("Lung Cancer among Industrial Sand Workers Exposed to Crystalline Silica | American Journal of Epidemiology | Oxford Academic," n.d.)
11	Monomers Vinyl chloride	Aerosol propellants	angiosarcoma	("Increased morbidity odds ratio of primary liver cancer and cirrhosis of the liver among vinyl chloride monomer workers. | Occupational & Environmental Medicine," n.d.)
12	Bis(chloromethyl) ether	plastic manufacturing	Lung	("LUNG CANCER DUE TO EXPOSURE TO BIS (CHLOROMETHYL) ETHER," n.d.)
13	chloromethyl methyl ether	resins and polymers	Lung	Figueroa et al. (1973)
14	Naphthylamine	Production; dyestuffs and pigment manufacture	Bladder	("Lifetime carcinogenicity study of 1- and 2-naphthylamine in dogs | British Journal of Cancer," n.d.)
15	benzidine	Production; dyestuffs and pigment manufacture	Bladder	Hayes et al. (1993)
16	Aminobiphenyl	Production; dyestuffs and pigment manufacture	Bladder	Airoldi et al. (2002)
17	Tetrachlorodibenzoparadioxin	pulp and paper bleaching	Non-Hodgkin lymphoma	Jana et al. (1999)
18	Aflatoxin	Feed production industry	liver	("Aflatoxin Exposure in Human Populations: Measurements and Relationship to Cancer: CRC Critical Reviews in Toxicology: Vol 19, No 2," n.d.)
19	Mustard gas	military personnel	Larynx	("EXPERIMENTAL AND CLINICAL STUDIES ON THE TREATMENT OF CANCER BY DICHLORETHYLSULPHIDE (MUSTARD GAS," n.d.)
20	sulfuric acid	Fertilizer	Lung	Beaumont et al. (1987)
21	Ultraviolet radiation	welding	Melanoma	("Review: Ultraviolet radiation and skin cancer - Narayanan - 2010 - International Journal of Dermatology - Wiley Online Library," n.d.)
22	Polyaromatic hydrocarbons benz	Mechanical industry	lung and bladder	Morris and Seifter (1992)
23	Dibenz	steel mills	Lung, bladder and skin, breast	("The effects of different social conditions on breast cancer induction in three genetic types of mice by dibenz[a,h]anthracene and a comparison with breast carcinogenesis by 3-methylcholanthrene.," n.d.)
24	Creosotes	wood preserving	Skin	("Cancer incidence among creosote-exposed workers on JSTOR," n.d.)
25	Methylene bis(2-chloroaniline)	Roofing and wood sealing	Bladder	Chen et al. (2005)
26	α-Chlorinated toluenes	dye and pesticide manufacture	Lung	("Report on Carcinogens (12th Ed.) - Nat. Toxicology Program (NTP) (NIH) - Google Books," n.d.)
27	Polychlorinated biphenyls	dye and pesticide manufacture	Liver and biliary tract	Loomis et al. (1997)
28	Tetrachloroethylene	dry cleaning; metal degreasing	Cervix, Esophagus, Non-Hodgkin lymphomad	Bois et al. (1990)
29	Acrylamide	water and wastewater treatment	Pancreas	Pelucchi et al. (2006)
30	Butadiene	Chemical and rubber industries	Lymphohematopoietic	("Lymphohematopoietic Cancer in Styrene-Butadiene Polymerization Workers | American Journal of Epidemiology | Oxford Academic," n.d.)
31	Epichlorohydrin	resins	Lung	("Comparison of Contact Site Cancer Potency Across Dose Routes: Case Study with Epichlorohydrin* - Ginsberg - 1996 - Risk Analysis - Wiley Online Library," n.d.)
32	Vinyl bromide	plastic production	Lymphohematopoietic	("1,3-Butadiene, ethylene oxide and vinyl halides (vinyl fluoride, vinyl chloride and vinyl bromide).," n.d.)
33	Vinyl florid	fluropolymer production	adenicarcinoma	Chattopadhyay and Podder (2014)
34	benzidine-based dyes	textile, paper and leather indusrty	Bladder	("Carcinogenic and Mutagenic N-substituted Aryl Compounds: Proceedings of an … - Google Books," n.d.)
35	Chloro-ortho-toluidine	Dye and pigment manufacture	Bladder	("DNA Damage Response of 4-Chloro-Ortho-Toluidine in Various Rat Tissues | Toxicological Sciences | Oxford Academic," n.d.)
36	Dimethylcarbamoyl chloride	pharmaceuticals	Bladder	("Discovery of N1-(4-((7-Cyclopentyl-6-(dimethylcarbamoyl)-7H-pyrrolo[2,3-d]pyrimidin-2-yl)amino)phenyl)-N8-hydroxyoctanediamide as a Novel Inhibitor Targeting Cyclin-dependent Kinase 4/9 (CDK4/9) and Histone

(*continued on next page*)

Table 5 (*continued*)

S. No.	Compound	Industry	Cancer	Reference
				Deacetlyase1 (HDAC1) against Malignant Cancer | Journal of Medicinal Chemistry," n.d.)
37	Captafol	fungicide	Bladder	Perocco et al. (1995)
38	Ethylene dibromide	petroleum refining	Bladder	("Carcinogenic risk assessment: Ethylene dibromide - ScienceDirect," n.d.)
39	Non arsenical insecticide	grain mill workers	Brain, Leukemia, Lung, Multiple myeloma,Non-Hodgkilymphoma	Bonner et al. (2010)
40	Diethyl sulfate	Ethanol production	Leukemia	Lynch et al. (1979)

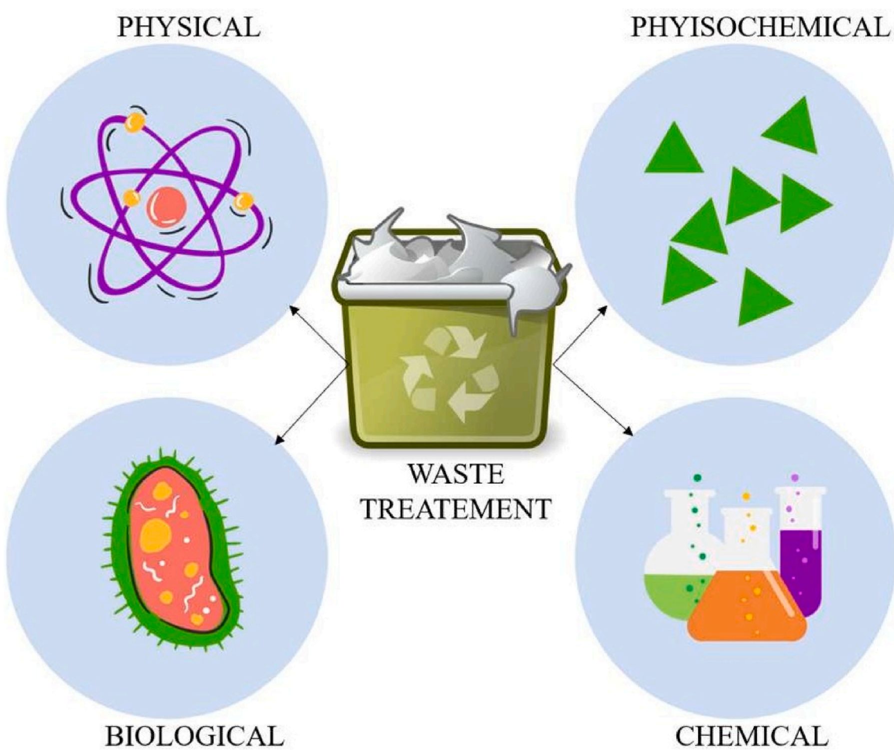

Fig. 3. Types of waste water treatment methods.

to other methods because it is not time-consuming nor requires sensitive micro-organisms compared to biological processes. This technique finds its applications in several areas such as industrial effluent treatment, wastewater treatment and healthcare treatments. Electrocoagulation deals with the removal of any size of suspended solids without filters which is considered to be one of the major advantages of this technique. Along with this, it does not require frequent maintenance, ease in operation, minimal sludge generation and not require any chemical aids to remove the pollutants (Kabdaşlı et al., 2012; Lu et al., 2021). Electrocoagulation as a process can filter a broad spectrum of organic wastes and filter both smaller and larger suspended particles (Jing et al., 2021; Kabdaşlı et al., 2012). Thus, electrocoagulation may be considered a potential candidate for treating organic waste discharges.

A number of publications in the recent years describes the contaminant removal by electrocoagulation when used as a single treatment process or as an integrated process (Al-Qodah et al., 2020; Al-Qodah and Al-Shannag, 2019). Specific examples of EC combined with other treatment processes are: (i) treatment of oil washing wastewater using combined of electrocoagulation and phytodegradation (Ates et al., 2017), (ii) biological treatment processes combined with electrocoagulation as post-treatment processes (Al-Qodah et al., 2020). The published results have shown that this advanced combined system offers high potential and promise for large-scale applications.

Combined biological and EC treatment was primarily performed in removing waste water from pulp wastewater. This was performed with the help of an up flow anaerobic sludge Blanket (UASB). From the experiment conducted by Buzzinia et al., it was identified that stainless steel electrodes removed 82% of the coloured residue and 84% of COD compared to aluminium that removed 98% of the coloured residue and 67% of COD. The arrangement of integrated Bioreactor-electrocoagulation comprises of two categories. In the first category, the biological process is performed with microbes and an EC treatment is done later to remove organic wastes. (Buzzini et al., 2007).

6.2. Limitations of electrocoagulation

Though electrocoagulation has remarkable advantages in water treatment, there are some disadvantages mainly the cyclic replacement of electrodes as it dissolves in waste water due to oxidation, and the cost of electrical energy consumption for treatment (Mousazadeh et al., 2021a). Currently, the process of EC is aided by non-renewable energy sources. Hence, operational cost and the pollution caused by these resources is extremely high. With a high COD load, electrode passivation is a major problem that leads to less efficiency in removing waste. In addition, anodic oxidation can also reduce the efficiency of the process of electrocoagulation which can be controlled with the help of an upgraded electrolyte (Fig. 5). Hence, EC efficiency can be improved for better outcomes, with optimization of electrode type, arrangements and

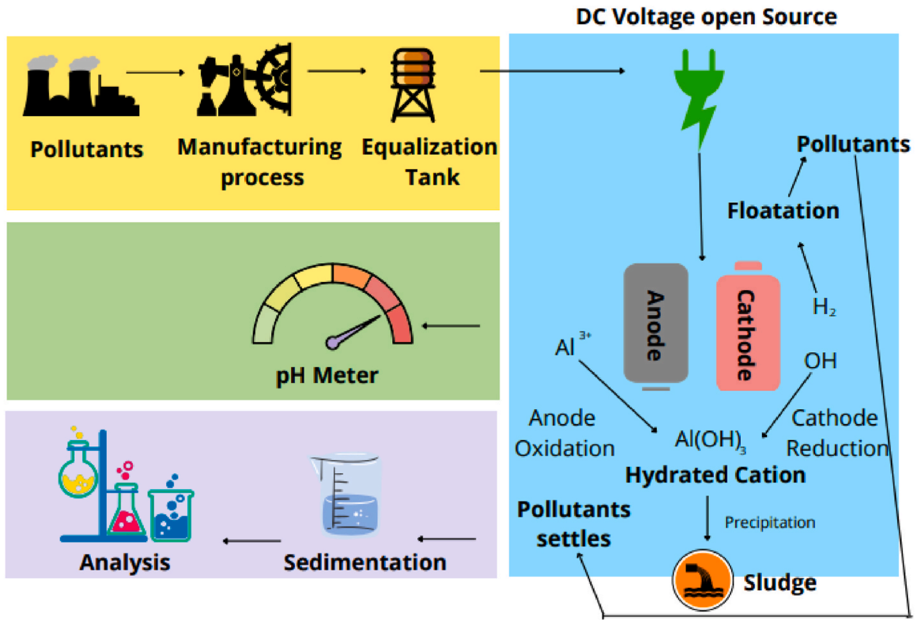

Fig. 4. Pollutant removal using electrocoagulation process.

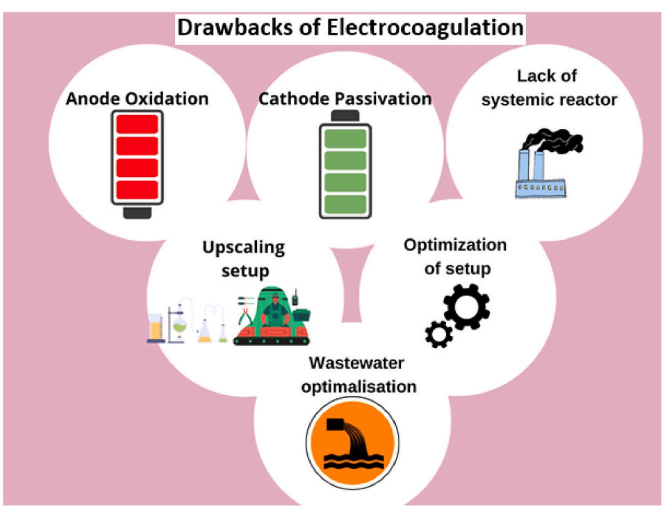

Fig. 5. Limitations of electrocoagulation during treatment of organic wastewater.

number (Al-Hamamre et al., 2017; Jing et al., 2020; Mousazadeh et al., 2021b).

7. Application of electrocoagulation in different industry wastewater

7.1. Paper industry

Effluents from the paper and pulp industries, as well as their recycling methods, include a complex mix of elements and hazardous chemicals, making treatment difficult (Patel et al., 2021). Electrocoagulation outperforms its equivalents in terms of efficiency, convenience of use and cost-effectiveness among the several treatments used to treat them (Mehmood et al., 2019). The earlier study was performed on the treatment of wastewater from paper recycling to reduce COD, TSS and ammonium salts. Experiments were performed using Fe and Al electrodes and ranging some operating conditions such as pH, electrolysis time and voltage usage. Under optimized conditions of neutral pH, 1 h of electrolysis time and a voltage of 10 V, COD, TSS and ammonia were removed in the range of 80%–90% (Izadi et al., 2018).

7.2. Oil industry

Oil wastewater is generated by a variety of industries, including oil refineries, crude oil industries, food processing industries and lubricant manufacturing industries. Distillation, hydro-treating, desalting, and cooling systems consume a considerable amount of water, resulting in a massive volume of effluent having high concentrations of heavy metals. (Adetunji and Olaniran, 2021). This effluent is broadly very high in BOD/COD and therefore requires relevant treatment before discharge. Only a few studies had examined the treatment of oil wastewater using the electrocoagulation process (An et al., 2017; Xu and Zhu, 2004). Prior research looked into COD removal from oil effluent by electrocoagulation using aluminium and iron electrodes. The process was evaluated under various operating conditions such as pH, voltage, response time and electrolyte concentration. The maximum COD removal of 99% was attained at an operating condition of neutral pH $>$ 10 V, a reaction time of 40 min and sodium chloride as the supporting electrolyte. Altogether, the findings suggested that electrocoagulation is a suitable treatment option for eliminating COD from oil effluent (Safari et al., 2016).

7.3. Leather industry

Leather production is linked to the tannery sector, which generates a lot of wastewater with complicated properties and a large proportion of inorganic and organic components, especially chromium and a high COD (Hansen et al., 2021). Many experiments have been conducted to use electrocoagulation to minimize COD in tannery wastewater (de la Luz-Pedro et al., 2019; Varank et al., 2014; Villalobos-Lara et al., 2021). Previously, wastewater samples were collected from a localized tannery industry for a treatment analysis. They employed electrodes made of aluminium and alloys of aluminium which were tested at various current densities, reaction times and electrode material values. The results showed that electrocoagulation is an effective approach for treating tannery wastewater by lowering the high initial COD concentration (5000 mg/L) while consuming very little energy (Elabbas et al., 2016).

7.4. Food industry

In comparison to other sectors, the food industry necessitates more water per tonne of goods. Different toxins are present in food industry wastewater depending on the industry, but the basic attributes of wastewater are that it is readily biodegradable and harmless, with high levels of suspended solids and chemical-biological oxygen demand (Moussa et al., 2017; Slavov, 2017). Colour, oil and fat are further issues in meat processing. The effluent stream from the dairy industry has a significant organic loading, as well as high COD and BOD values and TSS. A prior study conducted in the Sistan and Balochistan Province used electrocoagulation to treat dairy waste streams. The wastewater for this investigation was collected from a local dairy business with a daily processing capacity of >20 kg of milk. Experiments on electrocoagulation were carried out in a bipolar bioreactor made up of series-connected aluminium electrodes. They used a supportive electrolyte and varied the voltage (50 V–60 V) and reaction duration (1 h). The method was optimized at 60 V and 60 min to yield 97 percent reductions in the effluent components. The energy consumption was calculated to be 95 Wh/L, demonstrating that the electrocoagulation approach is suitable for treating dairy effluent (Bazrafshan et al., 2012).

7.5. Pharmaceutical industry

Wastewater from the pharmaceutical industry has a high level of COD and nitrogen-containing chemicals, requiring further treatment. Discharging such wastewater into the surrounding environment without sufficient treatment might harm plants and animals (Alam et al., 2021; Mitra et al., 2021). The presence of a high quantity of estrogen in the wastewater streams may increase a fish's mortality rate (Jukosky et al., 2008) and cause male fish to feminize (Gross et al., 2006). Long-term exposure to several complex pharmaceutical chemicals found in water bodies can result in both chronic and acute pollution (Crane et al., 2006), behavioural abnormalities (Quinn et al., 2008), reproductive damage (Gaworecki and Klaine, 2008) and cell proliferation suppression in humans (Pomati et al., 2006). By entering the food chain, these harmful by-products produce additional microbiological dangers (Stackelberg et al., 2004), chemical hazards (Emmanuel et al., 2009), and agronomic effects (Kümmerer, 2001).

8. Removal of carcinogens by electrocoagulation

Haloacetic acids are a prevalent group of noxious by-products derived through the disinfection of water bodies. The electrocoagulation process dwells as the best option to remove these disinfection products from water treatment plants (Ghernaout and Elboughdiri, 2020). Interestingly, they can also be removed through diverse treatment strategies viz., reverse osmosis (XLE and SB50) and nanofiltration using (NF90 and NF270) membranes namely, chloroacetic acid, bromodichloroacetic acid, dibromochloroacetic acid, tribromoacetic acid, trichloroacetic acid, dibromoacetic acid, bromochloroacetic acid, dichloroacetic acidand bromoacetic acid (Yang et al., 2017). In a similar vein, the adoption of statistical methods channelizes a successful streamlining for the eradication of haloacetic acids. To be specific, haloacetic acids such as monochloroacetic acids, monobromoacetic acid, trichloroacetic acid, tribromoacetic acidand dibromoacetic acidcan be chemically transformed by iron powder following the response surfacestatistics aided approach (Behbahani and Seo, 2016).

With advancements in these techno-effective processes, haloacetic acids can also be remediated by photolysis and photocatalysis by Ultraviolet (UV) based technologies. This can be ascribed as the classification of UV techniques into photoreduction, photooxidation and photolysis (Wang et al., 2020). In addition to these techniques, Fenton's process and nanofiltration are highly efficacious for the removal of haloacetic acids and trihalomethanes in terms of dissolved organic carbon (Sinha et al., 2021). Moreover, these bromo and chloroacetic acids can also be treated by electrochemical approaches usingcopper and gold electrodes (Korshin and ensen, 2001).

Formaldehyde, a major chemical compound used in personal care products and cosmetics can be treated by distinct techno-effective chemical methods. For instance, the formaldehyde compound present in the car grey water is mineralized by prolific electrocoagulation technique using iron and aluminium as the electrodes; where a maximum removal efficacy of electrocoagulation was evinced to be 99.98% with a contact time of 90 min and a neutral pH of 7 (Mohammadi et al., 2017). In a similar vein, electrocoagulation of beam house wastewater propounded an interesting removal rate with iron and aluminium electrodes requiring a contact time of 60 min (de la Luz-Pedro et al., 2019). Phenacetin, an analgesic and anti-arthritic agent dwells as a major carcinogen and can also be mineralized by a three-dimensional reactor with a particle electrode (Xiao and Zhang, 2016).

Coal tar, an essential product of the coking industry can be subjected to chemical treatment by electrocoagulation. To cite an example, a coal tar wastewater remediated by electrocoagulation by lead dioxide anodes supported the successful conversion of highly toxic recalcitrant such as ethyl-2-pyrenemethanol to a low toxic metabolite, propane-1,3-diol (Zhao et al., 2019). Benzene-based compounds are major emerging contaminants namely, polyaromatic hydrocarbons (PAH). Interestingly, electrocoagulation dwells as the promising strategy to eliminate a broad battery of PAH compounds such as acenaphthene, acenaphthylene, anthracene, dichloronaphthalene, fluoranthene, fluorene, phenanthrene, dimethyl naphthalene and naphthalene with a removal efficiency of 75% of PAHs (Gong et al., 2017).

The wastewater from oil industries is a perilous threat to ecological niches, humans and aquatic biomes. Electrocoagulation undoubtedly meets the criteria to eradicate these pollutants from wastewater streams. Supporting the above statement, the bench-scale reactors used in electrocoagulation with aluminium as the sacrificial anode and electrodes are arranged in distinct configurations. The influential parameters aiding the mineral oil treatment are time, diameter of anode, current density and electrolyte concentration. The optimal time required to transform the mineral oil was 30 min (Fadali et al., 2016). On the other hand, the electrocoagulation coupled liquid-liquid extraction processes for the treatment of worn mineral oil resulted in the 99.56, 98.83, and 93.02% respectively of unsaturated hydrocarbons, aliphatic fraction, and polycyclic aromatic hydrocarbons (Lactio et al., 2020).

Heavy metals like chromium ions are major environmental pollutants that created havoc for human and aquatic biota. Electrocoagulation relies on its remediation aptitude to remove chromium hexavalent ions from the wastewater streams of distinct industrial sectors. The chromium ions from aqueous solutions were successfully removed by electrocoagulation using an iron electrode and electrochemical batch reactor in a shorter coagulation time. The vital parameters influencing the removal of chromium are pH, energy consumption, operating cost and chromium concentration (El-Taweel et al., 2015). In supplementary to the above efficacy, electrocoagulation can also contribute to chromium removal from real tannery wastewater by a composite anode modified with titanium (Li et al., 2019). In an optimized removal study of chromium from an aqueous solution with the application of an iron electrode, electrocoagulation evinced the complete removal at an optimal pH of 3.0 with a contact time of 21.47 min coupled with an adsorption kinetic study (Khan et al., 2019). Moreover, in the case of the monopolar arrangement of the graphite and aluminium electrodes, the maximum removal of chromium ions was achieved at a pH of 7.29 with a processing time of 23 min (Singh et al., 2018).

The Chromium ions are classified by the International Anti-Cancer Research Center, USA (IARC) as a potent carcinogen with an adverse influence on living beings (Wang et al., 2017). Chrome plating industries, textile industries, and leather tanneries are some of the sectors that employ hexavalent chromium. Tanning is the process of manufacturing leather from raw hides or skins where they use a compound called tanning powder, mainly composed of chromium sulfate, which is made by reducing Cr^{6+} to Cr^{3+} with SO_2 (Zuriaga-Agustí et al., 2015). The tanning process water contains approximately 40% of the Cr utilized in the reduction process. The United States Environmental Protection Agency permits 150 ppm of chromium in wastewater discharged from the leather tanning industry (Nur-E-Alam et al., 2020). Chemical precipitation, adsorption, ion exchange, membrane filtration, flotation and coagulation are some of the other methods used for the removal of hexavalent chromium ions from wastewater as depicted in Fig. 6 (Vidu et al., 2020).

Electrocoagulation is demonstrated to be a preferred technique over traditional coagulation in the treatment of wastewater containing chromium with high concentrations. The earlier studies revealed that the (iron-aluminium) anode and cathode outperformed the other electrode configurations (iron-iron/aluminium-aluminium) in the removal of chromium from wastewater as shown in Fig. 7 (Kabdaşlı et al., 2012). In addition, an increase intemperature and current density also improved the removal efficiency. The increase ininitial Cr concentration, on the other hand, lowered the removal efficiency (Gao et al., 2005; Martín-Domínguez et al., 2018). (ELKaramany et al., 2021)) depicted that the 100% chromium removal was achieved using iron-aluminium electrodes by maintaining the pH and current density as 7 and 12.50 mA cm^{-2} respectively. The concentration of Cr was decreased from 280 ppm to 120 ppm with the above set input conditions.

Optimization studies were also performed for the effective removal of chromium obtained from tannery effluent by electrocoagulation using response surface methodology. The research findings revealed that the starting Cr concentration, current density and solution pH all had a significant impact on the efficacy of electrocoagulation in chromium removal. The results revealed that at a neutral pH and a current density of 13 $mAcm^{-2}$, chromium removal may reach up to 100 percent (Genawi et al., 2020).

Revealing the multifaceted potency, electrocoagulation can also exhibit the degradation of Cadmium, a highly carcinogenic heavy metal in addition to chromium and other heavy metals. In this perspective, the electrocoagulation coupled phytoremediation technique (macrophytes, *Typha latifolia*) was established to remove cadmium from the aqueous solution using aluminium electrodes resulting in an 81.3% removal

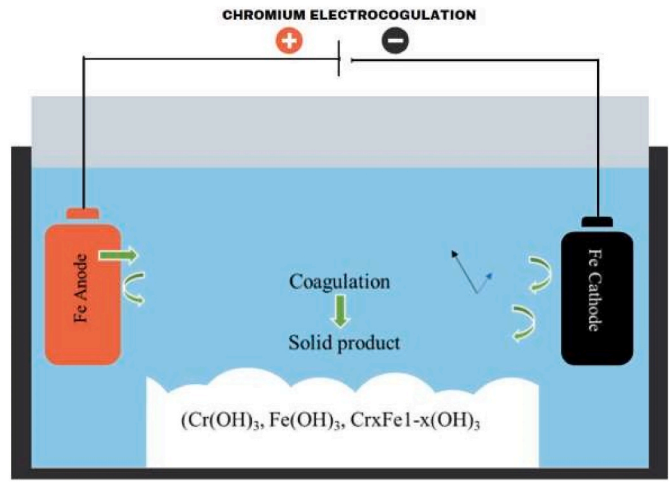

Fig. 7. Removal of chromium by electrocoagulation using Fe–Fe electrodes.

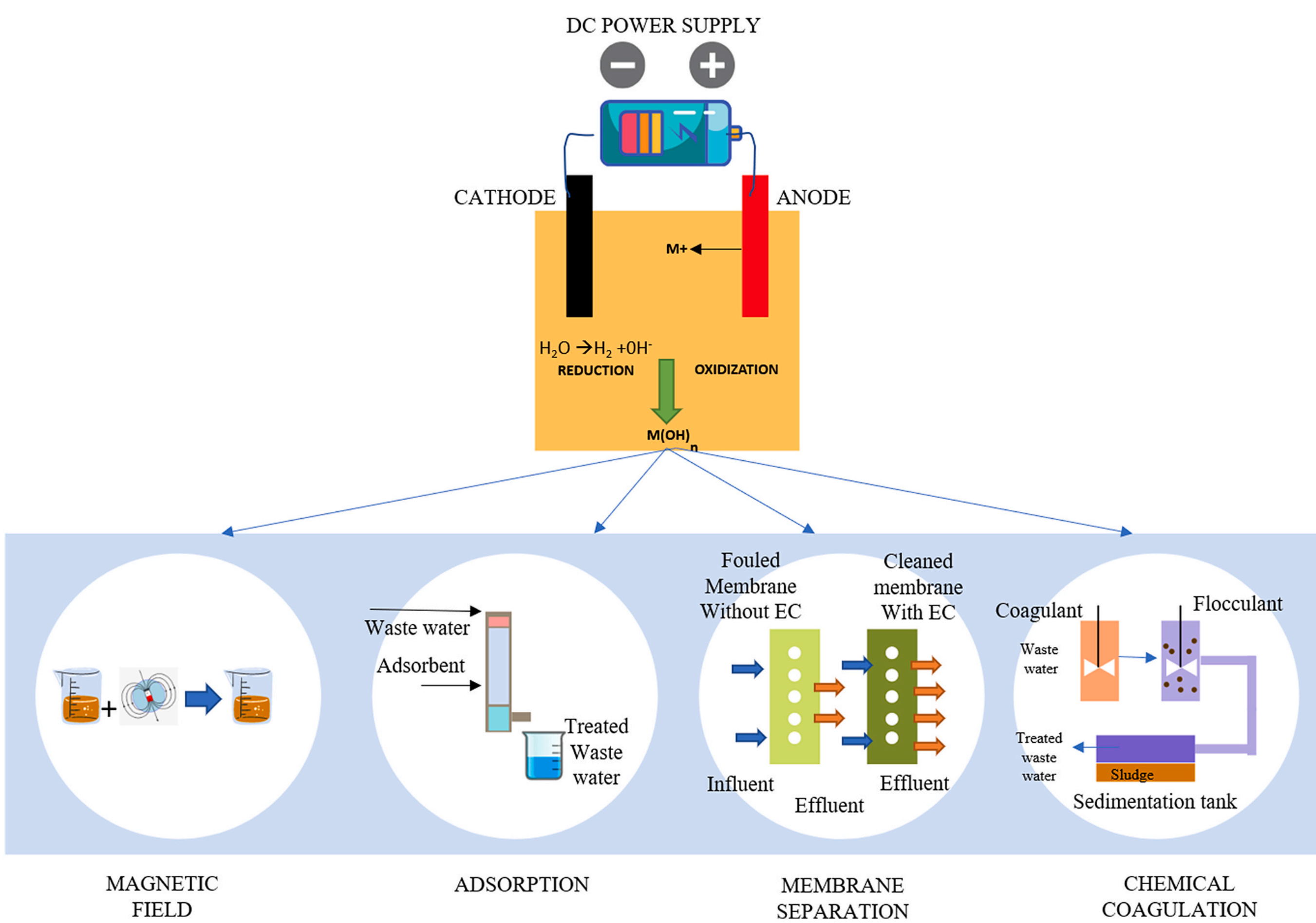

Fig. 6. Types of methods employed in the removal of chromium from industrial wastewater.

percentage of cadmium (Ferniza-García et al., 2017). Cadmium can also be found in landfill leachate, where heavy metals are predominant factors for major pollution in landfill leachate.

In these studies, the electrodes used were aluminium and stainless steel. Howbeit, the removal efficiency of cadmium by stainless steel was comparatively higher than the aluminium electrode (22.45% and 18.37%) with maximum voltage and appropriate pH (Murshed et al., 2016). Heffron and co-workers investigated the removal of cadmium trace metal from drinking water system by the application of electro-coagulation and membrane filtration with aluminium and iron electrodes, where iron electrodes outperformed aluminium electrodes for the removal activity (Heffron et al., 2016).

Even though there are several applications of arsenic (As), most of the As-containing compounds are completely banned due to their harmful effects. Humans are exposed to this harmful element, mostly through the consumption of arsenic-containing water, foodstuffs, and skin creams (Hughes et al., 2011). Arsenic has the most complicated metabolism, which makes it the most prevalent and potentially carcinogenic element to treat (Tchounwou et al., 2012). This element was categorized as Group 1 human carcinogen by the WHO (Tokar et al., 2010). Major sources of As contamination include effluents generated by firms producing wool and textiles, glass, oil refining, ceramic materials, electronic components, agrochemicals, etc (Nidheesh and Singh, 2017). Furthermore, As can also be found in mining activities, mineral processing, and waste disposal sites (Stafilov et al., 2010).

Arsenic pollution in drinking water is a serious problem in today's globe. Arsenicosis is a disease produced by drinking As-contaminated water frequently, even if the water is slightly polluted. The number of arsenicosis sufferers is growing day by day (Chung et al., 2014; Thakur et al., 2011) and it has to be completely removed from the water system. Water treatment technologies based on segregation techniques like air-chemical oxidation, reverse osmosis and nanofiltration can be used to remove arsenic as shown in Fig. 8 (Nicomel et al., 2016). One of the viable techniques used for the removal of As from contaminated water sources is the electrocoagulation process (Fig. 9). Electrocoagulation with different expendable metal anodes such as Al, Cu, Fe and Mg has shown to be particularly successful for As-detoxification (Nidheesh and Singh, 2017).

Among the arsenic species, arsenate (AsO_4^{3-}) is simpler to remove than arsenite (AsO_3^{3-}). Earlier studies reported that the complete removal of $AsO_4^{3-}$was achieved mainly by the Electrocoagulation process (Ali et al., 2011; Ratna Kumar et al., 2004). The Electrocoagulation method is capable of converting $AsO_3^{3-}$to AsO_4^{3-}, which is necessary for the effective removal of arsenite (Roy et al., 2021). Kobya and co-workers examined the effectiveness of Al and Fe electrodes for the removal of $AsO_3^{3-}$from an aqueous medium and discovered that both electrodes had equal removal capacity for AsO_3^{3-}concentrations ranging from 74.91 mg/L to 499.43 mg/L (Kobya et al., 2014).

The effectiveness of the electrocoagulation technique with Al, Fe and hybrid Al/Fe sacrificial anodes in the removal of $AsO_3^{3-}$and $AsO_3^{3-}{}_4$ in biopharmaceutical effluents was also analyzed. Several operating parameters, including pH, density, contact duration, and metal ion

Fig. 8. Separation techniques used in arsenic removal.

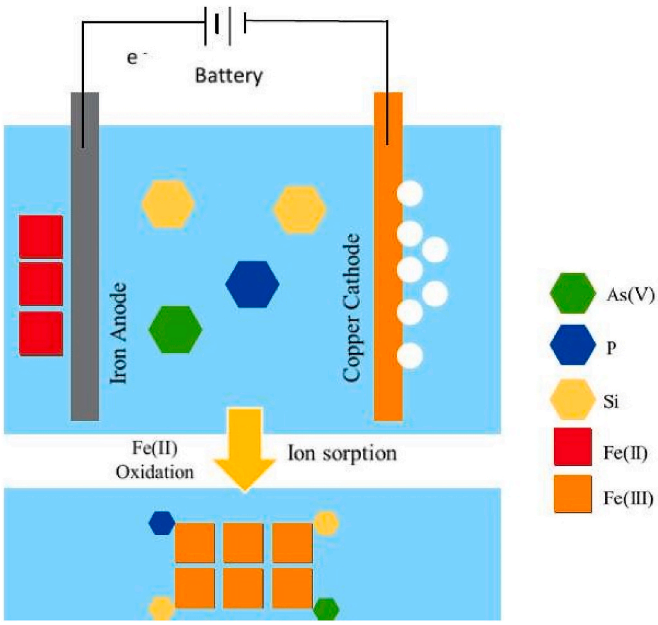

Fig. 9. Schematic representation for the removal of arsenic using electrocoagulation.

concentration, were investigated to obtain the highest possible percentage removal. The findings obtained with industrial wastewater samples demonstrated that an increase in pH resulted in the most successful removal of $AsO_3^{3-}$and AsO_4^{3-}, whereas the increase in current density from 8.2×10^{-3} to 8.16×10^{-2} mA cm^{-1} enhanced the treatment rate. When compared to Al and hybrid Al/Fe electrodes, the removal efficiency of Fe electrodes was fairly high. Using this approach, a pharmaceutical effluent containing 2.8×10^{1} ppm of arsenic was reduced to 5×10^{-3} ppm in 15 min at 0.08 A (pH 2–10). When compared to other traditional procedures, such as coagulation/flocculation, this approach was shown to be effective, relatively quick, and tidy (Deniel et al., 2008).

The carbon tetrachloride, a colourless liquid also known as tetrachloromethane are refrigerant compound with a sweet-smelling odour and are recalcitrant carcinogen requiring appropriate treatment by techno effective methods. Lei and co-workers projected the removal of carbon tetrachloride from wastewater with a cathode-based chamber electrochemical reactor (dual-chamber) showing a desirable removal percentage of 41.44% using the Titanium electrode as the anode and the iron electrode as the cathode (Lei et al., 2021).

The anaesthetic agent, trichloroethylene a chemical solvent system used in pharmaceutical and medical therapeutics is a predominant carcinogen released from the hospitals, ascribed as the pharmaceutical and personal care products (PPCPs). The electrocoagulation proves to be a promising candidate in such a scenario to eradicate the carcinogenic trichloroethylene to a higher extent of 99.1% with an iron foam cathode in comparison to the iron plate cathode (Mao et al., 2015). In addition to trichloroethylene, tetrachloroethylene is another example of polychloroethylene compounds with their characteristic carcinogenic impacts. Interestingly, the transformation of tetrachloroethylene can be achieved by an electrochemical process in the presence of a saturated porous matrix, cathode-bipolar electrode-anode arrangement, supported by a palladium load to contribute a removal rate of 86% (Hyldegaard et al., 2020).

Phenol and aldehyde-derived compounds are auxiliary carcinogens used in the chemical industries such as solvents, explosives and pharmaceuticals. Electrocoagulation deployed to remove aldehyde and phenol-based contaminants from the resin effluent using solar energy resulted in higher removal efficiency of 93% for phenol and 95% of an aldehyde; the Fe–Fe combination of electrodes required a meagre amount of energy (Olya and Pirkarami, 2013). A similar strategy can also be executed for the transformation of chlorinated phenols, aldehydes and ketones.

Calcium tends to occur in water bodies as a natural mineral and is highly responsible for the hardness of the water and exhibits anegative and toxicological impact on the environment. In a recent study, electrocoagulation with three distinct metal electrodes used, stainless steel, iron and aluminium electrodes for effectual removal of calcium from Gaza wastewater was achieved with 93.3%, 93.0% and 88% respectively (Hamada et al., 2018). Anilines are nitroaromatic xenobiotics which are predominant candidates for emerging contaminants. Tamne et al. proposed an electrocoagulation study of river water to remove nitroaniline carcinogens with a contact time of 5 min and pH value of 11 (Tamne et al., 2016).

Wastewaters, obtained from electroplating and mining industries, mainly contain hazardous metals such as copper, nickel, and zinc, which cause serious effects on the environment if released without treatment. Ni compounds are designated as Group 1 carcinogen by the IARC and studies have shown that continuous exposure tonickel would increase the incidence of lung cancer and nasal malignancies (Heidmann and Calmano, 2008). Adsorption, biosorption, ion exchange, electrodialysis, precipitation and nanofiltration are some of the few techniques used to handle heavy metals. Precipitation is the most widely used of these approaches in wastewater treatment which refers to the transformation of dissolved elements in water into solid particles (Ahmed Basha et al., 2008; Kumar et al., 2022). Chemical coagulation is used to remove colloidal matters such as hydroxides achieved by adding lime to raise the pH and Al or Fe salts Chemical coagulation is successful in cleaning industrial effluents, however, it may generate secondary contamination due to the addition of chemical compounds. This disadvantage, along with the requirement for a low-cost, effective treatment, prompted a surge of research into the application of electrocoagulation for the treatment of a variety of industrial effluents (Adhoum et al., 2004).

The study performed by Akbal and Camcı (2011) indicated that electrocoagulation with a Fe–Al electrode pair was very efficient and was able to achieve 98%–99% of Ni removal from the wastewater discharged from the electroplating industry at an electrocoagulation time of 20 min, a current density of 10 mA cm^{-2} and initial concentration of 394 ppm under acidic conditions (pH). In addition, previous research has shown that electrocoagulation may remove up to 98 percent of Ni from synthetic wastewater under the following operating conditions: pH 6, 60 min duration, concentration 2.5 ppm, and current 1.5 Å. The findings of the electrocoagulation procedure revealed that a lower concentration and a pH close to neutral aided the system in reaching its full capacity (Kumar et al., 2022).

Dyes are of great concern because of their widespread use, releasing toxic aromatic by-products (such as aromatic amines), and a bio recalcitrant that has to be removed using traditional aerobic wastewater treatment. According to the class of chromophore, the two classes of dyes mostly used are azo and anthraquinone dyes. Xanthene dyes are also often used in the textile industry, biological stains, and cosmetics. The textile dyes are highly toxic and potentially carcinogenic, which severely affects the environment and causes various diseases in animals and humans.

Many techniques have been applied for the treatment of dye wastewater, including activated carbon adsorption, ozonation, chlorine oxidation, advanced oxidation, and combined anaerobic-aerobic treatment. For example, the removal of azo dyes by electrocoagulation with an iron anode is more rapid than that with an aluminium anode (Durango-Usuga et al., 2010; Merzouk et al., 2009). In addition, electrocoagulation with an anode having a large surface can enhance the iron anodic dissolution, which improves dye removal (Daneshvar et al., 2003; Mollah et al., 2001). However, studies on dye removal using electrocoagulation with the three-dimensional cathode, with a large electrode surface area, are limited.

When textile dyes (azo Acid Black 1, anthraquinone Reactive Blue 4, xanthene Eosin Yellow) of 100 mg $L^{-1}$are treated in a process having iron plate anode and steel wool as a cathode (591 cm^{-2}) operating with an electric current of 0.3 A, were removed maximum concentration of dye than Fe plate as an anode (28 cm^{-2}) and stainless-steel plate cathode (28 cm^{-2}). In the electrocoagulation with the steel wool cathode, an increase in electric current and mixing speed increases the dye removal (Wei et al., 2012).

The electrocoagulation method is found to be quite effective in removing orange II. Prior experimental results from the literature revealed that the colour of orange II in the aqueous phase was effectively removed (>98%) and also the (COD) was reduced by greater than 84% when iron was used as a sacrificial anode with an initial concentration of orange II less than 200 ppm. The experimental results were assessed in terms of colour and COD reduction. The optimum current density was 34.62 A/m^2 for effectively removing orange II (Daneshvar et al., 2003).

9. Conclusion and future directions

Wastewater treatment is one of the challenging aspects of modern-day problems. Untreated industrial wastewater along with carcinogens that get discharged into the water sources pose a constant threat to both terrestrial and aquatic life that depend on this. Although, there are extensive chemical strategies for the treatment of recalcitrant carcinogenic pollutants from industrial wastewater and sludges, the emerging trends and current perspectives highlight the application of novel techniques such as membrane filtration (MF) and thermal hydrolysis (TH); the MF technique can be further fractionated into microfiltration (MIF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). In the MIF process,a microporous membrane is employed for the eradication of micron-sized particles such as viruses, protozoa, bacteria, pollutants and contaminants from industrial effluents.

Supplementarily, the UF process consists of a larger membrane pore compared to the heavy metal ions and additives. Adding on to these filtration techniques, the advanced NF process comprises membranes made up of polymer composites of a multi-layered thin film with CeO_2/Ce_7O_{12} and polyether sulfone displaying a high rate of removal efficiency. Ultimately, the reverse osmosis process (RO) consists of a semi-permeable membrane (0.5–1.5 nm) allowing only small molecules and impurities to pass for extracting the 95–99% of inorganic salts and charged organic pollutants. They also exhibit a higher potential to remove heavy metals such as Ni^{2+}, Cr^{6+}, Fe^{3+}, Zn^{2+}, Ni^{2+}, As^{3+}, and $Sb^{3+}$and Cu^{2+}.

On the other hand, TH offers the triple advantages of wastewater remediation, waste by-product reduction and biogas-production; where, the generation of biogas requires the wastewater as an indispensable load. These approaches can be further categorized into biothelys thermal hydrolysis (BTH) and exelys thermal hydrolysis (ETH); the former technique requires large tracts of land for biogas production; while a small land space is arequisite for the latter.

In addition to these trending approaches, the other cutting-edge technique is microbial fuel cells (MFC), a holistic process, that requires the microbes for wastewater treatment and propounds a simultaneous discharge of charged electrons as a by-product of wastewater consumption generating resourceful electricity. Interestingly, the solar photocatalytic wastewater treatment (SPWT), the other promising methodology for treating wastewater by reducing the organic carbon content in the sludge by 80% when combined with hydrogen peroxide in comparison to the other conventional methods.

The present review made an extensive investigation of the carcinogens present in the industrial effluent; carcinogens discharged from the selected industries and the removal of heavy metals from the various industries using electrocoagulation techniques. Through this study, it may be inferred that electrocoagulation as a treatment strategy for organic wastewater, maybe a robust candidate in comparison to others due to its sustainable and cost-efficient process. Hence, a combinatorial approach of amalgamating the current trending methods like MF, MFC, TH, and SPWT with electrocoagulation will be a highly resourceful broad-spectrum treatment strategy to achieve higher carcinogen-removal efficiency and to treat effluents from different industries with variegated effluent properties for establishing a sustainable and green environment.

Credit author statement

Madhavan Yasasve, Muralidharan Manjusha, P.Sai Preethi: Writing – original draft, Resources, Investigation. Dhinakaran Manojj: Formal analysis, Software, Writing – original draft. N. M. Hariharan, Muthupandian Saravanan: Conceptualization, Supervision, Writing – review & editing, Validation. Perumal Asaithambi, Natchimuthu Karmegam: Methodology, Data curation, Writing – review & editing

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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