Methods to alleviate the inhibition of sludge anaerobic digestion by emerging contaminants: a review

Ahmed Tawfik1 · Mohamed Mohsen2,3 · Sherif Ismail4,5 · Nawaf S. Alhajeri6 · Ahmed I. Osman7 · David W. Rooney7

Received: 7 April 2022 / Accepted: 27 May 2022 / Published online: 11 July 2022
© The Author(s) 2022

Abstract
The rising occurrence of emerging contaminants in sludges both inhibits the anaerobic digestion of sludges and induces health issues when sludges are recycled in agriculture, calling for methods to remove contaminants. Here we review emerging pollutants in wastewater treatment plants, before and after anaerobic digestion. We present their inhibitory effects and remediation methods to alleviate inhibition. Pharmaceuticals have been detected in about 50% of the sludge samples. Sewage sludge contaminants include 19% of diuretics, 16–21% of lipid-modifying agents, hydrochlorothiazide, diclofenac, furosemide, clarithromycin, atorvastatin, and carbamazepine. Levels of antibiotics, azithromycin, ciprofloxacin, and estrone range from 500 to 600 ng/g in sludges from wastewater treatment plants. Remediation methods comprise electrooxidation, ultrasound, thermal hydrolysis, ozonation, and bioaugmentation. Fermenting the sludges with acidogenic bacteria reduces the level of emerging pollutants in the supernatant. Nonetheless, liquid digestates still contains emerging pollutants such as sunscreen octocrylene at 147 ug/L and acetaminophen at 58.6 ug/L. As a result, pretreatment of sludge containing emerging pollutants is required.

Keywords Emerging pollutants · Sewage sludge · Anaerobic digestion · Valorization · Climate change

Introduction
Sewage sludge or biosolids are organic and inorganic compounds produced by the biological activity of microbes in wastewater treatment plants (Tawfik et al. 2012; Xie et al. 2022). The production of biosolids has grown in recent decades as a result of the use of aerobic methods in sewage treatment, such as the activated sludge process (Abdul et al. 2022b; Tawfik et al. 2022a). Anaerobic digestion has been increasingly accepted as a low-cost and sustainable treatment approach for sewage sludge stabilization, in which microorganisms break down the organic matter under anaerobic conditions (Zhao et al. 2021b; Abdul et al. 2022a). Sewage sludge is characterized by high organic matter and nutrient concentrations (Tawfik et al. 2006). Two byproducts of anaerobic digestion are produced: biogas and stabilized sewage sludge or biosolids, considered valuable resources under the circular economy concept (Tawfik et al. 2015).
Biogas produced from the anaerobic digestion of sewage sludge is considered a promising sustainable clean energy, representing a commercial value as renewable energy (Tawfik et al. 2021b). Likewise, stabilized sewage sludge is high in organics and nutrients that could be reused as biofertilizers in agricultural applications (Rawoof et al. 2021; Kani et al. 2022).

However, the anaerobic digestion process is driven by the high level of emerging pollutants that has lately increased due to increased human activity (Morin-Crini et al. 2022). There is currently no legislation governing the reuse of biosolids for agricultural applications, particularly those containing emerging contaminants (Petrice et al. 2015). Emerging pollutants, including pharmaceuticals, hormones, pesticides, and household and industrial chemicals, pose potential environmental and human health risks (Saravanan et al. 2021; Ahmad et al. 2022). Furthermore, emerging pollutants are known to impede the anaerobic digestion of sewage sludge, resulting in a decrease in biogas productivity (Tawfik and ElBatrawy 2012).

Pharmaceuticals are the most abundant emerging pollutants in wastewater because pharmaceuticals are widely and intensively used by humans and veterinarians in medicine (Tijani et al. 2016). Furthermore, several pharmaceuticals are used to promote the growth of fish and livestock farms (El-Gohary et al. 2010). Pharmaceuticals are easily metabolized into polar and soluble forms in the human body (Nikolaou et al. 2007). Therefore, these pharmaceuticals and their metabolites are mostly discharged into wastewater treatment plants via urine and feces (Bassuney and Tawfik 2017). Other emerging pollutants such as herbicides, insecticides, food additives, fungicides, preservatives, protective coatings, plasticizers, flame retardants, corrosion inhibitors, sunscreen agents, textiles, and microplastics may also enter wastewater treatment plants as a result of the unregulated discharge of these wastes into the sewage system. Some of these compounds could be removed from wastewater treatment plants by chemicals and biodegraded by biological treatment processes (Allam et al. 2016). The removal of emerging pollutants from the aqueous phase occurs, and emerging pollutants are mainly adsorbed onto the biosolids (Jones et al. 2005).

The presence of emerging pollutants in the sludge causes serious problems, notably in agricultural sectors, and these emerging pollutants also have a detrimental impact on the efficacy of the anaerobic digestion process; thus, sludge treatment and removal of emerging pollutants are high priorities (Jelic et al. 2011; Ahmad et al. 2022). The sludge produced by wastewater treatment facilities mostly comprises emerging contaminants that need to be eliminated prior to agriculture uses (Sena et al. 2010). Morales et al. (2016) investigated the fate of emerging pollutants in an anaerobic digester fed with sewage sludge and operated at an organic loading rate of 1.1–1.4 kg/m³·d and sludge residence time of 20 days. Sweeteners such as acesulfame, pesticides such as thiadiazoxide, and pharmaceuticals such as venlafaxine, carbamazepine, ibesartan, valsartan, diclofenac were detected in the aqueous and solid phase, while metabolites byproducts were also observed, i.e., salicylic acid, a metabolite of acetylsalicylic acid, and fenofibrate. Moreover, metabolites of 4-formyl aminoantipyrine, fenofibrate, 4-acetyl aminoantipyrine, 4-aminoantipyrine, and metabolites of dipyrene were highly detected in the solid phase. The adsorption of the emerging pollutants was the removal mechanism due to the presence of the emerging pollutants in the solid phase during the anaerobic digestion process.

Therefore, this review aims to provide a complete overview of sources and types of emerging pollutants that enter wastewater treatment facilities. The contents of such contaminants before and after the anaerobic digestion process and their inhibitory effects and mechanisms are assessed. In addition, the recent trends of mitigation approaches to tackle the inhibition effects of emerging pollutants on the anaerobic digestion of sewage sludge are also thoroughly discussed. We expect our work to contribute to the advancement of value-added byproducts from sludge-containing emerging pollutants and their commercial viability.

Emerging pollutants in wastewater

Wastewater treatment plants are typically designed to remove nitrogen, phosphorus, and chemical oxygen demand from wastewater (Ismail and Tawfik 2016; Ismail et al. 2021). As a result, the presence of emerging pollutants in the influent wastewater may impact the treatment processes and the quality of the treated effluent (Tyagi et al. 2021). The types and concentrations of emerging pollutants that could reach wastewater treatment plants vary according to the source, dose management, and persistent nature of the emerging pollutants (Tawfik et al. 2022b). Figure 1 depicts the path emerging contaminants take from their origins all the way to the environment.

Industrial wastewater

Industrialization has resulted in a significant deterioration in the integrity of the water resources as a result of unmanaged wastewater disposal from industrial operations such as mining, pharmaceuticals, and textile (Ali et al. 2017; Xie et al. 2022). Industrial activities contribute a range of inorganic and organic contaminants to water systems, altering the water quality upon which biological life relies (Azam and Tawfik 2015). The major pollutants in industrial water include pesticides, herbicides, petroleum, refinery, heavy metals, pharmaceuticals and personal care products due
to their toxicity and the presence of refractory compounds (Gar Alalm et al. 2017). Pharmaceuticals and personal care products are chemical substances utilized in personal care, medicinal items, and cosmetics (Gar Alalm et al. 2016). Pharmaceuticals include antibiotics, anticancer, antidiabetics, antiseptics, antimicrobials, antianxiety, anti-inflammatory and anticonvulsant medications, barbiturates, analgesics and lipid regulators (Nikolaou et al. 2007; Okuda et al. 2008; Bulloch et al. 2015; Chen et al. 2016; Archer et al. 2017). The major emerging contaminants that are released from pharmaceuticals are sulfamethazine, carbamazepine, diclofenac, caffeine, clofibric acid diclofenac, ibuprofen, ciprofloxacin, bisphenol A, metronidazole, metalaxyl, dimetridazole, diatrizoate, atenolol, tricyclazole, fluoxetine, carbofuran, bentazon, and iopamidol (Tijani et al. 2013; Zenker et al. 2014; Lin et al. 2015). Personal care industries produce an end-off pipe effluent rich in emerging contaminants, such as triclosan, benzophenones, ethylparaben, and methyl-dihydrojasmonate (Daughton and Ternes 1999; Snyder et al. 2003; Matamoros et al. 2007; Kasprzyk-Hordern et al. 2009).

Power plants generate the most toxic emerging pollutants, such as nitrogen and carbon, oxides of sulfur, formaldehyde, particulate matter, dioxins, furans, and heavy metals, e.g., mercury, copper, cadmium, lead, zinc, and chromium (Demirak et al. 2005; Rahman et al. 2020). Also, petroleum refineries industries cause severe pollution since these industries discharge effluent rich in benzene, acetone, phenol, nitrogen, and petroleum byproducts (Damian 2013). Electroplating factories and printed circuit boards discharge wastewater containing heavy metals, e.g., zinc, magnesium, calcium, potassium, and sodium (Sage and Schnitzer 1994; Gerić et al. 2017; Xiu et al. 2019; Chen et al. 2021). Furthermore, pesticide industry effluent contains high chemical oxygen demand and compounds such as phenols, halomethanes, and volatile aromatics (Bachmann Pinto et al. 2018; Lin et al. 2020), causing the wastewater to be highly contaminated and toxic (Zeyad et al. 2019). For paper mill and pulp industries, various toxic substances are generated, such as diterpene alcohols, resin acids, juvianones, unsaturated fatty acids and chlorinated resin acids (Pokhrel and Viraraghavan 2004; Kamali and Khodaparast 2015), which has the
potential to cause adverse effects to aquatic organisms (Ali and Sreekrishnan 2001).

Moreover, the textile industry generates wastewater high in colorants, salts, pH, temperature, dissolved solids, metals, and chemical oxygen demand (Sharma et al. 2007; Sekomo et al. 2012; Afanga et al. 2020). Additionally, the printing industry effluent containing nickel, lead, copper, and chromium as major contaminants lead to their accumulation in aquatic organisms (Kiurski et al. 2012; Papadopoulos et al. 2019; Safwat 2020). Both dyeing and textile printing wastewater contain a high amount of microfibers (Xu et al. 2018; Zhou et al. 2020b), defined as particles less than 5 mm in length. Such microfibers can be ingested by aquatic organisms and cause adverse biological effects (Mohsen et al. 2020; Rebelein et al. 2021). Microfibers are a type of microplastics that have been extensively detected in industrial wastewater. Microplastic abundance in industrial and municipal wastewater treatment plants ranged from 16,000 to 31,400 particles (Liu et al. 2021a). Table 1 summarizes the emerging pollutants contained in industrial effluents.

### Domestic wastewater

Domestic wastewater is released from human activities in households, industries, offices, institutions, and premises (Xu et al. 2022). This sewage contains organic and inorganic pollutants in a complex mixture composed primarily of around 99% water (Tawfik et al. 2008). Domestic wastewater is mainly the source of emerging pollutants, where most of the pharmaceuticals and personal care products are consumed by humans and reach the environment via urinating and defecation processes (Ismail and Tawfik 2017). According to metropolitan Melbourne’s water utilities, the major contaminants in sewage include color, total dissolved solids, mercury, cadmium, copper, arsenic, nickel, zinc, lead, and boron. Also, caffeine, acetaminophen, and paraxanthine are the most emerging contaminants in sewage (Rosal et al. 2010; Sophia and Lima 2018). Furthermore, naproxen, diclofenac, and ketoprofen were highly detected in sewage at concentrations of 4.2–7.2, 0.4–1.5, and 1.1–2.3 mg/L, respectively (Jelic et al. 2011).

Moreover, lipid modifying agents were detected at considerable amounts in the influent wastewater (i.e., 7–12% for fibrates, 8–10% for statins, and 5–9% for diuretics). The amounts of furosemide, atenolol, carbamazepine, and bezafibrate in sewage ranged from 0.4 to 1.4 mg/L. There were 35–44% non-steroidal anti-inflammatory drugs, 8–29% lipid-modifying compounds, and 17–30% psychiatric pharmaceuticals, e.g., benzodiazepine and antiepileptic derivative drugs, in the influent wastewater treatment facility in Spain (Jelic et al. 2011). The highest quantities of naproxen, carbamazepine, and diclofenac were found in wastewater at 0.4–1.0 mg/L (Table 2).

The discovery of microplastics as pervasive contaminants in the environment has sparked worldwide concern and led to extensive research on this topic. Numerous products in personal care and cosmetics include microplastics in their ingredients, such as toothpaste, scrubbers, and facial cleanser. For instance, polyethylene microbeads are applied in facial cleansers. An exfoliant might emit between 4,594 and 94,500 microbeads with a single use (Napper et al. 2015; Anderson et al. 2016; Hu et al. 2019). Urban areas generate a large amount of microplastics into wastewater treatment plants, which enter the environment due to the huge quantities of microplastics discharged from wastewater treatment plants (Talvitie et al. 2017). Recent research estimated that a single and medium-sized wastewater treatment plant with a flow rate of 30–50,000 m³/day might emit up to 1.8·10¹⁰ microplastics/day (Leslie et al. 2017; Ben-David et al. 2021). Table 2 lists the most significant emerging pollutants found in the household or domestic wastewater.

### Animal farming waste

Animal waste dumping in water pollutes the receiving water bodies and contributes to the spread of water-borne diseases, resulting in a scarcity of safe drinking water (Tawfik et al. 2021a). For instance, the pollution of water by cattle excrement caused several deaths in the Canadian community of Walkerton (Singh and Rashid 2017). The runoff of animal wastes is a major potential source of decomposable organic matter, nutrients, antibiotics, and hormones (Al Salah et al. 2019). Antibiotics, which are used to prevent or cure animal illnesses, and steroid hormones, which are used to fatten farmed animals, are considered emerging pollutants (Senarathna et al. 2021). Furthermore, the excessive quantity of animal waste fertilizing could leach high nitrogen content and runoff into the surface and groundwater, contaminating both animal and human drinking water sources with excessive concentrations of nitrates (Sahoo et al. 2016). As shown in Table 3, the principal components of emerging pollutants in animal farming wastewater are hormones and antibiotics. Additionally, Fig. 2 illustrates the sources of emerging pollutants in the environment and their associated kinds. In summary, the separation of animal farming waste for treatment prior to reuse in agriculture is needed to avoid the accumulation of hormones and antibiotics.

### Removal of emerging contaminants in wastewater treatment plants

Emergent contaminants, such as dissolved organics, colloidal and suspended particulates, pathogens, and nutrients, are removed with 20–50% efficiency during primary treatment. Those contaminants are further removed by 30–70%
Table 1  Majority of emerging pollutants presented in industrial wastewater. Pesticides and herbicides are the most emerging contaminants. The insecticides are the lowest. Food additives, fungicides, preservatives, protective coatings, plasticizers, flame retardants, corrosion inhibitors, sunscreen agents, and textile are detected in the end-off pipe effluent. Microfibers are presented in textile wastewater

| Industry            | Emerging contaminants | References                                                                 |
|---------------------|-----------------------|-----------------------------------------------------------------------------|
| Pesticides          | 2,4-dichloroaniline   | Birch et al. (2015), Thompson et al. (2021)                                |
|                     | 3,4 dichloroaniline   |                                                                             |
|                     | Aldrin                | Hirooka et al. (2006), Buttiglieri and Knepper (2008)                      |
|                     | Atrazine              |                                                                             |
|                     | Bentazone             |                                                                             |
|                     | Carbaryl              | Häggblom et al. (2003), Birch et al. (2015)                                |
|                     | Chlorpyrifos-methyl   | Baun et al. (2004), Smital et al. (2004)                                   |
|                     | Desethylatrazine      | Buttiglieri and Knepper (2008)                                             |
|                     | Diazinon              | Smital et al. (2004)                                                       |
|                     | Dichlobenil           | Buttiglieri and Knepper (2008)                                             |
|                     | Dichlorvos            | Smital et al. (2004)                                                       |
|                     | Dieldrin              | Buttiglieri and Knepper (2008)                                             |
|                     | Dimethoate            | Smital et al. (2004)                                                       |
|                     | Diuron                | Birch et al. (2015)                                                        |
|                     | Endosulfan            | Smital et al. (2004)                                                       |
|                     | Endrin                | Buttiglieri and Knepper (2008)                                             |
|                     | Fenoxycarb            | Smital et al. (2004)                                                       |
|                     | Glifosfate            |                                                                             |
|                     | Heptachlor            | Buttiglieri and Knepper (2008), Vilar et al. (2012)                        |
|                     | Hexachlorobenzene     |                                                                             |
|                     | Hexachlorobutadine    |                                                                             |
|                     | Isobenzan             |                                                                             |
|                     | Isodrin               |                                                                             |
|                     | Isoproturon           |                                                                             |
|                     | Malathion             | Smital et al. (2004), Gar Alalm et al. (2015)                              |
|                     | Malic hidrazid        |                                                                             |
|                     | 2-methyl-4-chlorophenoxyacetic acid | Birch et al. (2015)                           |
|                     | Metamitron            | Smital et al. (2004)                                                       |
|                     | Methomil              |                                                                             |
|                     | Phosalone             |                                                                             |
|                     | Pirimicarb            |                                                                             |
|                     | Propiconasole         |                                                                             |
|                     | Quintozene            | Buttiglieri and Knepper (2008)                                             |
|                     | Simazine              |                                                                             |
|                     | Simazine              | Birch et al. (2015)                                                        |
|                     | Terbutylazine         | Buttiglieri and Knepper (2008)                                             |
| α-endosulfan        |                       |                                                                             |

α-endosulfan
in the secondary treatment process (Rout et al. 2021). Jelic et al. (2011) analyzed pharmaceuticals in 43 sludge samples that resulted from conventional wastewater treatment plants. Their findings revealed that 50% of the sludge samples had significant levels of pharmaceuticals. 19% of diuretics and 16–21% of lipid-modifying agents were detected in the sludge. Hydrochlorothiazide, diclofenac, furosemide, clarithromycin, atorvastatin, and carbamazepine were detected in the sludge samples of the wastewater treatments at the levels of 30–60 µg/g total solids. In sludge samples, low concentrations of beta-blockers, histamine H2-receptor antagonists, and beta-agonists were found. Otherwise, the sludge from the sewage treatment plant included high concentrations of pharmaceuticals (Castiglioni et al. 2006; Zorita et al. 2009).

Removal of about 80% of naproxen, ketoprofen, and antihypertensive enalapril was achieved with no accumulation in the sludge (Lishman et al. 2006; Sim et al. 2010).

Table 1 (continued)

| Industry     | Emerging contaminants                                                                 |
|--------------|----------------------------------------------------------------------------------------|
| Herbicides   | 2,4-dinitrophenol<br>2,3- and 3,4-dichloronitrobenzene<br>3,4-dichloro aniline<br>Ametryn<br>Asulam<br>Atrazine<br>Bromacil<br>Bromoxylin<br>Chlorpyriphos<br>Dalapon<br>Dicamba<br>Desethyl atrazine<br>Desisopropyl atrazine<br>Diuron<br>Flumeturon<br>Fluroxypyr | John et al. (1982), Hirooka et al. (2006), Birch et al. (2015), Palatucci et al. (2019) |
| Insecticide  | Aldrin<br>Dichlorodiphenyltrichloroethane<br>Dieldrin<br>Endrin<br>Lindane | Singh and Walker (2006), Daneshvar et al. (2007), Navarro et al. (2009), Murray et al. (2010) |
| Food additive| Anti-oxidants<br>Benomyl<br>Carbendazim | Kasprzyk-Hordern et al. (2009), Sophia and Lima (2018) |
| Fungicide    | Butylparaben<br>Propylparaben | Murray et al. (2010), Stasinakis (2012), Mailler et al. (2017) |
| Preservatives| Perfluorate<br>Phthalates | Kasprzyk-Hordern et al. (2009), Badia-Fabregat et al. (2012) |
| Protective coatings| Polybrominated diphenylether | Xu et al. (2018), Zhou et al. (2020b) |
| Plasticizer  | Triazole | Kasprzyk-Hordern et al. (2009), Badia-Fabregat et al. (2012) |
| Flame retardant| Benzophenone-1<br>Benzophenone-3<br>Benzophenone-2<br>Benzophenone-4 | Kasprzyk-Hordern et al. (2009), Badia-Fabregat et al. (2012) |
| Textile      | Microfibers | Kasprzyk-Hordern et al. (2009), Badia-Fabregat et al. (2012) |
Also, anticonvulsant carbamazepine was removed only by lower than 25% in conventional wastewater treatment plants (Joss et al. 2005; Pérez and Barceló 2007; Radjenović et al. 2009). Additionally, partial removal of lower than 30% of antibiotics, including trimethoprim and benzodiazepine, lorazepam and metronidazole, was taken place by aerobic bacteria (Bendz et al. 2005; Göbel et al. 2007; Kasprzyk-Hordern et al. 2009). On the other hand, no removal of salbutamol, bezafibrate, and furosemide was observed during the aerobic treatment process (Castiglia et al. 2006). However, over 85% of 55 different pharmaceuticals and personal care products were removed by an activated sludge treatment plant (Kasprzyk-Hordern et al. 2009). Furthermore, histamine H2-receptor antagonist removal efficiency was quite low in the wastewater treatment plant (Radjenović et al. 2009), but the removal performance can reach as high as 86% (Kasprzyk-Hordern et al. 2009; Petrie et al. 2015). Moreover, the activated sludge plant removed diclofenac up to 24–60% (Kimura et al. 2007; Cirja et al. 2008).

Microplastic removal from wastewater is a critical contribution. Microplastics are removed via the primary treatment stage, with an average removal efficiency of 72–93% (Ateia et al. 2022). Also, the removal of biodegradable microplastics during the secondary treatment stage occurs via microorganisms. Furthermore, numerous technologies have been proposed for microplastic removals, such as ozonation and membrane bioreactor (Bui et al. 2020).

In conclusion, the primary treatment of emergent pollutants is necessary before discharge into wastewater treatment plants. The pretreatment process will undoubtedly improve the efficiency of existing wastewater treatment plants.

### Table 2: Emerging pollutants found in domestic wastewater.

| Sources                          | Emerging contaminants                                                                 | References                                         |
|----------------------------------|----------------------------------------------------------------------------------------|----------------------------------------------------|
| Endocrine disruptors             | 4-tert-octylphenol, Bisphenol A                                                       | Kasprzyk-Hordern et al. (2009)                     |
| Pharmaceuticals—analgesics and anti-inflammatories | Acetaminophen, Ibuprofen                                                               | Rivera-Utrilla et al. (2013), Pietrini (2015)      |
| Pharmaceuticals—β-blockers       | Atenolol                                                                               |                                                    |
| Pharmaceuticals—antibiotics       | Azithromycin, Metronidazole, Trimethoprim                                               |                                                    |
| Pharmaceuticals                   | Benzafibrate, Carbamazepine, Clofibric acid, Diclofenac, Gemfibrozil, Microplastics    | Petrović et al. (2003), Larsen et al. (2019)       |
| Pharmaceuticals—antiepileptics    | Carbamazepine, Ibuprofen, Ketoprofen, Naproxen, Triclosan                              | Rivera-Utrilla et al. (2013), Harris and Logan (2014), Petrović et al. (2003), Gottschall et al. (2012) |
| Pharmaceuticals—lipid-lowering drugs | Bezafibrate, Clofibric acid, Gemfibrozil                                                | Rivera-Utrilla et al. (2013), Ding et al. (2017)  |
| Pharmaceuticals—analgesics and anti-inflammatories | Diclofenac, Ketoprofen, Naproxen                                                       |                                                    |
| Surfactant                        | Phenol                                                                                 | Murray et al. (2010), Okada et al. (2013)          |
| Pharmaceuticals—antacids          | Ranitidine                                                                             | Rivera-Utrilla et al. (2013), Reddy et al. (2021) |
| Pharmaceuticals—β-blockers        | Sotalol                                                                                |                                                    |
Emerging contaminants in sludges

The recovery of sludge and biosolids from wastewater treatment plants has recently received great attention for the circular economy (Meky et al. 2019). Biosolids are mainly produced due to biological activities or chemical processes (Tawfik and Elsamadony 2017). The biosolids' characteristics have various chemical, biological and physical compositions. The recovery and re-utilization of biosolids are feasible; however, the presence of emerging contaminants in the municipal, hazardous sludge from industry, and biosolids from treating industrial wastewater makes a big barrier to the re-utilization of such natural resources. In 2001, the United States Environmental Protection Agency identified 38 out of 72 emerging pollutants in 110 biosolid samples at mg/kg level in a countrywide survey and reported environmental contaminants with concentrations up to several hundred parts per million in 74 wastewater treatment plants. Additionally, by 2006, sewage sludge worldwide had been shown to include 516 different chemicals belonging to 15 different emerging contaminants classes (Dubey et al. 2021). Benedetti et al. (2020) found that azithromycin, antibiotics, ciprofloxacin, and estrone were abundant at about 500–600 ng/g in the sludge generated from wastewater treatment plants.

Polycyclic aromatic hydrocarbons of 24 compounds are detected and identified in Table 2. This list of emerging pollutants includes 16 polycyclic aromatic hydrocarbons. For the petroleum fuel and oil industry, 2,6-dimethyl naphthalene, 2-methyl naphthalene, and 2,3,6-trimethyl naphthalene were the majority abundant chemicals. Additionally, lighter polycyclic aromatic hydrocarbon compounds such as fluorene and phenanthrene were abundant. Those contaminants

Table 3 Animal farming wastewater is rich with emerging pollutants. Dumping the runoff of animal wastes into the environment causes severe pollution. The leachate of animal waste after utilization in agriculture contaminates the groundwater. The animal farming waste is rich in nitrogen species. Antibiotics and hormones are the major contaminants in animal farming wastewater

| Source       | Emerging contaminants                             | References                                    |
|--------------|--------------------------------------------------|----------------------------------------------|
| Hormone      | 4-androstene-3,17-dione                           | Blair et al. (2013), Sami and Fatma (2019), Wang et al. (2020) |
|              | 17-alpha-estradiol                                |                                              |
|              | 17-beta-estradiol                                 |                                              |
|              | 17,20-dihydroxyprogesterone                       |                                              |
|              | Estriol                                          |                                              |
|              | Estrone                                          |                                              |
|              | Lincomycin                                       |                                              |
|              | Progesterone                                      |                                              |
|              | Testosterone                                      |                                              |
| Antibiotic   | Azithromycin                                      | Blair et al. (2013), Zhang et al. (2019), Leng et al. (2020) |
|              | Ciprofloxacin                                     |                                              |
|              | Clarithromycin                                    |                                              |
|              | Lomefloxacin                                      |                                              |
|              | Miconazole                                        |                                              |
|              | Norfloxacin                                       |                                              |
|              | Ofloxacin                                         |                                              |
|              | Sarafloxacin                                      |                                              |
|              | Sulfachloropyridazine                             |                                              |
|              | Sulfadiazine                                      |                                              |
|              | Trimethoprim                                      |                                              |

Emerging contaminants

- Hormone: 4-androstene-3,17-dione, 17-alpha-estradiol, 17-beta-estradiol, 17,20-dihydroxyprogesterone, Estriol, Estrone, Lincomycin, Progesterone, Testosterone
- Antibiotic: Azithromycin, Ciprofloxacin, Clarithromycin, Lomefloxacin, Miconazole, Norfloxacin, Ofloxacin, Sarafloxacin, Sulfachloropyridazine, Sulfadiazine, Trimethoprim

Fig. 2 Main discharge route of emerging contaminants. Industrial wastewater should be treated prior to reaching the wastewater treatment plant. Hospital sewage, agricultural effluent, domestic wastewater, and animal farming wastewater are the main sources of emerging contaminants in the environment. Treatment plants receive wastewater-rich emerging contaminants. The effluent quality of wastewater treatment plants depends on the loading rate of the emerging contaminants.
are rapidly biodegraded and/or volatilized from the soil, of which 2,6-dimethyl naphthalene and 2-methyl naphthalene are particularly 20–30% dominant. The summation of the polycyclic aromatic hydrocarbons including benzo[b]fluoranthene, acenaphthene, fluoranthene, phenanthrene, fluorene, pyrene, benzo[ghi]perylene, indeno[1,2,3-cd]pyrene and benzo[al]pyrene should not exceed 6 mg/kg dry matter, according to European Union regulations.

Table 4 shows that total polycyclic aromatic hydrocarbons concentrations varied from 18 to 50 mg/kg dry weight in the sludge, complying with the standards (Moreda et al. 1998; Manoli and Samara 1999; Duan et al. 2021). Polychlorinated biphenyl congeners of 46 were detected in the sludge samples. Fortunately, the congeners of 54, 104, 114, 105, 155, and 188 were not quantified. Total polychlorinated biphenyl concentration was 220 ug/kg dry weight. Polychlorinated naphthalenes had 35 congeners, 17 of which were found in the sludge samples, and their mean concentration was 83 ug/kg dry weight.

**Anaerobic digestion of sludges containing emerging contaminants**

Food waste is almost free from emerging contaminants; however, biogas productivity from anaerobic digestion of food waste as a standalone substrate is quite low (Chew et al. 2021; Liu et al. 2021b). The bioenergy productivity is highly increased by anaerobic digestion of food waste with co-substrate, i.e., agricultural, biosolids or sludge, and manures. The latter contains emerging contaminants that make a barrier to the reuse of the digestate that resulted from the anaerobic co-digestion process (Zhang et al. 2021). Acidogenic fermentation of the aluminum-sludge and iron-sludge resulted from chemically enhanced primary sedimentation of sewage provided removal efficiencies of 50% and 58% of retinoids, and 50% and 47% of endocrine-disrupting chemicals (4-nonylphenol, estrone, diethylstilbestrol, triclosan, triclocarban, and bisphenol A), respectively, in bulk liquid (Zhou et al. 2020a). However, the concentrations of retinoids and endocrine-disrupting chemicals increased after fermentation in the solid phase, indicating that these chemicals were adsorbed in the sludge. After the acidogenic fermentation process, the retinoid 13-cis-RA concentrations in aluminum-sludge and iron-sludge increased from 19 to 140 ng/g dry weight and 25 to 97 ng/g dry weight, respectively.

This was not the case for endocrine-disrupting chemicals, which slightly increased in the sludge after acidogenic fermentation. The anaerobic microbial community greatly contributed to removing antibiotic resistance genes from sludge (Jang et al. 2017). The presence of endocrine-disrupting chemicals, such as 4-nonylphenol and triclocarban, improved the activities and diversities of the microbial community and subsequently enhanced the solubilization and acidogenesis process of sludge (Duan et al. 2016; Wang et al. 2017). However, 4-nonylphenol in the activated sludge could be biodegraded by acidogenic microorganisms (Duan et al. 2016, 2018). On the contrary, the microbial activities were quite low for removing antibacterial agents, i.e., triclocarban and triclosan (Wang et al. 2017; Yan et al. 2019a). A high concentration of both triclocarban and triclosan was found in the fermented sludge.

Likely, Wang et al. (2017) found that triclocarban was slightly removed from sludge during the anaerobic digestion of activated sludge. This indicates that the risks of triclocarban and triclosan in the fermented sludge are still causing severe pollution. Triclocarban and triclosan should be removed from fermented sludge before disposal. Triclocarban and triclosan were mainly accumulated in the sludge during the anaerobic digestion process due to the sorption of solid materials (Zhou et al. 2019). The fermentation of the sludge by acidogenesis only minimized the levels of retinoids by 3.3% and for endocrine-disrupting chemicals by 1.4% in the supernatant, confirming a low contribution of anaerobic digestion to remove emerging contaminants from sludge (Zhou et al. 2020a).

Lin et al. (2017) reported that the sludge fermentation with acidogenic bacteria could successfully lower the level of emerging pollutants in the supernatant, which is suitable for resource recovery. Additional research is needed to optimize the removal of endocrine-disrupting chemicals from the solid sludge phase to reduce their health hazard and environmental impact. The supernatant (liquid) digestate that resulted from anaerobic digestion of sludge containing emerging pollutants had the highest concentration of 147 ug/L for sunscreen octocrylene and 58.6 ug/L for acetaminophen (Ali et al. 2019).

However, lower fractions of octocrylene (more than 600 ng/g wet weight) and tris-1-chloro-2-propyl-phosphate (more than 500 ng/g wet weight) were observed in solid digestates. The total contaminants of emerging concern were 1411 ng/g in solid digestates and 354 ng/g in liquid digestates. The behavior of irbesartan, benzoylecgonine, and venlafaxine in the sludge after mesophilic and thermophilic anaerobic digestion was reported by Morales et al. (2016). Apparently, benzoylecgonine and irbesartan in the sludge were probably biodegraded by fermentation. Venlafaxine concentrations were substantially lower in the aqueous stage and significantly higher in the solid stage. Irbesartan, benzoylecgonine, and venlafaxine concentrations in the solid stage were significantly greater than in the aqueous stage, indicating that irbesartan, benzoylecgonine, and venlafaxine were substantially adsorbed onto the biosolids. The emerging pollutants found in the treated sludge are listed in Table 5.
Emerging contaminants detected in sewage sludges (Stevens et al. 2003; Mailler et al. 2017). The emerging contaminants include polycyclic aromatic hydrocarbons. The polychlorinated biphenyls and polychlorinated naphthalene are detected in sewage sludge. Azithromycin, antibiotics, ciprofloxacin, and estrone are abundant in the sludge generated from wastewater treatment plants. The petroleum fuel and oil industry contain 2,6-dimethyl naphthalene, 2-methyl naphthalene, and 2,3,6-trimethyl naphthalene, nd: non-detected

| Polycyclic aromatic hydrocarbons (mg/kg dry weight) | Min | Max | Mean | Median |
|---------------------------------------------------|-----|-----|------|--------|
| Naphthalene                                       | 0.15| 19  | 3.7  | 1.4    |
| 2-methylnaphthalene                               | 5.9 | 93  | 24   | 13     |
| 1-methylnaphthalene                               | 2.4 | 39  | 9.9  | 5.0    |
| Biphenyl                                          | 1.7 | 28  | 6.3  | 4.0    |
| 2,6-dimethylnaphthalene                           | 5.0 | 110 | 30   | 18     |
| Acenaphthylene                                    | 0.030| 0.10| 0.060| 0.050 |
| Acenaphthene                                      | 1.7 | 6.6 | 4.0  | 3.9    |
| 2,3,6-trimethylnaphthalene                        | 0.96| 15  | 6.9  | 5.7    |
| Fluorene                                          | 3.6 | 8.1 | 5.7  | 5.7    |
| Phenanthrene                                      | 1.4 | 7.4 | 4.9  | 5.4    |
| Anthracene                                        | 0.38| 1.8 | 0.72 | 0.65   |
| 1-methylphenanthrene                              | 0.46| 8.1 | 3.9  | 3.5    |
| Fluoranthenne                                     | 1.4 | 7.4 | 4.9  | 5.4    |
| Pyrene                                            | 2.1 | 5.6 | 4.2  | 4.5    |
| Benz[a]anthracene                                 | 0.6 | 2.8 | 1.8  | 1.8    |
| Chrysene                                          | 1.0 | 6.0 | 2.6  | 2.3    |
| Benzo[b]fluoranthene                              | 1.1 | 7.2 | 3.0  | 2.9    |
| Benzo[jk]fluoranthene                             | 0.7 | 4.5 | 2.2  | 1.9    |
| Benzo[c]pyrene                                    | 0.82| 4.4 | 2.2  | 2.0    |
| Benzo[a]pyrene                                    | 0.69| 4.0 | 2.1  | 2.1    |
| Perylene                                          | 0.12| 0.61| 0.36 | 0.35   |
| Indeno[1,2,3-cd]pyrene                             | 0.39| 2.7 | 1.3  | 1.1    |
| Dibenzo[ab]anthracene                              | 0.060| 0.38| 0.19 | 0.19   |
| Benzo[ghi]perylene                                | 0.47| 2.3 | 1.3  | 1.1    |
| Total                                             | 67  | 370 | 130  | 93     |

| Polychlorinated biphenyls concentrations (ug/kg dry weight) | Min | Max | Mean | Median |
|-------------------------------------------------------------|-----|-----|------|--------|
| 18                                                          | 1.5 | 14  | 5.7  | 5.0    |
| 22                                                          | 1.7 | 43  | 9.3  | 6.0    |
| 28                                                          | 5.1 | 26  | 12   | 11     |
| 31                                                          | 3.5 | 56  | 13   | 8.1    |
| 44                                                          | 1.0 | 6.5 | 3.1  | 2.8    |
| 41/64                                                       | 1.3 | 7.3 | 3.4  | 3.1    |
| 49                                                          | 1.7 | 13  | 4.6  | 3.8    |
| 52                                                          | 3.1 | 28  | 12   | 8.7    |
| 60/56                                                       | 0.4 | 4.8 | 1.8  | 1.9    |
| 70                                                          | 2.7 | 33  | 8.3  | 6.1    |
| 74                                                          | 1.7 | 8.7 | 3.5  | 3.0    |
| 87                                                          | 0.9 | 5.3 | 2.6  | 2.1    |
| 90/101                                                      | 3.8 | 74  | 13   | 8.2    |
| 95                                                          | 2.3 | 22  | 6.4  | 4.4    |
| 99                                                          | 1.1 | 4.9 | 2.6  | 2.1    |
| 110                                                         | 1.5 | 10  | 4.6  | 4.0    |
| 118                                                         | 1.6 | 20  | 6.1  | 5.2    |
| 123                                                         | 0.3 | 8.4 | 4.0  | 3.4    |
| 132                                                         | 10  | 39  | 20   | 19     |
| 138                                                         | 6.9 | 23  | 13   | 12     |
Table 4 (continued)

| Polychlorinated biphenyls concentrations (ug/kg dry weight) | Min  | Max  | Mean | Median |
|------------------------------------------------------------|------|------|------|--------|
| 141                                                        | 1.3  | 5.7  | 2.8  | 2.3    |
| 149                                                        | 5.7  | 20   | 11   | 8.9    |
| 151                                                        | 2.1  | 7.6  | 3.8  | 2.9    |
| 153                                                        | 7.3  | 27   | 14   | 13     |
| 156                                                        | 0.5  | 2.1  | 1.1  | 0.97   |
| 157                                                        | 0.1  | 0.49 | 0.31 | 0.29   |
| 158                                                        | 0.2  | 2.3  | 1.2  | 1.0    |
| 167                                                        | 0.2  | 1.1  | 0.49 | 0.40   |
| 170                                                        | 1.3  | 8.6  | 3.3  | 2.3    |
| 174                                                        | 1.6  | 9.7  | 3.9  | 2.9    |
| 180                                                        | 4.7  | 23   | 10   | 8.5    |
| 183                                                        | 1.2  | 5.7  | 2.6  | 2.1    |
| 187                                                        | 2.6  | 12   | 5.8  | 4.8    |
| 189                                                        | 0.010| 0.35 | 0.17 | 0.17   |
| 194                                                        | 0.1  | 7.5  | 2.6  | 2.0    |
| 199                                                        | 0.090| 1.3  | 0.35 | 0.26   |
| 203                                                        | 1.4  | 11   | 3.1  | 2.5    |
| Total                                                      | 110  | 440  | 220  | 190    |

| Polychlorinated napthalene (ug/kg dry weight) | Min | Max | Mean | Median |
|----------------------------------------------|-----|-----|------|--------|
| 19                                           | nd  | 1.8 | 0.50 | 0.20   |
| 23                                           | nd  | 20  | 10   | 9.7    |
| 15                                           | 12  | 78  | 27   | 23     |
| 16                                           | 13  | 97  | 31   | 26     |
| 42                                           | 0.3 | 0.8 | 0.5  | 0.5    |
| Polychlorinated napthalene 4–11               | nd  | 0.4 | 0.2  | 0.2    |
| 38 (40)                                      | 1.5 | 3.9 | 2.4  | 2.2    |
| 46                                           | nd  | 1.5 | 0.9  | 0.9    |
| 33/34/37                                     | 1.9 | 4.4 | 3.0  | 2.9    |
| 47                                           | 0.6 | 3.2 | 1.1  | 0.9    |
| 36/35                                        | 0.2 | 1.1 | 0.6  | 0.6    |
| 52/60                                        | nd  | 0.9 | 0.3  | 0.3    |
| 59                                           | nd  | 1.9 | 0.4  | nd     |
| Total                                        | 50  | 190 | 83   | 76     |

| Synthetic musks                                | Min | Max | Mean | Median |
|------------------------------------------------|-----|-----|------|--------|
| Celestolide                                    | 0.010| 0.26| 0.071| 0.035  |
| Phantolide                                     | 0.032| 1.1 | 0.41 | 0.39   |
| Traseolide                                     | 0.044| 1.1 | 0.45 | 0.45   |
| Galaxolide                                     | 1.9 | 81  | 27   | 26     |
| Tonalide                                       | 0.12| 16  | 4.7  | 4.0    |
| Total                                          | 2.1 | 99  | 32   | 31     |

| Polychlorinated (chain length)                  | Min | Max | Mean | Median |
|------------------------------------------------|-----|-----|------|--------|
| ΣC10                                          | 0.99| 21  | 3.8  | 1.80   |
| ΣC11                                          | 1.6 | 60  | 12   | 4.7    |
| ΣC12                                          | 2.5 | 62  | 14   | 5.7    |
| ΣC13                                          | 1.8 | 69  | 13   | 4.2    |
| Total short-chain                              | 6.9 | 200 | 42   | 16     |
| ΣC14                                          | 19  | 6000| 1000 | 290    |
Inhibition effects of the emerging pollutants on anaerobic digestion of sludges

Methanogenesis and methane productivity

Fluoxetine inhibited the anaerobic digestion of excess sludge (Zhao et al. 2021a) at concentrations exceeding 2.0 mg/kg. However, methane productivity was unaffected by a fluoxetine dose of 0.1 mg/kg. Nevertheless, a fluoxetine dose of 2.0 mg/kg resulted in a 91.2 ± 4.3 mL/g reduction in methane productivity of volatile suspended solids. This reduction in methane productivity was equivalent to 59.9 ± 3.4% of the control. The fluoxetine declined hydrolysis process, acidification, and methanogenesis activities due to inhibiting enzyme activities.

Sludge reduction and solubilization

Volatile solids reduction mainly occurs due to the hydrolysis and anaerobic metabolism activities where a portion of organic matter is solubilized during sludge fermentation. However, the presence of emerging pollutants in the sludge would affect volatile solids reduction (Zhang et al. 2012; Fang et al. 2020). The volatile solids reduction of sludge free emerging pollutants was optimized at a level of 26.9 ± 1.1% during anaerobic digestion (Zhao et al. 2021a), which was reduced to 26.5 ± 1.1, 20.3 ± 0.9, and 16.9 ± 0.8% for sludge containing fluoxetine of 0.1, 0.5, and 2.0 mg/kg, respectively. This indicates that the presence of fluoxetine in the sludge reduced the hydrolysis and conversion of organics by anaerobes (Zhao et al. 2017). Fluoxetine strongly destroys the metabolism activities of anaerobes, resulting in a low volatile solids reduction in the digested sludge. Brooks et al. (2003) reported a significant inhibition of fluoxetine on the anaerobic digestion of sludge, which inhibited bacterial growth and cell malformation.

Hydrolysis, acidification and methanogenesis process

Hydrolysis of sludge under anaerobic digestion is the rate-limiting step due to the limited secretion of hydrolytic enzymes in the presence of emerging pollutants. The acidification process is also negatively affected due to the toxicity inhibition of emerging pollutants (Zhao et al. 2017). The organics hydrolysis increased the solubilization of coarse particles, increasing soluble chemical oxygen demand in the fermentation medium. However, the presence of fluoxetine would inhibit the solubilization process and, subsequently, the acidification activities. Zhao et al. (2021a, b) found that the highest solubilization was 695 ± 12.3 mg soluble chemical oxygen demand/L at a fluoxetine concentration of 0.1 mg/kg and decreased to 659 ± 20.6 mg/L at a fluoxetine dose of 2.0 mg/kg. The authors also found that fluoxetine in the sludge inhibited the solubilization of proteins and polysaccharides of the sludge under anaerobic conditions, which negatively affects methane productivity.

Volatile fatty acid productivity and accumulation

Acidification of sludge by acidogenesis produces volatile fatty acids and hydrogen gas. This biological activity resulted in a drop in pH value and alkalinity. Moreover, the anaerobes are suffered from buffering capacity (Li et al. 2019). The volatile fatty acid variations during sludge fermentation are highly affected by emerging pollutants such as fluoxetine. The volatile fatty acids production of 456 ± 26 mg/L was quite high for fermentation of sludge free emerging pollutants, which was dropped to 425 ± 16 mg/L, 406 ± 21 mg/L, and 358 ± 19 mg/L for sludge containing fluoxetine of 0.1, 0.5, and 1.0 mg fluoxetine/kg, respectively, and volatile fatty acids concentration remained at the same level at a higher dose of 2.0 mg fluoxetine/kg. The inhibition of volatile fatty acids productivity occurred at concentrations exceeding 1.0 mg fluoxetine/kg.

Enzyme activities

Anaerobic degradation of biosolids is mainly taken place by the presence of enzymes secreted by the microorganisms. However, emerging pollutants would negatively affect enzyme activities and, subsequently, bioenergy productivity. Proteins and polysaccharides hydrolysis by protease and cellulase enzymes occur under anaerobic conditions. α-glucosidase, acetate kinase, coenzyme F420, and butyrate kinase are responsible for methane productivity (Li et al. 2016; Zhao et al. 2017; Zhu et al. 2019). The presence of fluoxetine in the sludge inhibited the enzyme activities of

| Table 4 (continued) |
|---------------------|
| Polychlorinated (chain length) | Min | Max | Mean | Median |
| Σ C15 | 7.3 | 2500 | 490 | 150 |
| ΣC16 | 3.0 | 1100 | 210 | 56 |
| ΣC17 | 0.92 | 310 | 50 | 18 |
| Total medium-chain | 30 | 9700 | 1800 | 540 |
| Total short and medium-chain | 45 | 9900 | 1800 | 560 |
Table 5 Micropollutants in treated sludges. The concentrations of various types of micropollutants discovered in several types of sludge are quantified. The total contaminants of emerging concern are 1411 ng/g in solid digestates and 354 ng/g in liquid digestates. The micropollutants type in the sludge depends on the treatment process. Adsorption is followed by biodegradation which is the main removal mechanism of micropollutants.

| Micropollutants                        | Type of sludge | Mean (mg/kg dry matter) | Range (mg/kg dry matter) | References                      |
|----------------------------------------|----------------|-------------------------|--------------------------|---------------------------------|
| **Organotins**                         |                |                         |                          |                                 |
| Triphenyltin                           | Various        | 0.63                    | Less than 0.02–9         | Clarke and Smith (2011)         |
| Tributyltin                            | Various        | 0.86                    | 0.02–6.0                 | Clarke and Smith (2011)         |
|                                        | Digested       | 0.004                   |                          | Olofsson et al. (2012)          |
|                                        | Digested       | 1.1 ± 0.4               |                          | Fent (1996)                     |
| Dibutyltin                             | Various        | 1.28                    | 0.41–7.5                 | Clarke and Smith (2011)         |
|                                        | Digested       | 1.5 ± 0.5               |                          | Fent (1996)                     |
| Monobutyltin                           | Various        | 0.93                    | 0.1–6.0                  | Clarke and Smith (2011)         |
|                                        | Digested       | 0.074                   |                          | Olofsson et al. (2012)          |
|                                        | Digested       | 0.5 ± 0.2               |                          | Fent (1996)                     |
| **Phthalates**                         |                |                         |                          |                                 |
| Di2-(ethylhexyl)phthalate              | Digested       | 126                     | 91–179                   | Marttinen et al. (2003)         |
| Di2-(ethylhexyl)phthalate              | Various        | 58                      | Less than 0.02–3,514     | Clarke and Smith (2011)         |
|                                        | Digested       | 159                     | 13–345                   | Aparicio et al. (2009)          |
|                                        | Thermally dried| 148.8                   | 1.5–3,514                | Abad et al. (2005)              |
| Σ8 Polybrominated diphenyl ethers     | Various        | 1.360                   | 0.005–4.690              | Clarke and Smith (2011)         |
| **Polycyclic aromatic hydrocarbons**   |                |                         |                          |                                 |
| Σ11 Polycyclic aromatic hydrocarbons  | Thermally dried| 1.89                    | 0.13–7.35                | Abad et al. (2005)              |
| **Polychlorinated biphenyls**          |                |                         |                          |                                 |
| Σ7 Polychlorinated biphenyls           | Thermally dried| 0.041                   | Less than 0.006–0.131    | Abad et al. (2005)              |
| **Alkylphenols**                       |                |                         |                          |                                 |
| Nonylphenol                            | Digested       | 0.17                    | Less than 0.04–0.45      | Stasinakis et al. (2008), Stasinakis (2012) |
|                                        | Digested       | 102.1                   | 16.5–25.3                | Gonzalez et al. (2010)          |
|                                        | Thermally dried| 61.7                    | 16.5–124.9               | Stasinakis et al. (2008), Bergé et al. (2012) |
|                                        | Various        | 128                     | 0.02–2.30               | Bergé et al. (2012)             |
| Nonylphenol mono-ethoxylate            | Digested       | 12.3                    | 0.01–4.1                 | Stasinakis et al. (2008)        |
|                                        | Digested       | 53.2                    | Less than 0.75–287.8     | Gonzalez et al. (2010)          |
|                                        | Various        | 40.2                    | 0.15–8.5                 | Bergé et al. (2012)             |
| Various                                |                |                         | Less than 0.020–2.400    |                                 |
| Tributylphosphate                      | Various        | 0.011                   |                            | Olofsson et al. (2012)          |
| Polychlorinated diphenyl ethers        |                |                         |                          |                                 |
| Brominated diphenyl ether 209          | Various        | 0.120                   | 0.006–1.000              | Law et al. (2006)               |
|                                        | Digested       | 0.443                   | 0.133–1.339              | Knoth et al. (2007)             |
|                                        | Various        | 1.039                   | 0.003–18.632             | Clarke and Smith (2011)         |
| Σ6 Polybrominated diphenyl ethers      | Various        | 0.250                   | 0.024–1.260              | Law et al. (2006)               |
| Σ8 Polybrominated diphenyl ethers      | Digested       | 0.577                   | 0.186–1.627              | Knoth et al. (2007)             |
| Polycyclic aromatic hydrocarbons       | Various        | 1.360                   | 0.005–4.690              | Clarke and Smith (2011)         |
| Σ6 Polycyclic aromatic hydrocarbons    | Digested       | 14.8                    | 4.75–28.1                | Stevens et al. (2003), Stevens-Garmon et al. (2011) |
|                                        | Dewatered      | 1.68                    | 0.52–3.36                | Blanchard et al. (2004)         |
| Σ11 Polycyclic aromatic hydrocarbons   | Thermally dried| 1.89                    | 0.13–7.35                | Abad et al. (2005)              |
| Polychlorinated biphenyls              |                |                         |                          |                                 |
| Σ7 Polychlorinated biphenyls           | Digested       | 0.080                   | 0.033–0.221              | Stevens-Garmon et al. (2011)    |
|                                        | Thermally dried| 0.041                   | Less than 0.006–0.131    | Abad et al. (2005)              |
|                                        | Dewatered      | 0.617                   | 0.12–1.93                | Blanchard et al. (2004)         |
α-glucosidase, acetate kinase, coenzyme F420, and butyrate kinase at concentrations exceeding 0.5 mg/kg and, subsequently, affected the methane productivity (Zhao et al. 2021a). Fluoxetine significantly inhibited cytochrome P450 activity in the liver of fish (Laville et al. 2004; Zhang et al. 2014). Zhang et al. (2013) found that fluoxetine caused inhibition pathways to convert the enzyme of P-glycoprotein and glutathione and suppress the microorganism’s metabolic activity, thereby reducing the methanogenesis process.

Mitigation of the inhibition effect of emerging pollutants on the anaerobic digestion of sludges

Sludge solubilization could be highly achieved by the pretreatment process (Eq. 1), which might rupture the microbial cells, solubilize the coarse suspended solids, and increase the soluble chemical oxygen demand, resulting in a high degradation efficiency of refractory compounds, mineralization of organics and biodegradability, thereby improving the methanogenesis process in the presence of the emerging pollutants in the sludge (Mohapatra et al. 2011, 2012; Samaras et al. 2014). Pretreatment of the sludge reduces the required hydrolysis time (Carballa et al. 2007). The pretreatment process will increase the solubility of emerging pollutants in the sludge and subsequently enhance the biodegradation and biomethanization process (Zhang et al. 2021). Sonication and ozonation were effective for sludge solubilization, resulting in a high removal of emerging pollutants from sludge (Mohapatra et al. 2012). Different pretreatment techniques were reported to mitigate anaerobic digestion inhibition by emerging pollutants.

\[
\text{Sludge} \xrightarrow{\text{pretreatment}} \text{Solubilized sludge} \quad (1)
\]

Electro-oxidation

Electrochemical conversion and combustion of organics, such as phenol and hormones, occur due to the generation of free radicals, particularly hydroxyl radicals (•OH), by which a constant direct current is applied (Rivera-Utrilla et al. 2013). A boron-doped diamond electrode was reported to be the most active anode for the oxidation and mineralization of emerging pollutants (Chen 2004). The electro-oxidation using boron-doped diamond electrodes oxidizing sludge achieved 4,4-(propane-2,2-diyl)diphenol, nonylphenol, 5-chloro-2-(2,4-dichlorophenoxy)phenol removal of 89, 73, and 82% at a pH value of 3.0 and current density of 40 mA/cm² for 1 h. The volatile solids of the sludge were mineralized by 23%, and chemical oxygen demand was removed by a value of 27% (Barrios et al. 2015). 42% mineralization of emerging pollutants was achieved at a pH of 3.0 and decreased to 25% and 14% for pH values of 5 and 7, respectively (Barrios et al. 2015).

Moreover, zeta potential decreased from ~17 to ~10 mV due to mineralization, destroying and destabilizing of negatively colloidal particles and eventually improving sludge quality. Chemical oxygen demand removal was maximized at a level of 31% at the current density of 40 mA/cm² and highly dropped at 10 mA/cm². Titanium (Ti) anodes removed pathogens and enhanced sludge dewatering (Drogui et al. 2012).

Emerging pollutants are destabilized and destroyed by hydroxyl radical (•OH) released by electrodes. The •OH radical reacts with emerging pollutants (Eq. 2),

\[
\text{RH} + \cdot \text{OH} \rightarrow \text{R} + \text{H}_2\text{O} \quad (2)
\]

The electrochemical cell produces hydroxyl radical, which reacts with emerging pollutants in the sludge. The extracellular polymeric substances further react with hydroxyl radical or oxygen to generate oxidative byproducts (Eqs. 3 and 4).

\[
\text{•R} + \text{O}_2 \rightarrow \text{Products} \quad (3)
\]

\[
\text{•R} + \text{•OH} \rightarrow \text{Products} \quad (4)
\]

The oxidation of 4,4-(propane-2,2-diyl)diphenol by •OH radicals breaks the adjacent bonds, i.e., methyl bridge, into phenol and iso-propylene alcohol, as shown in Fig. 3. The iso-propylene alcohol molecule is further oxidized by •OH producing short-chain carboxylic acid, while catechol, hydroquinone, and resorcinol compounds might be produced from the hydroxylation of the phenolic ring. Hydroquinone was the main byproduct in earlier studies (Gözmen et al. 2003). Subsequently, quinone is formed by a dehydrogenation reaction with •OH radicals. Phenolic ring molecules are mainly oxidized and converted into small fragmented byproducts, resulting in short-chain aliphatic acids. Maleic, oxalic, fumaric, formic, and acetic acid are the main aliphatic acids. Those byproducts could be efficiently utilized by anaerobes for bioenergy production. However, extending the reaction time will allow the attack of •OH on those acids, resulting in carbon dioxide of complete degradation of bisphenol A (Gözmen et al. 2003).

Carboxylic acids are the main byproducts of the degradation of chlorophenols, as shown in Fig. 4. 5-chloro-2-(2,4-dichlorophenoxy)phenol, known as triclosan, molecules are completely oxidized with conductive-diamond electrochemical (Gözmen et al. 2003). Electro-oxidation cell was initially operated at pH of 3.0, current density of 40 mA/cm² and reaction time of 60 min, and achieved removal efficiency of 73% for 4,4-(propane-2,2-diyl) diphenol, known as bisphenol A; 89% for nonylphenol;
and 82% for 5-chloro-2-(2,4-dichlorophenoxy)phenol (Barrios et al. 2015).

Ultrasonication

Ultrasonication is an efficient mechanical pretreatment process of the sludge to enhance biodegradability (Pilli et al. 2011). Ultrasonication is regarded as digesting the sludge easier by changing sludge's physical, biological, and chemical properties. The degree of sludge breakdown is mainly affected by the sonication parameters and sludge characteristics. The full-scale applications of the ultrasonication system efficiently demonstrated a 50% increase in biogas productivity. Moreover, a net energy gain to electricity consumption ratio of 2.5 was found in the energy balance by the ultrasonic system. According to the frequency, the ultrasound range diagram could be separated into three sections: power ultrasound (20–100 kHz), high-frequency ultrasound (100 kHz–1 MHz), and diagnostic ultrasound (1–500 MHz).

Thermal hydrolysis

Thermal hydrolysis is a viable method of making sewage sludge more susceptible to anaerobic digestion. Thermal hydrolysis is a procedure that involves heating sludge to the desired temperature, typically using saturated steam injection, to facilitate subsequent anaerobic digestion (Díaz et al. 2020). The best treatment temperature for thermal hydrolysis is between 160 and 180 °C with a pressure ranging from 600 to 2500 kPa in several experiments (Stuckey and McCarty 1984; Neyens and Baeyens 2003; Bougrier et al. 2008; Carrère et al. 2010; Barber 2016). Furthermore, some thermal hydrolysis investigations have been conducted at temperatures ranging from 60 to 220 °C and for durations ranging from 1 to 4320 min (Gavala et al. 2003; Climent et al. 2007; Ferrer et al. 2008; Wilson and Novak 2009). There are many advantages of raising the temperature of thermal hydrolysis to an ideal range, including reducing the average particle size and apparent viscosity, improving sludge digestibility, and enhancing biopolymers solubilities, such as proteins and carbohydrates, while lipids are not largely affected. Also, there is a potential for refractory compounds reproduction, such as color, chemical oxygen demand, and nitrogen (Barber 2016; Kor-Bicakci and Eskicioglu 2019).

Ozonation

The aim of ozonation during sludge pretreatment is to induce organic matter partial oxidation and hydrolyzation. Ozonation destroys pathogens and volatile solids during the anaerobic digestion of sludge. Ozone damages bacteria's cell walls at low doses, resulting in their lysis. At higher levels, ozone destroys flocks by directly attacking the bacterial extracellular polymeric matrices critical for bacterium colonies in the flocks (Chiellini et al. 2014). Furthermore, many studies have also demonstrated that ozonation may help eliminate or increase the biodegradation of emerging pollutants. Ozone doses from 0.1 to 30 mg/L were used to remove the contaminants by 60–99%, such as antibiotics, pesticides, natural and synthetic estrogens, anti-epileptics, and anti-inflammatory (Carballa et al. 2007).

Moreover, organic solids reduction and methane generation have both improved significantly during ozonation. Anaerobic biodegradability and biomethanation were increased with sludge pretreatment aided by ozone dosage. An ozone dosage of 0.06 g O3/g total suspended solids was used to achieve the greatest daily elimination efficiency of 32% total solids, 69% volatile suspended solids, 42% volatile solids, 35% chemical oxygen demand, and 60% total suspended solids. Ozone also resulted in a 48% increase in methane-enriched biogas generation via the acetotrophic route (Tuncay et al. 2022).
Degradation and transformation of emergent contaminants during sludge pretreatment

Including transformation products during studying emergent contaminants removal is critical as the transformed products might be more toxic than the original compound. For instance, carbamazepine is converted into acridone and acridine, which are more poisonous to algae, bacteria, and daphnia magna than the original compound (Donner et al. 2013). During wastewater biological treatment, nonylphenol ethoxylates are bio-transformed into various metabolites, including nonylphenol diethoxylate, nonylphenol, and nonylphenol monoethoxylate (Chang et al. 2005; Patureau et al. 2008). Also, estrogen E1 is transformed into E2 during anaerobic conditions with various kinds of sludge (des Mes et al. 2008; Paterakis et al. 2012). Furthermore, the anti-microbial triclocarban can be converted partly or entirely into a variety of products through a variety of abiotic and biotic mechanisms. Triclocarban is biotransformed into similar compounds with decreased chlorine content in anaerobic and anoxic environments through the reductive dechlorination process (Kor-Bicakci et al. 2020).

Moreover, naproxen, a non-steroidal anti-inflammatory drug, is biotransformed into 6-O-desmethynaproxen, which persists in the anaerobic therapy for up to 161 days (Lahti and Oikari 2011; Azizan et al. 2021). Additionally the antibiotic spiramycin I was degraded into three molecules during the anaerobic digestion through the hydrolysis of mycaminose-mycarose and the hydrogenation of the aldehyde group (Zhu et al. 2014). The retransformation of N4-acetyl sulfamethoxazole to sulfamethoxazole was strongly indicated during activated sludge treatment (Göbel et al. 2005).

Bioaugmentation

The addition of certain microorganisms is a potential technique for improving the performance of degrading specific contaminant compounds for suboptimal anaerobic digestion systems. This process aims to transform hazardous contaminants into less harmful ones to reduce the contaminant load. Also, adding nutrients or electron acceptors may stimulate the local microbiota, which might help improve the microbial breakdown of pollutants. However, some strains may not develop due to a lack of adaptation to environmental factors, predation, or competition with microbes. Studies showed that microorganisms that degrade pharmaceuticals and personal care products accelerated their breakdown in the activated sludge (Dubey et al. 2021).

Using Caseobacter sp. can get rid of oil and grease by 66.15% in bakery wastewater (Keenan and Sabelnikov 2000). Also, Paracoccus sp. LZ-G1 was shown to adsorb
cadmium (Cd\(^{2+}\)) on the cell surface and reduce Cd\(^{2+}\) content in the microbial community, thereby improving anaerobic digestion, hydrolysis efficiency, and methane production (Guo et al. 2021). Furthermore, the addition of *Coprothermobacter proteolyticus* increased the hydrolysis and fermentation of proteins and polysaccharides (Lü et al. 2014). Additionally, mono-oxygenase enzymes, which have a broad variety of substrates, have been shown to break down pharmaceuticals and personal care products in several microorganisms (Zhou et al. 2014). Moreover, Roh and Chu (2011) revealed that starting with identical biomass of the 17-estradiol-degrading bacteria, *Sphingomonas* KC8, removing 1 mg/L of 17-estradiol in lab-scale sequencing batch reactors resulted in substantial amounts of elimination (Roh and Chu 2011).

Algae treatment has been shown to remove heavy metals and excess nutrients from wastewater more effectively compared to chemical treatment (Maryjoseph and Ketehesan 2020; Singh et al. 2021). For instance, *Chlorella pyrenoidosa* mixotrophic was cultured in an anaerobic digestate of sludge, resulting in 95% of orthophosphate, 99% of ammonium, and 62% of total organic carbon removal (Tan et al. 2020). Microalgae strains of *Scenedesmus* sp., *Chlorella*, and *Chlamydomonas* are highly adaptable to severe environmental circumstances. Microalgae species have been shown to remove pharmaceuticals. For instance, *Chlamydomonas* sp. Tai-03 was reported to remove 54.53% of ciprofloxacin and 100% of sulfadiazone (Xie et al. 2020). Also, *Haematococcus pluvialis* removed 84% of sulfamerazine, 74% of sulfamethoxazole, and 75% of sulfamonomethoxine (Kiki et al. 2020). Also, a range of microalgae species has been shown to contribute to the removal of personal care products, such as methylisothiazolinone, bisphenol A, clinambazole, and triclosan (Wang et al. 2013; Bai and Acharya 2016; Pan et al. 2018; Xie et al. 2020); hormones, such as progesterone, estrone, and estriol (Peng et al. 2014; Maes et al. 2014); pesticides, such as propamocarb, trichlorfon, and isoproturon (Dosnon-Olette et al. 2010; Ardal 2014; Wan et al. 2020); and surfactants, such as nonylphenol (He et al. 2016).

Fungal bioremediation has emerged as a more cost-effective and long-term solution. Studies have shown that fungi can digest a broad range of chemicals, including emerging contaminants created by human activities. In biopiles systems, the sludge being treated is combined with a bulking substance used as a co-substrate by the fungi and enhances aeration (Khan et al. 2004; Llorens-Blanch et al. 2018). Furthermore, the whit-rot fungus *Tinea versicolor* is capable of degrading a broad variety of organic contaminants through the intracellular system, such as cytochrome P450, and extracellular ligninolytic highly oxidative enzymes (Asgher et al. 2008; Yang et al. 2013; Rodriguez-Rodriguez et al. 2014).

### The role of extracellular polymeric substances in the removal of emerging contaminant

Extracellular polymeric substances are a complex combination of polymers released by microorganisms with a high molecular weight. Extracellular polymeric substances have a strong affinity for binding with organic pollutants, such as triclosan (Yan et al. 2019a), sulfamethazine (Xu et al. 2013), sulfonamides (Xu and Sheng 2020), phenanthrene (Bai et al. 2016), and heavy metals (Wei et al. 2017). Sorption of bisphenol A during the fermentation process takes place by sludge via strong binding to extracellular polymeric substances (Yan et al. 2019b), and subsequently biodegradation mechanism removal (Zhao et al. 2008). As Zhou et al. (2019) reported, triclocarban was partitioned onto the sludge. The removal of triclocarban mainly occurred due to the binding of the contaminant in sludge by extracellular polymeric enzymes (Yan et al. 2019b). Kindly check the section headings are correctly identified. yes, it is correctly identified.

### Anaerobic digestion and the circular economy

The goal of a circular economy is to reduce waste and increase the amount of recycling and reuse. Anaerobic digestion provides an appropriate scenario for the circular economy. Nutrient recycling and sustainable biosolids management difficulties may be solved through anaerobic digestion, which is considered environmentally friendly, protecting the environment and reusing the materials more wisely. Sustainable-renewable resources and fuels can be produced through anaerobic digestion. For instance, in 2016, 40% of food waste was processed to recover nutrients, and 32% was treated to recover both nutrients and energy (Fagerström et al. 2018). For a gas-powered automobile, 1200 kWh of biogas from one ton of food waste is needed for 1900 km. Also, a gas bus powered by food waste of 3000 families can run for a full year (Fagerström et al. 2018).

Additionally, anaerobic digestion is regarded as the most cost-effective biowaste treatment approach. Anaerobic digestion allows for the recovery of energy and the production of digestate rich in nutrients while reducing the natural consequences of waste transportation. Because of the high concentration of nutrients in the digestate derived from the raw materials, digestate is suitable for use as a fertilizer or organic amendment in agricultural operations (Wainaina et al. 2020).
Conclusion

The detection of emerging contaminants in nature has increased as detection technology has improved. Numerous emerging contaminants, such as personal care compounds, endocrine-disrupting chemicals, medicines, and converted products, whose presence at trace levels in treated wastewater poses a threat to human health and aquatic ecosystems. Despite this, little is known about the fate of these pollutants, how emerging pollutants interact with the environment, and the most effective methods for removing them from the environment. Anaerobic digestion has been studied as a potential method for removing these contaminants. The effect of extracellular polymeric enzymes on anaerobic digestion and the associated inhibitory mechanisms were thoroughly discussed. However, following treatment of these highly toxic and damaging pollutants, the concentration of their persistent transformation products is still limited, which needs to be a major focus in future studies. A funding declaration is mandatory for publication in this journal. Please confirm that this declaration is accurate, or provide an alternative.

Furthermore, combining multiple treatments to remove emerging pollutants may be more effective than single traditional technology. As a result, pretreatment procedures such as electro-oxidation, ultrasonication, thermal hydrolysis, and ozonation have been used to mitigate anaerobic digestion inhibition caused by emerging contaminants. Finally, future research should summarize all important factors influencing sewage sludge treatment with emerging pollutants. Kindly check the affiliations are correctly identified.

Acknowledgements The first author acknowledged the Science Technology Innovation Funding Agency (STIFA)—Egypt (Project ID: 41591) for fully financially supporting this research and bilateral research project between academy of Scientific Research and Technology (ASRT)-Egypt and National Natural Science Foundation of China. The first author is grateful to the National Research Centre-Egypt for partially supporting this research (Project ID: 12030202). Dr Ahmed I. Osman wishes to acknowledge the support of The Bryden Centre project (Project ID VA5048). The Bryden Centre project is supported by the European Union’s INTERREG VA Programme, managed by the Special EU Programmes Body (SEUPB).

Funding The authors have not disclosed any funding.

Declarations

Conflict of interest The views and opinions expressed in this review do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB). The authors declare no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Abad E, Martínez K, Planas C et al (2005) Priority organic pollutant assessment of sludges for agricultural purposes. Chemosphere 61:1358–1369. https://doi.org/10.1016/j.chemosphere.2005.03.018
Abdul M, Ihsanullah I, Ahmad R et al (2022a) Biohydrogen production from real industrial wastewater: potential bioreactors, challenges in commercialization and future directions. Int J Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2022.01.195
Abdul M, Ismail S, Ni S et al (2022b) Harvesting biohydrogen from industrial wastewater: production potential, pilot-scale bioreactors, commercialization status, techno-economics, and policy analysis. J Clean Prod 340:130809. https://doi.org/10.1016/j.jclepro.2022.130809
Afangha H, Zazou H, Titchou FE et al (2020) Integrated electrochemical processes for textile industry wastewater treatment: system performances and sludge settling characteristics. Sustain Environ Res 30:1–11. https://doi.org/10.1186/s42834-019-0043-2
Ahmad HA, Ahmad S, Cui Q et al (2022) The environmental distribution and removal of emerging pollutants, highlighting the importance of using microbes as a potential degrader: a review. Sci Total Environ 809:151926. https://doi.org/10.1016/j.scitotenv.2021.151926
Al Salah DMM, Laflite A, Poté J (2019) Occurrence of bacterial markers and antibiotic resistance genes in Sub-Saharan rivers receiving animal farm wastewaters. Sci Rep 9:14847. https://doi.org/10.1038/s41598-019-51421-4
Ali AM, Nesse AS, Eich-Greatorex S et al (2019) Organic contaminants of emerging concern in Norwegian digestates from biogas production. Environ Sci Process Impacts 21:1498–1508. https://doi.org/10.1039/C9EM00175A
Ali M, Danial A, Tawfik A (2017) Self-dark fermentation of lipids rich wastewater for 2-biofuels (H2 and Et-OH) production. Process Saf Environ Prot 109:257–267. https://doi.org/10.1016/j.prosper.2017.04.007
Ali M, Sreekrishnan TR (2001) Aquatic toxicity from pulp and paper mill effluents: a review. Adv Environ Res 5:175–196. https://doi.org/10.1016/S1093-0919(00)00055-1
Allam A, Tawfik A, Yoshimura C (2016) Phytoremediation of drain- age water containing mono ethylene glycol using a duckweed (lemna gibba) pond system. J Environ Eng 142:04016014. https://doi.org/10.1061/(ASCE)EE1.1943-7870.0001070
Anderson AG, Grose J, Pahl S et al (2016) Microplastics in personal care products: exploring perceptions of environmentalists, beauticians and students. Mar Pollut Bull 113:454–460. https://doi.org/10.1016/j.marpolbul.2016.10.048
Aparicio I, Santos JL, Alonso E (2009) Limitation of the concentration of organic pollutants in sewage sludge for agricultural purposes: a case study in South Spain. Waste Manag 29:1747–1753. https://doi.org/10.1016/j.wasman.2008.11.003
Archer E, Petrie B, Kasprzyk-Hordern B, Wollaardt GM (2017) The fate of pharmaceuticals and personal care products (PPCPs), endocrine disrupting contaminants (EDCs), metabolites and
illicit drugs in a WWTW and environmental waters. Chemosphere 174:437–446. https://doi.org/10.1016/j.chemosphere.2017.01.101

Ardal E (2014) Phycocoeometry of pesticides using microalgae. Asgher M, Bhatti HN, Ashraf M, Legge RL (2008) Recent developments in biodegradation of industrial pollutants by white rot fungi and their enzyme system. Biodegradation 19:771–783. https://doi.org/10.1007/s10532-008-9185-3

Ateia M, Ersan G, Alalm MG et al (2022) Emerging investigator series: microbial processes, fate, toxicity, detection, and interactions with micropolllutants in aquatic ecosystems—a review of reviews. Environ Sci Process Impacts 24:172–195. https://doi.org/10.1039/d1em00443c

Azizan NAZ, Yuzir A, Abdullah N (2021) Pharmaceutical compounds in anaerobic digestion: a review on the removals and effect to the process performance. J Environ Chem Eng 9:105926. https://doi.org/10.1016/j.jece.2021.105926

Azzam AM, Tawfik A (2015) Removal of heavy metals using bacterial bio-floculants of Bacillus sp. and Pseudomonas sp. J Environ Eng Landsc Manag 23:288–294. https://doi.org/10.3846/16848697.2015.1068781

Bachmann Pinto H, Miguel de Souza B, Dezotti M (2018) Treatment of a pesticide industry wastewater mixture in a moving bed biofilm reactor followed by conventional and membrane processes for water reuse. J Clean Prod 201:1061–1070. https://doi.org/10.1016/j.jclepro.2018.08.113

Badia-Fabregat M, Rodríguez-Rodríguez CE, Gago-Ferrero P et al (2012) Degradation of UV filters in sewage sludge and 4-MBC in liquid medium by the lignonolysis fungus Trametes versicolor. J Environ Manage 104:114–120. https://doi.org/10.1016/j.jenvman.2012.03.039

Bai L, Xu H, Wang C et al (2016) Extracellular polymeric substances facilitate the biosorption of phenanthrene on cyanobacteria Microcystis aeruginosa. Chemosphere 162:172–180. https://doi.org/10.1016/j.chemosphere.2016.07.063

Bai X, Acharya K (2016) Removal of trimethoprim, sulfamethoxazole, and triazolecon by the green alga Nannochloris sp. J Hazard Mater 315:70–75. https://doi.org/10.1016/j.jhazmat.2016.04.067

Barber WPF (2016) Thermal hydrolysis for sewage treatment: a critical review. Water Res 104:53–71. https://doi.org/10.1016/j.watres.2016.07.069

Barrioss JO, Becerril E, De LC et al (2015) Electrooxidation treatment for removal of emerging pollutants in wastewater sludge. Fuel 149:26–33. https://doi.org/10.1016/j.fuel.2014.10.055

Bassuney D, Tawfik A (2017) Baffled duckweed pond system for treatment of agricultural drainage water containing pharmaceuticals. Int J Phytoremediation 19:774–780. https://doi.org/10.1080/15226514.2017.1284756

Baun A, Ledin A, Reitzel LA et al (2004) Xenobiotic organic compounds in leachates from ten Danish MSW landfills - chemical analysis and toxicity tests. Water Res 38:3845–3858. https://doi.org/10.1016/j.watres.2004.07.006

Ben-David EA, Habibi M, Haddad E et al (2021) Microplastic distributions in a domestic wastewater treatment plant: Removal efficiency, seasonal variation and influence of sampling technique. Sci Total Environ 752:141880. https://doi.org/10.1016/j.scitotenv.2020.141880

Benz D, Paxéus NA, Ginn TR, Lole FJ (2005) Occurrence and fate of pharmaceutically active compounds in the environment, a case study: Höje River in Sweden. J Hazard Mater 122:195–204. https://doi.org/10.1016/j.jhazmat.2005.03.012

Benedetti B, Majone M, Cavaliere C et al (2020) Determination of multi-class emerging contaminants in sludge and recovery materials from waste water treatment plants: development of a modified QuEChERS method coupled to LC–MS/MS. Microchem J 155:104732. https://doi.org/10.1016/j.microc.2020.104732

Bergé A, Cladière M, Gasperi J et al (2012) Meta-analysis of environmental contamination by alkylphenols. Environ Sci Pollut Res 19:3798–3819. https://doi.org/10.1007/s11356-012-1094-7

Birch GF, Drage DS, Thompson K et al (2015) Emerging contaminants (pharmaceuticals, personal care products, a food additive and pesticides) in waters of Sydney estuary, Australia. Mar Pollut Bull 97:56–66. https://doi.org/10.1016/j.marpolbul.2015.06.038

Blair BD, Crago JP, Hedman CJ et al (2013) Evaluation of a model for the removal of pharmaceuticals, personal care products, and hormones from wastewater. Sci Total Environ 444:515–521. https://doi.org/10.1016/j.scitotenv.2012.11.103

Blanchard M, Teil MJ, Ollivon D et al (2004) Polycyclic aromatic hydrocarbons and polychlorobiphenyls in wastewaters and sewage sludges from the Paris area (France). Environ Res 95:184–197. https://doi.org/10.1016/j.envres.2003.07.003

Bougrier C, Delgenès JP, Carrère H (2008) Effects of thermal treatments on five different wastewater sludge samples solubilisation, physical properties and anaerobic digestion. Chem Eng J 139:236–244. https://doi.org/10.1016/j.cej.2007.07.099

Brooks BW, Turner PK, Stanley JK et al (2003) Waterborne and sediment toxicity of fluoxetine to select organisms. Chemosphere 52:135–142. https://doi.org/10.1016/S0045-6535(03)00103-6

Bui X-T, Vo T-D-H, Nguyen P-T et al (2020) Microplastics pollution in wastewater: characteristics, occurrence and removal technologies. Environ Technol Innov 19:101013. https://doi.org/10.1016/j.eti.2020.101013

Bulloch DN, Nelson ED, Carr SA et al (2015) Occurrence of halogenated transformation products of selected pharmaceuticals and personal care products in secondary and tertiary treated wastewaters from Southern California. Environ Sci Technol 49:2044–2051. https://doi.org/10.1021/acs.est.0504565n

Buttiglieri G, Knepper TP (2008) Removal of emerging contaminants in wastewater treatment: conventional activated sludge treatment. In: Barceló D, Petrovic M (eds) Emerging contaminants from wastewater. Springer

Carballa M, Manterola G, Larrea L et al (2007) Influence of ozone pre-treatment on sludge anaerobic digestion: removal of pharmaceutical and personal care products. Chemosphere 67:1444–1452. https://doi.org/10.1016/j.chemosphere.2006.10.004

Carrère H, Dumas C, Battimelli A et al (2010) Pretreatment methods to improve sludge anaerobic degradability: a review. J Hazard Mater 183:1–15. https://doi.org/10.1016/j.jhazmat.2010.06.129

Cascigioni S, Bagnati R, Fanelli R et al (2006) Removal of pharmaceuticals and transformation products in wastewater treatment plants in Italy. Environ Sci Technol 40:357–363. https://doi.org/10.1021/es050991m

Chang BV, Chiang F, Yuan SY (2005) Anaerobic degradation of nonylphenol in sludge. Chemosphere 59:1415–1420. https://doi.org/10.1016/j.chemosphere.2004.12.055

Chen G (2004) Electrochemical technologies in wastewater treatment. Sep Purif Technol 38:11–41. https://doi.org/10.1016/j.seppur.2003.10.006

Chen Y, Vymazal J, Březinová T et al (2016) Occurrence, removal and environmental risk assessment of pharmaceuticals and personal care products in rural wastewater treatment wetlands. Sci Total Environ 566:1660–1669. https://doi.org/10.1016/j.scitotenv.2016.06.069

Chen Y, Yang J, Liang S et al (2021) New insights into the debromination mechanism of non-metallic fractions of waste printed circuit boards via alkaline-enhanced subcritical water route. Resour Conserv Recycl 165:105227. https://doi.org/10.1016/j.resconrec.2020.105227

Chew KR, Leong HY, Khoo KS et al (2021) Effects of anaerobic digestion of food waste on biogas production and environmental impacts: a review. Environ Chem Lett 19:2921–2939. https://doi.org/10.1007/s10311-021-01220-z
Water Sci Technol 57:65–71. https://doi.org/10.2166/wst.2008.822

Olofsson U, Bigner A, Haglund P (2012) Time-trends of metals and organic contaminants in sewage sludge. Water Res 46:4841–4851. https://doi.org/10.1016/j.watres.2012.05.048

Palatucci ML, Waidner LA, Mack EE, Spain JC (2019) Aerobic bio-degradation of 2,3- and 3,4-dichloronitrobenzene. J Hazard Mater 378:120717. https://doi.org/10.1016/j.jhazmat.2019.05.110

Pan CG, Peng FJ, Ying GG (2018) Removal, biotransformation and toxicity variations of climbazole by freshwater algae Scenedesmus obliquus. Environ Pollut 240:534–540. https://doi.org/10.1016/j.envpol.2018.05.020

Papadopoulos KP, Argyriou R, Economou CN et al (2019) Treatment of printing ink wastewater using electrocoagulation. J Environ Manage 237:442–448. https://doi.org/10.1016/j.jenvman.2019.02.080

Paterakis N, Chiu TY, Koh YKK et al (2012) The effectiveness of anaerobic digestion in removing estrogens and nonylphenol ethoxylates. J Hazard Mater 199–200:88–95. https://doi.org/10.1016/j.jhazmat.2011.10.075

Patureau D, Delgenes N, Delgenes JP (2008) Impact of sewage sludge treatment processes on the removal of the endocrine disruptors nonylphenol ethoxylates. Chemosphere 72:586–591. https://doi.org/10.1016/j.chemosphere.2008.03.007

Peng FQ, Ying GG, Yang B et al (2014) Biotransformation of progesterone and norgestrel by two freshwater microalgae (Scenedesmus obliquus and Chlorella pyrenoidosa): transformation kinetics and products identification. Chemosphere 95:581–588. https://doi.org/10.1016/j.chemosphere.2013.10.013

Pérez S, Barceló D (2007) Application of advanced MS techniques to analysis and identification of human and microbial metabolites of pharmaceuticals in the aquatic environment. TrAC - Trends Anal Chem 26:494–514. https://doi.org/10.1016/j.trac.2007.05.004

Petrie B, Barden R, Kasprzyk-Hordern B (2015) A review on emerging contaminants in wastewaters and the environment: Current knowledge, understudied areas and recommendations for future monitoring. Water Res 72:3–27. https://doi.org/10.1016/j.watres.2014.08.053

Petrović M, González S, Barceló D (2003) Analysis and removal of emerging contaminants in wastewater and drinking water. TrAC - Trends Anal Chem 22:685–696. https://doi.org/10.1016/S0165-9936(03)00105-1

Pietrini F, Di Baccio D, Aceña J et al (2015) Ibuprofen exposure in Lenma gibba L.: evaluation of growth and phytotoxic indicators, detection of ibuprofen and identification of its metabolites in plant and in the medium. J Hazard Mater 300:189–193. https://doi.org/10.1016/j.jhazmat.2015.06.068

Pilli S, Bhunia P, Yan S et al (2011) Ultrasonic pretreatment of sludge: a review. Ultrason Sonochem 18:1–18. https://doi.org/10.1016/j.ultsonch.2010.02.014

Pokhrel D, Viraraghavan T (2004) Treatment of pulp and paper mill wastewater - a review. Sci Total Environ 333:37–58. https://doi.org/10.1016/j.scitotenv.2004.05.017

Radjenović J, Jelić A, Petrović M, Barceló D (2009) Determination of pharmaceuticals in sewage sludge by pressurized liquid extraction (PLE) coupled to liquid chromatography-tandem mass spectrometry (LC-MS/MS). Anal Bioanal Chem 393:1685–1695. https://doi.org/10.1007/s00216-009-2604-4

Rahman MM, Howlader MF, Hossain MA et al (2020) Impact assessment of anthropogenic activities on water environment of Tittalai River and its surroundings, Barapukuria Thermal Power Plant, Dinajpur, Bangladesh Groundw Sustain Dev 10:100310. https://doi.org/10.1016/j.gsd.2019.100310

Rawoof SAA, Kumar PS, Vo DVN, Subramanian S (2021) Sequen-tial production of hydrogen and methane by anaerobic digestion of organic wastes: a review. Environ Chem Lett 19:1043–1063. https://doi.org/10.1007/s10311-020-01122-6

Rebelein A, Int-Veen I, Kammann U, Scharsack JP (2021) Microplastic fibers — Underestimated threat to aquatic organisms? Sci Total Environ 777:146045. https://doi.org/10.1016/j.scitotenv.2021.146045

Reddy K, Renuka N, Kumari S, Bux F (2021) Algae-mediated processes for the treatment of antiretroviral drugs in wastewater: Prospects and challenges. Chemosphere 280:130674. https://doi.org/10.1016/j.chemosphere.2021.130674

Rivera-Utrilla J, Sánchez-Polo M, Ferro-García MA et al (2013) Pharmaceuticals as emerging contaminants and their removal from water. A Review Chemosphere 93:1268–1287. https://doi.org/10.1016/j.chemosphere.2013.07.059

Rodriguez-Rodriguez CE, Lucas D, Barón E et al (2014) Re-inoculation strategies enhance the degradation of emerging pollutants in fungal bioaugmentation of sewage sludge. Bioresour Technol 168:180–189. https://doi.org/10.1016/j.biortech.2014.01.124

Roh H, Chu KH (2011) Effects of solids retention time on the performance of bioreactors bioaugmented with a 17β-estradiol-utilizing bacterium, Sphingomonas strain KC8. Chemosphere 84:227–233. https://doi.org/10.1016/j.chemosphere.2011.04.029

Rosal R, Rodriguez A, Perdigón-Melón JA et al (2010) Occurrence of emerging pollutants in urban wastewater and their removal through biological treatment followed by ozonation. Water Res 44:578–588. https://doi.org/10.1016/j.watres.2009.07.004

Rout PR, Zhang TC, Bhunia P, Surampalli RY (2021) Treatment technologies for emerging contaminants in wastewater treatment plants: a review, Sci Total Environ 753:141990. https://doi.org/10.1016/j.scitotenv.2020.141990

Safwat SM (2020) Treatment of real printing wastewater using electrocoagulation process with titanium and zinc electrodes. J Water Process Eng 34:101137. https://doi.org/10.1016/j.watproce.2020.101137

Sage J, Schnitzer H (1994) Waste minimization and its ecological evaluation: a case study in printed circuit board manufacture. J Clean Prod 2:185–195. https://doi.org/10.1016/0959-6526(94)90042-6

Sahoo PK, Kim K, Powell MA (2016) Managing groundwater nitrate contamination from livestock farms: implication for nitrate management guidelines. Curr Pollut Reports 2:178–187. https://doi.org/10.1007/s40726-016-0033-5

Samaras VG, Stasinakis AS, Thomaidis NS et al (2014) Fate of selected emerging micropollutants during mesophilic, thermophilic and temperature co-phased anaerobic digestion of sewage sludge. Bioresour Technol 162:365–372. https://doi.org/10.1016/j.biortech.2014.03.154

Samil N, Fatima T (2019) Studies on estrone biodegradation potential of cyanobacterial species. Biocatal Agric Biotechnol 17:576–582. https://doi.org/10.1016/j.bcab.2019.01.022

Saravanan A, Kumar PS, Vo DVN et al (2021) Photocatalysis for removal of environmental pollutants and fuel production: a review. Environ Chem Lett 19:441–463. https://doi.org/10.1007/s10311-020-01077-8

Sekomo CB, Rousseau DPL, Saleh SA, Lens PNL (2012) Heavy metal removal in duckweed and algae ponds as a polishing step for textile wastewater treatment. Ecol Eng 44:102–110. https://doi.org/10.1016/j.ecoleng.2012.03.003

Senarathna DD, Abeyesoriya KN, Vithushana T, Dissanayake D (2021) Veterinary pharmaceuticals in aquaculture wastewater as emerging contaminant substances in aquatic environment and potential treatment method. MOJ Eco Envi Sci 6:98–102. https://doi.org/10.15406/mojes.2021.06.00221

Sharma KP, Sharma S, Sharma S et al (2007) A comparative study on characterization of textile wastewaters (untreated and treated) toxicity by chemical and biological tests. Chemosphere 69:48–54. https://doi.org/10.1016/j.chemosphere.2007.04.086

© Springer
1. Tawfik A, ElBatrawy O (2012) Anaerobic biodegradation of personnel care products (PCPs) wastewater in an up-flow anaerobic sludge blanket (UASB) reactor. Desalin Water Treat 41:232–239. https://doi.org/10.1080/19443994.2012.664719
2. Tawfik A, Elsamadony M (2017) Development of dry anaerobic technologies of bio-waste and unlock the barriers for valorization. In: Purohit HJ, Kalia VC, Vaidya AN, Khandenavis AA (eds) Optimization and applicability of bioprocesses. Springer, Singapore
3. Tawfik A, Hassan GK, Awad H et al (2021a) Strengthen “the sustainable farm” concept via efficacious conversion of farm wastes into methane. Bioresour Technol 341:125838. https://doi.org/10.1016/j.biortech.2021.125838
4. Tawfik A, Ismail S, Elsayed M et al (2022a) Sustainable microalgal biomass valorization to bioenergy: key challenges and future perspectives. Chemosphere 296:133812. https://doi.org/10.1016/j.chemosphere.2022.133812
5. Tawfik A, Ni S, Awad HM et al (2021b) Recent approaches for the production of high value-added biofuels from gelatinous wastewater. Energies 14:4936. https://doi.org/10.3390/en14164936
6. Tawfik A, Niaz H, Qadeer K et al (2022b) Valorization of algal cells for biomass and bioenergy production from wastewater: sustainable strategies, challenges, and techno-economic limitations. Renew Sustain Energy Rev 157:112024. https://doi.org/10.1016/j.rser.2021.112024
7. Tawfik A, Tenmink H, Zeeman G, Klapwijk B (2006) Sewage treatment in a rotating biological contactor (RBC) system. Water Air Soil Pollut 175:275–289. https://doi.org/10.1007/s11270-006-9138-6
8. Thompson MA, Mohajeri A, Mirkouei A (2021) Comparison of pyrolysis and hydrolysis processes for furfural production from sugar beet pulp: a case study in southern Idaho, USA. J Clean Prod 311:127695. https://doi.org/10.1016/j.jclepro.2021.127695
9. Tijani JO, Fatoba OO, Babajide OO, Petrik LF (2016) Pharmaceuticals, endocrine disruptors, personal care products, nanomaterials and perfluorinated pollutants: a review. Environ Chem Lett 14:27–49. https://doi.org/10.1007/s10311-015-0537-z
10. Tijani JO, Fatoba OO, Petrik LF (2013) A review of pharmaceuticals and endocrine-disrupting compounds: sources, effects, removal, and detections. Water, Air, Soil Pollut 224:1770. https://doi.org/10.1007/s11270-013-1770-3
11. Tun drużyn S, Akçakaya M, Kegen B (2022) Oxonation of sewage sludge prior to anaerobic digestion led to Methanoseta dominated biomethanation. Fuel 313:122690. https://doi.org/10.1016/j.fuel.2021.122690
12. Tyagi VK, Ali M, Tawfik A et al (2021) Future perspectives of energy saving down-flow hanging sponge (DHS) technology for wastewater valorization—a review. Rev Environ Sci Bio/technology 20:389–418. https://doi.org/10.1007/s10311-021-09573-1
13. Vilar VIP, Moreira FC, Ferreira ACC et al (2012) Biodegradability enhancement of a pesticide-containing bio-treated wastewater using a solar photo-Fenton treatment step followed by a biological oxidation process. Water Res 46:4599–4613. https://doi.org/10.1016/j.watres.2012.06.038
14. Wainaina S, Awasthi MK, Sasaiya S et al (2020) Resource recovery and circular economy from organic solid waste using aerobic and anaerobic digestion technologies. Bioresour Technol 301:122778. https://doi.org/10.1016/j.biortech.2020.122778
15. Wang L, Wu Y, Ding H, Zhang W (2020) Toxicity, biodegradation, and metabolic fate of organophosphorus pesticide trichlorfon on the freshwater algae chlamydomonas reinhardtii. J Agric Food Chem 68:1645–1653. https://doi.org/10.1021/acs.jafc.9b05765
16. Wang R, Li F, Ruan W et al (2020) Removal and degradation pathway analysis of 17β-estradiol from raw domestic wastewater using
immobilised functional microalgae under repeated loading. Biochem Eng J 161:107700. https://doi.org/10.1016/j.bej.2020.107700

Wang S, Wang X, Poon K et al (2013) Removal and reductive dechlorination of tricosan by Chlorella pyrenoidosa. Chemosphere 92:1498–1505. https://doi.org/10.1016/j.chemosphere.2013.03.067

Wang Y, Wang D, Liu Y et al (2017) Triclocarban enhances short-chain fatty acids production from anaerobic fermentation of waste activated sludge. Water Res 127:150–161. https://doi.org/10.1016/j.watres.2017.09.062

Wei L, Li Y, Noguera DR et al (2017) Adsorption of Cu2+ and Zn2+ by extracellular polymeric substances (EPS) in different sludges: Effect of EPS fractional polarity on binding mechanism. J Hazard Mater 321:473–483. https://doi.org/10.1016/j.jhazmat.2016.05.016

Wilson CA, Novak JT (2009) Hydrolysis of macromolecular components of primary and secondary wastewater sludge by thermal hydrolytic pretreatment. Water Res 43:4489–4498. https://doi.org/10.1016/j.watres.2009.07.022

Xie P, Chen C, Zhang C et al (2020) Revealing the role of adsorption in ciprofloxacin and sulfadiazine elimination routes in microalgae. Water Res 172:115475. https://doi.org/10.1016/j.watres.2020.115475

Xie Y, Liu X, Wei H et al (2022) Insight into impact of sewage discharge on microbial dynamics and pathogenicity in river ecosystem. Sci Rep 12:6894. https://doi.org/10.1038/s41598-022-09579-x

Xiu FR, Li Y, Qi Y et al (2019) A novel treatment of waste printed circuit boards by low-temperature near-critical aqueous ammonia: Debromination and preparation of nitrogen-containing fine chemicals. Waste Manag 84:355–363. https://doi.org/10.1016/j.wasman.2018.12.010

Xu J, Cui Q, Bu C et al (2022) Partition of anammox and nitrifiers through bio-carriers for full-scale sidestream partial nitrification-anammox plant. Front Bioeng Biotechnol 10:1–9. https://doi.org/10.3389/fbioe.2022.819937

Xu J, Sheng GP (2020) Microbial extracellular polymeric substances (EPS) acted as a potential reservoir in responding to high concentrations of sulfonamides shocks during biological wastewater treatment. Bioresour Technol 313:123654. https://doi.org/10.1016/j.biortech.2020.123654

Xu J, Sheng GP, Ma Y et al (2013) Roles of extracellular polymeric substances (EPS) in the migration and removal of sulfamethazine in activated sludge system. Water Res 47:5298–5306. https://doi.org/10.1016/j.watres.2013.06.009

Xu X, Hou Q, Xue Y et al (2018) Pollution characteristics and fate of microfibres in the wastewater from textile dying wastewater treatment plant. Water Sci Technol 78:2046–2054. https://doi.org/10.2166/wst.2018.476

Yan Z, Meng HD, Yang XY et al (2019a) Insights into the interactions between triclosan (TCS) and extracellular polymeric substance (EPS) of activated sludge. J Environ Manage 232:219–225. https://doi.org/10.1016/j.jenvman.2018.11.059

Yan Z, Zhu YY, Meng HS et al (2019b) Insights into thermodynamic mechanisms driving bisphenol A (BPA) binding to extracellular polymeric substances (EPS) of activated sludge. Sci Total Environ 677:502–510. https://doi.org/10.1016/j.scitotenv.2019.04.043

Yang S, Hai FL, Nghiem LD et al (2013) Understanding the factors controlling the removal of trace organic contaminants by white-rot fungi and their lignin modifying enzymes: A critical review. Bioresour Technol 141:97–108. https://doi.org/10.1016/j.biortech.2013.01.173

Zenker A, Cicero MR, Prestinaci F et al (2014) Bioaccumulation and biomagnification potential of pharmaceuticals with a focus to the aquatic environment. J Environ Manage 133:378–387. https://doi.org/10.1016/j.jenvman.2013.12.017

Zeyad MT, Kumar M, Malik A (2019) Mutagenicity, genotoxicity and oxidative stress induced by pesticide industry wastewater using bacterial and plant bioassays. Biotechnol Reports 24:e00389. https://doi.org/10.1016/j.btre.2019.e00389

Zhang H, Khanal SK, Jia Y et al (2019) Fundamental insights into ciprofloxacin adsorption by sulfate-reducing bacteria sludge: Mechanisms and thermodynamics. Chem Eng J 378:122103. https://doi.org/10.1016/j.cej.2019.122103

Zhang MY, Teng Y, Zhu Y et al (2014) Isolation and characterization of chlorothalonil-degrading bacterial strain b4 and its potential for remediation of contaminated soil. Pedsosphere 24:799–807. https://doi.org/10.1016/S1002-0160(14)60067-9

Zhang S, Zhang P, Zhang G et al (2012) Enhancement of anaerobic sludge digestion by high-pressure homogenization. Bioresour Technol 118:496–501. https://doi.org/10.1016/j.biorenew.2012.05.089

Zhang Y, Wu D, Su Y, Xie B (2021) Occurrence, influence and removal strategies of mycotoxins, antibiotics and microplastics in anaerobic digestion treating food waste and co-digestive biosolids: a critical review. Bioresour Technol 330:124987. https://doi.org/10.1016/j.biortech.2021.124987

Zhang Y, Zhou T, Duan J et al (2013) Inhibition of P-glycoprotein and Glutathione S-transferase–pi mediated resistance by fluoxetine in MCF-7/ADM cells. Biomed Pharmacother 67:757–762. https://doi.org/10.1016/j.biopha.2013.04.012

Zhao J, Gui L, Wang Q et al (2017) Aged refuse enhances anaerobic digestion of waste activated sludge. Water Res 123:724–733. https://doi.org/10.1016/j.watres.2017.07.026

Zhao J, Li Y, Zhang C et al (2008) Sorption and degradation of bisphenol A by aerobic activated sludge. J Hazard Mater 155:305–311. https://doi.org/10.1016/j.jhazmat.2007.11.075

Zhao J, Zhang J, Zhang D et al (2021a) Effect of emerging pollutant fl uoxetine on the excess sludge anaerobic digestion. Sci Total Environ 752:141932. https://doi.org/10.1016/j.scitotenv.2020.141932

Zhao M, Xu J, Xue H et al (2021b) Improving hydrogen recovery from anaerobic co-digestion of algae and food waste by high-pressure homogenisation pre-treatment. Environ Chem Lett 19:3489–3504. https://doi.org/10.1007/s10311-021-01234-7

Zhou G, Lin L, Li X et al (2020a) Removal of emerging contaminants from wastewater during chemically enhanced primary sedimentation and acidogenic sludge fermentation. Water Res 175:115646. https://doi.org/10.1016/j.watres.2020.115646

Zhou GJ, Li XY, Leung KMY (2019) Retinoids and oestrogenic endocrine disrupting chemicals in saline sewage treatment plants: Removal efficiencies and ecological risks to marine organisms. Environ Int 133:378–387. https://doi.org/10.1016/j.envint.2019.03.030

Zhou H, Zhou L, Ma K (2020b) Microfiber from textile dying and printing wastewater of a typical industrial park in China: Occurrence, removal and release. Sci Total Environ 739:141932. https://doi.org/10.1016/j.scitotenv.2020.141932

Zhou NA, Latovska AC, Andaker GL et al (2014) Kinetics modeling predicts bioaugmentation with Sphingomonad cultures as a viable technology for enhanced pharmaceutical and personal care products removal during wastewater treatment. Bioresour Technol 166:158–167. https://doi.org/10.1016/j.biortech.2014.05.020

Zou I, Fu L, Jin C et al (2019) Study on the isolation of two atrazine-degrading bacteria and the development of a microbial agent. Microorganisms 7:1–11. https://doi.org/10.3390/microorganisms7030080

Zhu P, Chen D, Liu W et al (2014) Hydroxylation and hydrolysis: Two main metabolic ways of spiramycin I in anaerobic digestion.
Bioresour Technol 153:95–100. https://doi.org/10.1016/j.biortech.2013.11.073
Zorita S, Mårtensson L, Mathiasson L (2009) Occurrence and removal of pharmaceuticals in a municipal sewage treatment system in the south of Sweden. Sci Total Environ 407:2760–2770. https://doi.org/10.1016/j.scitotenv.2008.12.030

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.