Progress in Emerging Contaminants Removal by Adsorption/Membrane Filtration-Based Technologies: A Review

Rosmaya Dewi1,2, Norazanita Shamsuddin1,*, Muhammad S. Abu Bakar2, Jose H. Santos3, Muhammad Roil Bilad1, Lee Hoon Lim3

1Faculty of Integrated Technologies, Universiti Brunei Darussalam, Brunei Darussalam
2Sekolah Tinggi Ilmu Kesehatan Bakti Tunas Husda, Indonesia
3Faculty of Science, Universiti Brunei Darussalam, Brunei Darussalam
Correspondence: E-mail: norazanita.shamsudin@ubd.edu.bn

Abstract

This paper discussed the removal and the remediation of emerging contaminants (ECs) in water using adsorption and membrane filtration as a single and hybrid system. The classifications, sources, effects, detection techniques, and available technologies for ECs removal were discussed. Next, an overview of both adsorption and membrane filtration processes in terms of materials, separation mechanisms, factors affecting their performances, and their applications for ECs removals was provided. It was followed by a comprehensive review of the combination of the membrane and the adsorption processes with other physical, chemical, or biological treatments. Finally, progress in research on a hybrid system between membrane filtration and adsorption was discussed. The combination included adsorption as the pre-treatment, integrated adsorption/membrane filtration system, or adsorption as the post-treatment. Generally, the hybrid systems showed improved performance than a single system. Nonetheless, further studies are recommended for applications of those systems on a wide range of ECs removals and the scale-up issue.

© 2021 Tim Pengembang Jurnal UPI
1. INTRODUCTION

Water bodies have been polluted not only by conventional pollutants but also by emerging contaminants (ECs). With advances in detection techniques, ECs have been found in the water even at low concentrations (ng/L to mg/L, or lower). The presence of ECs is not regulated yet; hence they are not appropriately monitored. Compounds belonging to ECs are extensive in numbers. The numbers are also developing with the discovery of new compounds. ECs are classified into pharmaceuticals and personal care products (PCPs). Their presence in water bodies is getting more attention from scientists, government agencies, and society. They negatively impact ecology and have drawbacks on human health and aquatic organisms (Rasheed et al., 2019).

Based on the SCOPUS database using keywords of “emerging contaminant,” 6326 publications on ECs from 2011 until 2020. The number of publications increased annually. Most of them were published by institutions based in the United States and China, as shown in Figure 1.

Production, usage, and application of chemicals and pharmaceuticals are usually associated with long-term environmental pollution and health problems (Kümmerer, 2011). When consumed, they can accumulate in humans, invertebrates, and other living organisms and persist in the food chain (Rodriguez-Narvaez et al., 2017). Some examples of major human/environmental health concerns of ECs include hormone activities, skin, brain, nervous system disruption, cancer, ecological toxicity, persistency, and accumulation (Smital, 2008).

The emergence of new contaminants has been reported globally. In European surface waters, pharmaceuticals were frequently detected in ppb level, in which there were 12 high-risk and 17 medium-risk compounds (Zhou et al., 2019b). In East and Southeast Asian countries, antibiotics were found in surface water (at concentrations of <1 ng/L – µg/L with median values of 10 - 100 ng/L). Yet, the lack of antibiotics monitoring in surface waters makes it difficult to know their distribution (Anh et al., 2020). In the Central Mexican Pacific, pharmaceuticals classified as non-steroidal anti-inflammatory drugs have also been detected. They included diclofenac, naproxen, ketorolac, and ibuprofen. Moreover, these compounds were also detected in muscle tissues of 14 fish species, which could end up in bioaccumulation in the environment and organisms (Arguello-Pérez et al., 2019). In another study, the presence of ECs in water bodies was found in Coruña, Galicia (NW Spain). From 53 target compounds, 19 compounds at concentrations of > 0.1 µg/L were detected in wastewater. The traditional wastewater treatment plant (WWTP) could not remove these chemicals efficiently (Rodil et al., 2012). The compounds with the highest concentration were ibuprofen, salicylic acid, and UV filter benzophenone. Some compounds (i.e., ibuprofen, tri (2-chloroethyl) phosphate, diphenyl phosphate, benzophenone-4, 2-phenyl benzimidazole-5-sulphonic acid, tri (choloropropyl) phosphate, atenolol, diethylhexyl phosphate, tri-n-butyl phosphate, and diclofenac) were also present at concentrations of 20-200 ng/L.

In many countries in Asia, North America, and Europe, several categories of ECs (i.e., anticonvulsants/antidepressants, antibiotics, antifungal/antimicrobial agents, steroid hormones, nonsteroidal anti-inflammatory drugs, beta-adrenoceptor, blocking agents, X-ray contrast media, UV filters, stimulants, antiitching drugs, insect lipid regulating drugs, repellents, plasticizers, artificial sweeteners) have also been detected in WWTPs (Tran et al., 2018).
Conventional treatment technologies such as activated sludge, coagulation, sedimentation, flocculation could not thoroughly remove ECs (e.g., antibiotics, x-ray contrast media, beta-blockers, anticonvulsants) (Rasheed et al., 2019; Tran et al., 2018). Therefore, advanced technologies (e.g., membrane filtration, oxidation, adsorption) either as standalone or in combination have been assessed (Patel et al., 2019; Rodriguez-Narvaez et al., 2017). Adsorption has been widely used to remove hazardous inorganic and organic materials (Ahmed et al., 2015). It is simple, cost-effective, and offers high removal efficiencies (Gopal et al., 2014). In adsorption, adsorbent and adsorbate (contaminant) interact either physically or chemically. Other essential aspects of adsorption include adsorbent type, modeling, mode of operation, and regeneration (Dotto & McKay, 2020).

Membrane filtration is attractive for ECs removal. It offers high removal capability, low energy requirement, ease of scale-up, rapid kinetics, and a small carbon footprint. However, it still imposes several challenges such as membrane fouling, limited lifespan, insufficient rejection, chemical resistance, additional treatment of concentrates, and lack of tools for modeling and simulations (Van der Bruggen et al., 2008).

The hybrid system comprising membrane filtration and adsorption is thus of interest which combines the advantage of both processes. Moreover, a hybrid system can be applied to overcome the shortcomings of each technology (Dhangar & Kumar, 2020). Both adsorption and membrane filtration can be combined with other treatments (i.e., physical, biological, or chemical) to improve their performances.

This review reported a systematic analysis of membrane filtration and adsorption-based technologies for ECs removals. In addition, this review discusses ECs classification, sources, effects, analysis, and general information about available technologies for ECs removals.

2. EMERGING CONTAMINANTS (ECs)

The advances in analytical techniques using gas chromatography or liquid chromatography-mass spectrometry (GC-MS/LC-MS) allow the detection of polar compounds such as pharmaceuticals, metabolites, and transformation products at low concentrations that could not be analyzed beforehand. These groups of compounds are called ECs. ECs are found in
the environment at very low concentrations (in µg/L or lower). Hence, they are often also called organic micro-pollutants (Kümmerer, 2011). Henceforth, the term EC is used in this review.

2.1. Classification of Emerging Contaminants

There is no comprehensive definition and a complete list of compounds classified as ECs (Kümmerer, 2011). Each study categorized ECs into different classes. For instance, ECs were ranked into algal toxins, biocide and their transformation products, bioterrorism and sabotage agents, industrial chemicals, PCPs, and pharmaceuticals. Another report categorized ECs into pesticides, pharmaceuticals, PCPs, food additives, x-ray contrasting agents, steroids and surfactants, flame retardants, industrial compounds, and veterinary medicines (Qureshi et al., 2020).

In general, the term ECs refers to three main categories. The first category consisted of substances that have recently entered the environment, such as industrial additives. The second category included substances that may have been in the environment for a long time but have recently detected and attracted much attention, such as pharmaceuticals. The third category was a group of substances that have been known, but their potential adverse effects on the environment and organisms have only recently been realized. The ECs categories that have attracted more attention and always existed in the ECs categorization in various studies are pharmaceuticals and PCPs.

The compounds classified into pharmaceuticals and PCPs have different physical and chemical properties. Pharmaceuticals and PCPs are manufactured to improve animals/humans’ health and enhance human life quality. Pharmaceuticals include antibiotics, steroids, diuretics, non-steroid anti-inflammatory drugs, stimulant drugs, analgesics, antimicrobials, beta-blockers, antiseptics, hormones, lipid regulators, illicit drugs (e.g., amphetamines, cocaine). In contrast, PCPs include cosmetics, sunscreen agents, fragrances, domestic insect repellents, personal hygiene products, food supplements, and their metabolites, as well as transformation products. Some lotions and shampoos can contain up to 10-20 compounds (i.e., dyes, surfactants, preservatives, and others). Most of the PCPs are rinsed and drained into the sewage (Kümmerer, 2011).

2.2. Sources of Emerging Contaminants

The primary sources of ECs are wastewater, sewage sludge, municipal solid waste, households, livestock and poultry, hospital and industrial effluents, and urban runoff (Sophia & Lima, 2018). The paths of ECs reaching the water bodies are illustrated in Figure 2.

Most ECs were originated from industries, hospitals, households, animal husbandries, and urban runoff and flowed into WWTPs. Physical and chemical processes in WWTPs produce a sludge containing heavy metal concentrates and organic compounds. For example, Southeast Spain (Almería) municipal WWTP had sludge that contained ECs. The analysis showed that there were 62 types of ECs detected (Klameth et al., 2013).

Pharmaceuticals and PCPs also entered the environment through drug residues excretion from the human body that later flowed into sewerage; externally used drugs or PCPs; or expired/unused pharmaceuticals(PCPs disposed of in the trash. Moreover, ineffective treatment in WWTPs also led to ECs discharge into rivers and ecosystems.
2.3. Adverse effect of emerging contaminants

A summary of potential human health risks, bioaccumulation, toxic effects, and regulatory status of some ECs frequently found in the environment is shown in Table 1. ECs have shown either substantial, probable, or limited evidence on human/environmental health problems. Pharmaceuticals have shown strong evidence of congenital disabilities, developmental delays, hormone activity, and endocrine system (including liver). While, they have probable and limited evidence on the accumulation in wildlife and/or people, cancer, respiratory system, skin, reproduction and fertility, wildlife and environmental toxicity, brain, and nervous system. The toxicities of pharmaceutical products toward plants and algae are shown in Table 2.

Sulfachlorpyridazine, oxytetracycline, and diclofenac are toxic to duckweed/ plant with EC50 of 2.33 mg/L, 4.92 mg/L, and 7.5 mg/L, respectively. While tiludronate, propranolol and metoprolol are toxic to algae with EC50 of 13.3, 5.8, and 7.3 mg/L, respectively.

ECs have shown potential adverse effects and need to be analyzed further. Some significant concerns of ECs on human’s health include glucose metabolism, infertility, abortion, cholesterol, weight, fetal growth, allergy, cancer, uric acid, semen quality, acute effects (Lei et al., 2015), nervous system syndrome, memory disruption, anemia, hypertension, carcinogenic, non-degradable, toxic in nature, oxidative stress, cardiovascular disorder, reproductive disorder, reduce IQs, and apoptosis (Rasheed et al., 2019). The toxicity effect of ECs (i.e., furosemide and tramadol) was detected on Prague’s surface water and WWTP to Artemia salina. They had a lethal concentration (LC50) of 225.01 mg/L and 14,000 mg/L for furosemide and tramadol, respectively (Diaz-Sosa et al., 2020). Further research and regulation of ECs and their detrimental effects are needed to protect human health and ecology.

DOI: http://dx.doi.org/10.xxxxx/jost.vXIX
p- ISSN 2528-1410 e- ISSN 2527-8045
**Table 1.** The priority of major human/environmental health issues of the most prominent categories of ECs (Smital, 2008).

| Health concern                                      | Chemical family                                      |
|-----------------------------------------------------|------------------------------------------------------|
|                                                      | Nonculturable biological                            |
|                                                      | Bisphenol & BADGE                                    |
|                                                      | Perfluorochemicals (PFCs)                            |
|                                                      | perchlorate                                          |
|                                                      | pharmaceuticals                                     |
|                                                      | nanomaterials                                        |
|                                                      | Fragrances (nitro- and polycyclic                    |
|                                                      | polychlorinated naphthalenes                         |
|                                                      | phthalates                                           |
|                                                      | triclosan                                            |
|                                                      | polybrominated diphenyl esters                      |
|                                                      | A Brominate dioxins and furans                       |
|                                                      | Alkyl phenols                                        |
| Persistent accumulates in wildlife and/or people    | ++                                                   |
| Birth defects and developmental delays               | +                                                   |
| Cancer                                              | +                                                   |
| Respiratory system                                  | +++                                                 |
| Hematologic (blood) system                          | +                                                   |
| Immune system (including sensitization and allergies)| +                                                   |
| Skin                                                | ++                                                  |
| Reproduction and fertility                          | ++                                                  |
| Hormone activity                                    | +++                                                 |
| Endocrine system (including liver)                  | +                                                   |
| Wildlife and environmental toxicity                  | +                                                   |
| Kidney and renal system                             | +                                                   |
| Brain and nervous system                            | +                                                   |
| USA, Canada, EU list of priority compound            | √                                                   |
| OSPAR list                                          | √                                                   |

Note: Weight of evidence: +++ strong, ++ probable, + limited. Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)}
Table 2. Pharmaceutical product toxicity toward plant and alga (Basheer, 2018).

| Pharmaceutical group                     | Substance              | Organism affected | Long-Term Exposure (mg/L) |
|------------------------------------------|------------------------|-------------------|---------------------------|
|                                          |                        | Duckweed/ Plant   | Alga  | EC 10 | EC50 |
| Anti-bacterial (sulfonamide)             | Sulfamethoxazole       | √                 | 0.011 |
|                                          | Sulfamethazine         | √                 | >1.00 |
|                                          | Sulfachlorpyridazine   | √                 | 2.33  |
|                                          | Sulfadimethoxine       | √                 | >0.04 |
|                                          |                        |                   | 4     |
| Nicotine metabolite                      | Cotinine               | √                 | > 1.00|
| Anti-protozoal                           | Metronidazole          | √                 | 2.03  |
| Oestrogen                                | Ethinylestradiol       | √                 | 0.054 |
| Anti-bacterial (tetracycline)            | Tetracycline           | √                 | 0.23  |
|                                          | Oxytetracycline        | √                 | 0.788 |
|                                          |                        |                   | 4.92  |
|                                          | Chlortetracycline      | √                 | 0.036 |
|                                          | Doxycycline            | √                 | 0.055 |
| Anti-bacterial (macrolide antibiotic)    | Erythromycin           | √                 | >1.00 |
|                                          | Lincomycin             | √                 | >1.00 |
|                                          | Roxithromycin          | √                 | >1.00 |
|                                          | Tylosin                | √                 | >1.00 |
| Fluvoxetine                              | Sertraline             | √                 | >1.00 |
| Anti-diabetic (biguanide)                | Metformin              | √                 | >320  |
|                                          |                        |                   | 110   |
| Antihyperlipoproteinememic               | Clofibric acid         | √                 | 5.40  |
|                                          |                        |                   | 115   |
|                                          |                        |                   | 12.5  |
| Anti-hyperlipidemic                      | Atorvastatin           | √                 | 0.085 |
| Anti-hypertensive                        | Captopril              | √                 | 168   |
|                                          |                        |                   | 25    |
| Bone resorption Inhibitor                | Tiludronate            | √                 | 13.3  |
Table 2 (Continue). Pharmaceutical product toxicity toward plant and alga (Basheer, 2018).

| Pharmaceutical group | Substance                          | Organism affected | Long-Term Exposure (mg/L) |
|-----------------------|------------------------------------|-------------------|---------------------------|
|                       |                                    | Duckweed/ Plant   | Alga | EC 10 | EC50 |
| Non-steroid antiInflammatory drug | Naproxen                            | √                 | √    | 36.6  |      |
|                       |                                    |                   |      | >320.0|      |
|                       | Ibuprofen                           | √                 |      | 24.2  |      |
|                       |                                    |                   |      | >1.0  |      |
|                       | Acetaminophen (paracetamol)         | √                 | √    | 22.0  |      |
|                       |                                    |                   |      | >1.0  |      |
| β-adrenergic receptor blocker | Propranolol                          | √                 | √    | 72.0  |      |
|                       |                                    |                   |      | 7.5   |      |
|                       | Metoprolol                           | √                 |      | 114.0 |      |
|                       |                                    |                   |      | 7.3   |      |
|                       |                                    |                   |      | >320.0|      |
| Anti-bacterial         | Trimethoprim                         | √                 |      | >1.0  |      |
|                       | Cephalexin                           | √                 |      | >1.0  |      |
|                       | Ciprofloxacin                        | √                 |      | 0.106 |      |
|                       | Norfloxacin                          | √                 |      | 0.206 |      |
| Anti-bacterial (aminogycoside) | Neomycin                            | √                 |      | >1.0  |      |
|                       | Streptomycin                         | √                 |      | >1.0  |      |
| Anti-epileptic         | Carbamazepine                        | √                 |      | 74.0  |      |
|                       |                                    |                   |      | >1.0  |      |
|                       |                                    |                   |      | 25.5  |      |
The presence of ketorolac, ibuprofen, estradiol, diclofenac, and pentachlorophenol ranged under toxic concentrations in the coastal zone of Mexico. It was found from an ecotoxicological analysis. These ECs can contaminate surface water and soil and later cause endocrine changes in organisms living in this ecosystem (Arguello-Pérez et al., 2019). Endocrine disruption chemicals interfere endocrine system by mimicking, disrupting, and blocking the hormone’s function (Bolong et al., 2009).

2.4. Emerging Contaminants Analysis

The data on the ECs presence in water bodies are still scarce and limited. It is partly due to the unavailability of instruments for analysis. Hence, improvement of ECs analysis methods is significant in ECs’ detection. Generally, ECs analysis can be classified based on the targeted compound, non-targeted compound, and unknown compound. The LC-MS/MS is commonly used to analyze ECs (Agüera et al., 2013). Nonetheless, research is still needed, especially for detecting non-target/unknown ECs. New methods are required to allow a more efficient, low-cost, and time-saving analysis (Rodriguez-Narvaez et al., 2017).

Figure 3 shows targeted compounds and non-targeted compounds analysis using LC-MS. The LC-QTOF-MS/MS method showed high-confidence results. In the targeted compound analysis, the high sensitivity of TOF-MS offered intelligent screening and quantitative analysis. In the study of non-targeted compounds, the data were obtained through processing data based on some parameters (i.e., full scan mode mass accuracy; MS/MS library data of spectral purity score grade; structure description and mass error of fragment ion). Although the commercial MS/MS library can accurately and simultaneously confirm the non-target compounds, it is recommended to use the library that contains 20,000-30,000 compounds to achieve higher accuracy (Bueno et al., 2012). A pharmaceutical product is the standard category of ECs. The general steps for analyzing the ECs include sample collection, filtration, extraction, derivatization (if necessary), and LC-MS or GC-MS analysis (Fatta et al., 2007).

Figure 3. Targeted and non-targeted compound analysis (Bueno et al., 2012).
2.5. Technologies for Emerging Contaminants Removal

ECs treatment technologies typically consist of physical, biological, and chemical treatments (Figure 4). Physical treatment does not employ a biological or chemical agent and does not change the biochemical properties of the ECs. Biological treatment is a process that involves living organisms or enzymatic degradation. Lastly, chemical treatment is a process that involves chemical reactions (Ahmed et al., 2021).

Some effective treatments for ECs removal are biological treatment, membrane filtration, adsorption, and advanced oxidation processes. The biological treatment is the most widely used because of its availability, low cost, and environmentally friendly. However, it was reported to be less effective due to its poor biodegradability. In chemical treatment, ECs are converted into more stable or into compounds that are biodegradable through mineralization or conversion into inorganics (e.g., H₂O, CO₂, and N₂). It is the most effective in eliminating various ECs, although posing some drawbacks. In several studies, physical treatment has also been shown effective in pharmaceutical removals (Dhangar & Kumar, 2020).

Recently, technologies for ECs removal have been developed (Rodriguez-Narvaez et al., 2017). Each technology offered different performances for a specific type of ECs. For instance, phosphorized carbonaceous adsorbent showed good performance for some ECs, with a removal efficiency of about 99%. Continuous ultrafiltration (UF) showed removals of less than 30%. Activated sludge and constructed wetland showed removal efficiencies of 10-95% for 14 types of ECs. Sono-fenton+photocatalysts showed different diethyl phthalate and dimethyl phthalate removal efficiencies of 35 and 47%, respectively.

Figure 4. Available technologies for ECs removals (Dhangar & Kumar, 2020).

DOI: http://dx.doi.org/10.xxxxx/ijost.vXIX
p- ISSN 2528-1410 e- ISSN 2527-8045
3. ADSORPTION

Adsorption is a surface phenomenon in which the solute (adsorbate) and the porous surface (adsorbent) interact through a particular mechanism (Rashed, 2013). Adsorption is one of the promising methods for ECs removal due to its simple operation, low cost, and high efficiency (Sophia & Lima, 2018). Several advantages of adsorption include (Rasheed et al., 2019): high selectivity, high efficiency, facile processing, no harsh chemicals used, high productivity, cost-effective, easy post-treatment, and less disruptive.

Like other methods, adsorption also faces some challenges. They include the cost aspect of the entire adsorption process; only a few studies available on the fixed-bed system typically used in the industry; the ability to regenerate and reuse adsorbents in an environmentally friendly manner; the need to develop isotherm models for multi-component systems; and the application of adsorption methods in actual cases (Dotto & McKay, 2020).

The main stages in the adsorption studies for ECs removal are shown in Figure 5. The first stage involves choosing raw material for the adsorbent. It can come from various sources such as natural, synthetic, waste, etc. The second stage is the development of adsorbent material through physical or chemical processes, such as changing the particle size, acidification, structure modification, etc. The third stage is the adsorbent characterization that reveals the physical and chemical characteristics of the adsorbents. The fourth stage is the selection of ECs types and concentrations due to the wide range of ECs. The fifth stage is sorption studies, which include optimizing parameters that affect adsorbent performance and investigating the adsorption equilibrium and the adsorption kinetic. The final stage is desorption and regeneration studies, where the effectiveness of adsorbent is investigated when used many times.

Figure 5. Adsorbent selection protocol for pharmaceutical product removals (Patel et al., 2019).

DOI: http://dx.doi.org/10.xxxxx/ijost.vXIX
p- ISSN 2528-1410 e- ISSN 2527-8045
3.1. Adsorbent Materials

The adsorbent’s selection, characterization, and development are essential aspects in ECs removal via the adsorption process. Some critical criteria are cost and adsorbent availability, chemical stability, good physicochemical and textural characteristics, fast kinetic rate, mechanical stability, ability to regenerate or reuse, and high adsorption capacity (Dotto & McKay, 2020).

Adsorbents are generally classified into five categories (Singh et al., 2018): natural, biomass, industrial waste, agriculture waste, and synthetic adsorbents. Low-cost adsorbents include the ones prepared from readily available materials (e.g., peat, natural zeolite, chitin/chitosan, clay, coal, wood, etc.), industrial wastes (e.g., saw dust, sunflower stalk, nuts and fruits peels, straw, corn cob waste, etc.), and agriculture wastes (e.g., palm oil ash, fly ash, blast furnace, red mud, shale oil ash, bagasse, and bagasse pith, bagasse fly ash, etc.).

An adsorbent is characterized in terms of absorption capacity, porosity, and pore structure. Natural adsorbents (e.g., clay, zeolite, charcoal) are cheap and abundant and can be modified to increase their adsorption capacity (Rashed, 2013). Agriculture wastes-based adsorbents have a porous structure and desirable functional groups (e.g., hydroxyl, carboxyl). They are also low-cost and renewable resources. Modification of agriculture waste-based adsorbents resulted in enhanced performance (Dai et al., 2018). Industrial wastes such as fly ash, red mud, waste slurry are also potential adsorbents. The adsorption capacity of industrial waste adsorbents depends on adsorbent characteristics, adsorbate concentration, and adsorbent modification (Ahmaruzzaman, 2011).

Biosorbs can be classified as living (e.g., bacteria, algae, fungi, yeast) or non-living organic materials (e.g., wastes of agricultural and food industries) (Shamim, 2018). Biosorption is a physical or a chemical process (i.e., adsorption, electrostatic interactions, micro-deposition, chelation, ion exchange) that occurs in the cell wall before the adsorbate is assimilated. It has high selectivity and efficiency, as well as low cost.

Another category is synthetic adsorbents, such as nano adsorbents. It has a high surface area and consists of several categories based on their roles in the adsorption process related to surface properties and their functionalities. They are nanoparticles, silicon nanomaterials, nanofibers, xerogels and aerogels, polymer-based nanomaterials, nano clays, and carbonaceous nanomaterials (Khajeh et al., 2013).

3.2. Adsorption Mechanism

Adsorbent and adsorbate interact in two ways: chemi- and physisorption. In the former, the adsorbate forms a monolayer. The adsorbate interacts with the external surface of the adsorbent, enters the internal pores through pore diffusion, and interacts with the active sites (Khulbe & Matsuura, 2018). The adsorbent and the adsorbate form a new electronic configuration through electron sharing or electron transfer, and chemical interaction occurs. In the latter, adsorbent and adsorbate interact through the Van der Waals force in solid-liquid or solid-gas systems (Khulbe & Matsuura, 2018). Electrostatic forces or Van der Waals forces occur without the transfer or sharing of electrons. The adsorbate retains its identity, although a surface force field may deform it.

The illustration of the adsorption process is shown in Figure 6. The process is related to pore surface areas, active sites, chemisorption, and/or physisorption. Cheng et al. (2021) explained that modified biochar could adsorb some ECs with different mechanisms: hydrophobic interaction (for tylosin), ion exchange (for tetracycline and endocrine-disrupting chemicals), electrostatic interaction, hydrogen bonding, and functional groups (for tetracycline and endocrine-disrupting chemicals), and π-π...
bond interaction (for ciprofloxacin, tetracycline, sulfate, and endocrine-disrupting chemicals).

The adsorption equilibrium state is reached when there is minimum solute adsorption from the bulk to the adsorbent. The adsorption amount \( (q_e, \text{mmol/g}) \) under equilibrium is given in Equation [1].

\[
q_e = \frac{V(\text{Co} - \text{Ce})}{M}
\]

where \( V \) is the volume of the solution (L); \( M \) is the adsorbent mass (g); \( \text{Co}, \text{Ce} \) are adsorbate concentrations in the initial and equilibrium condition, respectively (Rashed, 2013).

The adsorption isotherm is a function of the equilibrium concentration of the solution at a constant temperature. It is defined as the percentage of adsorbate per unit weight of adsorbent. Usually, the adsorption isotherm is given in the Langmuir or Freundlich model (Román et al., 2020), as shown in Equations [2] and [3], respectively.

\[
q_e = \frac{Q_0 \times \text{Ce} \times K_I}{1 + (\text{Ce} \times K_I)}
\]

(2)

\[
q_e = K_f \text{Ce}^{1/n}
\]

(3)

where \( K_I \) (L/mg) is the Langmuir constant; \( Q_0 \) (mg/g) is the monolayer maximum adsorption capacity; \( q_e \) (mg/g) is the measured adsorption at \( \text{Ce} \); \( K_f \) (mg/g)(L/mg)\(^{1/n}\) is the Freundlich constant representing the adsorption capacity, and \( n \) is the constant depicting the adsorption intensity.

Adsorption kinetic shows the retention rate or solute release from solution to adsorbent’s surface at certain conditions (i.e., the dose of adsorbent, pH, temperature, and flow rate). Examples of adsorption kinetics are pseudo-first-order, intra-particle diffusion, pseudo-second-order, and Elovich models.

**Figure 6.** Adsorption pathway (Singh et al., 2018).
3.3. Factors Affecting Adsorption

Internal and external factors influence the adsorption process. The internal factors include structure features (e.g., molecular weight, functional groups, pore size, surface area, etc.). The external factors include adsorbent dosage, adsorbate concentration, contact time, pH, temperature, and competitiveness.

Those factors need to be optimized to achieve desirable performances. A high concentration of adsorbate leads to lower adsorption efficiency. High temperature is preferred for endothermic reactions. Contact time relates to the saturation of all adsorbent active sites. The presence of competitive ions can also compete on the active site of the adsorbent. An adsorbent’s chemical properties (e.g., functional group, ionization, steric effect) also influence the adsorption capacity (Román et al., 2020). Pore size and surface area affect the number of available active sites on the adsorbent surface. There is also a relationship between pore size and surface area, in which smaller pore size results in higher surface area.

3.4. Adsorption for Emerging Contaminants Removal

Adsorption is a promising method for ECs removal. Research has shown the application of various types of adsorbents (e.g., nano-adsorbent, biochar, activated carbon, composite adsorbent) for ECs removals. The adsorbent surface can be modified chemically or thermally to convert it from a functional material to a multifunctional nano-adsorbent and increase its capacity to absorb ECs (Sophia & Lima, 2018).

Agricultural wastes have a prospect to be applied as an adsorbent. As such, it simultaneously reduces environmental waste and converts waste into functional and valuable materials. Physical and chemical modifications have been proved to improve their adsorption performances (Dai et al., 2018). After being modified to increase their porosity and surface area, most of the agricultural and industrial wastes were used as adsorbents. These modifications included nano-structuring, carbonization, activation, milling, sieving, derivatization, and grafting techniques (Mo et al., 2018).

The summary of reports on ECs removals using adsorbent is shown in Table 3. The performance of agricultural and industrial waste-based adsorbents for ECs removals depends on the type of ECs, modification of adsorbent material, and several external factors.

Peñafiel et al., (2019) investigated ciprofloxacin removal by corn cob and rice husk-based adsorbent. The removals obtained by the corn cob was 56.3%, and rice husk was 59.7%. The optimum doses were 2 g/L for the corn cob and 6 g/L for the rice husk-based adsorbent. The performance was strongly influenced by pH with an optimum value of 6, and the mechanism was well described by the Freundlich isotherm and pseudo-second-order kinetic models.

Oyehan et al., (2020) investigated phenol removal by a mesoporous fly ash-based adsorbent. It was coated by an ultrathin film of polydiallyldimethyl ammonium chloride. The highest removal was about 95%. The mechanism was fitted by Freundlich, Langmuir and Temkin isotherm models with physisorption mechanism.

Biomass-based adsorbents (i.e., living or dead microorganisms and their components) can be utilized for the biosorption of ECs. However, the commercialization of this group of adsorbents is still limited. Various physical and chemical modifications led to higher costs and created new environmental problems (Fomina & Gadd, 2014).

Bankole et al., (2020) investigated ibuprofen, diclofenac, celecoxib removal using two wood-rot fungi: Laetiporus sulphurous and Ganoderma applanatum. The combination of Laetiporus sulphurous and Ganoderma applanatum biomassed showed better performance than the standalone.
Table 3. Emerging contaminants removal using adsorbents.

| Category of adsorbent | Type of adsorbent | EC adsorbate | Adsorption Capacity | Adsorption isotherm model | Reference |
|-----------------------|-------------------|--------------|---------------------|---------------------------|-----------|
| Natural adsorbent     | Granulated cork   | Diclofenac, phenol, 2,4-dichlorophenol, methyl paraben, pentachlorophenol carbamazepine, ketoprofen, triclosan, 2-nitrophenol and 2-chlorophenol, naproxen | 2-chlorophenol (45%), 2,4-dichlorophenol (75%), methyl paraben (50%), 2-nitrophenol (55%), phenol (20%), pentachlorophenol (100%), naproxen (2%), triclosan (100%), sodium diclofenac (100%), ketoprofen (57%), carbamazepine (50%). | Freundlich and Langmuir | (Mallek et al., 2018) |
| Activated carbons obtained from peat magnetic poly(N-isopropylacrylamide)/chitosan hydrogel | poly(acrylic acid) | - | 265mg/g | - | (Wiśniewska & Nowicki, 2020) |
| Thermally modified bentonite clay Zeolite | poly(acrylic acid) | hydrophilic sulfamethoxazole (SMZ) and hydrophobic bisphenol A (BPA). Ciprofloxacin | SMZ = 33.95 mg/g, BPA = 747.53 mg/g | Freundlich (for SMZ) and Freundlich and Slips (for BPA) | (Zhou et al., 2019a) |
| Agriculture waste | Thermally modified bentonite clay Zeolite | Phenol, Ciprofloxacin | 114.4 mg/g | Langmuir | (Zhou et al., 2019a) |
| | Hydrochar-derived magnetic carbon composite from sawdust | Tetracyclin, Roxarsone | 37.92 mg/g at 55, 35, 45, and 25°C, respectively | Langmuir | (Antonelli et al., 2020) |
| | Corn cob, Rice husk | Ciprofloxacin | 56.3%, 59.7% | Freundlich | (Yousef et al., 2011) |
Table 3 (Continue). Emerging contaminants removal using adsorbents.

| Category of adsorbent | Type of adsorbent                                                                 | EC adsorbate                                                                 | Adsorption Capacity | Adsorption isotherm model | Reference                  |
|-----------------------|----------------------------------------------------------------------------------|------------------------------------------------------------------------------|---------------------|---------------------------|---------------------------|
| Industrial waste      | Activated carbons from peach stones                                              | Carbamazepine, diclofenac, caffeine                                          | caffeine (260 mg/g), carbamazepine (335 mg/g). Diclofenac adsorption capacity is lower than caffeine 98.33 mg/g | Sips                       | (Yu et al., 2020a)         |
|                       | Modification and magnetization of rice straw derived biochar tetracycline         | Hydralazine hydrochloride pharmaceutical pollutant                           | 131.63 mg/g         | Langmuir, Freundlich, Temkin | (Qureshi et al., 2020)     |
|                       | Waste tea residue                                                                | Hydralazine hydrochloride pharmaceutical pollutant                           | 131.63 mg/g         | Langmuir and Freundlich    | (Qureshi et al., 2020)     |
|                       | Pistachio shell coated with ZnO nanoparticles tetracycline                         | Mesoporous fly ash                                                          | 95.06 mg/g          | Freundlich                 | (Peñafiel et al., 2019)    |
|                       | Industrial waste Biochar derived from hydrothermal carbonization of sugarcane bagasse | sulfamethoxazole                                                            | 400 mg/g            | Freundlich                 | (Peñafiel et al., 2019)    |
|                       | Bagasse fly ash                                                                  | 2-picoline                                                                  | 98%                 | Langmuir and Redlich–Peterson | (Torrellas et al., 2015)    |
|                       | Activated carbon from effluent beverage industry treatment plant sludge           | ibuprofen, ketoprofen, and paracetamol                                      | ibuprofen (105 mg/g), paracetamol (57 mg/g), and ketoprofen (145 mg/g) | Sips                       | (Torrellas et al., 2015)    |
### Table 3 (Continue). Emerging contaminants removal using adsorbents.

| Category of adsorbent | Type of adsorbent                                                                 | EC adsorbate                                             | Adsorption Capacity                                           | Adsorption isotherm model          | Reference                        |
|-----------------------|----------------------------------------------------------------------------------|----------------------------------------------------------|---------------------------------------------------------------|------------------------------------|----------------------------------|
| Biomass adsorbent     | Chars from reprocessed wet olive mill waste pitted, olive tree pruning, olive stone. | Diclofenac, ibuprofen, triclosan.                        | Diclofenac (64%), ibuprofen (43%), triclosan (98%).           | Freundlich                         |                                  |
|                       | Novel modified red mud with polypyrrole                                          | Phosphorus (P) and diclofenac (DCF) amoxicillin          | DCF/P (115.7 mg/g), DCF (195 mg/g), 1:33,107 mg/g             | Freundlich                         | (Dai et al., 2020)               |
|                       | Unburned materials obtained by combustion in a conical spouted bed of four types of vegetable biomasses of forestry residues, grass, and food industry. Wood-rot fungi; *Laetiporus sulphureus* (LS, *Ganoderma applanatum* (GA). Yeast, *Saccharomyces cerevisiae*, *Pseudomonas aeruginosa* immobilizedFe$_3$O$_4$-multiwalled carbon nanotubes bioadsorbent Fungal Strains from Municipal Wastewater | Ibuprofen, diclofenac, celecoxib                        | Ibuprofen (95%), diclofenac (96%), celecoxib (98,96%)        | Langmuir and Temkin               | (Patil et al., 2019)             |
|                       |                                                                                 | Phenol                                                   | 27 mg/g                                                       | Langmuir                           |                                  |
|                       |                                                                                 | 2,4,6-trinitrophenol                                     | 100 mg/g                                                      | Langmuir                           | (Mohammed & Kareem, 2019)        |
|                       |                                                                                 | diclofenac                                               | >98%                                                          | -                                  |                                  |
Table 3 (Continue). Emerging contaminants removal using adsorbents.

| Category of adsorbent | Type of adsorbent | EC adsorbate | Adsorption Capacity | Adsorption Isotherm model | Reference |
|-----------------------|-------------------|--------------|---------------------|---------------------------|-----------|
| Nano-adsorbent        | composite iron nano adsorbent. | Ibuprofen = 92% | Freundlich, Langmuir, Dubinin-Radushkevich, Temkin and Sips | (Oyehan et al., 2020) |
| Carbon nanotubes impregnated with metallic nanoparticles. | Glyphosate-based herbicides | 43.66 mg/g | A two-step adsorption model | (Prasannamedha et al., 2021) |
| Surface modification of aluminum hydroxide nanoparticles | emerging pesticide lindane | 93.68% | | |
| Magnetic graphene/chitosan nanocomposite | 2-naphthol | 169.49 mg g$^{-1}$ | Freundlich | |
| Polypyrrole-functionalized magnetic $\text{Bi}_2\text{MoO}_6$ nanocomposites magnetic silica-based nanoadsorbents | ketoprofen and indomethacin | ketoprofen (87.03%) and indomethacin (86.24%) | Langmuir | (Lataye et al., 2008) |
| Carbamazepine, ibuprofen, diclofenac, Diclofenac (83.0%) ibuprofen (63.5%), carbamazepine (< 3%). | Freundlich model | | | |
Dalecka et al., (2020) investigated diclofenac removal from municipal wastewater by fungal strains: Aspergillus luchuensis, A. luchuensis indicate, and Trametes versicolor. The diclofenac removals by Aspergillus luchuensis, A. luchuensis and Trametes versicolor were >99.9, >98, and 100%, respectively. Each fungal strain required different pHs and incubation periods for achieving a good biosorption process.

Nano-adsorbent could remove ECs even at low concentrations (μg/L) under optimum temperature and pH. Moreover, the nano-adsorbent dose was low, and the time required for ECs removal was short (1-15 minutes). However, the application of nano-adsorbent is still limited. Therefore, further studies are still required to enhance the adsorption capacity, security level of materials, and application in various conditions (Basheer, 2018).

Nguyen et al. (2020) investigated lindane (pesticide) removal by using modified nanomaterial of aluminum hydroxide as adsorbent. The removal efficiency was 93.68% by applying an adsorbent dosage of 25 mg/L, adsorption time of 60 min, ionic strength of 10 Mm NaCl, and pH six.

4. MEMBRANE FILTRATION

Membrane-based processes have long been used in water and wastewater to remove microorganisms, organic materials, including emerging contaminants and other particles (Gómez-Espinosa & Arizmendi-Cotero, 2019). The membrane material can separate those constituents under specific driving forces. Various pressure-driven membrane processes (i.e., nanofiltration (NF), UF, reverse osmosis (RO)), and osmotically driven forward osmosis (FO) have been studied for ECs removal. The removal efficiency followed the order of the typical pore sizes being the highest for the one with the smallest one: RO≥FO> NF> UF.

Retention of ECs by the membrane is affected by the size/ steric exclusion, hydrophobic/hydrophilic interactions (adsorption), electrostatic forces, or a combination thereof. Polar ECs have less retention than less polar ones. UF is less effective for ECs removals but can act as a pre-treatment before FO, NF, or RO. Further studies are needed to study the transfer mechanism and evaluate the effects of draw solution type, concentration, permeation rate, and foulant accumulation (Kim et al., 2018).

4.1. Materials

Most of the commercial membranes were prepared from synthetic polymers. The materials often used for UF and MF are polysulfone, polyvinylidene fluoride, polyacrylonitrile, and polypropylene, including recently inorganic/ ceramic, which has been of great interest. The most common material for RO membrane is polyamide, while the materials for NF membrane are polysulfone, polyimide, and ceramic. The application of membrane technology for ECs removals is challenged by various limitations on membrane physicochemical characteristics and other factors that influence the separation process. Some membrane materials such as polymers, inorganic membranes, and others need further tests (Kárászová et al., 2020).

Membranes can have a porous or dense structure. The separation of ECs using membranes is related to the solubility and diffusivity of ECs and the applied pressure (Gómez-Espinosa & Arizmendi-Cotero, 2019). Detailed classification of membrane materials can be found elsewhere (Pendergast & Hoek, 2011).

Generally, different membrane materials (e.g., polyamide, ceramic, cellulose triacetate) are pretty similar in the rejection of ECs, only differ in some ways. In RO membrane prepared from cellulose triacetate had a less significant effect on the
electrostatic interaction than polyamide. The rejection of positively charged ECs is lower than negatively charged ECs when separated using ceramic membranes. In polyamide NF/RO membrane, the effect of positive/negative charge on ECs was not observed.

### 4.2. Separation Process

In membrane-based separation, membrane material acts as a physical barrier for pollutants/contaminants in the feed. The retention of contaminants is highly affected by the relative size of the pores to the contaminants. A membrane process requires a driving force (e.g., electrical force, concentration difference, pressure) to allow separation of a particular substance, as schematically illustrated in Figure 7. Membrane with tiny pores requires high transmembrane pressure to separate specific components from the feed and vice versa (Madhura et al., 2018).

The transport through the membrane pores is influenced by the material, physicochemical characteristics, and membrane morphology. In general, the ECs-membrane interaction mechanism consists of size exclusion, electrostatic and/or hydrophobic interactions. The size exclusion mechanism occurs through sieving, where large ECs molecules are retained while smaller ECs molecules pass through the membrane pores. The relative sizes of the ECs and the free volume of the active membrane layer is a factor that determines the efficiency of the separation.

Electrostatic interaction is related to electrostatic attraction or repulsion between the ECs and the membrane material. If the membrane surface is negatively charged, then ECs with negative charged ECs will be rejected, and vice versa. Moreover, neutral ECs are not affected by electrostatic interactions.

Hydrophobic interactions between hydrophobic ECs and hydrophobic membranes can also affect the separation process. Hydrophobic ECs do not fully dissolve but suspend in with water. When presented in the feed, they could be absorbed into the hydrophobic membrane material and concentrated on its surface. The use of membranes (especially MF and UF) for ECs removals can be done in a combined process (Gómez-Espinosa & Arizmendi-Cotero, 2019). UF is effective for pathogen removal, and MF is effective for particulates removal. RO and NF operate at higher transmembrane pressure and can remove contaminants up to 0.0001 μm and 0.001 μm, respectively. The RO and NF processes can remove a wide range of contaminants and requiring more pre-treatments. NF and RO effectively remove ECs such as pesticides, pharmaceutical products, endocrines, algal toxins, and other similar substances.

### Tables 4 and 5 compare NF and RO membranes and their performance for ECs removal. In ECs removals, RO has higher removal efficiency than NF. Generally, NF and RO membranes are different in some parameters, including adequate pore size, energy consumption, micropollutant removal, membrane availability, etc.

### 4.3. Factor Affecting Performance

The main parameter to judge membrane performance is permeability that is affected by membrane pore size, surface chemistry, morphology, porosity, thickness, etc. The increase in membrane thickness causes a decrease in permeation flux because of longer flow path across the membrane matric (Kárászová et al., 2020). Membrane permeability is also influenced by hydrophilic/ hydrophobic characteristics and morphology of membrane surface. Higher porosity leads to lower intrinsic membrane resistance (Shamsuddin et al., 2016).

DOI: http://dx.doi.org/10.xxxxx/Ijost.vXix
p- ISSN 2528-1410 e- ISSN 2527-8045
Transport through a membrane is affected by both the feed solution characteristics and the membrane properties (Hammami et al., 2017). In NF, ECs rejection is influenced by several factors. They are EC properties (i.e., molecular size, charge, hydrophobicity, polarity, diffusivity, solubility), membrane properties (i.e., surface charge, hydrophobicity, permeability, pore size), and membrane operating conditions (i.e., rejections/recovery, transmembrane pressure, flux, water feed quality) (Bolong et al., 2009). The efficiency of ECs removal is influenced by both the physicochemical characteristics of ECs and the membrane properties.

Membrane properties affect the interaction of the feed constituents and the membrane surface. Membranes can attract or repel water (i.e., hydrophilic and hydrophobic surfaces). The nature of the feed solution can also affect the membrane fouling propensity. The increased foulant material concentration in the feed lowers the permeability. The permeation rate is proportional to the trans-membrane pressure, in which higher pressure leads to higher fluid force.

**Table 4. A general comparison between NF vs. RO (Yangali-Quintanilla et al., 2011).**

| Condition                                      | NF                                     | RO                                     |
|------------------------------------------------|----------------------------------------|----------------------------------------|
| Effective pore size (range)                    | 1–2 nm                                 | < 1 nm                                 |
| Energy consumption                             | Low to moderate                        | High                                   |
| Removal of salts                               | Moderate                               | High                                   |
| Post-treatment for the addition of salts (ions)| Not necessary                          | Necessary                              |
| Removal of contaminants (micropollutants)     | Low to high, depending on “tight” or “loose” membrane and type of contaminant | Low to high, depending on the type of contaminant |
| Membrane availability                          | Low to moderate                        | Few                                    |
| Types of membranes by manufacturer             | Low to moderate                        | Plentiful                              |
|                                                 | Few                                    | Many                                   |
### Table 5. Removal efficiencies of specific ECs by NF and RO membranes.

| Type                  | Chemical            | NF Removal (%) | RO Removal (%) |
|-----------------------|---------------------|----------------|----------------|
| **Pharmaceuticals**   |                     |                |                |
| Analgesic             | Ibuprofen           | 98             | >98            |
|                       | Naproxen            | 23             | >95            |
| Antibiotic            | Trimethoprim        | 22             | 90             |
| Muscle relaxant       | Diazepam            | 55             | >95            |
| Steroid               | 17β-estradiol (estrogen) | 20          | 90             |
|                       | Testosterone (androgen) | 60         | 95             |
| **Personal Care Products** |                   |                |                |
| Antimicrobial         | Triclosan           | 45             | >96            |
| Insecticide           | DEET                | 75             | >90            |
| Surfactant            | Nonylphenol         | >99            | >99            |

### 4.4. Membrane Fouling

One of the main challenges of membrane-based filtration is membrane fouling (Van der Bruggen et al., 2008). It is caused by substance deposition on the membrane surface and/or in the membrane pores (Madhura et al., 2018). It lowers the membrane flux and could alter the membrane surface hydrophobicity through the formation of the cake layer, the surface charge, traces contaminant adsorption, and the overall surface roughness (Kárászová et al., 2020). Membrane fouling is affected by the foulant material characteristics, such as the functional groups, overall structure, size, etc. It dictates its physical/chemical interaction with the membrane material (Shamsuddin et al., 2016).

Based on the nature of the foulant materials, foulant materials can be classified into living cells (biological), organics, particulates, and inorganics (Bokhary et al., 2018). Several parameters also influence membrane fouling, namely membrane properties, feed characteristics, and operational parameters. These parameters must be considered when designing a membrane process (Bokhary et al., 2018).

There are several mechanisms of membrane fouling: adsorption, pore blocking, cake layer, and gel-layer formation. Some of them mostly co-occur. In the adsorption mechanism, the membrane and the foulant material interact, forming particles monolayer on the surface of the membrane. The layer causes additional hydraulic resistance and eventually lowers the hydraulic throughput. In the pore-blocking mechanism, the foulant blocks the membrane pores either wholly or partially, depending on the particle's relative size to the membrane pore size. In the cake layer fouling, particle deposition causes additional hydraulic resistance on the surface of the membrane. The firmly attached cake forms gel-layer on the membrane surface (Madhura et al., 2018).

Several methods can be implemented to reduce the severity of membrane fouling as summarized in Figure 8, namely pre-treatment of the feed, membrane modification, operation conditions, and cleanings (physical or chemical methods).
4.5. Application of Membrane Filtration for Emerging Contaminants Removal

Membrane-based processes (such as MF, UF, membrane bioreactor) have been proposed as the technologies for ECs removals (Couto et al., 2018). They have proven to offer good permeation and do not impose toxicity (i.e., excess chemicals) to the environment. Reports on membrane application for ECs removal showed that good selectivity could be achieved by implementing dense membrane (NF, RO, FO). Denser membrane (i.e., RO) had better selectivity in retaining ECs than more open pore membrane (i.e., NF). The mass transport through a dense membrane generally obeys the solution diffusion model. Porous membranes offer higher permeation but lower EC rejection (Kárászová et al., 2020).

Table 6 summarizes the applications of various types of membrane processes for ECs removals. The application of membrane filtration for the separation or concentration of pharmaceuticals has been extensively investigated. Most of the studies employed commercial membranes (especially polyamide) with an NF process. RO membranes have an efficiency of ≥ 80% removals for most pharmaceuticals. For the UF membrane, the results varied widely (Shojaee Nasirabadi et al., 2016).

Figure 8. Strategies for membrane fouling control (Bokhary et al., 2018).
Table 6. Application of membrane technology for emerging contaminant removals.

| Process          | Membrane material                                                                 | ECs                              | Removal efficiency                             | References                                      |
|------------------|-----------------------------------------------------------------------------------|----------------------------------|------------------------------------------------|------------------------------------------------|
| UF               | Polyether sulfone (PES)                                                           | 39 high-occurrence CEC           | < 30% except for amitriptyline (63%). 90%      | (Ferreiro et al., 2020)                         |
| Polyelectrolyte multilayer (PEM) nanofiltration (NF) | Poly(sodium styrene sulfonate) + poly(diallyl dimethylammonium chloride)         | Tetracycline, amoxicillin trihydrate, perfluorooctanesulfonic acid, perfluorooctanoic acid, and hydrochloride. 20 types of pharmaceuticals | > 99%                                          | (Wang et al., 2021)                             |
| MBR–RO           | RO: aromatic polyamide. MBR: flat sheet membranes (Kubota, porous size of 0.4 µm). | Ibuprofen                        |                                                | (Dolar et al., 2012)                           |
| UF               | Poly (vinylidene fluoride) (PVDF)-ZnO/Ag2CO3/Ag2O nanocomposite membrane          |                                  |                                                | (Rosman et al., 2020)                          |
| MF-FOMBR         | FO: CTA-ES MF: Polyvinylidene fluoride                                              | 20 antibiotics                   | 58.9-100%                                     | (Qiu et al., 2021)                             |
| UF               | UF: CuO/TiO2 ceramic                                                             | Ciprofloxacin                    | 99.5%                                         | (Bhattacharya et al., 2019)                     |
| MF               | MF: CuO/TiO2 ceramic                                                             |                                  |                                                | (De Souza et al., 2018)                        |
| NF               | UF: CuO/TiO2 ceramic                                                             | Ciprofloxacin                    | 99.5%                                         | (Bhattacharya et al., 2019)                     |
| NF               | NF: 270 and NF 90 (Filmtec–Minneapolis, MN). Thin-film (skin) of polyamide over a layer of polysulfone on a polyester support layer. | Norfloxacin                      | 87-99.5%                                      | (De Souza et al., 2018)                        |
| NF               | Chitosan-modified acrylic nanofiltration membrane                                | Diphenhydramine and mebeverine   | diphenhydramine (97%) and mebeverine (~98%)   | (Kamrani et al., 2018)                         |
| NF               | Polyamide Thin-Film Composite                                                    | Caffeine, theobromine, theophylline, amoxicillin, and penicillin G | amoxicillin (89%), caffeine (20%), theobromine (18%), penicillin G (70%), theophylline (7%) | (Egea-Corbacho et al., 2019)                    |
Table 6 (Continue). Application of membrane technology for emerging contaminant removals.

| Process | Membrane material                                                                 | ECs                                | Removal efficiency                    | References                          |
|---------|-----------------------------------------------------------------------------------|------------------------------------|---------------------------------------|-------------------------------------|
| NF      | Two thin film composite NF membranes: NF-200 and NF-90 (Dow-Filmtec), made of polyamide | 18 ECs                             | ionic contaminants (97%), neutral contaminants (82%) | (Yangali-Quintanilla et al., 2011) |
| RO      | BW30-2540 made from polyamide thin-film composite                                 | Caffeine, theobromine, theophylline, amoxicillin, and penicillin G | 100%                                 | (Lopera et al., 2019)               |
| RO      | RE2521-SHF made from polyamide thin-film composite                                | Ciprofloxacin                       | > 90%                                 | (Alonso et al., 2018)               |
| RO      | ESPA2, ESPAB, and LFC3 made from polyamide thin-film composite                    | N-nitrosodimethylamine              | 80%                                   | (Fujioka et al., 2020)              |
| FO      | Polyamide thin film composite and polysulfone (PS)                                | 24 ECs                             | > 93 %                                | (Salamanca et al., 2021)            |
| FO      | thin film composite membrane with aquaporin proteins embedded in a polyamide active layer supported by a porous polysulfone support layer | 21 ECs                             | > 80%                                 | (Li et al., 2021)                   |
| FO      | thin-film composite membrane with aquaporin protein embedded in the polyamide layer | N-nitrosodimethylamine (NDMA) and haloacetonitriles (HANS) | NDMA (31%), HANSs (48–76%)           | (Xu et al., 2018)                   |
| FOMBR   | cellulose triacetate                                                              | Ibuprofen                          | 96.32%                                | (Yao et al., 2021)                  |
| FO      | commercial cellulose triacetate (CTA) based membranes and thin-film composite (TFC) polyamide-based membranes | Carbamazepine, diclofenac, ibuprofen and naproxen | naproxen (93%), Diclofenac (99%), ibuprofen (93%), carbamazepine (95%). | (Jin et al., 2012)                  |

Ferreiro et al. (2020) studied ECs removals in WWTP using the biological treatment, followed by UF as the tertiary treatment. The removals of 39 types of ECs using UF were ≤ 30%, except for amitriptyline (63.0%). UF showed good performance in other studies on phenol, atenolol, ciprofloxacin, amoxilne, and sulfamethoxazole removals (Bhattacharya et al., 2019, 2020; Ali et al., 2021; Shakak et al., 2020).

Yangali-Quintanilla et al. (2011) compared NF and RO to remove 18 types of ECs. They found that the average removal efficiencies of neutral and ionic contaminants by NF were

DOI: http://dx.doi.org/10.xxxxx/ijost.vXIX
p- ISSN 2528-1410 e- ISSN 2527-8045
82 and 97%, respectively. Meanwhile, average removal efficiencies by RO were 85 and 99%, respectively.

5. HYBRID SYSTEMS

Various treatment technologies (i.e., biological, physical, chemical treatments) have been investigated for ECs removal and showed good performance. However, hybrid systems have been developed due to challenges and limitations of each technology (e.g., contaminant sludge disposal, high retention time, high cost, limited removals of a wide range of ECs) (Dhangar & Kumar, 2020). Recently, studies of various hybrid systems for ECs removal have increased significantly (Ahmed et al., 2017). One of the hybrid systems is adsorption/membrane filtration-based technologies. This hybrid system has some advantages: rapid kinetic, low pressure-drop, better separation efficiency, easier control and handling, lower discharge volume, higher reusability, lower fouling rate (in some cases), and low-energy footprint, lower discharge volume, higher reusability, and lower process cost, and potential use as biosorbents. In this section, an overview of the hybrid system involving adsorption or/and membrane is provided.

5.1. Adsorption-Based Hybrid Systems

Adsorption can be combined with biological treatments (e.g., activated sludge, MBR), chemical treatments (e.g., photo Fenton oxidation, ozonation), and other physical treatments (e.g., membrane filtration). Table 7 shows a summary of various adsorption-based hybrid systems for ECs removal.

Tagliavini & Schäfer, (2018) evaluated polymer-based activated carbon adsorption+UF/NF for steroid removals. They compared adsorption+UF and adsorption+NF. The result showed that the role of adsorption in the adsorption+NF hybrid system was not significant. Nonetheless, the adsorption+UF hybrid system showed more potential due to its higher permeability and good performance, with a removal efficiency of > 90%.

Granzoto et al., (2021) investigated ECs removals (i.e., phosphate, tri-n-butyl phosphate, tris (chloropropyl), triphenyl phosphate) by using a hybrid system. It combined adsorption (granulated activated carbon (GAC)) and ozonation (O₃)/ UV-H₂O₂. They evaluated different configurations, namely UV/H₂O₂+GAC+UV/H₂O₂; O₃+GAC+O₃; UV/H₂O₂+GAC+O₃; O₃+GAC+UV/H₂O₂. The performance of the O₃+GAC+O₃ configuration showed a good result and was found to be cost-effective. This configuration could remove the ECs almost entirely with the removals from various units as follow: the first O₃ treatment (15%), GAC treatment (80%), and last O₃ treatment (100%).

Dwivedi et al., (2018) assessed a hybrid system combining Fenton and GAC to treat carbamazepine in raw wastewater. The process was optimized by Response Surface Methodology tools and found the optimum condition of Fenton pretreatment with the concentration of H₂O₂ (8.5 g/L) and pH (3.5). The maximum removal was 99.51 ±0.02%. This result was higher than the standalone Fenton treatment (with the removal of merely 49.39%).

Ferrer-Polonio et al., (2020) assessed a hybrid system consisting of adsorption (activated carbon) and biological (activated sludge) treatments. The targeted ECs were caffeine, ibuprofen, and acetaminophen. The adsorption process was effective for acetaminophen removal but not for caffeine and ibuprofen. The hybrid system of activated sludge + activated carbon could altogether remove the targeted ECs in 35 days.
Table 7. Application of adsorption-based hybrid systems for ECs removal.

| Hybrid system | ECs (E2) | Removal efficiency | Reference |
|---------------|----------|--------------------|-----------|
| polymer-based activated carbon adsorption with UF/NF | Deuterated surrogate standard tris (phenyl) phosphate-D15 (TPHP-D15), Tri-n-butyl phosphate (TNBP), tris (chloropropyl) phosphate (TCIPP), triphenyl phosphate (TPHP) | > 90%. | (Tagliavini & Schäfer, 2018) |
| Ozone+ Granulated activated carbon (GAC) | Estradiol (E2) | 100% | (Granzoto et al., 2021) |
| Fenton pretreatment + granulated activated carbon (GAC) | Carbamazepine (CBZ) | 99.51 ±0.02% | (Dwivedi et al., 2018) |
| Electrochemical+ Adsorption (granular activated carbon (GAC)) | Iopromide (IPM), carbamazepine (CBZ), diatrizoate (DTR), DEET | DEET (40-57%), iopromide (22-46%), carbamazepine (15-34%) and diatrizoate (4-30%) | (Norra & Radjenovic, 2021) |
| sequencing batch reactor (SBR) + powdered composite adsorbent (CA) | Atenolol (ATN), ciprofloxacin (CIP) and diazepam (DIA) | DIA (95.5%), CIP (94.0%), ATN (90.2%) | (Mojiri et al., 2020) |
| adsorption/photo Fenton oxidation+ Microbial Fuel Cell | Fumaric acid, succinic acid | 40.8% | (Civan et al., 2021) |
| active carbon felt (ACF)+ electro-Fenton (EF) | Tetracycline | > 90% | (Zhang et al., 2018) |
| Ozonation + activated carbon adsorption | 28 ECs | 80% | (Guillossou et al., 2020) |

Based on results summarized in Table 7, an adsorption-based hybrid system offered better performances than single systems. The combination between adsorption and biological/physical/chemical treatments shows higher removal efficiencies than a single system. The range of removal efficiency is quite diverse depending on the type of ECs and the treatment processes.

5.2. Membrane Filtration-Based Hybrid System

The applications of membrane filtration-based hybrid systems for ECs removal are shown in Table 8. Pathak et al., (2018) assessed a combination of osmotic membrane bioreactor (OMBR) with MF to remove atenolol, caffeine, and atrazine. MF was required to solve the salt accumulation problems due to rejection by the FO, acting as the purging system. The process worked under oxic-anoxic conditions, and the performance was quite diverse for each targeted ECs. The highest removal was obtained for caffeine (94-100%), followed by atenolol (89-96%) and atrazine (16-40%). Atrazine removal was related to redox and microbial condition on the system.

Martinez et al., (2013) removed ECs (i.e., nicotine, hydrochlorothiazide 4-acetamido antipyrine, sulfamethoxazole, ranitidine hydrochloride, nicotine) by a combination of photocatalytic oxidation and membrane filtration. The photocatalytic oxidation
process was facilitated by the TiO$_2$ photocatalysis and Fe$_2$O$_3$/SBA-15 in H$_2$O$_2$ photo-Fenton. The membrane types were RO and NF. NF membrane showed a better choice for the hybrid system than the RO due to its lower energy footprint and higher flux while still offering good EC rejection. TiO$_2$ photocatalysis and Fe$_2$O$_3$/SBA-15 in H$_2$O$_2$ photo-Fenton showed ECs removal of 80-100%. Among all targeted ECs, nicotine has the lowest removal efficiency. However, Fe$_2$O$_3$/SBA-15 in H$_2$O$_2$ photo-Fenton showed better performance on nicotine removal than the TiO$_2$ photocatalysis system.

Chen et al., (2019) assessed the hybrid process between UF and magnetic ion exchange resin (MIEX) for carbamazepine removal. This hybrid system exploited the UF advantage of turbidity treatment and MIEX advantage in EC removal. MIEX was used as pre-treatment. The system could reduce the secondary contaminant of resin and increase the membrane lifespan.

The removal efficiencies of this system were 25-79%, depending on the water turbidity. Data in Table 8 suggest that membrane filtration-based hybrid systems offered a wide range of ECs removals. Some of them can achieve complete removal, while only achieved as low as 16%.

### 5.3. Membrane Filtration / Adsorption Hybrid Process

Membrane filtration and adsorption can be combined in many configurations. They include adsorption pre-treatment, integrated adsorption/membrane systems (IAMPs), and adsorption post-treatment. The integrated adsorption/membrane process can be done through (1) a low-pressure membrane combined with adsorption, (2) membrane adsorption bioreactor, and (3) membrane adsorption. Several studies assessed the performance of those configurations for ECs removal.

Wang et al., (2020) conducted the experiments on a hybrid system of NF/UF+adsorption, in which PAC was used for the pre-treatment to ease the membrane fouling. The result showed that PAC pre-treatment could reduce membrane fouling caused by organic foulant in UF and NF membranes.

### Table 8. Application of membrane filtration-based hybrid system for ECs removal.

| Hybrid system                                           | ECs                                                                 | Removal efficiency | Reference                     |
|---------------------------------------------------------|----------------------------------------------------------------------|--------------------|--------------------------------|
| Osmotic membrane bioreactor + microfiltration           | Caffein, atenolol, and atrazine                                       | Atenolol (89–96%), Caffeine (94–100%), Atrazine (16–40%) | (Pathak et al., 2018)          |
| Nanofiltration + TiO$_2$ and Fe$_2$O$_3$/SBA-15 photo-Fenton | Sulfamethoxazole, diclofenac, hydrochlorothiazide 4-acetamidoantipyrine, nicotine, ranitidine hydrochloride carbamazepine (CBZ) | 80-100%            | (Martínez et al., 2013)       |
| magnetic ion exchange resin + UF                        | clofibricacid(CA), bisphenolA(BPA), benzotriazole(BTZ)               | 38%                | (Lee et al., 2019)            |
| Catalytic ozonation + membrane filtration (catalytic ceramic membranes, CCMs) | ibuprofen, 17α-ethinyl estradiol oxytetracycline                      | 53.2%              | (Kim et al., 2020)            |
| metal-organic frameworks + UF                           |                                                                      | 49%                | (Espíndola et al., 2019)      |
| advanced oxidation processes + UF                       |                                                                      |                    |                                |
Huang et al., (2019) investigated a combination between activated carbon adsorption and NF to remove octyl phenol, diclofenac, and caffeine by involving coagulation as the pre-treatment. They compared the performances between adsorption+NF and NF+adsorption configurations. The result shows the hybrid system performance is better than the single systems. The adsorption+NF had better performance than the NF+adsorption configuration with removals of targeted ECs of ≥ 95%.

Ivancev-tumbas & Hobby (2010) assessed the adsorption+UF system for carbamazepine and p-nitrophenol removals by employing the integrated configuration. They compared three types of adsorbents with different properties. The found the best adsorbent was the one with the smallest particle size. The removal efficiency was influenced by the density and the particle size of the adsorbent. The presence of coagulant improved the removal efficiency of the treatment system. The maximum removals of carbamazepine and p-nitrophenol were 40.0 and 30.7%, respectively.

5.4. Application of Hybrid System Combining Membrane Filtration and Adsorption for Emerging Contaminants Removal

The application of the hybrid system for ECs removal has great attention because it combines the advantages of each technology. There are several configurations of hybrid adsorption-membrane filtration (AD+M), as summarized in Table 9. Most of ECs treated by AD+M hybrid system were pharmaceuticals. The common adsorbent and membrane processes were activated carbon and UF, respectively. Generally, the processes were applied with pressure and stirring under various adsorbent loadings. The removal efficiencies were quite diverse, depending on ECs, adsorbent characteristics, membrane properties, operating conditions, and the process configurations.

Sharma et al., (2017) investigated M+AD for antibiotic removals. The hybrid system used the adsorption pre-treatment followed by the membrane filtration. The adsorbent was synthesized through co-precipitation resulting in modified layered adsorbent material. The membrane material was a low-cost MF ceramic with an average pore size of 1 µm and a porosity of 47%. The result showed that the optimum conditions were pH (7), ECs concentration (of 10 mg/L), and adsorbent dosage (1 g/L). This system could achieve the removal efficiency of 98.7% for norfloxacin and 94.6% for ofloxacin. PH conditions highly influenced the performance.

Sheng et al., (2016) compared adsorption and coagulation as the pre-treatment of UF. It was used to remove 16 ECs, namely bezafibrate, acetaminophen, gemfibrozil, sulfamethazine, triclosan, naproxen, acetaminophen, sulfamethoxazole, cotinine, caffeine, diclofenac, ibuprofen, metoprolol, sulfadimethoxine, trimethoprim, and carbamazepine. These ECs were collected from many WWTPs in the USA. The adsorbent was the PAC, and the coagulant was poly-aluminum chloride. The result showed that the hybrid systems (adsorption+UF and coagulation+UF) had better performances than the single systems (adsorption, coagulation, or UF only). Adsorption has better performance than coagulation pre-treatment. The average removal efficiencies of coagulation, UF, adsorption, coagulation+UF, and adsorption+UF systems were 7, 29, 50, 33, and 90.3%, respectively. These results showed that the hybrid system combining adsorption and UF, in which adsorption acted as the pre-treatment, had an excellent prospect for ECs removal.
Table 9. Application of hybrid system combining membrane filtration and adsorption for ECs removal.

| ECs                                                                 | Adsorbent                                      | Membrane                        | Operating condition of adsorbent | Operating condition of the membrane | Removal efficiency | References          |
|---------------------------------------------------------------------|------------------------------------------------|---------------------------------|----------------------------------|-------------------------------------|--------------------|---------------------|
| Ofloxacin (OFL), norfloxacin (NOR)                                  | Ni-Al layered double hydroxide (LDH)           | MF (ceramic membrane)           | Adsorbent dose = 0.1 g antibiotic concentration 10 mg/L | Pressure = 34.47–172.36 kPa. transmembrane pressure= 100 psi; cross flow velocity= 0.27 mg/s. stirring speed (300 rpm), trans membrane pressure (520 kPa (75 psi) | NOR (98.7%), OFL (94.6%) | (Sharma et al., 2017) |
| Octylphenol, caffeine, diclofenac,                                  | Activated carbon F400                          | NF-270                          | Adsorbent dose = 10 mg/L          |                                     | > 95%               | (Huang et al., 2019a)|
| Ibuprofen (IBP), carbamazepine (CBM), 17 α-ethinyl estradiol (EE2) | Activated biochar                              | A commercial flat sheet polyamide UF membrane | Adsorbent dose = 10 mg/L initial concentration of ECs= 10 Mm. | Pressure = 6.9×10³ kPa (1000 Psi). maximum flow rate is 22.7 L/min | 45.2%              | (Kim et al., 2019)  |
| Bezafibrate, Gemfibrozil, Sulfamethazine, Naproxen, Sulfamethoxazole, Caffeine, Diclofenac, Ibuprofen, Metoprolol, Sulfadimethoxine, Sulfathiazole, Triclosan, Trimethoprim, Acetaminophen, Carbamazepine, Cotinine, Sulphametoxazol, Carbamazepine, Diclofenac, Diuron, Erythromycin | Powdered activated carbon                      | UF membrane with MWCO 100 kDa  | Adsorbent dosage = 100 ppm. Configuration: adsorption pre-treatment |                                     | 90.3%              | (Sheng et al., 2016) |
| Phenol                                                             | Cross-linked macronet polymer adsorbents       | UF with tight poly-ether sulfone | Adsorbent dose = 20 mg/l          | Feed pump pressure regulates permeate low | > 81±13%           | (Echevarría et al., 2020)|
|                                                                    |                                                |                                  |                                   | The flow rate = 4 L/min            | 90%                | (İpek et al., 2012)  |
Table 9 (Continue). Application of hybrid system combining membrane filtration and adsorption for ECs removal.

| ECs                                                                 | Adsorbent               | Membrane                        | Operating condition of adsorbent | Operating condition of the membrane | Removal efficiency | References                                      |
|----------------------------------------------------------------------|-------------------------|----------------------------------|----------------------------------|-------------------------------------|--------------------|------------------------------------------------|
| Octyl-phenol, diclofenac, caffeine                                    | Activated carbon        | NF-270                           | Adsorbent dosage = 10 mg/L       | Trans membrane pressure (100 psi); crossflow velocity (0.27m/s) | >95%               | (Huang et al., 2019)                           |
| Carbamazepine, p-nitrophenol                                         | Powdered activated carbon | UF membrane (non-ionic hydrophilic membrane) | Adsorbent dosage for p-nitrophenol removal= 5 or 10 mg/L Adsorbent dosage for carbamazepine removal is 0.3 mg/L | Flux = 20 L/m2/h Pressure = 10 bar | Carbamazepine (40%) and p-nitrophenol (30.7%) | (Ivancev-tumbas & Hobby, 2010)                  |
| Phenol                                                               | Hypercrosslinked macronet polymer (Purolite MN 202 and MN 200) | UF                               | Adsorbent dosage for purolite MN 202 and MN 200 is 0.2 g/50mL solution and 0.1 g/50 ml solution, respectively . Stirring = 250 rpm | Air flow rate = 4 L/min | 90%                | (Ipek et al., 2012)                           |
| Naproxen, triclosan, paracetamol, amitriptyline, clozapine, caffeine, verapamil, DEET, gemfibrozil, sulfamethoxazole, atenolol, ketoprofen, simazine, trimethoprim, fluoxetine, primidone, triclocarbon, carbamazepine, diclofenac | Granular activated carbon | MF                               | Adsorbent dosage = 10 mg/L with replacement of 10%/day | Flux: 10 L/m2 | 80%                | (Shanmuganathan et al., 2017)                  |
Shanmuganathan et al., (2017) investigated a combination of submerged membrane filtration-adsorption (M+AD) for removals of 19 ECs. They were naproxen, triclosan, paracetamol, amitriptyline, clozapine, caffeine, verapamil, DEET, gemfibrozil, sulfamethoxazole, atenolol, ketoprofen, simazine, trimethoprim, fluoxetine, primidone, triclocarban, carbamazepine, and diclofenac. These ECs were obtained from RO concentrate of water reclamation plant in Australia. The membrane-type was hydrophilic polyacrylonitrile MF. The adsorbent was GAC with a size of 300–600 μm. Most ECs were removed with a removal efficiency of 80% on day 1, except for sulfamethoxazole and DEET. The excellent performance was attributed to the electrostatic interaction between hydrophobic or neutral/positive charge ECs with the negative charge of GAC.

Generally, a combination between adsorption and membrane filtration shows high removal efficiency. However, some investigations still showed unsatisfied removal efficiencies of <50%. Further studies are still required to unravel the ECs removal mechanism and the most ideal process layout, including strategies for scale-up.

6. CONCLUSION

ECs need to be removed due to their potential adverse effects on the environment, human health, and other organisms. There are several available treatment technologies for ECs removal classified into physical, biological, and chemical treatments. Adsorption and membrane filtration are physical treatments that can be used for ECs removal as a single/standalone or in hybrid systems. As a single system, adsorption or membrane filtration had shown diverse removal efficiencies. Adsorption or membrane filtration can also be combined with various other technologies. Hybrid systems are of great interest due to their potential to overcome the shortcomings of standalone technology. The combinations between adsorption and membrane filtration have been done in three configurations: adsorption as the pre-treatment, integrated adsorption/membrane filtration, and adsorption as the post-treatment. Most of the hybrid systems offered better performance than the standalone systems due to the synergistic effects. However, further investigations are needed to assess the large-scale application and remove a wide range of ECs.

7. ACKNOWLEDGMENTS

The authors would like to thank for the financial support of Universiti Brunei Darussalam Graduate Scholarship (UGS).

8. AUTHORS’ NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.
9. REFERENCES

Agüera, A., Martínez Bueno, M. J., and Fernández-Alba, A. R. (2013). New trends in the analytical determination of emerging contaminants and their transformation products in environmental waters. *Environmental Science and Pollution Research, 20*(6), 3496–3515.

Ahmaruzzaman, M. (2011). Industrial wastes as low-cost potential adsorbents for the treatment of wastewater laden with heavy metals. *Advances in Colloid and Interface Science, 166*(1–2), 36–59.

Ahmed, M. B., Zhou, J. L., Ngo, H. H., and Guo, W. (2015). Adsorptive removal of antibiotics from water and wastewater: Progress and challenges. *Science of the Total Environment, 532*, 112–126.

Ahmed, M. B., Zhou, J. L., Ngo, H. H., Guo, W., Thomaidis, N. S., and Xu, J. (2017). Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: A critical review. *Journal of Hazardous Materials, 323*, 274–298.

Ahmed, S. F., Mofijur, M., Nuzhat, S., Chowdhury, A. T., Rafa, N., Uddin, M. A., Inayat, A., Mahlia, T. M. I., Ong, H. C., Chia, W. Y., and Show, P. L. (2021). Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater. *Journal of Hazardous Materials, 416*(March), 125912.

Ali, J. K., Chabib, C. M., Abi Jaoude, M., Alhseinat, E., Teotia, S., Patole, S., Anjum, D.H., and Qattan, I. (2021). Enhanced removal of aqueous phenol with polyimide ultrafiltration membranes embedded with deep eutectic solvent-coated nanosilica. *Chemical Engineering Journal, 408*, 128017.

Alonso, J. J. S., El Kori, N., Melián-Martel, N., and Del Río-Gamero, B. (2018). Removal of ciprofloxacin from seawater by reverse osmosis. *Journal of Environmental Management, 217*, 337–345.

Anh, H. Q., Le, T. P. Q., Da Le, N., Lu, X. X., Duong, T. T., Garnier, J., Rochelle-Newall, E., Zhang, S., Oh, N.-H., Oeurng, C., Ekkaawatpanit, C., Nguyen, T. D., Nguyen, Q. T., Nguyen, T. D., Nguyen, T. N., Tran, T. L., Kunisue, T., Tanoue, R., Takahashi, S., and Nguyen, T. A. H. (2020). Antibiotics in surface water of East and Southeast Asian countries: A focused review on contamination status, pollution sources, potential risks, and future perspectives. *Science of The Total Environment, 764*, 142865.

Antonelli, R., Malpass, G. R. P., Da Silva, M. G. C., and Vieira, M. G. A. (2020). Adsorption of ciprofloxacin onto thermally modified bentonite clay: Experimental design, characterization, and adsorbent regeneration. *Journal of Environmental Chemical Engineering, 8*(6), 104553.

Arguello-Pérez, M. Á., Mendoza-Pérez, J. A., Tintos-Gómez, A., Ramírez-Ayala, E., Godínez-Domínguez, E., and Silva-Bátiz, F. D. A. (2019). Ecotoxicological analysis of emerging contaminants from wastewater discharges in the coastal zone of cihuatlán (Jalisco, Mexico). *Water, 11*(7), 1386.
Bankole, P. O., Adekunle, A. A., Jeon, B. H., and Govindwar, S. P. (2020). Novel cobiomass degradation of NSAIDs by two wood rot fungi, Ganoderma applanatum and Laetiporus sulphureus: Ligninolytic enzymes induction, isotherm and kinetic studies. *Ecotoxicology and Environmental Safety, 203*(May), 110997.

Basheer, A. A. (2018). New generation nano-adsorbents for the removal of emerging contaminants in water. *Journal of Molecular Liquids, 261*, 583–593.

Bhattacharya, P., Mukherjee, D., Deb, N., Swarnakar, S., and Banerjee, S. (2020). Application of green synthesized ZnO nanoparticle coated ceramic ultrafiltration membrane for remediation of pharmaceutical components from synthetic water: Reusability assay of treated water on seed germination. *Journal of Environmental Chemical Engineering, 8*(3), 103803.

Bhattacharya, P., Mukherjee, D., Dey, S., Ghosh, S., and Banerjee, S. (2019). Development and performance evaluation of a novel CuO/TiO₂ ceramic ultrafiltration membrane for ciprofloxacin removal. *Materials Chemistry and Physics, 229*(February), 106–116.

Bokhary, A., Tikka, A., Leitch, M., and Liao, B. (2018). Membrane fouling prevention and control strategies in pulp and paper industry applications: A review. *Journal of Membrane Science and Research, 4*(4), 181–197.

Bolong, N., Ismail, A. F., Salim, M. R., and Matsuura, T. (2009). A review of the effects of emerging contaminants in wastewater and options for their removal. *Desalination, 239*(1–3), 229–246.

Bueno, M. M., Ulaszewska, M. M., Gomez, M. J., Hernando, M. D., and Fernández-Alba, A. R. (2012). Simultaneous measurement in mass and mass/mass mode for accurate qualitative and quantitative screening analysis of pharmaceuticals in river water. *Journal of Chromatography A, 1256*, 80–88.

Chen, Y., Xu, W., Zhu, H., Wei, D., He, F., Wang, D., Du, B., and Wei, Q. (2019). Effect of turbidity on micropollutant removal and membrane fouling by MIEX/ultrafiltration hybrid process. *Chemosphere, 216*, 488–498.

Cheng, N., Wang, B., Wu, P., Lee, X., Xing, Y., Chen, M., and Gao, B. (2021). Adsorption of emerging contaminants from water and wastewater by modified biochar: A review. *Environmental Pollution, 273*(January), 116448.

Civan, G., Palas, B., Ersöz, G., Atalay, S., Bavasso, I., and Di Palma, L. (2021). Experimental assessment of a hybrid process including adsorption/photo Fenton oxidation and Microbial Fuel Cell for the removal of dicarboxylic acids from aqueous solution. *Journal of Photochemistry and Photobiology A: Chemistry, 407*(October), 1–8.

Couto, C. F., Lange, L. C., and Amaral, M. C. S. (2018). A critical review on membrane separation processes applied to remove pharmaceutically active compounds from water and wastewater. *Journal of Water Process Engineering, 26*, 156-175.

Dai, J., Meng, X., Zhang, Y., and Huang, Y. (2020). Effects of modification and magnetization of rice straw derived biochar on adsorption of tetracycline from water. *Bioresource Technology, 311*(December), 123455.

Dai, Y., Sun, Q., Wang, W., Lu, L., Liu, M., Li, J., Yang, S., Sun, Y., Zhang, K., Xu, J., Zheng, W., Hu, Z., Yang, Y., Gao, Y., Chen, Y., Zhang, X., Gao, F., and Zhang, Y. (2018). Utilizations of
agricultural waste as adsorbent for the removal of contaminants: A review. *Chemosphere, 211*, 235–253.

Dalecka, B., Oskarsson, C., Juhna, T., and Kuttava Rajarao, G. (2020). Isolation of fungal strains from municipal wastewater for the removal of pharmaceutical substances. *Water, 12*(2), 524.

De Souza, D. I., Dottein, E. M., Giacobbo, A., Siqueira Rodrigues, M. A., De Pinho, M. N., and Bernardes, A. M. (2018). Nanofiltration for the removal of norfloxacin from pharmaceutical effluent. *Journal of Environmental Chemical Engineering, 6*(5), 6147–6153.

Dhangar, K., and Kumar, M. (2020). Tricks and tracks in removal of emerging contaminants from the wastewater through hybrid treatment systems: A review. *Science of the Total Environment, 738*(336), 140320.

Diaz-Sosa, V. R., Tapia-Salazar, M., Wanner, J., and Cardenas-Chavez, D. L. (2020). Monitoring and ecotoxicity assessment of emerging contaminants in wastewater discharge in the City of Prague (Czech Republic). *Water, 12*(4), 1079.

Dolar, D., Gros, M., Rodriguez-Mozaz, S., Moreno, J., Comas, J., Rodriguez-Roda, I., and Barceló, D. (2012). Removal of emerging contaminants from municipal wastewater with an integrated membrane system, MBR–RO. *Journal of Hazardous Materials, 239*, 64–69.

Dotto, G. L., and McKay, G. (2020). Current scenario and challenges in adsorption for water treatment. *Journal of Environmental Chemical Engineering, 8*(4), 103988.

Dwivedi, K., Morone, A., Chakrabarti, T., and Pandey, R. A. (2018). Evaluation and optimization of Fenton pretreatment integrated with granulated activated carbon (GAC) filtration for carbamazepine removal from complex wastewater of pharmaceutical industry. *Journal of Environmental Chemical Engineering, 6*(3), 3681–3689.

Echevarría, C., Valderrama, C., Cortina, J. L., Martín, I., Arnaldos, M., Bernat, X., De la Cal, A., Boleda, M. R., Vega, A., Teuler, A., and Castellví, E. (2020). Hybrid sorption and pressure-driven membrane technologies for organic micropollutants removal in advanced water reclamation: A techno-economic assessment. *Journal of Cleaner Production, 273*, 123108.

Egea-Corbacho, A., Gutiérrez Ruiz, S., and Quiroga Alonso, J. M. (2019). Removal of emerging contaminants from wastewater using nanofiltration for its subsequent reuse: Full-scale pilot plant. *Journal of Cleaner Production, 214*, 514–523.

Espíndola, J. C., Szymański, K., Cristóvão, R. O., Mendes, A., Vilar, V. J., and Mozia, S. (2019). Performance of hybrid systems coupling advanced oxidation processes and ultrafiltration for oxytetracycline removal. *Catalysis Today, 328*, 274-280.

Fatta, D., Achilleos, A., Nikolaou, A., and Merić, S. (2007). Analytical methods for tracing pharmaceutical residues in water and wastewater. *TrAC - Trends in Analytical Chemistry, 26*(6), 515–533.

Ferreiro, C., Gómez-Motos, I., Lombraña, J. I., de Luis, A., Villota, N., Ros, O., and Etxebarria, N. (2020). Contaminants of emerging concern removal in an effluent of wastewater
Dewi et al., *Progress in Emerging Contaminants Removal by Adsorption/Membrane…* | 612

treatment plant under biological and continuous mode ultrafiltration treatment. *Sustainability, 12*(2), 725.

Ferrer-Polonio, E., Fernández-Navarro, J., Iborra-Clar, M. I., Alcaina-Miranda, M. I., and Mendoza-Roca, J. A. (2020). Removal of pharmaceutical compounds commonly-found in wastewater through a hybrid biological and adsorption process. *Journal of Environmental Management, 263*, 110368.

Fomina, M., and Gadd, G. M. (2014). Biosorption: Current perspectives on concept, definition and application. *Bioresource Technology, 160*(November), 3–14.

Fujioka, T., Osako, M., Oda, K., Shintani, T., and Kodamatani, H. (2020). Impact of heat modification conditions on the removal of N-nitrosodimethylamine by polyamide reverse osmosis membranes. *Separation and Purification Technology, 247*(February), 116921.

Gómez-Espinosa, R. M., and Arizmendi-Cotero, D. (2019). Role of Membrane on Emerging Contaminant Removal. *Handbook of Environmental Chemistry, 66*, 157–174.

Gopal, N., Asaithambi, M., Sivakumar, P., and Sivakumar, V. (2014). Adsorption studies of a direct dye using polyaniline coated activated carbon prepared from Prosopis juliflora. *Journal of Water Process Engineering, 2*, 87-95.

Granzoto, M. R., Seabra, I., Malvestiti, J. A., Cristale, J., and Dantas, R. F. (2021). Integration of ozone, UV/H2O2 and GAC in a multi-barrier treatment for secondary effluent polishing: Reuse parameters and micropollutants removal. *Science of the Total Environment, 759*, 143498.

Guillossou, R., Le Roux, J., Brosillon, S., Mailler, R., Vulliet, E., Morlay, C., Nauleau, F., Rocher, V., and Gaspéri, J. (2020). Benefits of ozonation before activated carbon adsorption for the removal of organic micropollutants from wastewater effluents. *Chemosphere, 245*, 125530.

Hammami, A., Charcosset, C., and Ben Amar, R. R. (2017). Performances of Continuous Adsorption-Ultrafiltration Hybrid Process for AO7 Dye Removal from Aqueous Solution and Real Textile Wastewater Treatment. *Journal of Membrane Science and Technology, 07*(01), 1–8.

Huang, Z., Gong, B., Huang, C. P., Pan, S. Y., Wu, P., Dang, Z., and Chiang, P. C. (2019). Performance evaluation of integrated adsorption-nanofiltration system for emerging compounds removal: exemplified by caffeine, diclofenac and octylphenol. *Journal of Environmental Management, 231*, 121-128.

Huang, Z., Gong, B., Huang, C., Pan, S., Wu, P., and Dang, Z. (2019a). Performance evaluation of integrated adsorption-nanofiltration system for emerging compounds removal: Exemplified by caffeine, diclofenac and octylphenol. *231*(October 2018), 121–128.

İpek, İ. Y., Kabay, N., Yüksel, M., Yapıcı, D., and Yüksel, Ü. (2012). Application of adsorption–ultrafiltration hybrid method for removal of phenol from water by hypercrosslinked polymer adsorbents. *Desalination, 306*, 24-28.

Ivancev-Tumbas, I., and Hobby, R. (2010). Removal of organic xenobiotics by combined out/in ultrafiltration and powdered activated carbon adsorption. *Desalination, 255*(1-3), 124-128.
Jin, X., Shan, J., Wang, C., Wei, J., and Tang, C. Y. (2012). Rejection of pharmaceuticals by forward osmosis membranes. *Journal of Hazardous Materials*, 227, 55-61.

Kamrani, M., Akbari, A., and Yunessnia lehi, A. (2018). Chitosan-modified acrylic nanofiltration membrane for efficient removal of pharmaceutical compounds. *Journal of Environmental Chemical Engineering*, 6(1), 583–587.

Kárászová, M., Bourassi, M., and Gaállová, J. (2020). Membrane removal of emerging contaminants from water: Which kind of membranes should we use?. *Membranes*, 10(11), 1–23.

Khajeh, M., Laurent, S., and Dastafkan, K. (2013). Nanoadsorbents: Classification, preparation, and applications (with emphasis on aqueous media). *Chemical Reviews*, 113(10), 7728–7768.

Khulbe, K. C., and Matsuura, T. (2018). Removal of heavy metals and pollutants by membrane adsorption techniques. *Applied Water Science*, 8(1), 1–30.

Kim, S., Chu, K. H., Al-Hamadani, Y. A. J., Park, C. M., Jang, M., Kim, D. H., Yu, M., Heo, J., and Yoon, Y. (2018). Removal of contaminants of emerging concern by membranes in water and wastewater: A review. *Chemical Engineering Journal*, 335(November 2017), 896–914.

Kim, S., Muñoz-Senmache, J. C., Jun, B. M., Park, C. M., Jang, A., Yu, M., Hernández-Maldonado, A. J., and Yoon, Y. (2020). A metal organic framework-ultrafiltration hybrid system for removing selected pharmaceuticals and natural organic matter. *Chemical Engineering Journal*, 382(July 2019), 122920.

Kim, S., Park, C. M., Jang, A., Jang, M., Hernández-Maldonado, A. J., Yu, M., Heo, J., and Yoon, Y. (2019). Removal of selected pharmaceuticals in an ultrafiltration-activated biochar hybrid system. *Journal of Membrane Science*, 570, 77–84.

Klamerth, N., Malato, S., Agüera, A., and Fernández-Alba, A. (2013). Photo-Fenton and modified photo-Fenton at neutral pH for the treatment of emerging contaminants in wastewater treatment plant effluents: A comparison. *Water Research*, 47(2), 833-840.

Kümmerer, K. (2011). Emerging Contaminants. *Treatise on Water Science*, 3, 69–87.

Lataye, D. H., Mishra, I. M., and Mall, I. D. (2008). Adsorption of 2-picoline onto bagasse fly ash from aqueous solution. *Chemical Engineering Journal*, 138(1–3), 35–46.

Lee, W. J., Bao, Y., Hu, X., and Lim, T. T. (2019). Hybrid catalytic ozonation-membrane filtration process with CeOx and MnOx impregnated catalytic ceramic membranes for micropollutants degradation. *Chemical Engineering Journal*, 378(May), 121670.

Lei, M., Zhang, L., Lei, J., Zong, L., Li, J., Wu, Z., and Wang, Z. (2015). Overview of emerging contaminants and associated human health effects. *BioMed Research International*, 2015, 1-12.

Li, R., Braekevelt, S., De Carfort, J. L. N., Hussain, S., Bollmann, U. E., and Bester, K. (2021). Laboratory and pilot evaluation of aquaporin-based forward osmosis membranes for rejection of micropollutants. *Water Research*, 194, 116924.
Lopera, A. E. C., Ruiz, S. G., and Alonso, J. M. Q. (2019). Removal of emerging contaminants from wastewater using reverse osmosis for its subsequent reuse: pilot plant. Journal of Water Process Engineering, 29, 100800.

Madhura, L., Kanchi, S., Sabela, M. I., Singh, S., Bisetty, K., and Inamuddin. (2018). Membrane technology for water purification. Environmental Chemistry Letters, 16(2), 343–365.

Mallek, M., Chtourou, M., Portillo, M., Monclús, H., Walha, K., Salah, A. ben, and Salvadó, V. (2018). Granulated cork as biosorbent for the removal of phenol derivatives and emerging contaminants. Journal of Environmental Management, 223(June), 576–585.

Martínez, F., López-Muñoz, M. J., Aguado, J., Melero, J. A., Arsuaga, J., Sotto, A., Molina, R., Segura, Y., Pariente, M. I., Revilla, A., Cerro, L., and Carenas, G. (2013). Coupling membrane separation and photocatalytic oxidation processes for the degradation of pharmaceutical pollutants. Water Research, 47(15), 5647–5658.

Mo, J., Yang, Q., Zhang, N., Zhang, W., Zheng, Y., and Zhang, Z. (2018). A review on agro-industrial waste (AIW) derived adsorbents for water and wastewater treatment. Journal of Environmental Management, 227(April), 395–405.

Mohammed, A. A., and Kareem, S. L. (2019). Adsorption of tetracycline from wastewater by using Pistachio shell coated with ZnO nanoparticles: Equilibrium, kinetic and isotherm studies. Alexandria Engineering Journal, 58(3), 917–928.

Mojiri, A., Zhou, J., Vakili, M., and Van Le, H. (2020). Removal performance and optimisation of pharmaceutical micropollutants from synthetic domestic wastewater by hybrid treatment. Journal of Contaminant Hydrology, 235(October), 103736.

Nguyen, T. H., Nguyen, T. T. L., Pham, T. D., and Le, T. S. (2020). Removal of lindane from aqueous solution using aluminum hydroxide nanoparticles with surface modification by anionic surfactant. Polymers, 12(4), 960.

Norra, G. F., and Radjenovic, J. (2021). Removal of persistent organic contaminants from wastewater using a hybrid electrochemical-granular activated carbon (GAC) system. Journal of Hazardous Materials, 415, 125557.

Oyehan, T. A., Olabemiwo, F. A., Tawabin, B. S., and Saleh, T. A. (2020). The capacity of mesoporous fly ash grafted with ultrathin film of polydiallyldimethyl ammonium for enhanced removal of phenol from aqueous solutions. Journal of Cleaner Production, 263, 121280.

Patel, M., Kumar, R., Kishor, K., Mlsna, T., Pittman, C. U., and Mohan, D. (2019). Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. Chemical Reviews, 119(6), 3510–3673.

Pathak, N., Li, S., Kim, Y., Chekli, L., Phuntsho, S., Jang, A., Ghaffour, N., Leiknes, T. O., and Shon, H. K. (2018). Assessing the removal of organic micropollutants by a novel baffled osmotic membrane bioreactor-microfiltration hybrid system. Bioresource Technology, 262(April), 98–106.

Patil, C. S., Gunjal, D. B., Naik, V. M., Harale, N. S., Jagadale, S. D., Kadam, A. N., Patil, P. S., Kolekar, G. B., and Gore, A. H. (2019). Waste tea residue as a low cost adsorbent for removal of hydralazine hydrochloride pharmaceutical pollutant from aqueous media: An environmental remediation. Journal of Cleaner Production, 206, 407–418.

DOI: http://dx.doi.org/10.xxxxx/ijost.vXIX
p- ISSN 2528-1410 e- ISSN 2527-8045
Peñafiel, M. E., Vanegas, E., Bermejo, D., Matesanz, J. M., and Ormad, M. P. (2019). Organic residues as adsorbent for the removal of ciprofloxacin from aqueous solution. *Hyperfine Interactions, 240*(1), 1-13.

Pendergast, M. M., and Hoek, E. M. V. (2011). A review of water treatment membrane nanotechnologies. *Energy and Environmental Science, 4*(6), 1946–1971.

Peralta, M. E., Martíre, D. O., Moreno, M. S., Parolo, M. E., and Carlos, L. (2021). Versatile nanoadsorbents based on magnetic mesostructured silica nanoparticles with tailored surface properties for organic pollutants removal. *Journal of Environmental Chemical Engineering, 9*(1), 104841.

Prasannamedha, G., Kumar, P. S., Mehala, R., Sharumitha, T. J., and Surendhar, D. (2021). Enhanced adsorptive removal of sulfamethoxazole from water using biochar derived from hydrothermal carbonization of sugarcane bagasse. *Journal of Hazardous Materials, 407*(November 2020), 124825.

Qiu, G., Chen, H., Raghavan, D. S. S., and Ting, Y. P. (2021). Removal behaviors of antibiotics in a hybrid microfiltration-forward osmotic membrane bioreactor for real municipal wastewater treatment. *Chemical Engineering Journal, 417*, 129146.

Qureshi, U. A., Hameed, B. H., and Ahmed, M. J. (2020). Adsorption of endocrine disrupting compounds and other emerging contaminants using lignocellulosic biomass-derived porous carbons: A review. *Journal of Water Process Engineering, 38*(March), 101380.

Rashed, M. N. (2013). Adsorption technique for the removal of organic pollutants from water and wastewater. *Organic Pollutants-Monitoring, Risk and Treatment, 7*, 167-194.

Rasheed, T., Bilal, M., Nabeel, F., Adeel, M., and Iqbal, H. M. N. (2019). Environmentally-related contaminants of high concern: Potential sources and analytical modalities for detection, quantification, and treatment. *Environment International, 122*(November 2018), 52–66.

Rodil, R., Quintana, J. B., Concha-Graña, E., López-Mahía, P., Muniategui-Lorenzo, S., and Prada-Rodríguez, D. (2012). Emerging pollutants in sewage, surface and drinking water in Galicia (NW Spain). *Chemosphere, 86*(10), 1040–1049.

Rodriguez-Narvaez, O. M., Peralta-Hernandez, J. M., Goonetilleke, A., and Bandala, E. R. (2017). Treatment technologies for emerging contaminants in water: A review. *Chemical Engineering Journal, 323*, 361–380.

Román, S., Nabais, J. M. V., Ledesma, B., Laginhas, C., and Titirici, M. M. (2020). Surface interactions during the removal of emerging contaminants by hydrochar-based adsorbents. *Molecules, 25*(9), 1–12.

Rosman, N., Norharyati Wan Salleh, W., Aqilah Mohd Razali, N., Nurain Ahmad, S. Z., Hafiza Ismail, N., Aziz, F., Harun, Z., Fauzi Ismail, A., and Yusof, N. (2020). Ibuprofen removal through photocatalytic filtration using antifouling PVDF- ZnO/Ag2CO3/Ag2O nanocomposite membrane. *Materials Today: Proceedings, 42*, 69-74.

Salamanca, M., López-Serna, R., Palacio, L., Hernández, A., Prádanos, P., and Peña, M. (2021). Study of the rejection of contaminants of emerging concern by a biomimetic aquaporin
hollow fiber forward osmosis membrane. *Journal of Water Process Engineering, 40*, 101914.

Shakak, M., Rezaee, R., Maleki, A., Jafari, A., Safari, M., Shahmoradi, B., Daraei, H., and Lee, S. M. (2020). Synthesis and characterization of nanocomposite ultrafiltration membrane (PSF/PVP/SiO2) and performance evaluation for the removal of amoxicillin from aqueous solutions. *Environmental Technology and Innovation, 17*, 100529.

Shamim, S. (2018). Biosorption of heavy metals. *Biosorption, 2*, 21-49.

Shamsuddin, N., Das, D. B., and Starov, V. M. (2016). Membrane-Based Point-Of-Use Water Treatment (PoUWT) System in Emergency Situations. *Separation and Purification Reviews, 45*(1), 50–67.

Shanmuganathan, S., Loganathan, P., Kazner, C., Johir, M. A. H., and Vigneswaran, S. (2017). Submerged membrane filtration adsorption hybrid system for the removal of organic micropollutants from a water reclamation plant reverse osmosis concentrate. *Desalination, 401*, 134–141.

Sharma, V., Vinoth Kumar, R., Pakshirajan, K., and Pugazhenth, G. (2017). Integrated adsorption-membrane filtration process for antibiotic removal from aqueous solution. *Powder Technology, 321*, 259–269.

Sheng, C., Nnanna, A. G. A., Liu, Y., and Vargo, J. D. (2016). Science of the Total Environment Removal of Trace Pharmaceuticals from Water using coagulation and powdered activated carbon as pretreatment to ultra filtration membrane system. *Science of the Total Environment, 550*, 1075–1083.

Shojaee Nasirabadi, P., Saljoughi, E., and Mousavi, S. M. (2016). Membrane processes used for removal of pharmaceuticals, hormones, endocrine disruptors and their metabolites from wastewaters: A review. *Desalination and Water Treatment, 57*(51), 24146–24175.

Singh, N. B., Nagpal, G., Agrawal, S., and Rachna. (2018). Water purification by using Adsorbents: A Review. *Environmental Technology and Innovation, 11*, 187–240.

Smital, T. (2008). Acute and chronic effects of emerging contaminants. *Water Pollution, 5*(March), 105–142.

Sophia A., C., and Lima, E. C. (2018). Removal of emerging contaminants from the environment by adsorption. *Ecotoxicology and Environmental Safety, 150*(June 2017), 1–17.

Sun, J., Chen, Z., Shen, J., Wang, B., Zhao, S., Wang, W., Zhu, X., Wang, Z., and Kang, J. (2021). Improvement of the fabricated and application of aluminosilicate-based microfiltration membrane. *Chemosphere, 273*, 129628.

Tagliavini, M., and Schäfer, A. I. (2018). Removal of steroid micropollutants by polymer-based spherical activated carbon (PBSAC) assisted membrane filtration. *Journal of Hazardous Materials, 353*(July 2017), 514–521.

Torrellas, S. Á., García Lovera, R., Escalona, N., Sepúlveda, C., Sotelo, J. L., and García, J. (2015). Chemical-activated carbons from peach stones for the adsorption of emerging contaminants in aqueous solutions. *Chemical Engineering Journal, 279*, 788–798.
Tran, N. H., Reinhard, M., and Gin, K. Y. H. (2018). Occurrence and fate of emerging contaminants in municipal wastewater treatment plants from different geographical regions—a review. *Water Research*, 133, 182-207.

Van der Bruggen, B., Mänttäri, M., and Nyström, M. (2008). Drawbacks of applying nanofiltration and how to avoid them: A review. *Separation and Purification Technology*, 63(2), 251–263.

Wang, Y., He, L., Dang, G., Li, H., and Li, X. (2021). Polypyrrole-functionalized magnetic Bi2MoO6 nanocomposites as a fast, efficient and reusable adsorbent for removal of ketoprofen and indomethacin from aqueous solution. *Journal of Colloid and Interface Science*, 592, 51-65.

Wang, Y., Zucker, I., Boo, C., and Elimelech, M. (2020). Removal of Emerging Wastewater Organic Contaminants by Polyelectrolyte Multilayer Nanofiltration Membranes with Tailored Selectivity. *ACS ES and T Engineering*, 1(3), 404-414.

Wiśniewska, M., and Nowicki, P. (2020). Peat-based activated carbons as adsorbents for simultaneous separation of organic molecules from mixed solution of poly(acrylic acid) polymer and sodium dodecyl sulfate surfactant. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 585(August 2019), 124179.

Xu, J., Tran, T. N., Lin, H., and Dai, N. (2018). Removal of disinfection byproducts in forward osmosis for wastewater recycling. *Journal of Membrane Science*, 564(March), 352–360.

Yangali-Quintanilla, V., Maeng, S. K., Fujioka, T., Kennedy, M., Li, Z., and Amy, G. (2011). Nanofiltration vs. reverse osmosis for the removal of emerging organic contaminants in water reuse. *Desalination and Water Treatment*, 34(1–3), 50–56.

Yao, M., Duan, L., Song, Y., and Hermanowicz, S. W. (2021). Degradation mechanism of Ibuprofen via a forward osmosis membrane bioreactor. *Bioresource Technology*, 321(November 2020), 124448.

Yousef, R. I., El-Eswed, B., and Al-Muhtaseb, A. H. (2011). Adsorption characteristics of natural zeolites as solid adsorbents for phenol removal from aqueous solutions: Kinetics, mechanism, and thermodynamics studies. *Chemical Engineering Journal*, 171(3), 1143–1149.

Yu, H., Gu, L., Chen, L., Wen, H., Zhang, D., and Tao, H. (2020a). Activation of grapefruit derived biochar by its peel extracts and its performance for tetracycline removal. *Bioresource Technology*, 316(July), 123971.

Yu, S., Gao, Y., Khan, R., Liang, P., Zhang, X., and Huang, X. (2020b). Electrospun PAN-based graphene/SnO2 carbon nanofibers as anodic electrocatalyst microfiltration membrane for sulfamethoxazole degradation. *Journal of Membrane Science*, 614, 118368.

Zhang, Y., Zuo, S., Zhou, M., Liang, L., and Ren, G. (2018). Removal of tetracycline by coupling of flow-through electro-Fenton and in-situ regenerative active carbon felt adsorption. *Chemical Engineering Journal*, 335(November 2017), 685–692.

Zhou, A., Chen, W., Liao, L., Xie, P., Zhang, T. C., Wu, X., and Feng, X. (2019a). Comparative adsorption of emerging contaminants in water by functional designed magnetic poly(N-
isopropylacrylamide)/chitosan hydrogels. *Science of the Total Environment, 671*, 377–387.

Zhou, S., Di Paolo, C., Wu, X., Shao, Y., Seiler, T. B., and Hollert, H. (2019b). Optimization of screening-level risk assessment and priority selection of emerging pollutants – The case of pharmaceuticals in European surface waters. *Environment International, 128*(April), 1–10.