Water Practice & Technology

IWA PUBLISHING

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Water Practice & Technology Vol 19 No 8, 3154 doi: 10.2166/wpt.2024.189

Current research progress in the biological removal of emerging contaminants from the water environment

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ABSTRACT

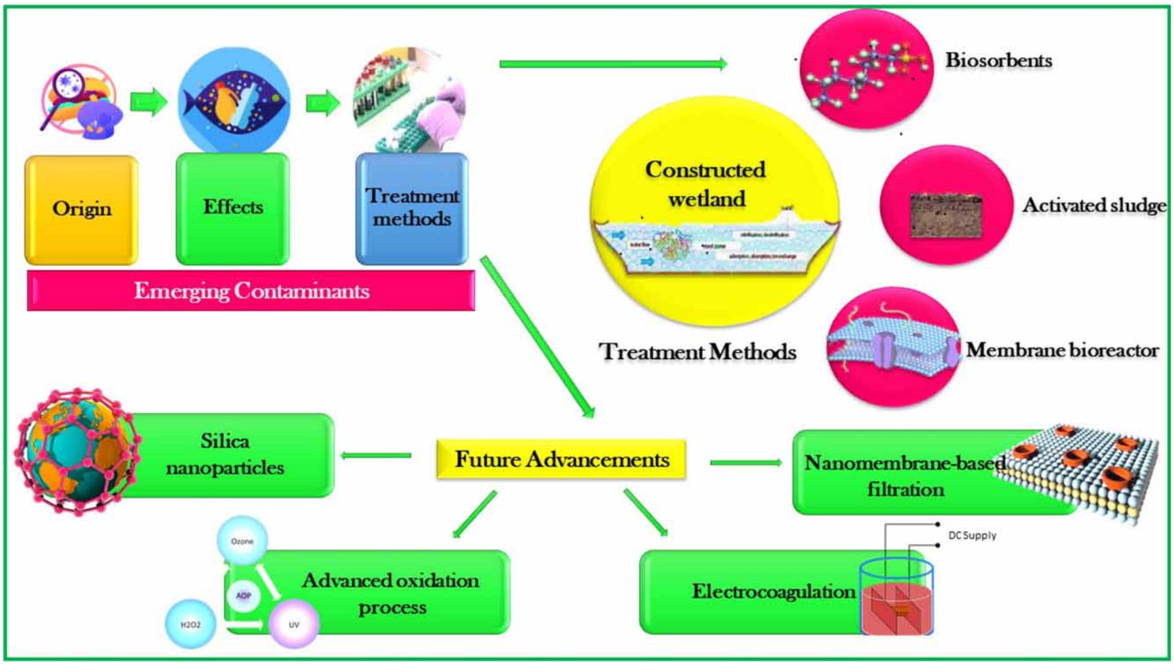
Hazardous pollutants include a variety of pollutants, including emerging contaminants (ECs), organic pollutants, inorganic pollutants, and heavy metals. Scientists have lately become interested in ECs in effluent because they represent serious hazards to both biodiversity and human health even at low concentrations. For the elimination of different ECs, several treatment technologies, including chemical-based, physical-based, and biological-based methods, have been developed. Nonetheless, no one technique can presently efficiently eradicate ECs; biological treatments are frequently found to be more beneficial. This review aims to give a brief analysis of the sources, kinds, impacts, and monitoring and detection techniques for ECs. This review provides information on such biological processes for the quick and eco-friendly removal methods of ECs from effluent. The article highlights the methodology used by the hybrid system to eliminate distinct EC types. The hybrid structure of a membrane bioreactor (MBR) accompanied by filtrations using membrane successfully got rid of a bunch of ECs. For the biosorptive elimination of pharmaceuticals various hybrid structures comprising constructed wetlands (CWs) and waste stabilization ponds demonstrated amazing possibilities. Future directions of study for the elimination of ECs using green, sustainable technologies and hybrid techniques have been proposed.

Key words: biological treatment, constructed wetlands (CWs), emerging contaminants, membrane bioreactor (MBR), wastewater

HIGHLIGHTS

- Sources of ECs and their threats to the environment have been discussed.
- Various monitoring and detection methods to manage the spread of ECs.
- Biological treatments of emerging contaminants and their benefits.
- Recent advancements in the field of emerging contaminants treatment.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Recent studies have focused on emerging contaminants (ECs) in wastewater because they possess severe hazards to health and wildlife (Gianico *et al.* 2021; Werkneh *et al.* 2022). The revolutionized development of technologies and resources has caused the manufacture of more compounds and chemicals, which increases the number of chemicals recognized as potential threats to living things (Deb *et al.* 2020). This growing count of shady chemicals poses a potential threat to living things and the environment (Werkneh *et al.* 2022). Waste water treatment plants (WWTPs) and sewage include pharmaceuticals, personal care products (PPCPs), surfactants, and a variety of industrial chemicals that are not metabolized and are considered to be endocrine disruptors (EDs). These present difficulties for the designers of upcoming treatment plants and associated eradication methodologies (Rotta *et al.* 2021). The issues accompanying these ECs are examined here to feature the difficulties in addressing the issues (Liu *et al.* 2019).

The first issue is the lack of restricting regulations, particularly for pharmaceuticals, by-products, and new compounds, in the wastewater treatment plant (Maryjoseph & Ketheesan 2020). Advancements in technology and industry exceeded conventional methods. Biological treatment technologies such as membrane bioreactors (MBRs), biofilm reactors (BFRs), and activated sludge process (ASP) are used to remove ECs (Aoudj *et al.* 2019). These systems can be created to focus on a narrow range of contaminants or a variety of contaminants (Bilal *et al.* 2019). In comparison to conventional techniques, biological treatment has a number of advantages for removing developing pollutants from wastewater (Nika *et al.* 2022). It is economical, energy-efficient, and environmentally friendly. It is also easy to incorporate into wastewater treatment plants that are already in operation. According to Ramakrishnan *et al.* (2015), biological treatment generally shows promise as a remedy for the issues caused by recently discovered toxins in wastewater. It can protect the environment and public health while raising the standard for wastewater treatment. Micro-range poisons and other unregulated or newly discovered substances were not being monitored or barely any safeguards were being taken to keep them out of water sources (Khan *et al.* 2022).

To achieve a comprehensive and effective removal of ECs by wastewater treatment plants, extensive research and improvement are thus needed, together with techno-economic acceptability evaluations of the treatment processes (Thuptimdang *et al.* 2021). Several ECs, especially pesticides and medicines, were shown to be considerably eliminated by a hybrid method using ozonation and activated carbon (AC) (Tong *et al.* 2022). Nanotechnology may be an effective strategy despite the paucity of thorough studies because nanomaterial-integrated technologies have shown promise in eliminating various toxins from wastewater (Pereira *et al.* 2015).

The treatment of emerging pollutants in wastewater has received a lot of attention because of potential risks to human health and the environment. Traditional wastewater treatment technologies often become inadequate in successfully eliminating these contaminants. This study explores the most recent trends and breakthroughs in biological treatment methods, highlighting their potential to overcome the limits of traditional treatments. This comprehensive research emphasises creative methods and hybrid strategies for removing emerging pollutants by using novel biosorbents, activated sludge processes, constructed wetlands (CWs), and membrane bioreactors. This paper also discusses future perspectives and potential developments in biological wastewater treatment, with the goal of promoting sustainable and effective environmental management systems.

2. EMERGING CONTAMINANTS

ECs are substances that exist naturally or artificially, or microbes that are not properly monitored have the ability to spread throughout the environment and produce known or suspected harmful environmental and/or human health impacts (Petrie *et al.* 2015). Personal care products (PCPs), pharmaceuticals, surfactants, pesticides, and industrial chemicals have been found in municipal wastewater, groundwater, surface water, food sources, and drinking water on a regular basis. They also comprise EDs, hormones, analgesics, antibiotics, and various other pharmaceuticals such as anti-diabetic, anti-inflammatory, and anti-epileptic medications (Stefanakis & Becker 2016).

2.1. Sources of ECs

The nutrients that are applied to agricultural and urban landscapes eventually result in drainage and leaching water, which feeds groundwater, rivers, lakes, streams, and other bodies of water. These excessive nutrient loadings are degrading the quality of the water and soil, which could have detrimental effects on human health and the ecosystem (Thomaidis *et al.* 2012). ECs including heavy metals are demonstrating an upward increase in soil and freshwater bodies in relation to nutrient and chemical pollution. These new contaminants not only harm freshwater resources and soil quality but also pose a risk to human and animal healthiness by entering into the food chain (Gil *et al.* 2012). Agricultural, industrial, and municipal applications are the principal origins of these new contaminants and pesticides. PPCPs, pharmaceuticals, industrial additives, insecticides, and various other substances that cannot be removed by standard WWT technologies may be present in municipal wastewater and hospital effluents (Fekete-Kertész *et al.* 2015). Domestic wastewater is regarded as one of the major sources for ECs such as stormwater, and industries, as well as sewage from houses and WWTPs into the surroundings (Gogoi *et al.* 2018). Table 1 explains the sources of ECs and their impacts and effects. Figure 1 depicts the sources and pathways from which ECs enter into the environment.

Reclaimed water is now more frequently used for irrigation as a result of population growth and diminishing freshwater supplies. Reclaimed water has a number of organic pollutants that have been considered to be emerging hazards, which is the main problem. Some of these might lead to cancer and harm nearby water and soil sources (Bayabil *et al.* 2022). Nutrients, suspended and dissolved particles, heavy metals, and solids are the most typical contaminants. The usage of chemicals as well as chemical fertilizers, such as those based on arsenic (As), as well as anthropogenic activities like mining and the dumping of industrial waste have all been listed as contributors to the rising levels of ECs in ecosystems (Gwenzi *et al.* 2018). Since conventional techniques of wastewater treatments (WWTs) like sedimentation, coagulation, Filtration, ASP and Chemical Precipitation are ineffective and expensive to entirely eliminate ECs, wastewater has also been described as a source of ECs (Yan *et al.* 2010). Pesticides, pharma, drugs of abuse (including legal and illegal drugs), surfactants, cosmetics, chemicals, personal care items, industrial mixtures and toiletries, food packaging, food products, rare elements, microplastics, metalloids, pathogens, and nanomaterials are just a hardly any of the numerous items and substances on the list (Rout *et al.* 2021). In addition to domestic wastewater and commercial emissions, the majority of these contaminants also exist in surface water and groundwater, which therefore affects potable water and food supplies (Morin-Crini *et al.* 2021). A completely hydrophobic alkyl chain which is fluorinated is joined to a hydrophilic group to form perfluorinated compounds (PFCs), that have been made since the late 1940s (Kannan & Subramanian 2015). The most important representative PFCs are perfluorooctanoic (PFOA), perfluoro octane sulfonate (PFOS), and salts which are broadly used in firefighting foams, lube, detergent products and metal spray plating, varnishes, inks, encasing formulations (for furniture, walls, flooring, and food packing), oils, and oil and water repellents for paper, leather, and textile PFCs have excellent light,

Table 1 | Various sources of ECs and its effects and impacts

Source/Contaminant	Origin of contaminants	Effects	Impact types	References
Bisphenol A (BPA)	• Food packaging. • Thermal paper receipts	HLs in humans, DF, Liver Damage (LD)	ED, RT, LT	Welshons *et al.* (2006)
Phthalates	• Soft plastics. • PCPs. • Food packaging.	HLs in humans, DF, LD	ED, RT, LT	Wittassek *et al.* (2011)
Triclosan	• PCPs. • Antibacterial soaps.	HLs in Aquatic Organisms (AO), Decreased Biodiversity (DB)	ED, Ecological Impact (EI)	James *et al.* (2023)
Microplastics	• Plastic waste. • Cosmetics.	HLs in AO, DB	ED, EI	Wu & Seebacher (2020)
Tetrabromobisphenol A (TBBPA)	• Electronic waste. • Flame retardants.	HLs in AO, DB	ED, EI	McGlade *et al.* (2021)
Polychlorinated Biphenyls (PCBs)	• Electrical equipment. • Old paints.	HLs, DF, LD	ED, RT, LT	Grandjean & Landrigan (2014)
Lead	• Old paint. • Plumbing. Contaminated soil.	Decreased IQ, Behavioral problems (BP), reproductive problems	Neurological toxicity (NT), RT	Lanphear *et al.* (2005)
Mercury	• Fossil fuel burning. • Dental fillings.	Decreased IQ, BP, reproductive problems	NT, RT	Davidson *et al.* (1998)
Discharge from pharmaceutical industries	• Wastewater discharge. • Unused medications.	HLs in AO, DB	ED, EI	Dey *et al.* (2019)
Discharge from textile industries	• Wastewater discharge. • Dye effluents.	HLs in AO, DB	ED, EI	Slama *et al.* (2021) and Vaddoriya *et al.* (2021)
Discharge from leather industries	• Wastewater discharge. • Tanning effluents.	HLs in AO, DB	ED, EI	Choudhary *et al.* (2004)
Discharge from metal industries	• Wastewater discharge. • Metal-working effluents.	HLs in AO, DB	ED, EI	Choudhary *et al.* (2004)
Agricultural runoff	• Runoff from fields. • Fertilizer and pesticide application.	HLs in AO, DB	ED, EI	Daughton (1999)
Wastewater discharge from treatment plants	• Treated wastewater discharge.	HLs in AO, DB	ED, EI	Duran & Esposito (2000)

HLs, altered hormone levels; AO, aquatic organism; BP, behavioral problem ; BPA, bisphenol A; DB, decreased biodiversity; DF, decreased fertility; EI, ecological impact; EDs, Endocrine disruptors; IQ, intelligence quotient; LD, liver damage; LT, liver toxicity; NT, neurological toxicity; PCBs, polychlorinated biphenyls; RT, reproductive toxicity; TBBPA, Tetrabromobisphenol A.

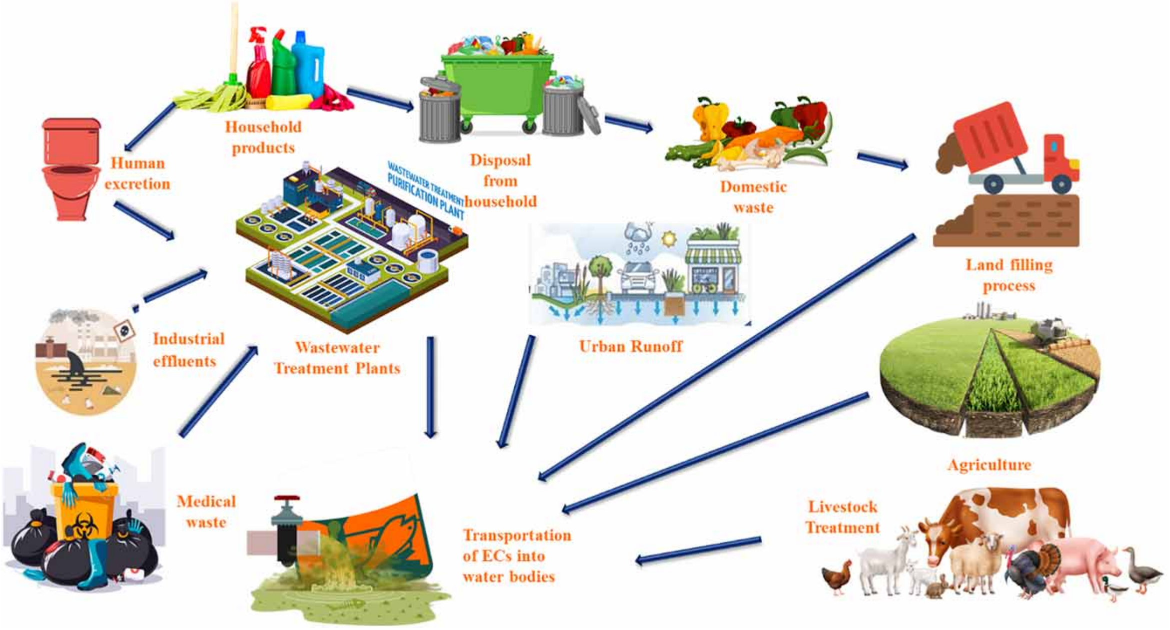


Figure 1 | Different pathways of ECs into water bodies.

heat, and chemical resistance and are difficult for microorganisms to break down. As a result, PFCs are thought to be persistent, bio-accumulative, and perhaps dangerous to both people and animals (Lei *et al.* 2015).

PPCPs fall within the category of ECs. PPCPs reach the water system through human and animal excretions as well as effluent from pharmaceutical manufacturing facilities. Once PPCPs are present in water, it can be very difficult to efficiently remove them (Beadle 2021). The primary sources of pharmacological contamination are either patients or animals under medications intended for human usage or veterinary usage (Ghelli 2021). The WWTP discharge, leaching through soil, surface runoff, or discharge to the blue water bodies are the two main ways that medicines and their toxins infiltrate aquatic nature (Stuart *et al.* 2012). The aquatic ecosystem's bioaccumulation of PPCPs is found to disrupt human hormonal equilibrium, leading to a number of unfavorable consequences such as lower fertility, reproductive deficits, and significantly increased testosterone and breast cancer risk (Shahid *et al.* 2021). One of the main global environmental issues is the documented occurrence of trace metal pollution in water bodies in developing nations. The trace metals can settle on the fine sediment or be held in the water column as they make their way into aquatic environments (Sivaranjanee & Kumar 2021). Aquatic creatures are impacted by trace metals biologically through the processes of accumulation and magnification (Srikanth *et al.* 2019).

Pharmaceutically active chemicals (PhACs) are a significant class of new environmental pollutants that have drawn growing attention from the scientific community worldwide (Samal *et al.* 2022). Naproxen, ciprofloxacin, Ibuprofen, atenolol, diclofenac, azithromycin, ketoprofen and were examples of ECs (Saidulu *et al.* 2021). Since there are over 3,000 distinct PhACs utilized in human medications (such as anti-inflammatory and analgesics medications, lipid regulators, β-blockers, and antibiotics), ingestion is the primary way they enter the aquatic environment after being excreted and disposed of through wastewater (Rathi & Kumar 2021). The enhanced polarity of drug metabolites can be predicted to make them bioactive and much more persistent. In addition, during sewage treatment in WWTPs, conjugates of raw material may cleave back again into the original medicament (Petrovic *et al.* 2008).

Pesticides, which are a diverse group of substances with various physicochemical properties, are applied in agricultural settings to control or inhibit the rise of undesirable weeds, insects, and microbes like fungi and bacteria (Egea-Corbacho *et al.* 2019). They enter the aquatic environment by discharge from the application premises, and depending on the chemical's solubility, these compounds may persist in soil, living organisms, or sediments (Khan *et al.* 2022).

In developing nations like India, where there is a higher degree of acute risk, insecticides are used more frequently than herbicides, which have a lower level of toxic effect than insecticides (Gani & Kazmi 2017).

2.2. Types of ECs

Pesticides, cosmetics, dioxins, PCPs, pharmaceuticals, alkyl phenolic compounds, and polycyclic aromatic hydrocarbons (PAHs) are common sources of ECs (Omi *et al.* 2022). Because of the rapid advancement of the industries, the pollutants have been found in dangerous quantities in groundwater, wastewater, and blue water (Yap *et al.* 2019). Waters include a varied spectrum of individual organic pollutants in addition to considerable volumes of complex high polymer organic substances, which often dominate the overall organic load, and various kinds of collective pollutants that consist of mineral oils, total lipids, and detergents (Noguera-Oviedo & Aga 2016). The type and quantities of organic pollutants have expanded significantly during the previous few decades. A large percentage of these compounds are found in detergents and PCPs, medicines, plasticizers, fire retardants, and other items (Kümmerer 2011).

Nanomaterials, pesticides, industrial compounds, pharmaceuticals, PCPs, water treatment (WT) by-products, fragrances, surfactants and fire retardants, and nicotine and caffeine are samples for ECs. Numerous of these are small minute pure substances that potable water treatments are not effective in eliminating these substances (Stuart *et al.* 2012). ECs have been found in practically every country's ecosystem, making them a worldwide concern, even if the actual source in many instances cannot be established. There is a scant understanding of the fate and movement of ECs in the surroundings, in addition to their toxicological effect (Naidu *et al.* 2016). However, ECs, whether natural or manufactured, have been linked to a range of harmful health and environmental impacts. Pharmaceutical compounds, for example, that are meant to elicit a biological reaction in a certain organism can cause the same effect in non-specific species after extended exposure to even trace levels of those substances (Khan *et al.* 2022). Even at low doses, antibiotics such as penicillin can create resistance in bacteria along with other microbes. Streptococcus pneumoniae, for instance, is classed as 'penicillin-non-susceptible' under the World Health Organization's (WHO's) list of priority infections to help prioritize research and development (R&D) of novel and effective antibiotic therapies.

Caffeine, theobromine, and stimulants, theophylline, have also been found in significant amounts in both effluent and incoming waters, in particular in some Mediterranean river basins where WWTP effluents account for a high percentage of total river flow, especially during drought periods (Lopera *et al.* 2019). Wetting agents, dispersants, Sulfonated azo dyes, pesticides, optical brighteners, concrete plasticizers, pharmaceuticals, ion-exchange resins, and leveling agents are all made from aryl sulfonates (Renau-Pruñonosa *et al.* 2020). Asbestos, red phosphorus, magnesium hydroxide, aluminum hydroxide, various hydrates, antimony trioxide, and boron substances, mainly borates, are utilized as fire retardants (Kümmerer 2011).

E-waste, Nanomaterials, and commonly existing radioactive materials (NORMs) have been given the least attention in the Middle East and North Africa (MENA). The MENA region has almost no experimentation on the elimination of nanoparticles from water systems (Singh *et al.* 2020a, 2020b). Previous regional assessments, on the other hand, have revealed an interest in the implementation of nanotechnologies in desalination operations. As a result, attempts to prevent nanomaterial pollution of water sources are becoming increasingly important (Ouda *et al.* 2021). The immune system's function during the instantaneous post-natal period is especially sensitive, according to the European Food Safety Authority's (EFSA) recommendations on risk analysis for chemicals in baby food, and exposure to immunized toxicants can result in long-lasting impacts on the body's immune system that persist or show up only after the exposure, however, might happen at lower levels than adult being exposed (Nobile *et al.* 2020).

2.3. Effects of ECs

For the safety and health of the people, the presence of developing or newly discovered contaminants in our water sources extends to be a concern. The standard WT facilities that are currently in place were not developed to handle these ECs. These are currently posing a threat to our water supply system (Mandaric *et al.* 2015). Due to the lack of strict regulations that are unique to these contaminants, the present effluent treatment systems are ineffective in removing these varieties of classes of emerging pollutants. Unwanted chemicals are being released into the marine habitat, either purposefully or inadvertently, that have an influence on every organism (Bolong *et al.* 2009). In recent years, ECs such as pesticides and their lifestyle compounds, metabolic products, industrial products, food additives and wastes, and nanomaterials have become an issue for the surroundings (Gomes *et al.* 2017).

Health impacts include cancer, reproductive issues, altered brain development, and allergies are the ones that grab the public's attention. Accordingly, the following substances become the 'culprits' at the top of any list of newly developing contaminants: possibly harmful compounds (Smital 2008). Several investigations have concentrated on the existence of organic pollutants on the Llobregat River, which serves as the primary drinking water supply for Barcelona and its surrounding areas and has been shown to have a diverse spectrum of contaminants (González *et al.* 2012).

TCS, TCC, fluoroquinolones, carbamazepine, TBT, and PFCs are not significantly removed; moreover, data on such compounds is still limited (Stasinakis 2012). Metabolomics applications include studying the economic and environmental consequences of various environmental concerns such as personal hygiene products, medicine and nanoparticles, pesticides, and alterations in naturally found compounds in the surroundings with an emphasis on plant communities (Matich *et al.* 2019). Recent research has brought attention to their potential toxicity, including oxidative stress, cytotoxicity, genotoxicity, and protein alterations, raising significant concern about their adverse effects on humans and aquatic environments (Farkas *et al.* 2010). Chemical pollution from ECs is a problem in the Noco River, even at high altitudes (Lencioni *et al.* 2020). Aside from that, WWTPs are ineffective at removing ECs and their microbial metabolites. As a result, these ECs will be unfavorably released into bodies of water in the future (Saidulu *et al.* 2021).

2.4. Monitoring and detection methods

In surface and groundwater, numerous chemicals from various classifications, including hormones and pharmaceuticals, illegal narcotics, personal care items, pesticides, PFCs, artificial sweeteners, UV filters, and disinfection by-products (DBPs), have been found recently (Riva *et al.* 2018). Potentiometry, Voltammetry, electrochemical impedance spectroscopy (EIS)-based electrochemical methods, amperometry, surface-enhanced Raman spectroscopy (SERS), colorimetry, fluorescence spectroscopy-based optical techniques, and fluorescence probes are some alternate ways for EC detection. These methods are superior to conventional methods in a number of ways, including minimal sample volume, high sensitivity, exclusion of solid phase extraction, portability, selectivity, speed, reproducibility, reduced cost, and the capability to detect ECs (Manivannan *et al.* 2022). Although selenium is a vital trace element for humans, its bioaccumulation potential makes its discharge at large concentrations a serious hazard for aquatic and terrestrial ecosystems (Fawell & Ong 2012). Among the largest causes of selenium discharged into the environment are mining and the processing of metals and minerals (Etteieb *et al.* 2020).

These chemicals are not monitored regularly in the surroundings. Some developing contaminants may have been released into the surroundings over a period of time, but they could not have been detected until the advancement of modern identification techniques. Currently, EPs are not a part of international routine surveillance systems (Chen *et al.* 2022a, 2022b). Understanding the incidence and destiny of EPs necessitates the monitoring, identification, and measurement of EPs as well as the products changed in various environmental divisions. This is extremely difficult for various reasons: There are already around 700 possible EPs (and corresponding transformation items) known in Europe. Their importance shifts throughout time because of modifications to (agro)chemical production, use, and disposal, as well as emerging knowledge on their incidence, fate, and risks. Some EPs, such as pyrethroids, hormones, and some organophosphorus insecticides, have such little influence on aquatic life that analytical procedures with low detection limits are required (Taheran *et al.* 2018). Improved ultra-sensitive instrumental methods (such as newer development LC-/MS/MS, GC-APCI-MS/MS) have become accessible in traditional approaches focusing on specific EPs, although they have so far hardly been used for regular monitoring. Utilization of such mechanisms would improve opportunities for simultaneous measurement of several EPs, simplify sample preparation, and/or greatly increase detection sensitivity for EPs with certain PNECs (Prajapati *et al.* 2023).

The employment of such instruments would be beneficial for the quantitative identification of targeted contaminants in soil, particulate matter, water, and biota, notwithstanding their higher cost. To replace or supplement existing focused methods, general chemicals screening methods rely on deep scan mass spectrometry (MS) with chromatography have gained popularity recently (Geissen *et al.* 2015). Due to its high sensitivity, nondestructive nature, and ability to simultaneously monitor many analytes with various optical properties, optical sensors have indeed been utilized as effective analytical tools in a variety of disciplines, from the chemical and medical industries to environmental monitoring. The main idea behind optical sensors is to use a light beam to excite the electrons in specially created molecules, then measure the resulting changes in optical properties to make a detection. A transducer and a recognition element often make up optical sensors. Typically, to interact with the target analyte through an enzymatic process, recognition elements such as enzymes, antibodies, customixed receptors, and/or bifunctional surfaces are utilized (Ryu *et al.* 2021). The application of deep scan and high-resolution MS with liquid chromatography (LC) to detect specific toxins – often the reaction products or degradation of the origin contaminant – or to increase the selectivity of analytes, has become one of the most popular trends in recent years. For decades, gas chromatography (GC) was previously employed in a similar way with full scan and high-resolution MS, enabling the identification of numerous environmental pollutants (Richardson 2009). Table 2 gives information about the various monitoring and detecting techniques and their operating conditions.

For the sake of assessing the elimination of developing pollutants in drainage water, advanced oxidation processes (AOPs) relying upon ozone treatment, supported by ultrasounds, were studied at a pilot plant scale (Ibáñez *et al.* 2013). Based on the large collection of various physicochemical characteristics of the contaminants evaluated, two distinct analytical procedures were used to analyze the samples obtained from water sources. Liquid–liquid extraction (LLE) with hexane was the specimen treatment method used for the separation and prior enrichment of non-polar and semipolar evaporative chemicals. This was subsequently followed by a GC/MS study (Robles-Molina *et al.* 2014).

3. BIOLOGICAL TREATMENT OF ECs

3.1. Biosorbents

A liquid or gas can be cleaned of impurities or other dangerous compounds using biosorbents, which are materials made from natural sources. These substances, which could be produced from algae, bacteria, and plants are frequently utilized in environmental cleanup and remediation projects (Varsha *et al.* 2022). When it comes to eliminating metals that are heavy, organic pollutants, and many poisons from water or the air, they can be extremely effective. Biosorbents can be applied in a variety of settings, such as beds, filters, and *in situ* (in-site) applications (Xie 1996). ECs, or pollutants that are not yet subject to regulation but might be damaging to the environment, and human health are frequently treated with biosorbents. Pharmaceuticals, personal care items, and microplastics are some examples of these pollutants (Richardson & Kimura 2019). Pollutants are bonded to the outermost layer of a biosorbent substance through the method of adsorption. It is one of the most typical applications for biosorbents in the management of developing pollutants. The biosorbent materials like sawdust, rice husk, coconut shell and so on can be found as powder, beads, or even granules (Sahay *et al.* 2023). These materials can adsorb a lot of contaminants since they have a wide surface area. The biosorbent material is brought into contact with the polluted liquid or gas during the adsorption process. The contaminants are subsequently drawn to the biosorbent material's surface and stick to it. The contaminants can then be extracted from the liquid or gas along with the biosorbent material. Pollutants can be eliminated by performing this procedure repeatedly (Karić *et al.* 2022). A rising number of investigations have been done in recent years to assess the functionality of emerging adsorbents like agricultural goods including by-products in elimination of ECs (Rossner *et al.* 2009). Sludge, waste slurry and Fly ash, red mud, blast furnace slag and black liquor lignin, in contrast, are now being researched as promising adsorbents for the elimination of ECs from effluent (Grassi *et al.* 2012). Figure 2 explains the step-by-step process of removal of ECs by biosorbents. Table 3 provides information about the various biological treatments of ECs.

The following are some instances of biosorbents that can be utilized for adsorption such as Peat moss, a naturally occurring substance, has a broad variety of contaminants it may absorb, is highly porous and manufactured from charcoal, AC is a powerful absorbent for organic contaminants (Chaukura *et al.* 2016). A byproduct of the rice industry called rice husk can be used to filter heavy metals out of water and Algae can be cultivated especially for their capability to eliminate impurities from the water (Yaashikaa *et al.* 2021).

Additionally, biosorbents can be utilized in the bioremediation (BR) procedure, which uses microorganisms to degrade contaminants. This procedure involves the addition of microorganisms to polluted water or soil, which then naturally eat the toxins as a food supply. Through procedures including oxidation, reduction, and hydrolysis, they can degrade contaminants (dos Santos Cardoso & Vitali 2021). Utilizing bacteria that can break down PAHs, a class of contaminants found in crude oil or other fossil fuels, is one example of using biosorbents in BR. The PAHs can be consumed by these bacteria, which then convert them into less dangerous substances. In BR, biosorbents can also be utilized to support microorganisms; for instance, bacteria can immobilize on a biosorbent material like alginate beads (Singh *et al.* 2020a, 2020b). Immobilizing biosorbents entails securing the biosorbent substance to a support, such as a filter or a column, to enable repeated use. The removal of

Table 2 | Different types of monitoring methods of ECs and their applications and operating conditions

Monitoring method	Effectiveness (%)	Extent of detection	Applications	Operating conditions	Reference
Liquid chromatography–mass spectrometry (LC–MS)	90%	Low parts per trillion (ppt)	Water quality monitoring	Controlled temperature, mobile phase composition	Parra-Saldivar *et al.* (2020)
High-performance liquid chromatography (HPLC)	70%	Parts per million (ppm)	Food and beverage analysis	Column temperature, mobile phase composition	Teng & Chen (2022)
Inductively coupled plasma–mass spectrometry (ICP–MS)	90%	ppt	Heavy metal monitoring	Argon gas flow rate, plasma power	Galindo-Miranda *et al.* (2019)
Gas chromatography–mass spectrometry (GC–MS)	80%	Parts per billion (ppb)	Soil and air contamination	Temperature, carrier gas flow rate	Delgado-Moreno *et al.* (2019)
Polymerase chain reaction (PCR)	80%	Copies per milliliter (cp/mL)	Microbial contamination detection	Temperature cycling, primer annealing temperature	Pruden *et al.* (2006)
Enzyme-Linked Immunosorbent Assay (ELISA)	60%	Micrograms per liter (μg/L)	Biomedical research	Incubation time, antibody concentration	Lee *et al.* (2022)
Biosensors	60%	(μg/L)	Environmental monitoring	pH, analyte binding time	Shen *et al.* (2014)
Ultraviolet–visible spectroscopy (UV–Vis)	50%	ppm	Organic compound analysis	Pathlength, solvent composition	Gaston *et al.* (2019)
Capillary Electrophoresis (CE)	70%	ppb	Pharmaceutical analysis	Applied voltage, buffer composition	Mohammadi *et al.* (2022)
Atomic absorption spectrometry (AAS)	70%	ppb	Metal analysis in wastewater	Lamp current, wavelength selection	Paszkiewicz *et al.* (2022)
X-ray fluorescence spectroscopy (XRF)	80%	ppm	Metal detection in soil	Excitation energy, detector type	Ahammad *et al.* (2022)
Liquid chromatography–tandem mass spectrometry (LC–MS/MS)	90%	ppt	Drug residue detection	Ionization mode, collision energy	Bayen *et al.* (2015)
Fourier transform infrared spectroscopy (FTIR)	60%	ppm	Chemical identification	Beam path length, spectral range	Quintelas *et al.* (2020)
Ion chromatography (IC)	70%	ppb	Environmental and food analysis	Eluent composition, flow rate	MacKeown *et al.* (2022)
Luminescence spectroscopy	60%	(μg/L)	Detection of fluorescence markers	Excitation wavelength, emission wavelength	Kumar *et al.* (2022)
Surface plasmon resonance (SPR)	80%	Nanograms per milliliter (ng/mL)	Biomolecular interaction analysis	Analyte concentration, regeneration steps	Jeevanantham *et al.* (2019)
Thin-layer chromatography (TLC)	60%	(μg/L)	Forensic analysis	Mobile phase composition, plate development	Li *et al.* (2023)
Voltammetry	70%	ppb	Electrochemical analysis	Electrode material, scan rate	Sivaranjanee *et al.* (2022)
	90%	ppb	Proteomics and metabolomics	Ionization method, mass range	Hayashida *et al.* (2009)

(*Continued.*)

Table 2 | Continued

Monitoring method	Effectiveness (%)	Extent of detection	Applications	Operating conditions	Reference
Time-of-flight mass spectrometry (TOF-MS)					
Flow injection analysis (FIA)	70%	ppm	Environmental monitoring	Sample injection volume, reagent flow rate	Ríos *et al.* (1984)

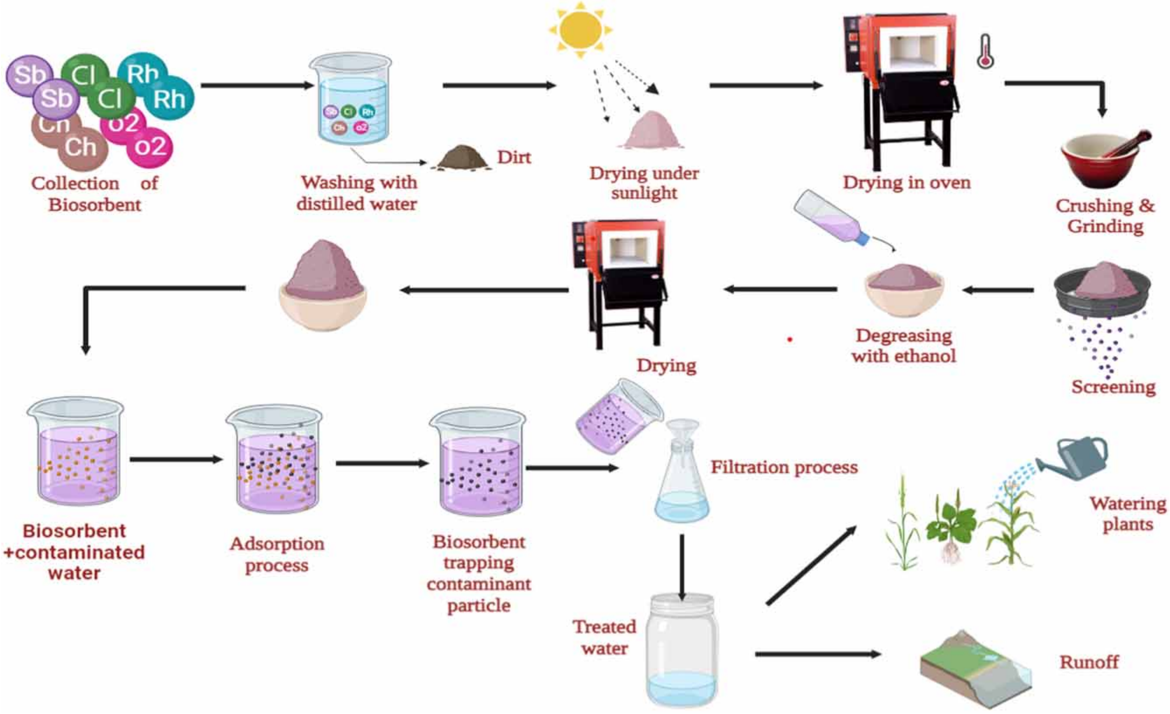


Figure 2 | Step-by-step procedure for preparation of biosorbent and its application in removal of ECs.

contaminants from huge quantities of liquid, such as wastewater, is possible with this technique (Ahmad & Zaidi 2020). The biosorbent substance is initially attached to a support, like a filter or a column, in the procedure. After passing through the support, where the pollutants are absorbed by the biosorbent material, the treated water is discharged. The biosorbent substance can then be taken off the support and utilized again. Entrapment is a method for immobilizing biosorbents in which the biosorbent is contained within a matrix made of alginate beads, cellulose fibers, or polymeric gels. This makes it simple to remove the biosorbent from the liquid once it is contaminated to saturation. Covalent binding is a method for immobilizing biosorbents that is also available (Velkova *et al.* 2018).

Air pollution can be removed using biosorbents called biofilters. Filters with a layer of biosorbent material can be used for this. Pollutants are adsorbed to the biosorbent material as air passes through the filter. Algae, peat moss, and AC are among biosorbents that can be utilized as biofilters. Chromium and copper, among other metals that are heavy, could be eliminated from wastewater using biofilters. In order to eliminate the metals that are heavy, the polluted water is passed through a filter that has a layer of biosorbent material, such as micro-organisms or plant-based materials. The plant-based substances or microbes can be immobilized on a substrate, such as a column or beads, allowing for repeated use (Jacinto *et al.* 2009).

When it comes to eliminating contaminants from water and the air, biosorbents have a number of advantages over conventional techniques, including high adsorption capacity because biosorbents are efficient in removing

Table 3 | Various biological treatment of ECs and its efficiency of removal

Treatment method	Description	Advantages	Examples	Removal efficiency (%)	Reference
AS process	Uses microbial communities to degrade contaminants	Effective in treating a wide range of contaminants	Triclosan, Bisphenol A	80–95	Mailler *et al.* (2014)
Membrane bioreactor (MBR)	Combines biological treatment with MF	Produces high-quality effluent	Pharmaceuticals, PCPs	90–99	Kamaz *et al.* (2019)
SBR	Treats wastewater in sequential batch operations	Flexible operation, low sludge production	Pesticides, EDs	70–95	Dubey *et al.* (2023)
Trickling filter	Biofilm-based treatment on a media surface	Simple operation, low energy requirements	Nitrogenous compounds, Ammonia	60–85	Shukla & Ahammad (2023)
CWs	Uses wetland vegetation and microorganisms	Natural treatment, provides habitat for wildlife	Heavy metals, Nitrate	60–90	Matamoros & Salvadó (2012)
Moving bed biofilm reactor (MBBR)	Utilizes suspended biofilm carriers	High treatment capacity, resistant to shock loads	Phenols, VOCs	70–95	Tak *et al.* (2020)
Anaerobic digestion	Decomposes organic matter in the absence of oxygen	Energy generation from biogas	Pharmaceutical residues, Fats, Oils	60–80	Tawfik *et al.* (2022)
Bioaugmentation	Introduces specific microorganisms for enhanced degradation	Customizable treatment, targets specific contaminants	Pesticides, Herbicides	70–90	Nzila *et al.* (2016)
Composting	Promotes the decomposition of organic waste	Produces nutrient-rich compost	Organic waste, Pesticides	60–80	Chang *et al.* (2018)
Aerated lagoons	Oxygenates wastewater to support microbial activity	Cost-effective, long-term treatment solution	Detergents, Bacteria	60–90	Matamoros *et al.* (2016)
Anaerobic BR	Treats contaminated environments without oxygen	Effective for persistent organic pollutants	Chlorinated solvents, PCBs	50–90	Bala *et al.* (2022)
Fungal BR	Utilizes fungi to degrade contaminants	Wide substrate range, efficient degradation	PAHs	50–90	Vaksmaa *et al.* (2023)
Vermicomposting	Composting with the aid of earthworms	Faster degradation, improved nutrient content	Organic waste, Paper waste	60–80	Das *et al.* (2023)
Algal treatment	Utilizes algae to remove nutrients and contaminants	Nutrient removal, CO2 fixation	Nitrogen, Phosphorus, Heavy metals	40–80	Norvill *et al.* (2016)
Aerobic BR	Breaks down contaminants in the presence of oxygen	Versatile treatment, applicable to various pollutants	Petroleum hydrocarbons, Solvents	50–90	Gimeno *et al.* (2016)
DNP	Converts nitrates into nitrogen gas	Reduces nutrient pollution, improves water quality	Nitrate, Nitrite	70–90	Wang & Chu (2016)
MFCs	Generates electricity while treating contaminants	Energy generation, WWT combined	Organic compounds, Heavy metals	40–70	Yaqoob *et al.* (2020)

(*Continued.*)

Table 3 | Continued

Treatment method	Description	Advantages	Examples	Removal efficiency (%)	Reference
Comamonas testosteroni	Bacterium capable of degrading endocrine-disrupting compounds	Effective for hormone-like substances	Bisphenol A, Estrogenic compounds	50–80	Duc (2017)
White-rot fungi	Fungi with enzymes capable of degrading complex organic pollutants	Efficient degradation of recalcitrant compounds	Polychlorinated biphenyls (PCBs)	60–90	Shreve *et al.* (2016)

AS, activated sludge; BR, bioremediation; CWs, constructed wetlands; DNP, denitrification; EDs, endocrine disruptors; MBR, membrane bioreactor; MF, membrane filtration; MFCs, microbial fuel cells; MBBR, moving bed biofilm reactor; PCBs, polychlorinated biphenyls; PAHs, polycyclic aromatic hydrocarbons; SBR, sequencing batch reactor; VOCs, volatile organic compounds; WWT, wastewater treatment.

pollutants from huge amounts of water or air because they are distinguished by a high capacity for adsorption for pollutants, selectivity because biosorbents have the ability to selectively remove pollutants, they can concentrate on a particular type of pollutant while leaving other elements of the water or air unaffected, environmental friendly because biosorbents do not release any toxic by-products because they are created from natural resources like microbes or plant fibers, cost-effective because biosorbents can be utilized in a smaller area and are frequently less expensive than conventional treatment procedures and Reusability because biosorbents can be used repeatedly, the cost of therapy as a whole may be decreased (Moghadas *et al.* 2022).

Depending on the type of biosorbent and the particular heavy metal being removed, different biosorbents have varying degrees of efficacy in removing heavy metals. It has also been discovered that plant-based biosorbents, such as agricultural waste, are efficient at removing metals that are heavy from water. Research has shown that metals that are heavy like cadmium, zinc, and lead may be eliminated from the water by over 70% using rice straws and banana peels. A popular type of biosorbent utilized to eliminate metals that are heavy from the water is AC; it can degrade 99% of metals that are heavy like lead and copper. It is crucial to remember that parameters like temperature, and pH, and when there are additional pollutants in water can all have an impact on how effective biosorbents are. Biosorbents can be highly effective at removing heavy metals from water (Qin *et al.* 2020). Bacterial biosorbents are microorganisms like bacteria and algae that can absorb or bioaccumulate contaminants like heavy metals from water and air. These bacteria may successfully remove contaminants from the environment by binding them to their cell surfaces or to the internal structures of their cells. They are vulnerable to microbial deterioration and need particular circumstances to operate at their best (Wang 2009; Wang & Chen 2009).

3.2. Activated sludge

Organic contaminants discharged into the environment by wastewater discharges have the potential to remain in the ecosystem, bioaccumulate in the food chain, infiltrate drinking water production, and damage human health and our surroundings. Conventional activated sludge (CAS) treatment procedures are usually intended to eliminate or reduce the levels of pathogens and bulk organic loads, but not to remove trace organic residues (Buttiglieri & Knepper 2008). The elimination of the traditional contaminants, particularly macro-contaminants (i.e., organic carbon, suspended solids, phosphorus, and nitrogen), was the focus of the WWT process. These contaminants were removed using renowned biochemical mechanisms like aerobic biodegradation of organic carbon using bacteria that are heterotrophic, denitrification (DNP)/nitrification (NP) for the removal of nitrogen employing a mixture of bacteria that are heterotrophic (for DNP) and nitrifiers (NP), and dephosphatation for the removal of phosphorus using phosphorus-accumulating microbes capable of absorbing dissolved phosphorus from sewage and storing it in granulates (Koumaki *et al.* 2021).

Sulfamethoxazole, trimethoprim, diclofenac, carbamazepine, methyl 3,5-dichloro-4-hydroxybenzoate, and triclosan were selected as the most often identified emerging organic micropollutants (EMOPs) in WWTPs effluent to adapt to AS and improve EMOP biodegradation. Sulfamethoxazole, trimethoprim, methyl 3,5-dichloro-4-hydroxybenzoate, triclosan, and diclofenac elimination were greatly enhanced by acclimated AS, whereas carbamazepine degradation was only modestly improved. The dispersal of 6 EMOPs across the sludge and water phases demonstrated that biodegradation was important in their elimination (Wang & Wang 2018). While being challenged by various micropollutants, gravity-driven membranes (GDMs) can effectively remove the water effluents with pathogenic microbes in rural areas (MPs). For the first time, this study researched the removal of sulfamethoxazole in GDM, and pre-adding acclimated AS was proposed to stimulate MP extraction (Chen *et al.* 2022a, 2022b). Some integrated systems of CWs and waste stabilization settings demonstrated promising biosorptive elimination of beta blockers and pharma products. Integrated systems that combine the AS process with physical processes like reverse osmosis (RO), ultra filtration (UF), and γ radiations are thought to be the most affordable and effective at removing trace organic pollutants (Dhangar & Kumar 2020). Traditional sewage treatment methods have demonstrated low elimination efficiency for ECs. As a result, more effective treatment mechanisms must be reported. According to the present research, an Integrated Fixed-Film Activated Sludge Process (IFAS) could be an option.

The elimination of the eight ECs in a traditional sequencing batch reactor (SBR)-based sewage treatment plant was compared to the deterioration of the eight ECs in domestic sewage during the steady-state conversion of a pilot IFAS plant (Ali *et al.* 2022). Ibuprofen and caffeine degraded up to 100% when treated separately at 30 mg/L concentrations, while metronidazole degraded between the region of 12–27%. They inhibited the NP process, whereas metronidazole inhibited the metabolic processes of microbes that denitrate. Biological treatments of synthetic waste water that contains all three substances (at conc of 10 mg/L) are shown in 100% ibuprofen and caffeine degradation, and 56% metronidazole degradation. Total eliminating nitrogen was decreased from 53 to 22% because both processes were impacted. (Kanafin *et al.* 2021).

AS was utilized in this study to adsorb perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in investigating their sorption behavior and potential absorption mechanisms in WWTPs in a solution of water. (Zhou *et al.* 2010). Based on the extensive literature on the subject, the techniques of micropollutant elimination are summarized and MBR working conditions. The dominant removal processes have been identified as micropollutant adsorption and ensuring decay, and they are affected by operational factors such pH, redox conditions, temperature, solid retention period and biomass content (Besha *et al.* 2017).

Investigations were conducted into the functions of sorption and decay as pharmaceutical elimination pathways throughout the AS process. The drug recoveries in the organism were good, varying between 94.9 and 99.2%, according to the QA/QC data. Micropollutant adsorption and subsequent degradation, as well as hydrolysis and volatilization, were studied in the blank–control studies and had no effect on pharmaceutical removal. Biodegradation and sorption show elimination under biotic conditions (Min *et al.* 2018). Figure 3 depicts the elimination of ECs by the AS process

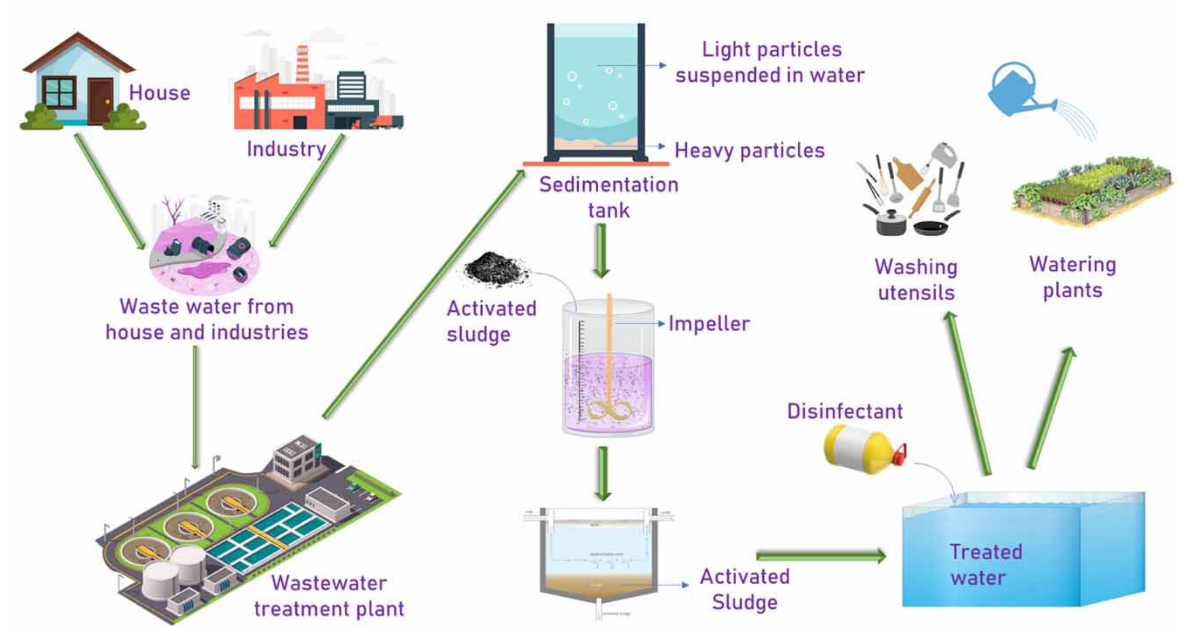


Figure 3 | Technical procedure for the ASP to remove contaminants from wastewater.

3.3. Constructed wetland

CWs are designed environments that treat wastewater secondary by utilizing the biological processes of plants, soil, and animals. The type of wastewater that needs to be treated must be taken into consideration when designing the created wetland. CWs are constructed according to the type of wastewater. They can also be categorized based on the direction of flow (that is horizontal, vertical) Figure 4. They are frequently employed to improve wildlife habitat, regulate runoff, and treat water. These systems purge contaminants and extra nutrients from water, preparing it for reuse or release into the environment (Vymazal 2010). In artificial wetlands, contaminants in the water are depleted of nutrients by microbes and plants. The microorganisms in the wetland degrade contaminants and surplus nutrients, making the water suitable for reuse (Stottmeister *et al.* 2003).

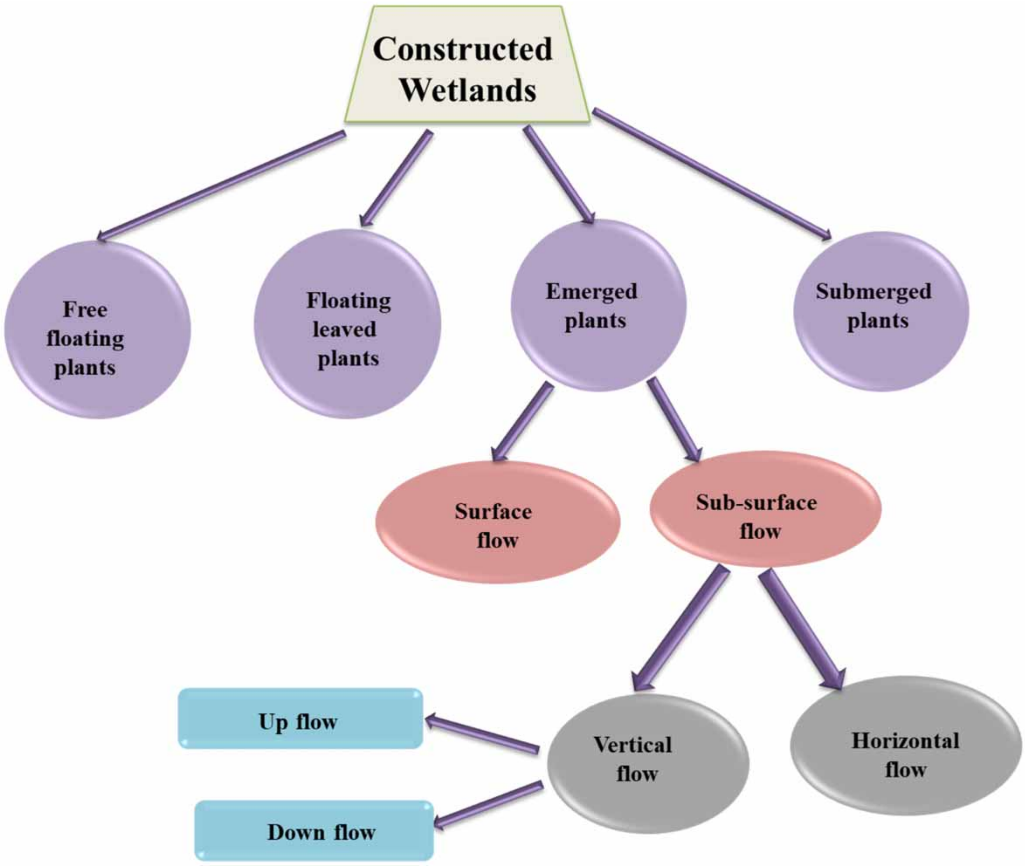


Figure 4 | Types of flows in constructed wetlands.

AS systems and oxidation ponds are two common conventional WWT methods that are frequently replaced with CWs because they are more affordable and environmentally beneficial (Scholz & Lee 2005). Microorganisms and plants clean the water before it is released into the environment or used again. SSF wetlands are frequently utilized to treat hazardous or high-strength wastewater (Garcia *et al.* 2010). Surface flow (SF) CWs, greywater, stormwater, and wastewater are usually treated in these wetlands. They are made up of a marsh or shallow pond where water flows (Kadlec 1995). Low-strength wastewater is treated in FWS wetlands (Su *et al.* 2009). Vertical flow constructed wetlands (VF) where Stormwater and wastewater are often treated in these wetlands. Low-strength wastewater is also frequently treated using VF wetlands (Kumar & Singh 2017). Hybrid wetlands (HWs) are more effective than conventional treatment systems and can be custom-tailored to the site circumstances and pollutant loads. They save money, require little upkeep, and take up little room (Maine *et al.* 2019).

As part of maintenance, it may be necessary to clear away trash and extra plants, keep an eye on water flow and level, and make any adjustments to the water supply (Jones-Lepp *et al.* 2012). In order to make sure that the wetland is successfully eliminating pollutants and surplus nutrients, it is also crucial to routinely evaluate the water quality (Carty *et al.* 2008). In order to offer a vast microorganisms' available surface area and plants for growth and purify the water, CWs use a range of media, including dirt, gravel, or sand medium help filter and eliminate impurities from the water while also acting as a habitat for microbes and plants. The type of pollutants to be treated and the unique site conditions will determine the medium utilized in a built wetland (Saeed *et al.* 2012).

CWs have a number of benefits, such as reduced maintenance requirements, high treatment effectiveness, improved habitat, and decreased water pollution. They are a good alternative for treating a variety of water sources since they may be customized to meet particular site circumstances and pollution loads (Stefanakis 2020). While the extra fertilizer supply might promote plant development and, thus, net nutrient uptake, the increasing loading of ions and other harmful compounds progressively converts the ecosystem into one made up of species more tolerant of pollution. In addition to nutrients, alterations in pH and salinity are examples of chemical changes that also impact the biotic community (Gopal 1999). They might also need routine upkeep and supervision, and some pollutants, such as heavy metals, might not be amenable to treatment (Huang *et al.* 2013). They can be tailored to fit particular site circumstances and pollutant loads (Verlicchi & Zambello 2014).

3.4. Membrane bioreactor

MBR is a suspended growth-activated sewage treatment that uses microporous membranes to separate particles from liquids rather than secondary clarifiers. It offers a major improvement in effluent quality through the creation of an effluent that is effectively pure and displays an outstanding degree of operational reliability (Radjenović *et al.* 2008). They can also be used to treat landfill leachate and recycle and reuse treated water. Wastewater contaminants such as organic matter, nitrogen, and phosphorus compounds are broken down by microorganisms. These bacteria feed on the contaminants, decomposing them into less complex substances like carbon dioxide and water. An MBR system typically uses bacteria, fungi, and protozoa as its microorganisms (Ji *et al.* 2020). During filtration, the flux decreases as it does in most membrane filtration procedures. The primary cause of this is membrane fouling. The main challenge in managing membrane fouling in an MBR is controlling it. The hydrodynamic situations, membrane form, module layout, and the presence of higher molecular weight compounds – which can be generated by microbial growth or added to the sludge bulking process – all have a substantial impact on the fouling of the membrane. Poly-electrolytes are one example of such a chemical. The technique of cross-flow filtration is appropriate for the continuous separation of activated sludge with high MLSS concentrations. It is possible to achieve a stable flow by managing the cake layer creation with shear pressures (Melin *et al.* 2006). Membrane performance (fouling) varies with loading rates and is dependent on the effluent quality of the biofilm reactor (HRT) (Leiknes & Ødegaard 2007).

The bioreactor and membranes module each execute a specific task: (i) the bioreactor uses appropriate microorganisms to biologically degrade organic pollution; (ii) the membrane module separates organisms from the treated wastewater; (iii) the membranes operate as a barrier for all suspended solids, allowing for the creation of permeate that is free of bacteria, viruses, and suspended debris in addition to enabling the recycling of AS into the bioreactor (Marrot *et al.* 2004). Although they are frequently found in wastewater, they can also be introduced to the system as seed sludge or AS (Roy & Saha 2021).

Additionally, the contaminants with molecular weights greater than the molecular weight cut-off of the barriers are preserved due to the sieving function of the membrane, bringing them into touch with the microorganisms responsible for their total destruction inside the MBR (Goswami *et al.* 2018). Aerobic treatment at large loadings and the more modern hydrogenation of oxyanions like nitrate, which is suitable for treatments by all three configurations, appear to be the main uses of MBR in biotreatment (Judd 2008). If not for membrane depreciation cost, operating costs are related to personnel expenditures (10–30%), sludge disposal (5–15%), chemical consumption (10–30%), energy consumption (40–60%), and others (5–20%) (Xiao *et al.* 2019).

The degree of EC adsorption on the membrane surface and their subsequent biodegradation are determined by the bond that exists between the ECs & the outermost layer of the membrane. (Sengupta *et al.* 2021) Industrial effluent treatment: MBRs are used to handle a variety of industrial effluents, including those generated during the production of semiconductors, medicines, and food and beverage products. Recycling and reuse in which MBRs are capable of treating and recycling wastewater for non-potable purposes like irrigation, process industries water, and flushing toilets (Chyoshi *et al.* 2022). MBRs could be used in combination with RO (Al-Asheh *et al.* 2021). In order to treat wastewater, an MBR system can employ a number of removal techniques: Filtration using membrane, Denitrogenation and NP, removing phosphorus, removing heavy metal Disinfection, and biological treatment (Bhattacharyya *et al.* 2022). MBRs have some disadvantages, including hefty upfront costs and ongoing expenses, upkeep requirements, the risk of membrane fouling, and the demand for a regular, high-quality feed in order to avoid membrane clogging (Gkotsis *et al.* 2014).

3.5. Others

Biodegradation is a process in which microorganisms degrade organic contaminants. Another fast and environmentally benign process is biodegradation to treat ECs. Microorganisms such as algae, fungi, and bacteria have the capability to eliminate various contaminants (Gan *et al.* 2022). In the process known as phytoremediation, plants are employed to remove pollutants from water. Plants can absorb and store contaminants in their tissues, and later these contaminants can be harvested and disposed of safely (Rai 2018). Electrochemical oxidation is an advanced treatment method that involves the use of electrical energy to oxidize contaminants. Electrochemical oxidation can be employed for treating a variety of ECs (Rodríguez-Narváez *et al.* 2021). Nanoparticles can be perhaps used as a treatment method to eliminate ECs from water. Nanoparticles including iron oxide and titanium dioxide can adsorb and degrade contaminants (Vicente-Martínez *et al.* 2020). AOPs involve utilizing chemical reactions to remove unwanted chemicals from water. AOPs can be employed for treating a variety of ECs, including PPCPs and pesticides (Wang *et al.* 2023). Enzymes are naturally occurring proteins that can be used to break down organic contaminants. Enzyme treatment is a practical and eco-friendly way to treat ECs. Enzymes such as peroxidases, dehalogenases and laccases can degrade various contaminants (Ouyang *et al.* 2022). Microbial fuel cells (MFCs) are a novel technology which uses microbes to generate electricity while also removing contaminants from water. MFCs can be used to treat a wide variety of ECs, including PPCPs and pesticides (Kumar *et al.* 2019). Biofiltration (BF) is a process in which microorganisms are used to remove contaminants from air or water. BF can be claimed to treat a wide variety of ECs, consisting of volatile organic compounds (VOCs) and nitrogen oxides (NOx). Biofilters can be designed to suit specific treatment needs and can be combined with other treatment methods for increased efficiency (Thuptimdang *et al.* 2021).

4. RECENT ADVANCES IN REMOVAL TECHNOLOGIES OF ECs

Technologies for removing new pollutants have made tremendous strides in recent years. ECs are compounds that have recently been recognized as having the potential to be detrimental to both human health and the environment and are not subject to regulation by environmental agencies (Petrovic 2003; McBean 2019).

Using sophisticated oxidation reactions, such as ozone and UV radiation, to convert developing pollutants into less hazardous chemicals is one significant innovation in removal technology. AC and graphene are two examples of adsorption materials that are being used increasingly in technology to purge water and air of impurities (Morin-Crini *et al.* 2022).

Moreover, researchers have created nanoparticles that can adhere to toxins and eliminate them from water sources, demonstrating the promise of nanotechnology in the elimination of new pollutants (Gondi *et al.* 2022). The catalytic sulfate radical-based AOPs are the ones that use affordable materials for proper and efficient remediation of ECs pollution (cSR-AOP) (Rivera-Utrilla *et al.* 2013). The core of this technique is the creation of SR (SO4•). SR is preferred because it has higher selectivity (in contrast to the hydroxyl radical (HR)), resulting in decreased secondary reactions (Parida *et al.* 2021). While several studies have shown that SR is effective, its formation is premised on the activation of peroxydisulfate (PDS) or peroxymonosulfate (PMS) or sulfite with flame, high pH, UV radiation, or a catalyst. The heterogeneous catalytic activation technique, which uses carbon-based substances, transition metals and their oxides as catalysts, and natural minerals, offers potential benefits like high pore sizes, considerable specific surface area, and extremely low activation temperatures (Yusuf *et al.* 2022). Catalytic AOPs, for example, have emerged as feasible options, but their application is constrained by the shortcomings of conventional catalysts (Ahmed *et al.* 2017). To address this problem, new materials with enhanced textural qualities have been created, demonstrating how Their capacity as a catalyst is impacted by their porosity and chemical makeup. This article discusses the most current developments in very porous catalysts and how to use them to successfully nano-remediate contaminated environmental matrices (González-González *et al.* 2022).

For the purpose of the elimination of dyes from water, silica along with silica-based composite nanoparticles are being investigated extensively. The excellent effectiveness of silica nanoparticles in eliminating dyes from water is due to the presence of exterior silanols that can intricate dyes, the simplicity of grafting extra features for better complexation, the potential for grafting photocatalysts to accelerate dye degradation, along excellent chemical stability (Jadhav *et al.* 2019). The electro-Fenton (EF) is a highly effective electrochemical AOP. Over the past three decades, its growth as a safe and efficient method for managing ECs has increased (da Silva Vilar *et al.* 2021). Despite the fact that the use of traditional EF has been proved to be a It has some limitations for industrial-scale development while being a strong method for the effective degradation/mineralization of hazardous and/or persistent organic contaminants. The present research has concentrated on increasing its productiveness (Nidheesh *et al.* 2023). The applicability of in silico methods as well as the computational framework, toxicity assessment, and the potential for decomposing complex resistant substances have all been adapted to predictive BR procedures to remove pollutants (Singh *et al.* 2021).

Conventional filtration techniques cannot remove ECs, and interest in adopting nanomembrane-based filtration is developing (Dolar *et al.* 2012). No special equipment is required to manipulate nanomembrane-based filtration. According to various research findings, better removal of ECs was achieved with filtering based on nanomembranes. Additionally, new advances have been studied and put into practice at different levels, and these developments are anticipated to continue (Tiruneh Adugna 2023). Environmental and health concerns would be there if there were a lot of toxins in the environment. Recent years have seen the development of photocatalytic technologies, which use sunshine to eliminate impurities. The primary goal of researchers is to create high-performance photocatalysts (Liang *et al.* 2019).

There is a growing need to look into PPCP elimination technologies on a deeper and more comprehensive level (Kumar *et al.* 2023). It begins by summarizing the types, attributes, and dangers of PPCPs to human health and the environment. The process of adsorption, among many other approaches for eliminating PPCPs from solutions of water, is then thoroughly discussed (Liu *et al.* 2022). Dyeing wastewater is harmful and cancer-causing to aquatic settings as well as humans. Adsorption technology has been widely utilized for decades to eliminate dyes from watery solutions because it is a simple and effective method. Many scientists have tried to locate or develop different dye adsorption materials (Zhou *et al.* 2019).

The electrocoagulation (ECoag) method has shown promise as an economical and environmentally responsible way to remove a variety of contaminants from a variety of water sources (Lima 2018). Numerous significant factors, including reactor geometry, pH, current density operating period, agitation speed and electrode gap have an impact on how well the EC method performs. The ECoag technology has some drawbacks, including the use of energy and electrodes in the passivation procedure in addition to its wider application (Al-Raad & Hanafiah 2021).

5. HYBRID TECHNIQUES FOR THE REMOVAL OF ECs

While they are also frequently referred to as 'composites,' 'hybrid materials' are difficult to define because this term is typically used to describe materials made by combining various components. A hybrid material, according to the IUPAC definition, is the outcome of a close-knit combination of inorganic as well as organic substances, or both of them, that traverse on a scale smaller than 1 m. On the other hand, different descriptions of hybrid materials are employed, and many classifications based on various criteria are being proposed (Rigoletto *et al.* 2022). Many treatment methods, such as physical, chemical, and biological methods, have been developed to remove a variety of ECs. Hybrid solutions have regularly been proven to be more effective, despite the fact that no one technique can now successfully eliminate ECs. A hybrid ozonation-AC method was found to be notably successful in eliminating some ECs, particularly pesticides and pharmaceuticals (Ahmed *et al.* 2021). Hybrid microbial electrochemical technologies (HMETs) are being used for the BR of ECs and toxic metals. An in-depth clarification and classification of *in situ* BR techniques and detailed explanations of individual technologies are provided (Ghangrekar *et al.* 2020).

The degradation of ECs from WWTP effluents using biological-based, chemical-based, and hybrid-based techniques. An MBR, AS, and aeration processes between a variety of biological processes are more effective at reducing endocrine-disrupting chemicals (EDCs). AS processes can effectively reduce PCPs, EDCs, and surfactants. Pesticides and pharmaceuticals were reduced effectively by biological AC (Ghernaout & Elboughdiri 2019). Because of the adverse impact on people's health and ecosystems, alternative technologies for adequate WWT are being developed. The Physical, chemical hybrid or biological technologies for treating EPs produce intriguing outcomes because they will improve the productivity of WWTPs. This mixture of biological/ adsorption systems may offer novel possibilities (García *et al.* 2021). A look at such hybrid systems that combine chemical, physical and biological methods to remove ECs from wastewater quickly and efficiently. Most of the hybrid systems used biological-based treatments first, followed by physical-based or chemical-based treatments (Rodriguez-Narvaez *et al.* 2017).

A suite of ECs such as PCPs, pesticides, EDCs and beta blockers were effectively removed using a hybrid system of MBRs followed by membrane filtrations (MFs). Some mixed systems of CWs and waste stabilization pools demonstrated removal through biosorption of PCPS and beta blockers (Dhangar & Kumar 2020). In terms of efficiency, cost-effectiveness, low energy consumption, and nanomaterial recovery, hybrid bionanotechnology is the best alternative to conventional treatment techniques (Paliya *et al.* 2023). In the area of chemical water analysis, we discuss some of our experiences using the integrated linear ion trap (LTQ) and FT Orbitrap mass spectrometer (Hogenboom *et al.* 2009). A brief examination of the combination photocatalytic membranes for the treatment of wastewaters containing POP: photocatalysis and membrane technology (Subramaniam *et al.* 2022). Adsorption is a crucial and adaptable remediation approach that has been utilized for many years to eliminate harmful components from water-based materials among all other ways of water purification (Alipoori *et al.* 2021). In a hybrid CWs comprised of several CW configurations: (i) unsaturated vertical subsurface flow (VF), (ii) free water surface (FWS) wetlands, (iii)partial saturated vertical subsurface flow (VF sat) saturated horizontal flow (HF), and (iv)saturated horizontal flow (HF), the elimination of conventional water quality parameters, emerging organic contaminants (EOCs), and fluorescence signature has been investigated (Sgroi *et al.* 2017). The PVA/gluten-integrated nanofibers that were created will be used as cost-effective adsorbents for metal nanoparticle recovery from aqueous environments (Dhandayuthapani *et al.* 2014).

6. CONCLUSION

Learning about ECs is becoming increasingly important to minimize the damage in the future and enable new monitoring techniques in the environment, which will help to enhance the relevant legislation. ECs in aquatic settings have received concern in recent decades because of their potential for both sudden and ongoing toxicity. Chemicals classified as ECs have a likelihood to produce undesirable ecological and (or) societal impacts that are not often examined throughout their surroundings (and are mostly neglected). A rising percentage of these are being built by industry and cannot be discovered in the surroundings naturally.

In general, three types of ECs can be distinguished depending on their frequency: (1) PPCPs; (2) PFASs; and (3) EDCs. They might dive into aquatic settings by farming. WT and refurbish using BF systems that use biologically enhanced activated carbon (BAC). Both treatment of toxins and biofilm formation have been addressed, as well as the operational elements impacting the outcome of the BAC system. Because adsorption and biodegradation govern contaminant removal by BAC, the link between the two procedures and the treatment strategies is looked at recent ECs such nitrates and deregulated DBPs and their precursors, including PFASs, micron-sized particles plasticizers, and plastic particles have been extracted by BAC, according to reports.

A lot of work has been put into finding fresh approaches for sample identification, quantification, and efficiency or bettering the remediation activities. More inventive methods for WT remediation can be developed, thanks to the rising interest in biotech and ecologic engineering. It has been discussed how to manage EC assessment and oversight over an extended period of time. It is possible to find bacteria that can break down ECs in cemeteries and their runoff by using genetic approaches. The waste water from landfills is thought to be a substantial isolated source of contaminating things, severely jeopardizing the natural systems and resources in the area. As an outcome, it is critical to keep an eye on the presence of harmful substances and create effective cleanup procedures; to do this, the desired level, of suspicious and non-target testing needs to be performed. Recent works that detail the chemical makeup of wellheads and sewage from landfills. Enzymes, particularly oxidoreductases, are a class of green biocatalysts with extraordinary potential for catalyzing without the use of any extra cofactors besides the readily available H_2O_2, the oxidizing or elimination of various substances or chemical impurities in soils and streams.

7. FUTURE PROSPECTS

Further research is needed in the future to advance the integrated technique's advancement and incorporate HC with technologies like electrochemical approaches. This type of process acceleration might result in 'organic pollutants conversion' or improved quality of water. These studies focus on the utilization of solar energy that are shown as a desirable way to reduce operational expenses. If a full-scale reactor is considered, when used to power integrated processes, renewable energy sources like solar PV would also lower the associated expenses.

The effectiveness of the discussion of the kinetics and characteristics involved by decomposition during WWT includes physicochemical features as well as the coefficient of sorption and constants of biodegradation. The most popular sampling and monitoring methodologies are scrutinized.

New investigation techniques are suggested for upcoming monitoring studies as well as the necessities for analytical study are indicated. More research is needed on biodegradation-assisted BR because of the fate of ECs in microalgal cells and the usage of algal biomasses can be selectively removed from a huge variety of species of extreme microalgae. In-depth research is required to characterize the effluent quality of wastewater after a microalgal biomass system. For instance, studies of the life cycle are necessary to determine the efficacy of EC BR supported by microalgae. Recent developments in biotech and ecology have led to the widespread adoption of genetically modified bacteria with a high capacity to remove environmental toxins in the domains of environmental restoration, making BR more effective and environmentally friendly. When released into fresh water, plastic particles serve as long-lasting substrates that can be colonized quickly. A preliminary study focuses on determining the composition of biological communities attached to microplastics understanding how microorganisms affect microplastics distribution and fate and determining whether the shape of microplastics affects community diversity. Because conventional WWT does not remove EDCs efficiently. Through mutualistic connections, soil bacteria are thought to have positive effects on plant health.

On the other hand, microbes are vulnerable to pollution, and in such polluted soils, microbial population decline, both in terms of variety and biomass, is widespread. A slight alteration in the physicochemical-biological characteristics of rhizosphere soils can have a substantial effect on how plants and microbes interact. Furthermore, isolating and characterizing suitable beneficial microorganisms connected with plants takes time. Sludge use in agriculture has a proven record of environmental acceptance and agricultural benefits. Sewage sludge might serve as a sustainable supply of phosphorus because tetra phosphorus and phosphate ions are two of the 20 key raw materials (CRM) for the EU, according to the European Commission's 'Report on Critical Raw Materials for the EU' published in 2017.

Fields to focus on in the future for improving biological treatment of ECs from wastewater such as Microbial BR where the modified microbes speed up the biodegradation of new pollutants is one potential field of research. These altered microbes can be engineered to break down particular pollutants and can boost the effectiveness of the BR procedure. AOPs might be combined with biological treatment to develop the removal of developing pollutants. Reactive oxygen species are used by AOPs to convert pollutants into safe molecules. Nanotechnology integration incorporating nanotechnology into biological therapy systems, the effectiveness and performance of the healing technique can be increased. For instance, nanoparticles can improve the biodegradation of microorganisms by enhancing the adsorption of pollutants onto them. Biological treatment system layout and functionality might be enhanced via means of artificial intelligence and machine learning. Prediction accuracy may be increased with these technologies, which will boost efficiency and save costs. Biological treatment systems' carbon footprints can be decreased by using sources of renewable energy including solar and wind energy. The financial impact of these systems can also be increased by integrating renewable energy sources.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 3 February 2024; accepted in revised form 26 June 2024. Available online 18 July 2024