# Pharmaceutical and Personal Care Products (PPCPs) in the environment: Plant uptake, translocation, bioaccumulation, and human health risks

S. Keerthanan, Chamila Jayasinghe, Jayanta Kumar Biswas & Meththika Vithanage

Published online: 06 May 2020.

Submit your article to this journal ⇗

View related articles ⇗

Taylor & Francis
Taylor & Francis Group

Check for updates

# Pharmaceutical and Personal Care Products (PPCPs) in the environment: Plant uptake, translocation, bioaccumulation, and human health risks
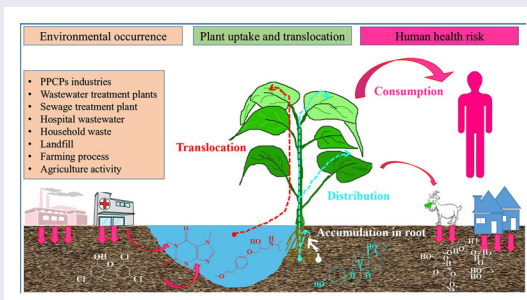
S. Keerthanan[a], Chamila Jayasinghe[b], Jayanta Kumar Biswas[c], and Meththika Vithanage[a] (iD)

[a]Ecosphere Resilience Research Center, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka; [b]Department of Food Science and Technology, Faculty of Livestock, Fisheries and Nutrition, Wayamba University of Sri Lanka, Gonawila, Sri Lanka; [c]Enviromicrobiology, Ecotoxicology and Ecotechnology Research Laboratory, Department of Ecological Studies, and International Centre for Ecological Engineering, University of Kalyani, Kalyani, West Bengal, India

## ABSTRACT

Pharmaceutical and personal care products (PPCPs) are considered as emerging contaminants (ECs) in the environment due to their known or suspected adverse ecological effects and human health risks. Wastewater, compost, and manure application release PPCPs into the agricultural soil systems. Since the plants can take up such ECs, they are considered as a primary window of human exposure to the PPCPs via the route of consumption of contaminated plants. This may lead to deleterious human health effects. However, as PPCPs are of various kinds, differential uptake and bioaccumulation in the plant have recently received research interest. Therefore, the present article reviewed the occurrence of PPCPs as antibiotics, anti-inflammatory drugs, hormones, cytostatic drugs, contrast media, β-blockers, blood lipid regulators, antiepileptic drugs, antimicrobials, ultra-violet filters, preservatives, insect repellents, and synthetic musks in the environment by assembling the literature. Moreover, plant uptake and translocation under the realistic and greenhouse condition, and the factors influencing the uptake and translocation through the plants are explicitly demonstrated in this review. Also, the human risk connected with the consumption of the contaminated plants and the research gap areas were investigated with future perspectives.

## 1. Introduction

Pharmaceuticals and Personal Care Products (PPCPs) are a group of chemical substances that are being widely used for human health, cosmetic,

CONTACT Meththika Vithanage ✉ meththika@sjp.ac.lk 🖴 Ecosphere Resilience Research Center, Faculty of Applied Sciences, University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

agriculture, and veterinary purposes. They are ubiquitously found in the water and soil environment throughout the world and have been implied for causing deleterious effects on human and non-target organisms (Liu & Wong, 2013; Wu et al., 2010). Recently, numerous studies have reported the presence of PPCPs in wastewater (Yang et al., 2017), groundwater (Balakrishna et al., 2017), surface water (Balakrishna et al., 2017), drinking water (Odendaal et al., 2015), soil (Boxall et al., 2006) and sludge (Cortés et al., 2013) arising from the usage of wastewater irrigation, biosolids, and manure application to agricultural soils which may result in the uptake of PPCPs into crops (Christou et al., 2019; Madikizela et al., 2018). Various sources have been identified for contributing PPCPs to the environment, including effluent from the wastewater and sewage treatment plants, household and hospital wastewater discharge, agricultural manure application, and farming activities (Evgenidou et al., 2015; Tasho & Cho, 2016). Most recently, the first nationwide investigation on surface water bodies in Sri Lanka reported 41 PPCPs in the range of 5.49 and 993 ng/L in water sources that abstract drinking water for the general public (Guruge et al., 2019).

In recent years, research publications have focused their special attention on plant uptake, translocation, and accumulation of PPCPs due to the inability of conventional water treatment systems to remove those ECs. Increased emphasis on biosolid and compost application to improve soil quality and urban and rooftop farming further provided opportunities for uptake of PPCPs by plants (Ahmed et al., 2015; Madikizela et al., 2018; Tasho & Cho, 2016; Wu et al., 2014; Zhang et al., 2017). Wastewater irrigation may introduce the PPCPs into the agricultural farmlands. For instance, the wastewater irrigation as a source of PPCPs loaded significant quantity of PPCPs including carbamazepine (4.4 μg/kg), chloramphenicol (2.7 μg/kg), gemfibrozil (0.98 μg/kg), N,N-diethyl-meta-toluamide (DEET) (0.68 μg/kg), and caffeine (2.9 μg/kg) to the soil surface (Ma et al., 2018).

Recently, sorption, plant uptake, and metabolism of benzodiazepines by *Raphanus sativus* and *Beta vulgaris* have been documented by Carter et al. (2018). Moreover, Ben Mordechay et al. (2018) have presented the data on uptake, translocation, and metabolism of carbamazepine by tomato, wheat, and lettuce. A contemporary hydroponic study detected sulfamethoxazole and trimethoprim at various concentrations in tomato fruit cultivated under controlled conditions (Christou et al., 2019). Similarly, another hydroponic study was undertaken by Chuang et al. (2019) to investigate the uptake and translocation of PPCPs in lettuce. Furthermore, some research articles assessed plant uptake of PPCPs (Ben Mordechay et al., 2018; Bhalsod et al., 2018; Riemenschneider et al., 2017). For example, the uptake, translocation, and transformation of pharmaceuticals in hydroponically grown intact tomato plants have been investigated (Riemenschneider

et al., 2017). A case study has been reported the effect of treated wastewater and composted biosolids on plant uptake of PPCPs (Ben Mordechay et al., 2018). The accumulation of pharmaceuticals in greenhouse lettuce have been investigated under the overhead and soil surface irrigation with pharmaceuticals contaminated water (Bhalsod et al., 2018). Further, the translocation of PPCPs in tomato plant irrigated with reclaimed water and its human risk was assessed under the field condition (Martínez-Piernas et al., 2019).

The dietary intake of PPCPs contaminated vegetables and fruits can cause a potentially harmful impact on human health. The daily consumption of PPCPs (especially antibiotics) contaminated vegetables can develop antibiotic-resistant pathogens in the human body, leaving humans at high risk of complex health complications. Further, some other medical issues, such as a weak estrogenic activity, immediate systemic hypersensitivity reactions, and inhibition of the enzyme responsible for the activity of the central nervous system have also been reported (Stuart et al., 2012). The plant uptake of PPCPs from the environment has created special attention over a decade. Only a limited number of reviews have been published, and the uptake data presented are limited to specific groups of PPCPs by plants (Al-Farsi et al. 2017; Madikizela et al., 2018; Tasho & Cho, 2016; Wu et al., 2015). These reviews are more focused on pharmaceuticals; however, lack of data is reported on personal care products (PCPs) and, together, lack of risk assessment data resulting in a vast knowledge gap.

Furthermore, the data on the plant uptake of personal care products have been on track recently due to their emerging concerns in the research area, which accounts the gap between this review and the previous works. Although PPCPs are essential in the modern life of the human, they pose serious environmental problems owing to their use, misuse, overuse, and uncontrolled disposal. It is essential to feed the knowledge and sensitize the ordinary people about the environmental implications and human health risks arising from the usage of PPCPs. The usage and the discharge of PPCPs into the environment have been increasing day by day with mounting environmental concerns. Therefore, the present paper attempts a comprehensive review based on the recently published peer-reviewed review and research articles, which reported the environmental occurrence, plant uptake and translocation, and human risk of PPCPs. Thus, the goals of this review are, to point out the occurrence of various groups of PPCPs in the environment, and their uptake, translocation, and bioaccumulation in the plant issues under the simulated greenhouse and realistic environmental conditions. Further, the human health effects of PPCPs exposure through ingesting the contaminated crops and vegetables are discussed here. Besides, the analysis methods to determine the PPCPs in the plant tissues and the current issues and future scope also discussed.

## 2. Types of pharmaceutical and personal care products

PPCPs including pharmaceutical products, for instance, antibiotics, anti-inflammatory drugs, hormones, cytostatic drugs, contrast media, β-blockers, blood lipid regulators, and antiepileptic drugs, and personal care products (PCPs), such as antimicrobials, ultra-violet filters, preservatives, insect repellents, and synthetic musks are the collection of chemical substances used in daily activities of human life (Liu & Wong, 2013). Antibiotics are being used as animal and human therapeutic medicines for the prevention and treatment of bacterial diseases; hence these are biologically active compounds (Pan & Chu, 2017). Recently antibiotics are being considered as emerging contaminants in the environment, and it is frequently reported because of the fact that the occurrence of antibiotics in the environment is a major threat for human and animal health as it may often lead to the development of antibiotic-resistant bacteria. These are mainly classified into many categories including tetracyclines (tetracycline, oxytetracycline, and chlortetracycline), sulfonamides (sulfachlorpyridazine, sulfadimidine, sulfadiazine, etc.), quinolone (ciprofloxacin, enrofloxacin, etc.), macrolide (erythromycin, tylosin, etc.), trimethoprim, thiamphenicol, chloramphenicol, lincomycin, and clindamycin (Jiang et al., 2014; Pan & Chu, 2017).

Anti-inflammatory drugs (such as Ibuprofen, Diclofenac, Acetaminophen, Indomethacin Aspirin, Naproxen, Nimesulide, Phenazone, and Ketoprofen) are also widely used as pharmaceutical products, and they are frequently found in the environment due to their unwarranted use (Lonappan et al., 2016; Veras et al., 2019). Further, the synthetic hormones (for instance, ethinylestradiol) (Gogoi et al., 2018), cytostatic drugs (examples, ifosfamide, and cyclophosphamide) (Liu & Wong, 2013), contrast media (iopromide, iomeprol, and diatrizoate) (Wang & Wang, 2016) are widely used pharmaceutical products detected in the environment. The β-blockers, including atenolol, metoprolol, nadolol, pindolol, acebutolol, and propranolol prescribed worldwide, also detected in the environment frequently. Moreover, the blood lipid regulators (such as Gemfibrozil) (Yang et al., 2017), antiepileptic drugs (such as Dilantin, Primidone, and Carbamazepine) (Madikizela et al., 2018), stimulant drugs (caffeine) also observed in the environment from ten of μg/L to thousands of ng/L.

The PPCPs including antimicrobials (triclocarban and triclosan), UV-filters (Oxybenzone, Enzacamene, and Sulisobenzone) (Aparicio et al., 2018; Ebele et al., 2017) are used in the daily lifespan to improve the quality of life. These reported in the environment due to the lack of technology to remove from the wastewater. Moreover, the preservatives (butylparaben, methylparaben, and propylparaben) (Yang et al., 2017), are widely applied to preserve the cosmetics, food, and pharmaceutical products also detected in the environment. Also, the insect repellents (DEET) (Murray et al., 2010), synthetic

musk (divided into nitro musks and polycyclic musks; polycyclic musks such as galaxolide (HHCB) being applied more frequently in a recent year than nitro musks) found in the environment in a range of few µg/L to ng/L. Another widely available PCPs is plasticizers, which are primarily used in cosmetics, shampoo, hair spray and gel, and plastic bottled water. Phthalate compounds such as bis(2-ethylhexyl)phthalate (BEPH) and di-n-butylphthalate (DBP) are the mostly used plasticizers (Saeidnia & Abdollahi, 2013). The artificial sweeteners, for, instance sucralose, saccharin, and acesulfame are another type of PCPs which are utilized to enhance the taste food during the food manufacturing process (Subedi et al., 2015). The perfluoroalkyl substances (PFASs) such as perfluorooctanesulfonate (PFOS), perfluorooctanoate (PFOA), perfluoropentanoate (PFPeA), perfluorohexanoate (PFHxA), perfluorodecanoate (PFDA), etc. are used as a surface activator used in the packaging, textiles, and paper industries, household-cleaning products, agricultural activities, cosmetic products, medical devices, etc. due to their hydrophilic and hydrophobic behaviors (Li et al., 2020; Shigei et al., 2020). The types of PPCPs and their physicochemical properties are displayed in Table 1.

## 3. Occurrence and persistence of PPCPs in the environment

The water and soil system are the critical reservoirs of PPCPs in the environment. As demonstrated in Figure 1, the introduction of PPCPs into the environment occurs through domestic and commercial sources. The domestic sources include landfills of urban solids, disposal of household wastes, animals, and human excretions (Madikizela et al., 2018; Yang et al., 2017), agricultural application of PPCPs laden manure. The commercial source includes effluent of water and sewage treatment plants, drug manufacturing processes, pharmaceutical companies (Tasho & Cho, 2016), and hospital wastes and effluents (Evgenidou et al., 2015), which may add an enormous quantity of PPCPs into the aquatic and soil ecosystem. The sewage treatment plants and water treatment plants are the primary pathway that introduces the PPCPs in the environment. Recently different types of PPCPs, including antibiotics, anti-inflammatory drugs, β-blockers, hormones, lipid regulators, were detected in the effluent from the sewage and water treatment plants (Hong et al., 2019; Tarpani & Azapagic, 2018; Yang et al., 2017). Moreover, PPCPs are frequently entered into bodies of humans and animals and are subjected to metabolic transformations. However, they do not undergo the complete metabolism, and are, therefore, excreted to the environment as either metabolites or unchanged form of PPCPs through the urine and feces (Tasho & Cho, 2016; Zhou et al., 2013). Furthermore, usage of life enhancement products, such as cosmetics, detergents, soap, sun-creams, toothpaste, perfumes, etc. leads to the

**Table 1.** Physiochemical profile of selected PPCPs.

| PPCPs | Molecular weight, g/mol | Chemical formula | Degradation half-life | Solubility mg/L | log Kow[s] | pka |
|---|---|---|---|---|---|---|
| Antibiotics | | | | | | |
| Tetracycline[a] | 444.43 | $C_{22}H_{24}N_2O_8$ | 19 days[x] | 231 | −1.3 | 3.3 |
| Oxytetracycline[a] | 460.43 | $C_{22}H_{24}N_2O_9$ | 17 days[x] | 313 | −0.9 | 3.27 |
| Chlortetracycline[a] | 478.88 | $C_{22}H_{23}ClN_2O_8$ | 18 days[x] | 288 | −0.62[q] | – |
| Sulfachlorpyridazine[b] | 284.72 | $C_{10}H_9ClN_4O_2S$ | | 133 | 1.30[r] | – |
| Sulfamethazine[c] | 278.33 | $C_{12}H_{14}N_4O_2S$ | 576 h[v] | 1500 | 0.89 | 7.59 |
| Sulfamethoxazole[b] | 253.28 | $C_{10}H_{11}N_3O_3S$ | 2 days[u] | 610 | 0.89[r] | 5.7[a] |
| Sulfadiazine[b] | 250.28 | $C_{10}H_{10}N_4O_2S$ | 42 h[y] | 77 | 0.39[r] | 6.36 |
| Ciprofloxacin[b] | 331.34 | $C_{17}H_{18}FN_3O_3$ | 378 h[v] | <1mg/mL | 0.28[r] | 6.09 |
| Enrofloxacin[b] | 359.40 | $C_{19}H_{22}FN_3O_3$ | 77 days[x] | 53.9 µg/mL[q] | 0.44[r] | – |
| Difloxacin[b] | 399.40 | $C_{21}H_{19}F_2N_3O_3$ | 06 days[x] | – | 0.89[q] | – |
| Flumequine[b] | 261.25 | $C_{14}H_{12}FNO_3$ | – | – | 1.6[q] | 6.5[q] |
| Norfloxacin[b] | 319.33 | $C_{16}H_{18}FN_3O_3$ | 363 h[v] | 1.78E + 005 | 0.46[r] | 6.34, 8.75[q] |
| Ofloxacin[b] | 361.37 | $C_{18}H_{20}FN_3O_4$ | 06 days[x] | 28.3 | −0.39[r] | 5.97, 9.28[q] |
| Pefloxacin[b] | 333.36 | $C_{17}H_{20}FN_3O_3$ | – | 11.4 | 0.27 | – |
| Roxithromycin[d] | 837.05 | $C_{41}H_{76}N_2O_{15}$ | 2.4–10 days[w] | 0.0189 | 2.75[r] | – |
| Tylosin[d] | 916.10 | $C_{46}H_{77}NO_{17}$ | | – | 1.63[q] | 7.73[q] |
| Erythromycin[d] | 733.93 | $C_{37}H_{67}NO_{13}$ | 2.4–10 days[w] | 2000 | 3.06[q] | 8.88 |
| Clarithromycin[e] | 747.95 | $C_{38}H_{69}NO_{13}$ | – | 0.33 | 3.16[r] | 8.99 |
| Trimethoprim[f] | 290.32 | $C_{14}H_{18}N_4O_3$ | **/**[v] | 400 | 0.79[r] | 7.12 |
| Thiamphenicol[e] | 356.22 | $C_{12}H_{15}Cl_2NO_5S$ | – | – | −0.27[q] | – |
| Chloramphenicol[g] | 323.13 | $C_{11}H_{12}Cl_2N_2O_5$ | – | 2500 | 1.14 | – |
| Lincomycin[h] | 406.54 | $C_{18}H_{34}N_2O_6S$ | – | 927[h] | 0.56 | 7.6[q] |
| Clindamycin[h] | 424.98 | $C_{18}H_{33}ClN_2O_5S$ | – | 30.6 | 2.16 | 7.6[q] |
| Anti-inflammatory drugs | | | | | | |
| Ibuprofen[i] | 206.28 | $C_{13}H_{18}O_2$ | 01 day[u] | 21 | 3.97 | 5.3 |
| Diclofenac[i] | 296.15 | $C_{14}H_{11}Cl_2NO_2$ | 3 or 4 days[u] | 2.37 | 4.51 | 4.15 |
| Acetaminophen[i] | 151.16 | $C_8H_9NO_2$ | 674 h[v] | 1.4E + 004 | 0.91 | 9.38[q] |
| Aspirin[i] | 180.16 | $C_9H_8O_4$ | – | 4600 | 1.18 | 3.5 |
| Indomethacin[i] | 357.79 | $C_{19}H_{16}ClNO_4$ | – | 0.937 | 4.27 | 4.5 |
| Naproxen[i] | 230.26 | $C_{14}H_{14}O_3$ | **[v] | 15.9 | 3.18 | 4.15 |
| Nimesulide[i] | 308.31 | $C_{13}H_{12}N_2O_5S$ | – | – | 2.6 | – |
| Phenazone[i] | 188.23 | $C_{11}H_{12}N_2O$ | – | 5.19E + 004 | 0.38 | 1.4 |
| Ketoprofen[i] | 254.28 | $C_{16}H_{14}O_3$ | **[v] | 51 | 3.12 | 4.45 |
| Synthetic hormone | | | | | | |
| Ethinylestradiol[j] | 296.40 | $C_{20}H_{24}O_2$ | – | 11.3 | 3.67 | 1.7[a] |
| Stimulant drug | | | | | | |
| Caffeine | 194.19 | $C_8H_{10}N_4O_2$ | **[v] | 2.17 g/100 mL | −0.07 | 14 |
| Cytostatic drugs | | | | | | |
| Ifosfamide[k] | 261.09 | $C_7H_{15}Cl_2N_2O_2P$ | – | 3780 | 0.86c | – |
| Cyclophosphamide[k] | 261.09 | $C_7H_{15}Cl_2N_2O_2P$ | – | 1–5 g/100 mL | 0.8 | – |
| Contrast media | | | | | | |
| Iopromide[i] | 791.11 | $C_{18}H_{24}I_3N_3O_8$ | – | – | −2.05[q] | >10.6[t] |
| Iomeprol[i] | 777.09 | $C_{17}H_{22}I_3N_3O_8$ | – | – | −2.79[q] | >11.3[t] |
| Diatrizoate[i] | 613.91 | $C_{11}H_9I_3N_2O_4$ | – | – | 3.3 | 1.13, 7.95[q] |
| β-blockers | | | | | | |
| Atenolol[i] | 266.34 | $C_{14}H_{22}N_2O_3$ | **[v] | 1.33E + 004 | 0.16 | 9.6 |
| Metoprolol[i] | 267.36 | $C_{15}H_{25}NO_3$ | 861 h[v] | – | 2.15 | 9.7 |
| Nadolol[i] | 309.40 | $C_{17}H_{27}NO_4$ | 2 or 3 days[u] | 8330 | 0.81 | 9.67 |
| Pindolol[i] | 248.32 | $C_{14}H_{20}N_2O_2$ | – | 7880 | 1.75 | 9.25 |
| Acebutolol[i] | 336.43 | $C_{18}H_{28}N_2O_4$ | – | 259 | 1.71 | – |
| Propranolol[i] | 259.34 | $C_{16}H_{21}NO_2$ | 255 h[v] | 61.7 | 3.48 | 9.42 |
| Sotalol[i] | 272.36 | $C_{12}H_{20}N_2O_3S$ | – | 5510 | 0.24[q] | – |
| Blood lipid regulators | | | | | | |
| Gemfibrozil[g] | 250.33 | $C_{15}H_{22}O_3$ | 4 or 3 days[u] | 10 mg/mL | 3.4 | 4.5[q] |
| Antiepileptic drugs | | | | | | |
| Dilantin[a] | 252.27 | $C_{15}H_{12}N_2O_2$ | – | 32 | 2.47 | 8.33 |
| Primidone[a] | 218.25 | $C_{12}H_{14}N_2O_2$ | – | 500 | 0.91 | 12.3[q] |
| Carbamazepine[a] | 236.27 | $C_{15}H_{12}N_2O$ | **[u, v] | 17.7 | 0.91 | 13.9[q] |

(*continued*)

**Table 1.** Continued.

| PPCPs | Molecular weight, g/mol | Chemical formula | Degradation half-life | Solubility mg/L | log Kow[s] | pka |
|---|---|---|---|---|---|---|
| Antimicrobials | | | | | | |
| Triclocarban[l] | 315.58 | $C_{13}H_9Cl_3N_2O$ | **[v] | Insoluble | 4.34[q] | 12.7[q] |
| Triclosan[l] | 289.54 | $C_{12}H_7Cl_3O_2$ | 866 h[v] | – | 4.76[q] | 7.9 |
| UV-Filters | | | | | | |
| Oxybenzone[m] | 228.24 | $C_{14}H_{12}O_3$ | – | – | 3.79 | 7.1[q] |
| Sulisobenzone[m] | 308.30 | $C_{14}H_{12}O_6S$ | – | 10 μg/mL | 0.37[q] | −2.4, 7.6[q] |
| Enzacamene[n] | 254.37 | $C_{18}H_{22}O$ | – | Poorly soluble | – | – |
| Preservatives | | | | | | |
| Propylparaben[g] | 180.20 | $C_{10}H_{12}O_3$ | – | – | 3.04[q] | 8.5[q] |
| Butylparaben[g] | 194.23 | $C_{11}H_{14}O_3$ | – | – | 3.57[q] | 8.47[q] |
| Methylparaben[g] | 152.15 | $C_8H_8O_3$ | – | – | 1.96[q] | 8.5[q] |
| Insect repellants | | | | | | |
| DEET[o] | 191.27 | $C_{12}H_{17}NO$ | – | – | 2.18[q] | – |
| HHCB[p] | 258.41[q] | $C_{18}H_{26}O_3$ | – | 1.75[q] | 5.90[q] | – |
| Plasticizer | | | | | | |
| BEPH | 390.60 | $C_{24}H_{38}O_4$ | – | 0.27[q] | – | – |
| DBP | 282.37 | $C_{16}H_{22}O_4$ | – | – | – | – |
| Artificial sweeteners | | | | | | |
| Sucralose | 397.60 | $C_{12}H_{19}Cl_3O_8$ | – | 22700[q] | −1.00[q] | – |
| Saccharine | 183.19 | $C_7H_5NO_3S$ | – | 4000[q] | 0.91[q] | 1.31[q] |
| Acesulfame | 163.15 | $C_4H_5NO_4S$ | – | 270g/L[q] | −1.33[q] | 2.0[q] |
| Surface activators (PFASs) | | | | | | |
| PFOS | 499.09 | $C_8F_{17}SO_3^-$ | – | – | – | 0.14 |
| PFOA | 413.08 | $C_7F_{15}CO_2^-$ | – | – | – | −0.21 |
| PFPeA | 263.05 | $C_4F_9CO_2^-$ | – | – | – | −0.10 |
| PFHxA | 313.06 | $C_5F_{11}CO_2^-$ | – | – | – | −0.17 |
| PFDA | 513.10 | $C_9F_{19}CO_2^-$ | – | – | – | −0.22 |

a: (Madikizela et al., 2018); b: (Lee et al., 2019), c: (Prosser & Sibley, 2015), d: (Jiang et al., 2014), e: (Xie et al., 2019), f: (Kumar et al., 2019), g: (Yang et al., 2017), h: (Subedi et al., 2014), i: (Wang & Wang, 2016), j: (Gogoi et al., 2018), k: (Liu & Wong, 2013), l: (Colon & Toor, 2016), m: (Aparicio et al., 2018) n: (Ebele et al., 2017) o: (Zhang et al., 2016) p: (Zeng et al., 2007) q: https://pubchem.ncbi.nlm.nih.gov r: (Liu et al., 2017), s: https://www.drugbank.ca/, t: (Riemenschneider et al., 2016), u: (Biel-Maeso et al., 2019), v: (Baena-Nogueras et al., 2017), w: (Batchu et al., 2014), x: (Liu et al., 2019), y: (Li & Zhang, 2010), ** No degradation.
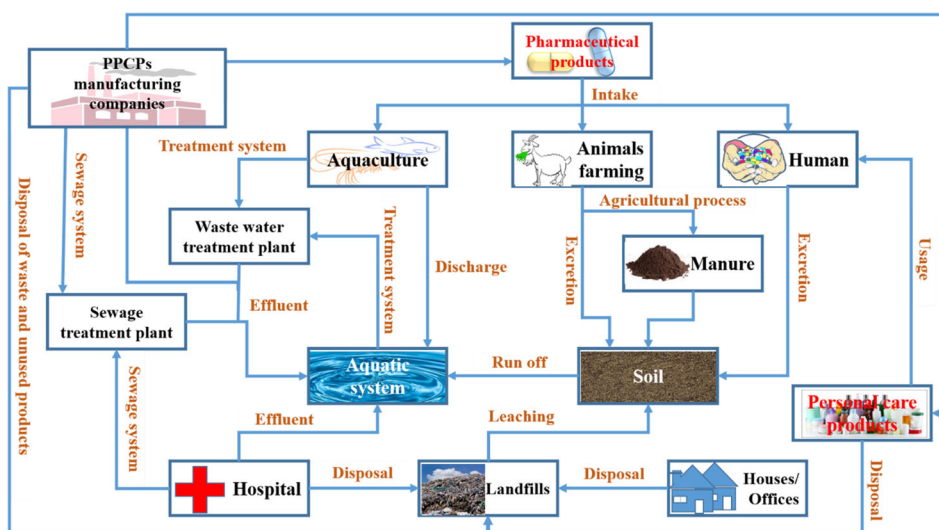


**Figure 1.** Sources of PPCPs in the environment.

persistence of personal care products into the environment (Yang et al., 2017). Moreover, the improper disposal of unused and expired PPCPs such as medicines and cosmetics products in landfills may introduce them into the land and water bodies (Al-Farsi et al., 2017). Finally, the stability and environmental metabolism of PPCPs are other essential factors that can regulate the occurrence and functional states of PPCPs in the environment (Al-Farsi et al., 2017). The state of the knowledge on the existence of selected PPCPs in the environment is presented in Table 2.

The assessment of PPCPs persistence is the most critical aspect which helps to understand the fate of PPCPs in the environment. The persistence of PPCPs in the environment is governed by many environmental facets, for instance, biodegradation, photolysis, redox reactions, and hydrolysis (Yamamoto et al., 2009). The persistence of PPCPs in the environment depends on the environmental conditions, such as temperature, sunlight exposure, microbial activity, redox status and the medium (soil/sediment/ air/water) (Bu et al., 2016). Usually, the persistence of PPCPs is determined by the respective half-life of the individual compound in the medium. The half-lives of chlortetracycline in soil have been reported as >30 days. The half-life of oxytetracycline has been reported as 150 days in the marine sediment. The half-lives of fluoroquinolones and sulfonamides in sediment have been reported >30, and >40 days, respectively. A minimum degradation of ciprofloxacin after 40 days exposure to the environment has also been reported (Brooks et al., 2008). The half-lives of naproxen, bisphenol A, ibuprofen, clofibric acid, diclofenac, and triclosan vary within the range of 5.68–16.82, 0.81–5.5, 0.91–6.09, 4.52–18.48, 3.07–20.44, and 12.65–15.68 days, respectively, in four types of agricultural soil (Xu et al., 2009). Similarly, the aerobic biodegradation of 13 PPCPs including sulfamethoxazole, gemfibrozil, carbamazepine, and sulfamethizole in soils with 30 days incubation was investigated by Biel-Maeso et al. (2019), and 12 PPCPs except carbamazepine were reported as biodegraded in the range of 36–100% with half-lives range 1–30 days, while carbamazepine behaved as a recalcitrant with no biodegradative decay after 30 days incubation (Biel-Maeso et al., 2019). The half-life of a few PPCPs is provided in Table 1. However, the persistence of all groups of PPCPs in the environment is not well understood.

## 4. Uptake of PPCPs by plants

Since the PPCPs are frequently encumbered into the environment through many pathways as already elaborated in Figure 1, the uptake of PPCPs by the plants is widespread which has been recently reported by many researchers (Carter et al., 2018; Knight et al., 2018). This review presents

**Table 2.** Types of PPCPs, and their environmental occurrence.

| Categories of PPCPs | Compounds | Country | Source | Quantity | References |
|---|---|---|---|---|---|
| Antibiotics | Tetracycline | Spain | Manure | 0.9 mg/kg | (Conde-Cid et al., 2018) |
| | Oxytetracycline | Spain | Manure | 28 mg/kg | (Conde-Cid et al., 2018) |
| | Chlortetracycline | Spain | Manure | 4.0 mg/kg | (Conde-Cid et al., 2018) |
| | Sulfachloropyridazine | Jordan | WWTP influent | <0.005 μg/L | (Al-Mashaqbeh et al., 2019) |
| | Sulfamethazine | China | Soil | 0.11 μg/kg | (Liu et al., 2020) |
| | Sulfamethoxazole | China | Soil | 1.31 μg/kg | (Liu et al., 2020) |
| | Sulfadiazine | Bangladesh | River water | 0.58 ng/L | (Hossain et al., 2018) |
| | Ciprofloxacin | Sri Lanka | Surface water | 36.2 ng/L | (Guruge et al., 2019) |
| | Enrofloxacin | Vietnam | Wastewater | 2869 ng/L | (Tran et al., 2019) |
| | Difloxacin | Argentina | wastewater | 14.2 μg/L | (Teglia et al., 2019) |
| | Flumequine | France | WWTP influent | <4.6 ng/L | (Miossec et al., 2019) |
| | Norfloxacin | France | WWTP influent | <3.4 ng/L | (Miossec et al., 2019) |
| | Ofloxacin | Vietnam | Wastewater | 2867 ng/L | (Tran et al., 2019) |
| | Pefloxacin | China | Wastewater | 0.127 ng/mL | (Wang et al., 2019) |
| | Roxithromycin | Sri Lanka | Surface water | 0.63 ng/L | (Guruge et al., 2019) |
| | Tylosin | Bangladesh | River water | 16.68 ng/L | (Hossain et al., 2018) |
| | Erythromycin | Sri Lanka | Surface water | 21.6 ng/L | (Guruge et al., 2019) |
| | Clarithromycin | Sri Lanka | Surface water | 119 ng/L | (Guruge et al., 2019) |
| | Trimethoprim | China | Soil | 0.05 μg/kg | (Liu et al., 2020) |
| | Thiamphenicol | China | Manure | 32.8 μg/kg | (Qian et al., 2016) |
| | Chloramphenicol | China | Soil | 2.68 μg/kg | (Liu et al., 2020) |
| | Lincomycin | Sri Lanka | Surface water | 3.08 ng/L | (Guruge et al., 2019) |
| | Clindamycin | Vietnam | Wastewater | 29 ng/L | (Tran et al., 2019) |
| Anti-inflammatory drugs | Ibuprofen | China | Soil | 1.71 μg/kg | (Liu et al., 2020) |
| | Diclofenac | Sri Lanka | Surface water | 80.0 ng/L | (Guruge et al., 2019) |
| | Acetaminophen | Mexico | WWTP influent | 14900 ng/L | (Rivera-Jaimes et al., 2018) |
| | Aspirin | India | River water | 0.777 μg/L | (Mutiyar et al., 2018) |
| | Indomethacin | Sri Lanka | Surface water | 3.18 ng/L | (Guruge et al., 2019) |
| | Naproxen | Mexico | WWTP influent | 4210 ng/L | (Rivera-Jaimes et al., 2018) |
| | Nimesulide | Portugal | Tap water | 9.24 ng/L | (Paíga & Delerue-Matos, 2016) |
| | Phenazone | France | WWTP influent | <0.91 ng/L | (Miossec et al., 2019) |
| | Ketoprofen | India | River water | 107 ng/L | (Sharma et al., 2019) |
| Synthetic hormone | Ethinylestradiol | Spain | Sewage sludge | 97.8 μg/kg | (Martín et al., 2015) |
| Stimulant drug | Caffeine | Canada | Effluent | 14200000 ng/L | (Kleywegt et al., 2019) |
| Cytostatic drugs | Cyclophosphamide | France | WWTP influent | <0.06 ng/L | (Miossec et al., 2019) |
| Contrast media | Iopromide | Korea | STP influent | 2462 ng/L | (Hong et al., 2019) |
| | Iomeprol | Spanish | Wastewater | 2093 μg/L | (Mendoza et al., 2015) |
| | Diatrizoate | China | Surface water | 19.6 ng/L | (Xu et al., 2017) |
| β-blockers | Atenolol | Mexico | Surface water | 32 ng/L | (Rivera-Jaimes et al., 2018) |
| | Metoprolol | France | WWTP influent | 192 ng/L | (Miossec et al., 2019) |
| | Nadolol | Spain | WWTP influent | 103 ng/L | (Biel-Maeso et al., 2018) |
| | Propranolol | Sri Lanka | Surface water | 2.64 ng/L | (Guruge et al., 2019) |
| Blood lipid regulators | Gemfibrozil | Sri Lanka | Surface water | 25.6 ng/L | (Guruge et al., 2019) |
| Antiepileptic drugs | Dilantin | Korea | Surface water | 4.3 ng/L | (Kim et al., 2007) |
| | Carbamazepine | Sri Lanka | Surface water | 71.2 ng/L | (Guruge et al., 2019) |
| Antimicrobials | Triclocarban | Sri Lanka | Surface water | 41.0 ng/L | (Guruge et al., 2019) |
| | Triclosan | China | Soil | 25.51 μg/kg | (Liu et al., 2020) |
| UV-filter | Oxybenzone | Canada | Effluent | 8160 ng/L | (Kleywegt et al., 2019) |
| Preservatives | propylparaben | Poland. | Landfill leachate | 0.77 μg/L | (Kapelewska et al., 2018) |
| | Butylparaben | Sri Lanka | Surface water | 0.25 ng/L | (Guruge et al., 2019) |
| | Methylparaben | Sri Lanka | Surface water | 12.9 ng/L | (Guruge et al., 2019) |
| Insect repellant | DEET | Sri Lanka | Surface water | 202 ng/L | (Guruge et al., 2019) |
| Synthetic musks | HHCB | USA | Effluent | 1.86 μg/L | (Sun et al., 2014) |
| Plasticizer | BEPH | China | Drinking water | 6.35 μg/L | (Liu et al., 2014) |

(*continued*)

**Table 2.** Continued.

| Categories of PPCPs | Compounds | Country | Source | Quantity | References |
|---|---|---|---|---|---|
| | DBP | China | Drinking water | 1.52 µg/L | (Liu et al., 2014) |
| Artificial sweetener | Sucralose | India | Sludge | 1870 ng/g | (Subedi et al., 2015) |
| | Saccharine | India | Sludge | 17900 ng/g | (Subedi et al., 2015) |
| | Acesulfame | India | Sludge | 8.81 ng/g | (Subedi et al., 2015) |
| Surface activators | PFOS | Uganda | River water | 3.89 ng/L | (Dalahmeh et al., 2018) |
| | PFOA | Uganda | River water | 3.90 ng/L | (Dalahmeh et al., 2018) |
| | PFPeA | Jordan | River water | 8.1 ng/L | (Shigei et al., 2020) |
| | PFHxA | Jordan | River water | 2.4 ng/L | (Shigei et al., 2020) |
| | PFDA | Jordan | River water | 2.3 ng/L | (Shigei et al., 2020) |

the uptake of PPCPs under two conditions; one is the uptake of PPCPs by plants under the greenhouse condition, and another is the uptake of PPCPs by plants in the natural environment. Here, uptake means the transfer of PPCPs into the plant tissues (especially roots) from the plants' environmental media (Wu et al., 2013; Zheng et al., 2014). The experiment under the greenhouse conditions is usually carried out in the laboratory with controlled light-period, relative-humidity, temperature, etc. (Bhalsod et al., 2018), whereas the natural environment means the realistic agricultural farming system with less controlled conditions (Riemenschneider et al., 2016). The greenhouse condition include hydroponic experiment where the experiment plant grows into the nutrient solution with the known spiked amount of PPCPs and pot experiment where the experiment plants subjected to the soil (Kodešová et al., 2019) or manure amended soil (Dolliver et al., 2007) or coconut fiber substrate (González García et al., 2019) or sewage sludge (Cortés et al., 2013). The bioavailability of PPCPs in the greenhouse condition relatively higher than realistic field conditions since the photo exposure, microorganisms play a major role in the persistence of PPCPs in the environment. Therefore, this review has gathered existing knowledge under both greenhouse and field condition separately.

## 4.1. Uptake of PPCPs by plants under greenhouse conditions

The uptake of PPCPs by plants under the greenhouse conditions has been investigated by different authors around the world (Ahmed et al., 2015; Bassil et al., 2013). In a greenhouse experiment, the plants are grown in the known quantity of PPCPs spiked media, either soil or water, for a particular period of time. Finally, PPCPs are extracted from the experimental plants and preconcentrated for the determination of PPCPs. There are several greenhouse investigations on the uptake of PPCPs by different plants, and their main facets and findings are presented in Table 3. The removal percentages of sulfamethoxazole (73%), trimethoprim (59%), and metronidazole

**Table 3.** Uptake of PPCPs under the greenhouse condition.

| Groups of PPCPs | Compounds | Plant samples | Spiked amount | Grown media | Root concentration | References |
|---|---|---|---|---|---|---|
| Anti-inflammatory drug | Acetaminophen | Cucumber (Cucumis sativus) | 5.0 mg/L | Nutrition solution | 1.7 µmol/g | (Sun et al., 2019) |
| Antibiotic | Clarithromycin | Lettuce (Lactuca sativa) | 1.0 mg/L | Hydroponic | 4977 µg/Kg | (Tian et al., 2019) |
| Antibiotic | sulfadiazine | Lettuce (Lactuca sativa) | 1.0 mg/L | Hydroponic | 24599 µg/Kg | (Tian et al., 2019) |
| Psychoactive | Carbamazepine | Spinach (Spinacia oleracea) | 100 µg/L | Hydroponic | >5µg/g | (Nason et al., 2019) |
| Psychoactive | Carbamazepine | Spinach (Spinacia oleracea) | 1 µg/L | Hydroponic | >0.5 µg/g | (Nason et al., 2019) |
| Psychoactive | Carbamazepine | Lettuce (Lactuca sativa) | 210 µg/L | Coconut fiber substrate irrigated with spiked treated waste water | ~ 550 ng/g | (González García, Fernández-López, Polesel, et al., 2019) |
| Anti-inflammatory drug | Ketoprofen | Lettuce (Lactuca sativa) | 210 µg/L | Coconut fiber substrate irrigated with spiked treated waste water | ~ 560 ng/g | (González García, Fernández-López, Polesel, et al., 2019) |
| Anti-inflammatory drugs | Ibuprofen | Lettuce (Lactuca sativa) | 210 µg/L | Coconut fiber substrate irrigated with spiked treated waste water | ~ 800 ng/g | (González García, Fernández-López, Polesel, et al., 2019) |
| Anti-inflammatory drugs | Naproxen | Lettuce (Lactuca sativa) | 210 µg/L | Coconut fiber substrate irrigated with spiked treated waste water | ~ 2000 ng/g | (González García, Fernández-López, Polesel, et al., 2019) |
| Antimicrobials | Triclocarban | Cucumber (Cucumis sativus) | 05 µg/L | Hydroponic | 2000 ng/g | (Sun et al., 2018) |
| Anti-inflammatory drug | Naproxen | Cucumber (Cucumis sativus) | 05 µg/L | Hydroponic | 690 ng/g | (Sun et al., 2018) |
| Antimicrobials | Triclosan | Cucumber (Cucumis sativus) | 05 µg/L | Hydroponic | 490 ng/g | (Sun et al., 2018) |
| Antibiotic | Sulfamethoxazole | Cucumber (Cucumis sativus) | 05 µg/L | Hydroponic | 460 ng/g | (Sun et al., 2018) |
| Stimulant drug | Caffeine | Cucumber (Cucumis sativus) | 05 µg/L | Hydroponic | 450 ng/g | (Sun et al., 2018) |
| Blood lipid regulators | Gemfibrozil | Cucumber (Cucumis sativus) | 05 µg/L | Hydroponic | 420 ng/g | (Sun et al., 2018) |
| Antibiotic | Tetracycline | Carrot (Daucus carota) Lettuce (Lactuca sativa) | 0.1–15 mg/L | Soil irrigated with antibiotics spiked water | 4.4–28.3 ng/g 12.0–36.8 ng/g | (Azanu et al., 2016) |
| Antibiotic | Amoxicillin | Carrot (Daucus carota) Lettuce (Lactuca sativa) | 0.1–15 mg/L | Soil irrigated with antibiotics spiked water | 13.7–33.6 ng/g 14.3–45.2 ng/g | (Azanu et al., 2016) |
| β-blockers | Atenolol | Reddish (Raphanus sativus) Lettuce (Valerianella locusta) Spinach (Spinacia oleracea) Arugula (Eruca sativa) | 1 mg/L | Soil irrigated with PPCPs contaminated water | 10 ng/g 430 ng/g 160 ng/g 420 ng/g | (Kodešová, Klement, Golovko, Fér, Nikodem, et al., 2019) |
| Antibiotic | Sulfamethoxazole | Reddish (Raphanus sativus) Lettuce (Valerianella locusta) Spinach (Spinacia oleracea) Arugula (Eruca sativa) | 1 mg/L | Soil irrigated with PPCPs contaminated water | 230 ng/g 1100 ng/g 1200 ng/g 1000 ng/g | (Kodešová, Klement, Golovko, Fér, Nikodem, et al., 2019) |
| Antiepileptic drug | Carbamazepine | Reddish (Raphanus sativus) Lettuce (Valerianella locusta) | 1 mg/L | Soil irrigated with PPCPs contaminated water | 2600 ng/g 1900 ng/g | (Kodešová, Klement, Golovko, Fér, Nikodem, et al., 2019) |

**Table 3.** Continued.

| Groups of PPCPs | Compounds | Plant samples | Spiked amount | Grown media | Root concentration | References |
|---|---|---|---|---|---|---|
| Antibiotic | Tylosin | Spinach (*Spinacia oleracea*) Arugula (*Eruca sativa*) | 50 ng/mL | Hydroponic | 1500 ng/g 1800 ng/g | (Chuang et al., 2019) (Chuang et al., 2019) |
| Antimicrobial | Triclosan | Lettuce (*Lactuca sativa*) | 50 ng/mL | Hydroponic | ∼ 309.38 ng/g | (Chuang et al., 2019) |
| Antibiotic | Sulfamethazine | Lettuce (*Lactuca sativa*) | 5 mg/kg | Soil spiked with antibiotic | 5.59 ng/g | (Rajapaksha et al., 2014) |
| Antibiotic | Sulfamethazine | Lettuce (*Lactuca sativa*) | 50 mg/kg | Soil spiked with antibiotic | 0.32 mg/kg 0.62 mg/kg | (Rajapaksha et al., 2014) |
| Surface activator | PFOS | Chicory (*Cichorium intybus*) | 62.5 µg/L | Hydroponic | 3158.5 ng/g | (Gredelj et al., 2020) |
| | PFOA | Chicory (*Cichorium intybus*) | 62.5 µg/L | Hydroponic | 653.0 ng/g | (Gredelj et al., 2020) |
| | PFDA | Chicory (*Cichorium intybus*) | 62.5 µg/L | Hydroponic | 4945.9 ng/g | (Gredelj et al., 2020) |
| | PFPeA | Chicory (*Cichorium intybus*) | 62.5 µg/L | Hydroponic | 105.8 ng/g | (Gredelj et al., 2020) |
| Plasticizer | BEPH | Lettuce (*Lactuca sativa*) Strawberry (*Fragaria x ananassa*) Carrot (*Daucus corota*) | 500 µg/kg | Soil | 852.17 µg/kg 967.86 µg/kg 1343.87 µg/kg | (Sun et al., 2015) |
| | DBP | Lettuce (*Lactuca sativa*) Strawberry (*Fragaria x ananassa*) Carrot (*Daucus corota*) | 500 µg/kg | Soil | 351.57 µg/kg 1286.02 µg/kg 2385.12 µg/kg | (Sun et al., 2015) |

(96%) after 24 days exposure, and cefadroxil (100%) after 14 days of exposure to the experimental solution using duckweed (*Lemna minor*) from the aquatic environment were reported (Iatrou et al., 2017). A similar study was carried out by Gatidou et al. (2017) with duckweed using five types of benzotriazoles, and it reported 26–72% removal of benzotriazoles by the duckweed from the wastewater. An interesting study investigated the uptake of PPCPs by greenhouse lettuce grown with the soil base and over-head irrigation of PPCPs contaminated water. The authors reported that over-head irrigation increased the uptake of PPCPs in lettuce plants (Bhalsod et al., 2018). Very recently, Rosa et al. (2019) made a study on the uptake of oxytetracycline by seaweed *Ulva* sp. under laboratory condition by exposing to the oxytetracycline spiked natural seawater solution containing two different initial concentrations of oxytetracycline (0.040 and 0.120 mg/L). After 24 h exposure, they detected 40 and 100 ng/g of oxytetracycline in the seaweed, respectively.

## 4.2. Uptake of PPCPs by plants in the natural environment

Many researchers have investigated the plant uptake of PPCPs under the laboratory conditions, but studies on the plant uptake under the natural environment or field condition are minimal. Nuel et al. (2018) conducted an interesting study on the role of local plants, such as sedge (*Carex caryophyllea*), callitriche (*Callitriche palustris*), yellow flag (*Iris pseudacorus*), soft rush (*Juncus effusus*), and white willow (*Salix alba*) of surface flow treatment wetland in the mitigation of PPCPs from the effluent of the wastewater treatment system. Moreover, authors investigated the seasonal variation on the plant uptake of PPCPs, suggested the removal efficiency of PPCPs was well improved in the summer than those in the winter (Nuel et al., 2018). Another study investigated the uptake of 141 PPCPs in plants sweet corn, potato, carrot, and tomato under the normal farming conditions but reported no PPCPs found in the plants above the limit of detection. This study reported, eight of 141 PPCPs, including atenolol, DEET, ibuprofen, lincomycin, and sulfamerazine were found in the range of 0.33–6.25 ng/g in dry weight (Sabourin et al., 2012). It suggested that the uptake of PPCPs in the plant was quite smaller under the rational/realistic farming conditions (Sabourin et al., 2012).

In another field experiment, Christou et al. (2017) detected the presence of diclofenac, sulfamethoxazole, and trimethoprim at 11.63, 5.26, and 3.40 μg/kg, respectively, in tomato fruits which was irrigated for long-term under the regular farming conditions with wastewater from municipal wastewater treatment plant (Christou et al., 2017). Riemenschneider et al. (2016) reported, 12 types out of 28 micropollutants were found in the

field-grown plants including potato, lettuce, carrot, and zucchini irrigated with Zarqa River in Jordan, with a concentration range of 1.7–216 ng/g in dried weight (Riemenschneider et al., 2016). Ben Mordechay et al. (2018) explored the uptake of carbamazepine and its metabolism by tomato, wheat, and lettuce with an introduction of treated wastewater and soil amended with biosolids in the realistic farming scenario. The same authors reported that the introduction of treated wastewater in the agricultural activity led to plant uptake of carbamazepine as a representative of PPCPs in a significantly higher than the introduction of biosolids (Ben Mordechay et al., 2018).

Very recently, a study reported the occurrence of PPCPs such as carbamazepine, methylparaben, and caffeine in seaweeds obtained from the Saudi red sea at 1.7, 44.3, and 41.3 ng/g, respectively (Ali et al., 2018). Further, phytoremediation study assessed the use of aquatic plants, including *Ipomoea aquatica*, *Phragmites australis*, *Typha latifolia*, *Azolla caroliniana*, *Lemna minor,* and *Salix atrocinerea* for the removal of PPCPs from the wastewater, which achieved 70–90% removal efficiency (Dhir, 2019). Moreover, a systematic analysis of the accumulation of 11 PPCPs, including sulfamethoxazole, ibuprofen, trimethoprim, triclosan, chloramphenicol, and sulfamethazine with long term reclaimed water irrigation (20, 30, and 40 years) in agriculture lands was reported by Liu et al. (2020). The authors stated that PPCPs were detected in eggplant, cucumber, wheat, and long bean at the range of 0.02–28.01 µg/kg (Liu et al., 2020). Table 4 provides a few studies conducted in realistic environmental conditions. However, the scientific investigation on the plant uptake of PPCPs in realistic field condition still remains very limited to this date.

## 5. Translocation of PPCPs in plants

The translocation of PPCPs can be referred to as the passage of PPCPs from the roots to the areal parts of the plants, such as leaves, stems, fruits and rhizomes (Cui & Schröder, 2016; Dodgen et al., 2015) as shown in Figure 2. The translocation of PPCPs in plants can be expressed by the translocation factor (TF), which is calculated by the ratio between the concentrations of PPCPs in areal parts and those in roots of the plants (Dodgen et al., 2015) (Eq. (1)).

$$TF = \frac{Concentration\ of\ PPCPs\ in\ areal\ part}{concentration\ of\ PPCPs\ in\ root} \qquad (1)$$

Moreover, the translocation of PPCPs depends on several factors, such as physicochemical properties of PPCPs (pKa, log $K_{ow}$, molecular size, etc.), properties of soil (soil pH, temperature, organic carbon content, etc.), and

**Table 4.** Plant uptake of PPCPs in realistic environment.

| PPCPs | Source of PPCPs | Plant | Country | Concentration in plant | References |
|---|---|---|---|---|---|
| Diclofenac | Wastewater | Tomato (Lycopersicon esculentum) | Cyprus | 11.62 µg/kg | (Christou et al., 2017) |
| Sulfamethoxazole | Wastewater | Tomato (Lycopersicon esculentum) | Cyprus | 5.26 µg/kg | (Christou et al., 2017) |
| Trimethoprim | Wastewater | Tomato (Lycopersicon esculentum) | Cyprus | 3.40 µg/kg | (Christou et al., 2017) |
| Carbamazepine | Treated wastewater | Tomato (Solanum lycopersicum) Wheat (Triticum aestivum) Lettuce (Lactuca sativa) | Israel | 29.30 ng/g 9.25 ng/g 69.72 ng/g | (Ben Mordechay et al., 2018) |
| Carbamazepine | Biosolid application | Tomato (Solanum lycopersicum) Wheat (Triticum aestivum) Lettuce (Lactuca sativa) | Israel | 6.65 ng/g 3.80 ng/g 1.83 ng/g | (Ben Mordechay et al., 2018) |
| Atenolol | Effluent of WWTP | Cabbage (Brassica oleracea) | Saudi Arabia | 55 ng/g | (Picó et al., 2019) |
| Caffeine | Effluent of WWTP | Cabbage (Brassica oleracea) | Saudi Arabia | 125 ng/g | (Picó et al., 2019) |
| Gemfibrozil | Effluent of WWTP | Cabbage (Brassica oleracea) Eggplant (Solanum melongena) Green beans (Phaseolus vulgaris) | Saudi Arabia | 72 ng/g 34 ng/g 45 ng/g | (Picó et al., 2019) |
| Malathion | Effluent of WWTP | Cabbage (Brassica oleracea) Chili plant (Capsicum frutescens) Tomato (Solanum lycopersicum) | Saudi Arabia | 1000 ng/g 84 ng/g 85 ng/g | (Picó et al., 2019) |
| Naproxen | Effluent of WWTP | Cabbage (Brassica oleracea) | Saudi Arabia | 38 ng/g | (Picó et al., 2019) |
| Triclosan | Reclaimed water | Eggplant (Solanum melongena) Long bean (Vigna unguiculate) Wheat (Triticum aestivum) Cucumber (Cucumis sativus) | China | 6.77 µg/kg 18.46 µg/kg 12.83 µg/kg 13.39 µg/kg | (Liu et al., 2020) |
| Sulfamethazine | | Eggplant (Solanum melongena) Long bean (Vigna unguiculate) Wheat (Triticum aestivum) Cucumber (Cucumis sativus) | China | 0.03 µg/kg 0.01 µg/kg 0.08 µg/kg 0.36 µg/kg | (Liu et al., 2020) |
| Trimethoprim | | Eggplant (Solanum melongena) Long bean (Vigna unguiculate) Wheat (Triticum aestivum) Cucumber (Cucumis sativus) | China | 0.02 µg/kg ND 0.05 µg/kg 0.08 µg/kg | (Liu et al., 2020) |
| Ibuprofen | | Eggplant (Solanum melongena) Long bean (Vigna unguiculate) Wheat (Triticum aestivum) Cucumber (Cucumis sativus) | China | 0.78 µg/kg 0.75 µg/kg 1.21 µg/kg 13.82 µg/kg | (Liu et al., 2020) |
| Sulfamethoxazole | | Eggplant (Solanum melongena) Long bean (Vigna unguiculate) Wheat (Triticum aestivum) Cucumber (Cucumis sativus) | China | 0.05 µg/kg 0.08 µg/kg 0.16 µg/kg 0.90 µg/kg | (Liu et al., 2020) |
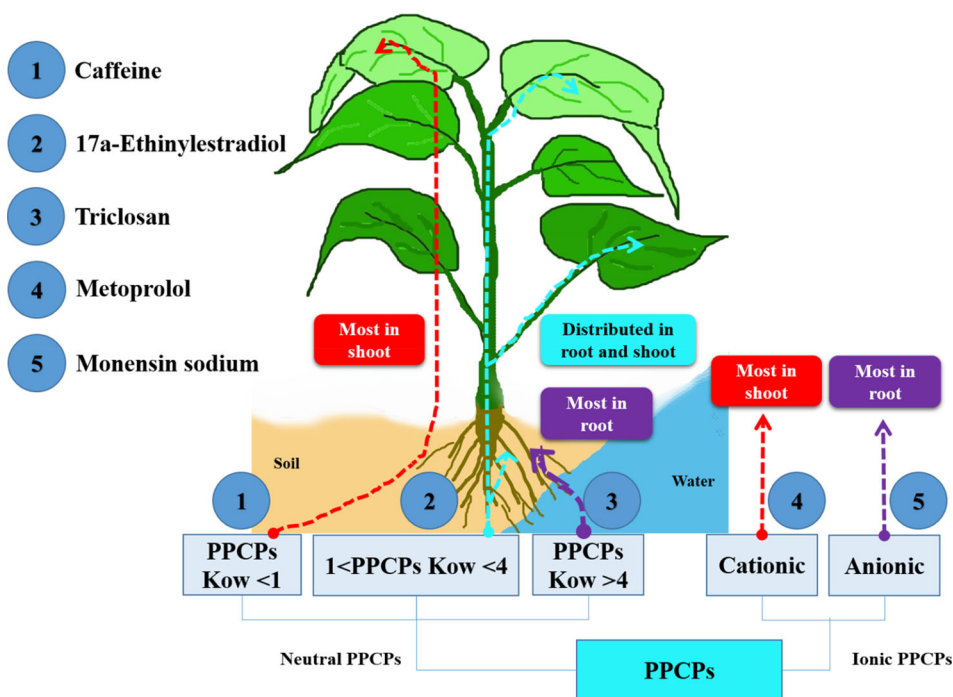
**Figure 2.** Plant uptake and translocation of PPCPs from the environment to different aerial parts. The examples are based on Chuang et al. (2019), He et al. (2017), Christou et al. (2016), and Goldstein et al. (2014).

environmental conditions (temperature, relative humidity, photo-period, etc.) (Madikizela et al., 2018). The effect of these factors on the plant uptake PPCPs has explained in the later section. This current study has reviewed the translocation of PPCPs in two ways; (1) the translocation of PPCPs in plants under the greenhouse/laboratory conditions, and (2) the translocation of PPCPs in plants in realistic environmental condition. Hence, the translocation of PPCPs may vary with environmental conditions, variety of plants, and physicochemical properties of PPCPs.

## 5.1. Translocation of PPCPs in plants under greenhouse conditions

Until recently, there is plenty of work which studied on the translocation of PPCPs from roots to the areal part of the plant once it is taken up (Li et al., 2018; Madikizela et al., 2018). A recent hydroponic study on lettuce reported that small-sized PPCPs such as carbamazepine and caffeine showed low affinity to roots, which was expressed by sorption coefficient (Kp) below 0.05 L/g while molecular weight (MW) below 300 g/mol showed high translocation to the areal parts of lettuce. The small-sized PPCPs such as trimethoprim, and lamotrigine with relatively high Kp above 12 L/g

showed high translocation to areal pieces of lettuce. Large-sized PPCPs such as tylosin, monensin sodium, and lincomycin with MW above 400 g/mol showed higher accumulation ability in lettuce roots (Chuang et al., 2019). Small-sized PPCPs took up with water through the symplast pathway could allow the passage of them across the Casparian strip to xylem, whereas large-sized PPCPs enter into root through the apoplast pathway, which blocked at the Casparian strip (Chuang et al., 2019). A comparatively higher concentration of PPCPs was detected in the plant roots and shoots under the greenhouse condition. He et al. (2017) reported very low translocation of triclosan in water spinach, penny grass, purple perilla, rice, cress, and cane shoot, and it might be due to its high hydrophobic nature (log $K_{ow}$; 4.76) and high affinity to the roots. Similarly, the high accumulation of triclosan was observed in the lettuce root (Chuang et al., 2019). Moreover, higher TFs of carbamazepine were observed (Table 5) in reddish (4.8), and arugula (6.8) than those in lettuce (0.6), and spinach (0.7) (Kodešová, Klement, Golovko, Fér, Nikodem, et al., 2019). The same authors detected higher translocation of atenolol in reddish (2.1), and spinach (4.6) than those in lettuce (0.2), and arugula (0.7). Recently investigated data on the translocation of PPCPs in the plant is assembled in Table 5.

## 5.2. Translocation of PPCPs in plants in the natural environment

Investigations on the translocation of PPCPs in the plant under the field condition are scarce. However, some studies reported a limited number of PPCPs and their translocation to the areal parts of the plant. Martínez-Piernas et al. (2019) found 17 PPCPs in the realistic field-grown tomato leaves irrigated with reclaimed water in the concentration range of 0.04–32 ng/g. Similarly, the long-term application of manure under the realistic farming condition introduced the antibiotics to the peanut plants as investigated by Zhao et al. (2019). Based on their results, sulfamethoxazole shows the highest TF, followed by enrofloxacin, erythromycin, and chlortetracycline, whereas ciprofloxacin shows the lowest TF (Table 6). This account, the PPCPs with less TF value, have the highest affinity toward the root, which led to the accumulation of them in root cell. Different TF values of carbamazepine, in cabbage, lettuce, and zucchini and caffeine in potato, and zucchini might indicate that the translocation of these compounds depends on the crop type (Riemenschneider et al., 2016). However, comparatively less concentration of PPCPs was detected in plant roots and shoots under the realistic field condition than those under the greenhouse condition.

**Table 5.** Translocation of PPCPs under the greenhouse condition.

| PPCPs | Plant | Spiked amount | Concentration in roots | Concentration in shoot | TF* | References |
|---|---|---|---|---|---|---|
| Caffeine | Lettuce (*Lactuca sativa*) | 50 ng/mL | ~ 42.75 ng/g | ~ 70.02 ng/g | 1.6379 | (Chuang et al., 2019) |
| Carbadox | Lettuce (*Lactuca sativa*) | 50 ng/mL | ~ 48.21 ng/g | ~ 3.85 ng/g | 0.0799 | (Chuang et al., 2019) |
| Carbamazepine | Lettuce (*Lactuca sativa*) | 50 ng/mL | ~ 84.83 ng/g | ~ 240.39 ng/g | 2.8338 | (Chuang et al., 2019) |
| Estrone | Lettuce (*Lactuca sativa*) | 50 ng/mL | ~ 13.28 ng/g | ~ 7.38 ng/g | 0.5557 | (Chuang et al., 2019) |
| Lincomycin | Lettuce (*Lactuca sativa*) | 50 ng/mL | ~ 128.2 ng/g | ~ 10.27 ng/g | 0.0801 | (Chuang et al., 2019) |
| Trimethoprim | Lettuce (*Lactuca sativa*) | 50 ng/mL | ~ 349.54 ng/g | ~ 49.35 ng/g | 0.1412 | (Chuang et al., 2019) |
| Lamotrigine | Lettuce (*Lactuca sativa*) | 50 ng/mL | ~ 80.66 | ~ 14.49 | 0.1796 | (Chuang et al., 2019) |
| Diclofenac | Alfalfa (*Medicago sativa*) | 10 µg/L | 162.83 µg/kg | ND | – | (Christou et al., 2016) |
| Sulfamethoxazole | Alfalfa (*Medicago sativa*) | 10 µg/L | 52.46 µg/kg | 3.48 µg/kg | 0.0663 | (Christou et al., 2016) |
| Trimethoprim | Alfalfa (*Medicago sativa*) | 10 µg/L | 311.90 µg/kg | 23.52 µg/kg | 0.0754 | (Christou et al., 2016) |
| 17α-ethinylestradiol | Alfalfa (*Medicago sativa*) | 10 µg/L | 28.85 µg/kg | 28.26 µg/kg | 0.9795 | (Christou et al., 2016) |
| Acetaminophen | Cucumber (*Cucumis sativus*) | 5.0 mg/g | 1.7 µmol/g | 0.5 µmol/g | 0.2941 | (Sun et al, 2019) |
| Atenolol | Reddish (*Raphanus sativus*) Lettuce (*Valerianella locusta*) Spinach (*Spinacia oleracea*) Arugula (*Eruca sativa*) | 1 mg/L | 53 ng/g 2400 ng/g 130 ng/g 390 ng/g | 110 ng/g 390 ng/g 600 ng/g 280 ng/g | 2.0755 0.1625 4.6154 0.7179 | (Kodešová, Klement, Golovko, Fér, Nikodem, et al., 2019) |
| Sulfamethoxazole | Reddish (*Raphanus sativus*) Lettuce (*Valerianella locusta*) Spinach (*Spinacia oleracea*) Arugula (*Eruca sativa*) | 1 mg/L | 120 ng/g 580 ng/g 800 ng/g 1600 ng/g | 48 ng/g 23 ng/g 300 ng/g 75 ng/g | 0.40 0.0397 0.3750 0.0469 | (Kodešová, Klement, Golovko, Fér, Nikodem, et al., 2019) |
| Carbamazepine | Reddish (*Raphanus sativus*) Lettuce (*Valerianella locusta*) Spinach (*Spinacia oleracea*) Arugula (*Eruca sativa*) | 1 mg/L | 3100 ng/g 2400 ng/g 2800 ng/g 3400 ng/g | 15000 ng/g 1400 ng/g 1900 ng/g 23000 ng/g | 4.8387 0.5833 0.6786 6.7647 | (Kodešová, Klement, Golovko, Fér, Nikodem, et al., 2019) |
| Triclosan | Water spinach (*Ipomoea aquatica*) Penny grass (*Hydrocotyle vulgaris*) Purple perilla (*Prilla frutescens*) Rice (*Oryza sativa*) Cress (*Oenanthe javanica*) Cane shoot (*Zizania latifolia*) | 0.042 µg/mL | 59.34 µg/g 60.43 µg/g 09.39 µg/g 33.75 µg/g 63.71 µg/g 14.04 µg/g | 0.143 µg/g 0.107 µg/g 0.040 µg/g 1.061 µg/g 0.209 µg/g 0.201 µg/g | 0.0024 0.0017 0.0043 0.0314 0.0033 0.0143 | (He et al., 2017) |
| Diclofenac | Chicory (*Cichorium intybus*) | 1 mg/L | 3.9 µg/100g | 2.6 µg/100g | 0.6667 | (Podio et al., 2020) |
| PFOS | Chicory (*Cichorium intybus*) | 65.2 µg/L | 3158.5 ng/g | 168.4 ng/g | 0.0533 | (Gredelj et al., 2020) |
| PFOA | Chicory (*Cichorium intybus*) | 65.2 µg/L | 653.0 ng/g | 230.7 ng/g | 0.3533 | |
| PFDA | Chicory (*Cichorium intybus*) | 65.2 µg/L | 4945.9 ng/g | 204.1 ng/g | 0.0413 | |
| PFPeA | Chicory (*Cichorium intybus*) | 65.2 µg/L | 105.8 ng/g | 460.0 ng/g | 4.3478 | |
| BEPH | Lettuce (*Lactuca sativa*) Strawberry (*Fragaria x ananassa*) Carrot (*Daucus corota*) | 500 µg/kg | 852.17 µg/kg 967.86 µg/kg 1343.87 µg/kg | 667.59 µg/kg 695.92 µg/kg 1220.08 µg/kg | 0.7834 0.7190 0.9079 | (Sun et al., 2015) |
| DBP | Lettuce (*Lactuca sativa*) Strawberry (*Fragaria x ananassa*) Carrot (*Daucus corota*) | 500 µg/kg | 351.57 µg/kg 1286.02 µg/kg 2385.12 µg/kg | 123.80 µg/kg 180.47 µg/kg 548.81 µg/kg | 0.3521 0.1403 0.2301 | (Sun et al., 2015) |
| DBP | *Brassica rapa var. perviridis* | 0.5 mg/L | 6.89 mg/kg | 0.05 mg/kg | 0.0073 | (Li et al., 2020) |

*TF was calculated.
ND: not detected.

**Table 6.** Translocation of PPCPs under the realistic environmental condition.

| PPCPs | Plant | Concentration in roots, ng/g | Concentration in shoot, ng/g | TF* | References |
|---|---|---|---|---|---|
| Acetaminophen | Tomato (Solanum lycopersicum) | NR | 2 | – | (Martinez-Piernas et al., 2019) |
| Antipyrine | Tomato (Solanum lycopersicum) | NR | 1 | – | (Martinez-Piernas et al., 2019) |
| Caffeine | Tomato (Solanum lycopersicum) | NR | 0.7 | – | (Martinez-Piernas et al., 2019) |
| Carbamazepine | Tomato (Solanum lycopersicum) | NR | 5 | – | (Martinez-Piernas et al., 2019) |
| Propranolol | Tomato (Solanum lycopersicum) | NR | 0.3 | – | (Martinez-Piernas et al., 2019) |
| Trimethoprim | Tomato (Solanum lycopersicum) | NR | 2 | – | (Martinez-Piernas et al., 2019) |
| Venlafaxine | Tomato (Solanum lycopersicum) | NR | 2 | – | (Martinez-Piernas et al., 2019) |
| Carbamazepine | Cabbage (Brassica oleracea) | 61.4 | 79.0 | 1.29 | (Riemenschneider et al., 2016) |
| Carbamazepine | Lettuce (Lactuca sativa) | 26.7 | 215.7 | 8.08 | (Riemenschneider et al., 2016) |
| Carbamazepine | Zucchini (Cucurbita pepo) | 69.0 | 41.9 | 0.61 | (Riemenschneider et al., 2016) |
| 10,11-epoxide carbamazepine | Carrot (Daucus corota) | 7.7 | 53.5 | 6.95 | (Riemenschneider et al., 2016) |
| Acesulfame | Cabbage (Brassica oleracea) | 72.3 | 56.0 | 0.77 | (Riemenschneider et al., 2016) |
| Caffeine | Potato (Solanum tuberosum) | 30.3 | 61.8 | 2.04 | (Riemenschneider et al., 2016) |
| Caffeine | Zucchini (Cucurbita pepo) | 169.0 | 23.7 | 0.14 | (Riemenschneider et al., 2016) |
| 2-hydroxy carbamazepine | Zucchini (Cucurbita pepo) | 42.2 | 6.9 | 0.16 | (Riemenschneider et al., 2016) |
| 3-hydroxy carbamazepine | Zucchini (Cucurbita pepo) | 34.9 | 3.8 | 0.11 | (Riemenschneider et al., 2016) |
| Carbamazepine | Lettuce (Lactuca sativa) | 1 | 1.4 | 1.40 | (Wu et al., 2014) |
| Meprobamate | Spinach (Spinacia oleracea) | ND | 0.03 | – | (Wu et al., 2014) |
| Dilantin | Spinach (Spinacia oleracea) | 0.32 | 0.27 | 0.84 | (Wu et al., 2014) |
| Naproxen | Cabbage (Brassica oleracea) | 0.31 | 0.26 | 0.84 | (Wu et al., 2014) |
| Carbamazepine | Cabbage (Brassica oleracea) | 0.74 | 0.18 | 0.24 | (Wu et al., 2014) |
| Tetracycline | Peanut (Arachis hypogaea) | 6.38 | 7.08 | 1.11 | (Zhao et al., 2019) |
| Oxytetracycline | Peanut (Arachis hypogaea) | 22.73 | ND | – | (Zhao et al., 2019) |
| Chlortetracycline | Peanut (Arachis hypogaea) | 8.33 | 21.84 | 2.62 | (Zhao et al., 2019) |
| Norfloxacin | Peanut (Arachis hypogaea) | 9.37 | 0.99 | 0.11 | (Zhao et al., 2019) |
| Ciprofloxacin | Peanut (Arachis hypogaea) | 3.35 | 0.07 | 0.02 | (Zhao et al., 2019) |
| Enrofloxacin | Peanut (Arachis hypogaea) | 0.50 | 4.26 | 8.52 | (Zhao et al., 2019) |
| Sulfamethoxazole | Peanut (Arachis hypogaea) | 0.12 | 3.10 | 25.83 | (Zhao et al., 2019) |
| Sulfamethazine | Peanut (Arachis hypogaea) | 3.19 | 2.35 | 0.74 | (Zhao et al., 2019) |
| Erythromycin | Peanut (Arachis hypogaea) | 1.16 | 3.41 | 2.94 | (Zhao et al., 2019) |
| Tylosin | Peanut (Arachis hypogaea) | 0.27 | 0.17 | 0.63 | (Zhao et al., 2019) |

*TF was calculated.
NR: not reported; ND: not detected.

## 6. Factors affecting the uptake and translocation of PPCPs in the plant

There are several factors that influence the plant's uptake and transloca-tion of PPCPs from planted media to roots and areal parts. Biological characteristics of plants (lipid and carbohydrate content of plant roots), physiochemical properties of PPCPs (molecular size, $K_{ow}$, and pKa), and environmental conditions of media are the primary categories that influ-ence the plant uptake of PPCPs (Zhang et al., 2017). Lipid and carbohy-drate content of root cell walls and permeability of root cell membranes are the dominant plant biological factors that play a strong influence on the uptake of PPCPs from external media to roots (Chen et al., 2009; Zhang et al., 2017; Zhang and Zhu, 2009). Moreover, the physicochemical parameters of PPCPs such as molecular weight, hydrophobicity parameter ($K_{ow}$; partition coefficient of PPCPs between octanol and water), and ionic nature of PPCPs, either cationic or neutral or anionic (Zhang et al., 2017) also affect the uptake and translocation of PPCPs significantly from the surrounding environment to the plants (Al-Farsi et al., 2017; Zhang et al., 2017). These physicochemical properties of selected PPCPs are pro-vided in Table 1. The PPCPs which have a molecular weight less than 1000 g/mol can be efficiently accumulated by the plant (Öztürk et al., 2016). The volatile and low molecular weight compounds can be taken by roots and shoot easily. However, the nonvolatile, higher molecular weight, and hydrophobic compounds can only be accumulated in roots (Zhang et al., 2017). Besides, the $K_{ow}$ of PPCPs is an essential quantitative param-eter that shows the remarkable effect on the PPCPs uptake by the plant; the PPCPs with significantly higher log $K_{ow}$ (>4) are considered as highly hydrophobic compounds. Usually, these compounds do not translocate through the plant since it has expressed strong interaction with soil or root tissues. The PPCPs with lower log $K_{ow}$ (<1), considered as highly hydrophilic compounds, and these compounds have a low tendency to move across the phospholipid membrane of root tissues. The PPCPs which have log $K_{ow}$ between 1 and 4, can be readily translocated in plant parts (Colon & Toor, 2016). The ionic nature of PPCPs is another factor that influences the uptake of PPCPs. For neutral PPCPs such as caffeine, carbamazepine, and estrone (Chuang et al., 2019), the $K_{ow}$ phenomena can be applied. In the case of ionic PPCPs, because of the repulsion or attraction between the ionized PPCPs, either anionic or cationic and negatively charged cell membrane of roots, the uptake and translocation of PPCPs by plant might be affected (Colon & Toor, 2016). The anionic PPCPs are likely to accumulate in the roots, whereas the neutral and cat-ionic PPCPs are likely to translocate in areal parts of plant either leaves, or steams, or fruits (Madikizela et al., 2018). It was reported by Goldstein et al. (2014), that the positively charged PPCPs such as metoprolol was

found in the cucumber and tomato leaves at quite high concentration compared to negatively charged PPCPs, probably as a result of the attraction of positively charged metoprolol with negatively charged cell membranes. The negatively charged PPCPs such as, ibuprofen, ketoprofen, gemfibrozil, and sulfamethoxazole are preferentially accumulated in the root cells since such weak acidic PPCPs undergo the dissociation into anionic forms in the cytosol once entered inside, which are repels by cell walls (Goldstein et al., 2014). Similarly, Christou et al. (2016) stated that being weak acidic property in nature, the diclofenac and sulfamethoxazole are accumulated at high concentration in the root but very less in leaves. In contrast, the trimethoprim as a basic PPCPs shows more accumulation in roots and high translocation to leaves when compared to the weak acidic PPCPs (Christou et al., 2016). The same author reported that the neutral PPCPs such as 17a-ethinylestradiol show almost quantitatively equal accumulation in roots and leaves. The environmental conditions such as the concentration of PPCPs in soil, pH of outside media, temperature, the concentration of available organic carbon in the soil also affect the plant uptake of PPCPs (Zhang et al., 2017).

## 7. Mechanism of uptake and translocation of PPCPs in the plant

Plants take up water along with dissolved solute such as minerals, organic compounds like PPCPs through the roots from the rhizosphere by passive diffusion. Generally, the passage of PPCPs through the plant starts at root hairs. Once PPCPs enter into root hairs, PPCPs reach the xylem/phloem through cortex, endodermis, and Casparian strip (Miller et al., 2016). The movement of PPCPs from root hair to xylem/phloem has been demonstrated by several pathways. (1) the movement of water and solute occurs through the space outside the cell membrane (apoplastic movement), (2) flux of water along with solute occurs through the cell cytoplasm (symplastic movement), and (3) the water and solute flow occurs via the vacuoles in cells (vacuolar movement) (Öztürk et al., 2016; Zhang & Zhu, 2009). Mainly, hydrophobic PPCPs move toward the xylem/phloem via the apoplastic movement, whereas the movement of hydrophilic PPCPs occurs via the symplastic movement (Zhang & Zhu, 2009). However, the apoplastic movement gets stopped at the Casparian strip because the deposition of lignin and suberin on the Casparian strip cell walls blocks the passive movement of water and solute. At this point, the flux of water and solute via apoplastic movement is forced into the symplastic movement (Cui & Schröder, 2016). Once the PPCPs reach the xylem/phloem, they get translocated upward to the aerial parts of the plant, such as stems, leaves, or fruits. Mainly, the water and PPCPs are pulled toward the leaves by the

combined action of transpiration steam, capillary action, and root pressure. Apart from this, the hydrophobic PPCPs are translocated to the shoot via the xylem sap, which contains latex-like-proteins which bind with hydrophobic PPCPs (Goto et al., 2019). The solubility enhancement of triclocarban and endosulfan in zucchini and soybean xylem sap was observed when those solubilities are compared with deionized water (Garvin et al., 2015).

Apart from the root uptake, there is another possibility of PPCPs uptake by the plant through stomata on the leaf surface, which function as an inlet for carbon dioxide and an outlet for water vapor. The gaseous contaminants can be taken up into the plant along with carbon dioxide through stomata (Colon & Toor, 2016). The recent study of Khuman and Chakraborty (2019) detected the occurrence of endosulfan, hexachlorocyclohexane, and dichlorodiphenyltrichloroethane in the air with a concentration of 429, 888, and 1689 pg/m$^3$. Therefore, it is now possible to identify the plant uptake of PPCPs through leaves and their uptake and translocation mechanism.

## 8. Human health exposure and risks of PPCPs through consumption of contaminated plants

The PPCPs as endocrine-disrupting contaminants enter into the human body through the consumption of the contaminated crops, vegetables and fruits. These PPCPs may cause several harmful effects on human health, especially in children. Recently, more than two PPCPs were found in the edible crops such as potato, lettuce, carrot, tomato, and zucchini (Christou et al., 2017; Riemenschneider et al., 2016). The consumption of two or more PPCPs at the same time may create interactive concerns in humans which cases were narrated in a review paper by Wu et al. (2015) showing 500 ng/day of each compound was ingested simultaneously through intake of the vegetable crops irrigated with PPCPs contaminated water. Daily exposure of PPCPs, especially antibiotics, will cause resistance to antimicrobial activity in humans, and it can increase the probability of risk of death. In a review on the risk assessment of personal care products, Stuart et al. (2012) showed that parabens suppressed the estrogenic activity and induced immunologically mediated, immediate systemic hypersensitivity reactions, while DEET inhibited the enzyme responsible for the operation of the central nervous system. However, Verslycke et al. (2016) found a large margin of safety for the exposure of triclosan through all routes, including biosolids – soil-plant – human, and they drew an inference that the contaminant could pose a minimal risk to human health. Furthermore, the human risk associated with exposure to PPCPs is determined in terms of risk quotient (RQ) and cumulative health hazard index (HI). The RQ is derived

from the ratio between estimated daily intake (EDI) and acceptable daily intake (ADI) (Liu et al., 2017) (Eq. (2)).

$$RQ = \frac{EDI\left(ngkg^{-1}day^{-1}\right)}{ADI\left(ngkg^{-1}day^{-1}\right)} \tag{2}$$

where the EDI value will be calculated by the equation expressed by Eq. (3).

$$EDI = \frac{Daily\ intake\ rate\ (g\ person^{-1}day^{-1})*PPCPs\ in\ vegetable\ (ng\ g^{-1})}{person\ average\ weight\ (kg\ person^{-1})} \tag{3}$$

and the value of HI is estimated by the tally of RQ of each PPCPs detected in a vegetable (Zhao et al., 2019), which mathematically expressed by Eq. (4).

$$HI = \sum_{j=1}^{n} RQ_i \tag{4}$$

It is considered as a negligible human risk when the value of RQ and HI < 0.01, as a considerable human risk if RQ and HI > 0.01, and as a distinct human risk if the value of RQ and HI > 0.05 (Liu et al., 2017; Zhao et al., 2019). Zhao et al. (2019) reported that PPCPs presence in human bodies living in both rural and urban areas was traced by ingesting PPCPs contaminated peanut kernels, where the RQ value for enrofloxacin, exceeded the threshold level of distinct human risk (RQ > 0.05), and for ofloxacin, norfloxacin, ciprofloxacin, and clarithromycin the RQ values reached the threshold level of considerable human risk (Zhao et al., 2019). Moreover, human health risk assessments through calculations of human exposure to the PPCPs are warranted when human exposure to PPCPs occurs concurrently via multiple pathways. Generally, human exposure (HE) of PPCPs is calculated using the mathematical equation expressed in Eq. (5),

$$HE = C*D*W*T \tag{5}$$

where C is the concentration of PPCPs in vegetables (ng/kg wet weight), D is the average daily consumption of vegetables (g wet weight/kg body weight/day), W is the human body weight, and T is the exposure time (day) (Wu et al., 2013). Typically, the acceptable annual human exposure range of PPCPs is 20–200 mg. Many laboratory experiments suggested that the human exposure of PPCPs, including carbamazepine, sulfamethazine, fluoxetine, and diclofenac through ingesting the contaminated plants, was much lower than the accepted range of 20–200 mg (Carter et al., 2014; Wu et al., 2013). However, to the best of the knowledge of the authors, no such

investigation is available in the literature about the human risks associated with the consumption of the contaminated vegetables.

## 9. Instrumental analysis methods to determine the PPCPs in plant tissues

The extraction of PPCPs in the plant tissues is a bit challenging task when compared to those in water and soil. The occurrence of primary and secondary metabolites, pigments, and other cellular compounds in plant tissues can interfere with PPCPs during the analysis. Therefore, the PPCPs extraction procedure from the plant tissue is essential in order to achieve accurate analysis. Previous studies have utilized various extraction techniques for the extraction of PPCPs from the plant tissues, for instance, solid-phase extraction (Petrie et al., 2017; Rajapaksha et al., 2014), liquid-liquid extraction (Loos et al., 2013), accelerated solvent extraction (Azanu et al., 2018), QuEChERS (**Qu**ick, **E**asy, **Ch**eap, **E**ffective, **R**ugged, and **S**afe) extraction (Podio et al., 2020). The QuEChERS method is frequently used by researchers nowadays due to the diversification in the physiochemical properties of PPCPs.

Moreover, many instrumental analyses (gas and liquid chromatography) have been employed in the quantification of PPCPs in the plant tissues after the extraction process. Mostly, the combination of liquid chromatography (LC) with mass spectroscopy (MS) can be used to quantify the various PPCPs accurately in the plant tissue extraction. The detection sensitivity of instruments toward the various PPCPs further increased in the liquid chromatography-tandem MS system. Many researchers have used different instruments, for instance, liquid chromatography-tandem mass spectroscopy (LC-MS/MS), high-performance liquid chromatography coupled mass spectroscopy (HPLC-MS/MS), and ultra-performance liquid chromatography coupled mass spectroscopy (UPLC-MS/MS) with electrospray ionizer. Further, the mobile phases and their flow gradient also crucial during the analysis of PPCPs in plant tissue extraction. Mostly, acetonitrile, formic acid, ultra-pure water, and methanol used as mobile phase solvents during the analysis. The different mobile phases composition with different flow gradients were reported in previous studies. The ultra-pure water as mobile phase A and acetonitrile as mobile phase B with 35–90% flow gradient of B were used in Liu et al. (2020). Similarly, 0.3% of formic acid as mobile phase A and 0.3% of formic acid with 65/35 v/v of acetonitrile and methanol as mobile phase B, with 40–100% gradient of B were used by Chuang et al. (2019). Table 7 provided commonly used analytical methods for PPCP analysis with preconcentrated techniques.

**Table 7.** Analysis methods of PPCPs in plant tissues.

| PPCPs | Plants | Grown media | Pre-concentration and clean up | Instrument | Reference |
|---|---|---|---|---|---|
| Diclofenac | Chicory (Cichorium intybus) | Soil | QuEChERS extraction | HPLC-MS/MS | (Podio et al., 2020) |
| Carbamazepine and Diclofenac | Lettuce (Lactuca sativa) | Coconut fiber | SPE extraction | UPLC | (González García, Fernández-López, Bueno-Crespo, et al., 2019) |
| 4 PPCPs | Spinach (Spinacia oleracea) | Hydroponic | Accelerated solvent extraction | LC-MS | (Nason et al., 2019) |
| Chlorotetracycline, sulfamethoxazole, and sulfathiazole | Maize (Zea mays) | Hydroponic | SPE extraction | HPLC-MS/MS | (Zhang et al., 2019) |
| Diclofenac, sulfamethoxazole, and trimethoprim | Tomato (Solanum lycopersicum) | Silica sand | SPE extraction | UPLC-MS/MS | (Christou et al., 2019) |
| Atenolol, sulfamethoxazole and carbamazepine | Spinach (Spinacea oleracea) | Sludge amended soils | – | Hybrid quadrupole - orbital trap -MS | (Kodešová, Klement, Golovko, Fér, Kočárek, et al., 2019) |
| 5 PPCPs | Beetroot (Beta vulgaris) | Soil | QuEChERS extraction | LC-MS | (Papaioannou et al., 2019) |
| 11 PPCPs | 4 plants including Cucumber (Cucumis sativus) | Real agricultural land | SPE extraction | HPLC-MS/MS | (Liu et al., 2020) |
| Clarithromycin and sulfadiazine | Lettuce (Lactuca sativa) | Nutrient solution | SPE extraction | UPLC-MS/MS | (Tian et al., 2019) |
| 12 PPCPs | Lettuce (Lactuca sativa) | Farming land | Accelerated solvent extraction and SPE | LC-MS/MS | (Azanu et al., 2018) |
| Chlortetracycline, enrofloxacin, and sulfathiazol | Reddish (Raphanus sativus) | Soil | QuEChERS extraction | LC-MS/MS | (Chung et al., 2017) |

## 10. Contemporary issues and future scope

We have briefly explained the available groups of PPCPs and respected compounds come under each group. The physicochemical properties of each compound play a significant role in their uptake by the plant. It has been identified that the bioavailability of PPCPs under the realistic field condition is scarcer than those under the greenhouse condition, and the translocation of PPCPs from root to shoot occurs along with the water flow though they are influenced by several factors: plant types, and physiochemical properties of PPCPs. Based on the literature, the authors suggested, human exposure and risk were minimal through the consumption of contaminated crops/vegetables. However, the research on human risk and exposure is premature due to the lack of comprehensive studies.

Several recent studies have investigated the accumulation of PPCPs in the edible plants such as water spinach, cucumber, and spinach under the greenhouse condition (Kurade et al., 2019; Nason et al., 2019; Sun et al., 2019). In a field study, Christou et al. (2017) reported uptake of diclofenac, sulfamethoxazole, and trimethoprim in tomato fruits, which were irrigated with wastewater from municipal wastewater treatment plant for long-term under the realistic farming conditions. However, the investigation on the plant uptake of PPCPs under the practical field conditions is minimal. Therefore, researchers should strive to explore more about the uptake and transformations of PPCPs under real-life environmental scenarios. Furthermore, there are very few studies reported so far on the occurrence of anti-viral drugs in the urban water cycle (Funke et al., 2016). Nevertheless, there is no such study conducted yet on the uptake of an anti-viral medication in the plants, neither in the laboratory nor under outdoor environmental conditions. Therefore, it leaves an ample opportunity for conducting experiments to explore such issues and put some insight into the future.

The PPCPs undergo the biodegradation process once they are taken up by the plants. Recently, several studies have found some metabolites of respective PPCPs in the plant system, which are resulted from the metabolic transformation of the xenobiotics in the individual plant's body. Tian et al. (2019) detected eight metabolites of clarithromycin, and two metabolites of sulfadiazine in lettuce (*Lactuca sativa*). Similarly, Kurade et al. (2019) reported five metabolites of sulfamethoxazole in water spinach (*Ipomoea aquatica*). These metabolites may produce more adverse health issues than their corresponding parent compounds. Therefore, it is urgently required in the future to appraise the human health risks of the metabolites of important PPCPs along with their parent counterparts since health risks for parent compounds only are mostly estimated in such toxicological studies. On the other hand, further mechanistic understanding of uptake,

toxicity, and persistence of all groups of PPCPs needs to be elucidated evidently by future research.

Studies have established that the mechanism of plant uptake of PPCPs depends on the physicochemical properties of PPCPs, and environmental conditions. Goto et al. (2019) showed that the translocation of polychlorinated biphenyls to the shoot via the xylem sap involves latex-like-proteins, which bind with hydrophobic PPCPs. Therefore, further investigation needs to be carried out on other groups of PPCPs how they are translocated to different aerial parts of the plants employing a suite of biochemical working horses. Although several studies have reported the plant uptake and translocation of PPCPs, most of them have studied well about pharmaceutical products. Only a few studies have reported the PCPs such as triclosan, triclocarban, caffeine, and phthalate. Therefore, this study suggested, plant uptake of PCPs should be carried out in future research since the use and misuse of PCPs have increased in the modern world.

Apart from the root uptake, stomata are the minuscule 'windows' on the surface of plant leaves, which can allow the intake of volatile organic compounds from the air. A greenhouse experiment by Bhalsod et al. (2018) elaborated how the over-head irrigation using PPCPs contaminated water could increase the accumulation of PPCPs, which even exceeded the root uptake in lettuce (*Lactuca sativa*). Although the research on the uptake of PPCPs through the plant leaves remains in a nascent stage in the mostly unexplored territory. Future research investigations need to be directed toward the plants' uptake of PPCPs through their leaves since PPCPs such as endosulfan, dichlorodiphenyltrichloroethane, and hexachlorocyclohexane are found in the air and enter into the plant system through stomata. However, this route of exposure with associated risks remains entirely ignored without drawing its due attention to date.

## 11. Conclusion

The pathways which loaded the PPCPs in the environment, plant uptake and translocate of PPCPs under the greenhouse condition and realistic field condition, and the mechanism of plant uptake of PPCPs are discussed in detail. Currently, PPCPs are reported in plant parts, which may end up in the human bodies. The uptake of PPCPs under the greenhouse condition comparatively higher than those under the field condition. Furthermore, only a few studies have investigated the human health issues by ingesting the contaminated vegetables showed that the human exposure of these PPCPs is much lower than the accepted intake margin. More research is needed on personal care products whereas pharmaceuticals have been well studied.

## ORCID

Meththika Vithanage https://orcid.org/0000-0003-2923-4065

## References

Ahmed, M. B. M., Rajapaksha, A. U., Lim, J. E., Vu, N. T., Kim, I. S., Kang, H. M., Lee, S. S., & Ok, Y. S. (2015). Distribution and accumulative pattern of tetracyclines and sulfonamides in edible vegetables of cucumber, tomato, and lettuce. *Journal of Agricultural and Food Chemistry*, 63(2), 398–405. doi:10.1021/jf5034637

Al-Farsi, R. S., Ahmed, M., Al-Busaidi, A., & Choudri, B. S. (2017). Translocation of pharmaceuticals and personal care products (PPCPs) into plant tissues: A review. *Emerging Contaminants*, 3(4), 132–137. doi:10.1016/j.emcon.2018.02.001

Ali, A. M., Rønning, H. T., Sydnes, L. K., Alarif, W. M., Kallenborn, R., & Al-Lihaibi, S. S. (2018). Detection of PPCPs in marine organisms from contaminated coastal waters of the Saudi Red Sea. *Science of the Total Environment*, 621, 654–662. doi:10.1016/j.scitotenv.2017.11.298

Al-Mashaqbeh, O., Alsafadi, D., Dalahmeh, S., Bartelt-Hunt, S., & Snow, D. (2019). Removal of selected pharmaceuticals and personal care products in wastewater treatment plant in Jordan. *Water (Switzerland)*, 11(10). doi:10.3390/w11102004

Aparicio, I., Martín, J., Abril, C., Santos, J. L., & Alonso, E. (2018). Determination of household and industrial chemicals, personal care products and hormones in leafy and root vegetables by liquid chromatography-tandem mass spectrometry. *Journal of Chromatography A*, 1533, 49–56. doi:10.1016/j.chroma.2017.12.011

Azanu, D., Mortey, C., Darko, G., Weisser, J. J., Styrishave, B., & Abaidoo, R. C. (2016). Uptake of antibiotics from irrigation water by plants. *Chemosphere*, 157, 107–114. doi:10.1016/j.chemosphere.2016.05.035

Azanu, D., Styrishave, B., Darko, G., Weisser, J. J., & Abaidoo, R. C. (2018). Occurrence and risk assessment of antibiotics in water and lettuce in Ghana. *Science of the Total Environment*, 622-623, 293–305. doi:10.1016/j.scitotenv.2017.11.287

Baena-Nogueras, R. M., González-Mazo, E., & Lara-Martín, P. A. (2017). Degradation kinetics of pharmaceuticals and personal care products in surface waters: Photolysis vs biodegradation. *Science of the Total Environment*, 590-591, 643–654. doi:10.1016/j.scitotenv.2017.03.015

Balakrishna, K., Rath, A., Praveenkumarreddy, Y., Guruge, K. S., & Subedi, B. (2017). A review of the occurrence of pharmaceuticals and personal care products in Indian water bodies. *Ecotoxicology and Environmental Safety*, 137(Nov), 113–120. doi:10.1016/j.ecoenv.2016.11.014

Bassil, R. J., Bashour, I. I., Sleiman, F. T., & Abou-Jawdeh, Y. A. (2013). Antibiotic uptake by plants from manure-amended soils. *Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes*, 48(7), 570–574. doi:10.1080/03601234.2013.774898

Batchu, S. R., Panditi, V. R., O'Shea, K. E., & Gardinali, P. R. (2014). Photodegradation of antibiotics under simulated solar radiation: Implications for their environmental fate. *Science of the Total Environment*, 470-471, 299–310. doi:10.1016/j.scitotenv.2013.09.057

Ben Mordechay, E., Tarchitzky, J., Chen, Y., Shenker, M., & Chefetz, B. (2018). Composted biosolids and treated wastewater as sources of pharmaceuticals and personal care products for plant uptake: A case study with carbamazepine. *Environmental Pollution*, *232*, 164–172. doi:10.1016/j.envpol.2017.09.029

Bhalsod, G. D., Chuang, Y. H., Jeon, S., Gui, W., Li, H., Ryser, E. T., Guber, A. K., & Zhang, W. (2018). Uptake and accumulation of pharmaceuticals in overhead- and surface-irrigated greenhouse lettuce. *Journal of Agricultural and Food Chemistry*, *66*(4), 822–830. doi:10.1021/acs.jafc.7b04355

Biel-Maeso, M., Corada-Fernández, C., & Lara-Martín, P. A. (2018). Monitoring the occurrence of pharmaceuticals in soils irrigated with reclaimed wastewater. *Environmental Pollution*, *235*, 312–321. doi:10.1016/j.envpol.2017.12.085

Biel-Maeso, M., González-González, C., Lara-Martín, P. A., & Corada-Fernández, C. (2019). Sorption and degradation of contaminants of emerging concern in soils under aerobic and anaerobic conditions. *Science of the Total Environment*, *666*, 662–671. doi:10.1016/j.scitotenv.2019.02.279

Boxall, A. B. A., Johnson, P., Smith, E. J., Sinclair, C. J., Stutt, E., & Levy, L. S. (2006). Uptake of veterinary medicines from soils into plants. *Journal of Agricultural and Food Chemistry*, *54*(6), 2288–2297. doi:10.1021/jf053041t

Brooks, B. W., Maul, J. D., & Belden, J. B. (2008). Antibiotics in aquatic and terrestrial ecosystems. *Encyclopedia of Ecologyt*, *2002*, 210–217. 10.1016/B978-008045405-4.00370-0

Bu, Q., Shi, X., Yu, G., Huang, J., & Wang, B. (2016). Assessing the persistence of pharmaceuticals in the aquatic environment: Challenges and needs. *Emerging Contaminants*, *2*(3), 145–147. doi:10.1016/j.emcon.2016.05.003

Carter, L. J., Harris, E., Williams, M., Ryan, J. J., Kookana, R. S., & Boxall, A. B. A. (2014). Fate and uptake of pharmaceuticals in soil-plant systems. *Journal of Agricultural and Food Chemistry*, *62*(4), 816–825. doi:10.1021/jf404282y

Carter, L. J., Williams, M., Martin, S., Kamaludeen, S. P. B., & Kookana, R. S. (2018). Sorption, plant uptake and metabolism of benzodiazepines. *Science of the Total Environment*, *628-629*, 18–25. doi:10.1016/j.scitotenv.2018.01.337

Chen, L., Zhang, S., Huang, H., Wen, B., & Christie, P. (2009). Partitioning of phenanthrene by root cell walls and cell wall fractions of wheat (*Triticum aestivum* L.).*Environmental Science & Technology*, *43*(24), 9136–9141. doi:10.1021/es902098p

Christou, A., Antoniou, C., Christodoulou, C., Hapeshi, E., Stavrou, I., Michael, C., Fatta-Kassinos, D., & Fotopoulos, V. (2016). Stress-related phenomena and detoxification mechanisms induced by common pharmaceuticals in alfalfa (*Medicago sativa* L.) plants. *Science of the Total Environment*, *557-558*, 652–664. doi:10.1016/j.scitotenv.2016.03.054

Christou, A., Karaolia, P., Hapeshi, E., Michael, C., & Fatta-Kassinos, D. (2017). Long-term wastewater irrigation of vegetables in real agricultural systems: Concentration of pharmaceuticals in soil, uptake and bioaccumulation in tomato fruits and human health risk assessment. *Water Research*, *109*, 24–34. doi:10.1016/j.watres.2016.11.033

Christou, A., Kyriacou, M. C., Georgiadou, E. C., Papamarkou, R., Hapeshi, E., Karaolia, P., Michael, C., Fotopoulos, V., & Fatta-Kassinos, D. (2019). Uptake and bioaccumulation of three widely prescribed pharmaceutically active compounds in tomato fruits and mediated effects on fruit quality attributes. *Science of the Total Environment*, *647*, 1169–1178. doi:10.1016/j.scitotenv.2018.08.053

Chuang, Y. H., Liu, C. H., Sallach, J. B., Hammerschmidt, R., Zhang, W., Boyd, S. A., & Li, H. (2019). Mechanistic study on uptake and transport of pharmaceuticals in lettuce from water. *Environment International*, *131*(April), 104976. doi:10.1016/j.envint.2019.104976

Chung, H. S., Lee, Y. J., Rahman, M. M., Abd El-Aty, A. M., Lee, H. S., Kabir, M. H., Kim, S. W., Park, B. J., Kim, J. E., Hacımüftüoğlu, F., Nahar, N., Shin, H. C., & Shim, J. H. (2017). Uptake of the veterinary antibiotics chlortetracycline, enrofloxacin, and sulphathiazole from soil by radish. *Science of the Total Environment*, *605-606*, 322–331. doi:10.1016/j.scitotenv.2017.06.231

Colon, B., & Toor, G. S. (2016). A review of uptake and translocation of pharmaceuticals and personal care products by food crops irrigated with treated wastewater. In *Advances in agronomy* (Vol. *140*, pp. 75–100). Academic Press. 10.1016/bs.agron.2016.07.001

Conde-Cid, M., Álvarez-Esmorís, C., Paradelo-Núñez, R., Nóvoa-Muñoz, J. C., Arias-Estévez, M., Álvarez-Rodríguez, E., Fernández-Sanjurjo, M. J., & Núñez-Delgado, A. (2018). Occurrence of tetracyclines and sulfonamides in manures, agricultural soils and crops from different areas in Galicia (NW Spain). *Journal of Cleaner Production*, *197*, 491–500. doi:10.1016/j.jclepro.2018.06.217

Cortés, J. M., Larsson, E., & Jönsson, J. Å. (2013). Study of the uptake of non-steroid anti-inflammatory drugs in wheat and soybean after application of sewage sludge as a fertilizer. *Science of the Total Environment*, *449*, 385–389. doi:10.1016/j.scitotenv.2013.01.061

Cui, H., & Schröder, P. (2016). Uptake, translocation and possible biodegradation of the antidiabetic agent metformin by hydroponically grown *Typha latifolia*. *Journal of Hazardous Materials*, *308*, 355–361. doi:10.1016/j.jhazmat.2016.01.054

Dalahmeh, S., Tirgani, S., Komakech, A. J., Niwagaba, C. B., & Ahrens, L. (2018). Per- and polyfluoroalkyl substances (PFASs) in water, soil and plants in wetlands and agricultural areas in Kampala. *Science of the Total Environment*, *631-632*, 660–667. doi:10.1016/j.scitotenv.2018.03.024

Dhir, B. (2019). Removal of pharmaceuticals and personal care products by aquatic plants. In *Pharmaceuticals and personal care products: Waste management and treatment technology*. Elsevier Inc. 10.1016/b978-0-12-816189-0.00014-7

Dodgen, L. K., Ueda, A., Wu, X., Parker, D. R., & Gan, J. (2015). Effect of transpiration on plant accumulation and translocation of PPCP/EDCs. *Environmental Pollution*, *198*, 144–153. doi:10.1016/j.envpol.2015.01.002

Dolliver, H., Kumar, K., & Gupta, S. (2007). Sulfamethazine uptake by plants from manure-amended soil. *Journal of Environmental Quality*, *36*(4), 1224–1230. doi:10.2134/jeq2006.0266

Ebele, A. J., Abou-Elwafa Abdallah, M., & Harrad, S. (2017). Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment. *Emerging Contaminants*, *3*(1), 1–16. doi:10.1016/j.emcon.2016.12.004

Evgenidou, E. N., Konstantinou, I. K., & Lambropoulou, D. A. (2015). Occurrence and removal of transformation products of PPCPs and illicit drugs in wastewaters: A review. *Science of the Total Environment*, *505*, 905–926. doi:10.1016/j.scitotenv.2014.10.021

Funke, J., Prasse, C., & Ternes, T. A. (2016). Identification of transformation products of antiviral drugs formed during biological wastewater treatment and their occurrence in the urban water cycle. *Water Research*, *98*, 75–83. doi:10.1016/j.watres.2016.03.045

Garvin, N., Doucette, W. J., & White, J. C. (2015). Investigating differences in the root to shoot transfer and xylem sap solubility of organic compounds between zucchini, squash and soybean using a pressure chamber method. *Chemosphere*, *130*, 98–102. doi:10.1016/j.chemosphere.2014.11.075

Gatidou, G., Oursouzidou, M., Stefanatou, A., & Stasinakis, A. S. (2017). Removal mechanisms of benzotriazoles in duckweed *Lemna minor* wastewater treatment systems. *Science of the Total Environment*, *596-597*, 12–17. doi:10.1016/j.scitotenv.2017.04.051

Gogoi, A., Mazumder, P., Tyagi, V. K., Tushara Chaminda, G. G., An, A. K., & Kumar, M. (2018). Occurrence and fate of emerging contaminants in water environment: A review. *Groundwater for Sustainable Development*, 6(Sept), 169–180. doi:10.1016/j.gsd.2017.12.009

Goldstein, M., Shenker, M., & Chefetz, B. (2014). Insights into the uptake processes of wastewater-borne pharmaceuticals by vegetables. *Environmental Science & Technology*, 48(10), 5593–5600. doi:10.1021/es5008615

González García, M., Fernández-López, C., Bueno-Crespo, A., & Martínez-España, R. (2019). Extreme learning machine-based prediction of uptake of pharmaceuticals in reclaimed water-irrigated lettuces in the Region of Murcia. *Biosystems Engineering*, 177, 78–89. doi:10.1016/j.biosystemseng.2018.09.006

González García, M., Fernández-López, C., Polesel, F., & Trapp, S. (2019). Predicting the uptake of emerging organic contaminants in vegetables irrigated with treated wastewater – Implications for food safety assessment. *Environmental Research*, 172, 175–181. doi:10.1016/j.envres.2019.02.011

Goto, J., Iwabuchi, A., Yoshihara, R., Kodama, N., Matsui, T., Hirota, M., Eun, H., & Inui, H. (2019). Uptake mechanisms of polychlorinated biphenyls in *Cucurbita pepo* via xylem sap containing major latex-like proteins. *Environmental and Experimental Botany*, 162(March), 399–405. doi:10.1016/j.envexpbot.2019.03.019

Gredelj, A., Nicoletto, C., Polesello, S., Ferrario, C., Valsecchi, S., Lava, R., Barausse, A., Zanon, F., Palmeri, L., Guidolin, L., & Bonato, M. (2020). Uptake and translocation of per fluoroalkyl acids (PFAAs) in hydroponically grown red chicory (*Cichorium intybus* L.): Growth and developmental toxicity, comparison with growth in soil and bioavailability implications. *Science of the Total Environment*, 720, 137333. doi:10.1016/j.scitotenv.2020.137333

Guruge, K. S., Goswami, P., Tanoue, R., Nomiyama, K., Wijesekara, R. G. S., & Dharmaratne, T. S. (2019). First nationwide investigation and environmental risk assessment of 72 pharmaceuticals and personal care products from Sri Lankan surface waterways. *Science of the Total Environment*, 690, 683–695. doi:10.1016/j.scitotenv.2019.07.042

He, Y., Nie, E., Li, C., Ye, Q., & Wang, H. (2017). Uptake and subcellular distribution of triclosan in typical hydrophytes under hydroponic conditions. *Environmental Pollution*, 220, 400–406. doi:10.1016/j.envpol.2016.09.076

Hong, Y., Lee, I., Lee, W., & Kim, H. (2019). Mass-balance-model-based evaluation of sewage treatment plant contribution to residual pharmaceuticals in environmental waters. *Chemosphere*, 225, 378–387. doi:10.1016/j.chemosphere.2019.03.046

Hossain, A., Nakamichi, S., Habibullah-Al-Mamun, M., Tani, K., Masunaga, S., & Matsuda, H. (2018). Occurrence and ecological risk of pharmaceuticals in river surface water of Bangladesh. *Environmental Research*, 165(March), 258–266. doi:10.1016/j.envres.2018.04.030

Iatrou, E. I., Gatidou, G., Damalas, D., Thomaidis, N. S., & Stasinakis, A. S. (2017). Fate of antimicrobials in duckweed *Lemna minor* wastewater treatment systems. *Journal of Hazardous Materials*, 330, 116–126. doi:10.1016/j.jhazmat.2017.02.005

Jiang, Y., Li, M., Guo, C., An, D., Xu, J., Zhang, Y., & Xi, B. (2014). Distribution and ecological risk of antibiotics in a typical effluent-receiving river (Wangyang River) in north China. *Chemosphere*, 112, 267–274. doi:10.1016/j.chemosphere.2014.04.075

Kapelewska, J., Kotowska, U., Karpińska, J., Kowalczuk, D., Arciszewska, A., & Świrydo, A. (2018). Occurrence, removal, mass loading and environmental risk assessment of emerging organic contaminants in leachates, groundwaters and wastewaters. *Microchemical Journal*, 137, 292–301. doi:10.1016/j.microc.2017.11.008

Khuman, S. N., & Chakraborty, P. (2019). Air-water exchange of pesticidal persistent organic pollutants in the lower stretch of the transboundary river Ganga, India. *Chemosphere*, *233*, 966–974. doi:10.1016/j.chemosphere.2019.05.223

Kim, S. D., Cho, J., Kim, I. S., Vanderford, B. J., & Snyder, S. A. (2007). Occurrence and removal of pharmaceuticals and endocrine disruptors in South Korean surface, drinking, and waste waters. *Water Research*, *41*(5), 1013–1021. doi:10.1016/j.watres.2006.06.034

Kleywegt, S., Payne, M., Raby, M., Filippi, D., Ng, C. F., & Fletcher, T. (2019). The final discharge: Quantifying contaminants in embalming process effluents discharged to sewers in ontario. *Environmental Pollution*, *252*, 1476–1482. doi:10.1016/j.envpol.2019.06.036

Knight, E. R., Carter, L. J., & McLaughlin, M. J. (2018). Bioaccumulation, uptake, and toxicity of carbamazepine in soil–plant systems. *Environmental Toxicology and Chemistry*, *37*(4), 1122–1130. doi:10.1002/etc.4053

Kodešová, R., Klement, A., Golovko, O., Fér, M., Kočárek, M., Nikodem, A., & Grabic, R. (2019). Soil influences on uptake and transfer of pharmaceuticals from sewage sludge amended soils to spinach. *Journal of Environmental Management*, *250*(Aug), 109407. doi:10.1016/j.jenvman.2019.109407

Kodešová, R., Klement, A., Golovko, O., Fér, M., Nikodem, A., Kočárek, M., & Grabic, R. (2019). Root uptake of atenolol, sulfamethoxazole and carbamazepine, and their transformation in three soils and four plants. *Environmental Science and Pollution Research*, *26*(10), 9876–9891. doi:10.1007/s11356-019-04333-9

Kumar, R., Sarmah, A. K., & Padhye, L. P. (2019). Fate of pharmaceuticals and personal care products in a wastewater treatment plant with parallel secondary wastewater treatment train. *Journal of Environmental Management*, *233*(Dec), 649–659. doi:10.1016/j.jenvman.2018.12.062

Kurade, M. B., Xiong, J. Q., Govindwar, S. P., Roh, H. S., Saratale, G. D., Jeon, B. H., & Lim, H. (2019). Uptake and biodegradation of emerging contaminant sulfamethoxazole from aqueous phase using *Ipomoea aquatica*. *Chemosphere*, *225*, 696–704. doi:10.1016/j.chemosphere.2019.03.086

Lee, H. J., Kim, K. Y., Hamm, S. Y., Kim, M. S., Kim, H. K., & Oh, J. E. (2019). Occurrence and distribution of pharmaceutical and personal care products, artificial sweeteners, and pesticides in groundwater from an agricultural area in Korea. *Science of the Total Environment*, *659*, 168–176. doi:10.1016/j.scitotenv.2018.12.258

Li, B., & Zhang, T. (2010). Biodegradation and adsorption of antibiotics in the activated sludge process. *Environmental Science & Technology*, *44*(9), 3468–3473. doi:10.1021/es903490h

Li, M., Ding, T., Wang, H., Wang, W., Li, J., & Ye, Q. (2018). Uptake and translocation of 14C-Carbamazepine in soil-plant systems. *Environmental Pollution*, *243*, 1352–1359. doi:10.1016/j.envpol.2018.09.079

Li, Y., Yan, H., Liu, Q., Li, X., Ge, J., & Yu, X. (2020). Accumulation and transport patterns of six phthalic acid esters (PAEs) in two leafy vegetables under hydroponic conditions. *Chemosphere*, *249*, 126457. doi:10.1016/j.chemosphere.2020.126457

Liu, H., Huang, X., Yu, X., Pu, C., Sun, Y., & Luo, W. (2019). Dissipation and persistence of sulfonamides, quinolones and tetracyclines in anaerobically digested biosolids and compost during short-term storage under natural conditions. *Science of the Total Environment*, *684*, 58–66. doi:10.1016/j.scitotenv.2019.05.341

Liu, J. L., & Wong, M. H. (2013). Pharmaceuticals and personal care products (PPCPs): A review on environmental contamination in China. *Environment International*, *59*, 208–224. doi:10.1016/j.envint.2013.06.012

Liu, S., Zhao, H., Lehmler, H. J., Cai, X., & Chen, J. (2017). Antibiotic pollution in marine food webs in Laizhou Bay, North China: Trophodynamics and human exposure implication. *Environmental Science & Technology*, *51*(4), 2392–2400. doi:10.1021/acs.est.6b04556

Liu, X., Liang, C., Liu, X., Zhao, F., & Han, C. (2020). Occurrence and human health risk assessment of pharmaceuticals and personal care products in real agricultural systems with long-term reclaimed wastewater irrigation in Beijing, China. *Ecotoxicology and Environmental Safety*, *190*, 110022. doi:10.1016/j.ecoenv.2019.110022

Liu, X., Shi, J., Bo, T., Zhang, H., Wu, W., Chen, Q., & Zhan, X. (2014). Occurrence of phthalic acid esters in source waters: A nationwide survey in China during the period of 2009-2012. *Environmental Pollution*, *184*, 262–270. doi:10.1016/j.envpol.2013.08.035

Lonappan, L., Pulicharla, R., Rouissi, T., Brar, S. K., Verma, M., Surampalli, R. Y., & Valero, J. R. (2016). Diclofenac in municipal wastewater treatment plant: Quantification using laser diode thermal desorption-atmospheric pressure chemical ionization-tandem mass spectrometry approach in comparison with an established liquid chromatography-electrospray ionizat. *Journal of Chromatography A*, *1433*, 106–113. doi:10.1016/j.chroma.2016.01.030

Loos, R., Carvalho, R., António, D. C., Comero, S., Locoro, G., Tavazzi, S., Paracchini, B., Ghiani, M., Lettieri, T., Blaha, L., Jarosova, B., Voorspoels, S., Servaes, K., Haglund, P., Fick, J., Lindberg, R. H., Schwesig, D., & Gawlik, B. M. (2013). EU-wide monitoring survey on emerging polar organic contaminants in wastewater treatment plant effluents. *Water Research*, *47*(17), 6475–6487. doi:10.1016/j.watres.2013.08.024

Ma, L., Liu, Y., Zhang, J., Yang, Q., Li, G., & Zhang, D. (2018). Impacts of irrigation water sources and geochemical conditions on vertical distribution of pharmaceutical and personal care products (PPCPs) in the vadose zone soils. *Science of the Total Environment*, *626*, 1148–1156. doi:10.1016/j.scitotenv.2018.01.168

Madikizela, L. M., Ncube, S., & Chimuka, L. (2018). Uptake of pharmaceuticals by plants grown under hydroponic conditions and natural occurring plant species: A review. *Science of the Total Environment*, *636*, 477–486. doi:10.1016/j.scitotenv.2018.04.297

Martín, J., Santos, J. L., Aparicio, I., & Alonso, E. (2015). Pharmaceutically active compounds in sludge stabilization treatments: Anaerobic and aerobic digestion, wastewater stabilization ponds and composting. *Science of the Total Environment*, *503-504*, 97–104. doi:10.1016/j.scitotenv.2014.05.089

Martínez-Piernas, A. B., Plaza-Bolaños, P., Fernández-Ibáñez, P., & Agüera, A. (2019). Organic microcontaminants in tomato crops irrigated with reclaimed water grown under field conditions: Occurrence, uptake, and health risk assessment. *Journal of Agricultural and Food Chemistry*, *67*(25), 6930–—6939. doi:10.1021/acs.jafc.9b01656

Mendoza, A., Aceña, J., Pérez, S., López de Alda, M., Barceló, D., Gil, A., & Valcárcel, Y. (2015). Pharmaceuticals and iodinated contrast media in a hospital wastewater: A case study to analyse their presence and characterise their environmental risk and hazard. *Environmental Research*, *140*, 225–241. doi:10.1016/j.envres.2015.04.003

Miller, E. L., Nason, S. L., Karthikeyan, K. G., & Pedersen, J. A. (2016). Root uptake of pharmaceuticals and personal care product ingredients. *Environmental Science & Technology*, *50*(2), 525–541. doi:10.1021/acs.est.5b01546

Miossec, C., Lanceleur, L., & Monperrus, M. (2019). Multi-residue analysis of 44 pharmaceutical compounds in environmental water samples by solid-phase extraction coupled to liquid chromatography-tandem mass spectrometry. *Journal of Separation Science*, *42*(10), 1853–1866. doi:10.1002/jssc.201801214

Murray, K. E., Thomas, S. M., & Bodour, A. A. (2010). Prioritizing research for trace pollutants and emerging contaminants in the freshwater environment. *Environmental Pollution*, *158*(12), 3462–3471. doi:10.1016/j.envpol.2010.08.009

Mutiyar, P. K., Gupta, S. K., & Mittal, A. K. (2018). Fate of pharmaceutical active compounds (PhACs) from River Yamuna, India: An ecotoxicological risk assessment approach. *Ecotoxicology and Environmental Safety*, *150*(December 2017), 297–304. doi:10.1016/j.ecoenv.2017.12.041

Nason, S. L., Miller, E. L., Karthikeyan, K. G., & Pedersen, J. A. (2019). Effects of binary mixtures and transpiration on accumulation of pharmaceuticals by spinach. *Environmental Science & Technology*, *53*(9), 4850–4859. doi:10.1021/acs.est.8b05515

Nuel, M., Laurent, J., Bois, P., Heintz, D., & Wanko, A. (2018). Seasonal and ageing effect on the behaviour of 86 drugs in a full-scale surface treatment wetland: Removal efficiencies and distribution in plants and sediments. *Science of the Total Environment*, *615*, 1099–1109. doi:10.1016/j.scitotenv.2017.10.061

Odendaal, C., Seaman, M. T., Kemp, G., Patterton, H. E., & Patterton, H. G. (2015). An LC-MS/MS based survey of contaminants of emerging concern in drinking water in South Africa. *South African Journal of Science*, *111*(9/10), 1–6. doi:10.17159/sajs.2015/20140401

Öztürk, M., Ashraf, M., Aksoy, A., Ahmad, M. S. A., & Hakeem, K. R. (2016). Plants, pollutants and remediation. In *Plants, pollutants and remediation*. Springer. 10.1007/978-94-017-7194-8

Paíga, P., & Delerue-Matos, C. (2016). Determination of pharmaceuticals in groundwater collected in five cemeteries' areas (Portugal). *Science of the Total Environment*, *569-570*, 16–22. doi:10.1016/j.scitotenv.2016.06.090

Pan, M., & Chu, L. M. (2017). Fate of antibiotics in soil and their uptake by edible crops. *Science of the Total Environment*, *599-600*, 500–512. doi:10.1016/j.scitotenv.2017.04.214

Papaioannou, D., Koukoulakis, P. H., Lambropoulou, D., Papageorgiou, M., & Kalavrouziotis, I. K. (2019). The dynamics of the pharmaceutical and personal care product interactive capacity under the effect of artificial enrichment of soil with heavy metals and of wastewater reuse. *Science of the Total Environment*, *662*, 537–546. doi:10.1016/j.scitotenv.2019.01.111

Petrie, B., Smith, B. D., Youdan, J., Barden, R., & Kasprzyk-Hordern, B. (2017). Multi-residue determination of micropollutants in *Phragmites australis* from constructed wetlands using microwave assisted extraction and ultra-high-performance liquid chromatography tandem mass spectrometry. *Analytica Chimica Acta*, *959*, 91–101. doi:10.1016/j.aca.2016.12.042

Picó, Y., Alvarez-Ruiz, R., Alfarhan, A. H., El-Sheikh, M. A., Alobaid, S. M., & Barceló, D. (2019). Uptake and accumulation of emerging contaminants in soil and plant treated with wastewater under real-world environmental conditions in the Al Hayer area (Saudi Arabia). *Science of the Total Environment*, *652*, 562–572. doi:10.1016/j.scitotenv.2018.10.224

Podio, N. S., Bertrand, L., Wunderlin, D. A., & Santiago, A. N. (2020). Assessment of phytotoxic effects, uptake and translocation of diclofenac in chicory (*Cichorium intybus*). *Chemosphere*, *241*, 125057. doi:10.1016/j.chemosphere.2019.125057

Prosser, R. S., & Sibley, P. K. (2015). Human health risk assessment of pharmaceuticals and personal care products in plant tissue due to biosolids and manure amendments, and wastewater irrigation. *Environment International*, *75*, 223–233. doi:10.1016/j.envint.2014.11.020

Qian, M., Wu, H., Wang, J., Zhang, H., Zhang, Z., Zhang, Y., Lin, H., & Ma, J. (2016). Occurrence of trace elements and antibiotics in manure-based fertilizers from the

Zhejiang Province of China. *Science of the Total Environment, 559*, 174–181. doi:10.1016/j.scitotenv.2016.03.123

Rajapaksha, A. U., Vithanage, M., Lim, J. E., Ahmed, M. B. M., Zhang, M., Lee, S. S., & Ok, Y. S. (2014). Invasive plant-derived biochar inhibits sulfamethazine uptake by lettuce in soil. *Chemosphere, 111*, 500–504. doi:10.1016/j.chemosphere.2014.04.040

Riemenschneider, C., Al-Raggad, M., Moeder, M., Seiwert, B., Salameh, E., & Reemtsma, T. (2016). Pharmaceuticals, their metabolites, and other polar pollutants in field-grown vegetables irrigated with treated municipal wastewater. *Journal of Agricultural and Food Chemistry, 64*(29), 5784–5792. doi:10.1021/acs.jafc.6b01696

Riemenschneider, C., Seiwert, B., Moeder, M., Schwarz, D., & Reemtsma, T. (2017). Extensive transformation of the pharmaceutical carbamazepine following uptake into intact tomato plants. *Environmental Science & Technology, 51*(11), 6100–6109. doi:10.1021/acs.est.6b06485

Rivera-Jaimes, J. A., Postigo, C., Melgoza-Alemán, R. M., Aceña, J., Barceló, D., & López de Alda, M. (2018). Study of pharmaceuticals in surface and wastewater from Cuernavaca, Morelos, Mexico: Occurrence and environmental risk assessment. *Science of the Total Environment, 613-614*, 1263–1274. doi:10.1016/j.scitotenv.2017.09.134

Rosa, J., Leston, S., Freitas, A., Vila Pouca, A. S., Barbosa, J., Lemos, M. F. L., Pardal, M. A., & Ramos, F. (2019). Oxytetracycline accumulation in the macroalgae *Ulva*: Potential risks for IMTA systems. *Chemosphere, 226*, 60–66. doi:10.1016/j.chemosphere.2019.03.112

Sabourin, L., Duenk, P., Bonte-Gelok, S., Payne, M., Lapen, D. R., & Topp, E. (2012). Uptake of pharmaceuticals, hormones and parabens into vegetables grown in soil fertilized with municipal biosolids. *Science of the Total Environment, 431*, 233–236. doi:10.1016/j.scitotenv.2012.05.017

Saeidnia, S., & Abdollahi, M. (2013). Are medicinal plants polluted with phthalates? *DARU. Journal of Pharmaceutical Sciences, 21*(1), 2–4. 10.1186/2008-2231-21-43

Sharma, B. M., Bečanová, J., Scheringer, M., Sharma, A., Bharat, G. K., Whitehead, P. G., Klánová, J., & Nizzetto, L. (2019). Health and ecological risk assessment of emerging contaminants (pharmaceuticals, personal care products, and artificial sweeteners) in surface and groundwater (drinking water) in the Ganges River Basin, India. *Science of the Total Environment, 646*, 1459–1467. doi:10.1016/j.scitotenv.2018.07.235

Shigei, M., Ahren, L., Hazaymeh, A., & Dalahmeh, S. S. (2020). Per- and polyfluoroalkyl substances in water and soil in wastewater-irrigated farmland in Jordan. *Science of the Total Environment, 716*, 137057. doi:10.1016/j.scitotenv.2020.137057

Stuart, M., Lapworth, D., Crane, E., & Hart, A. (2012). Review of risk from potential emerging contaminants in UK groundwater. *Science of the Total Environment, 416*, 1–21. doi:10.1016/j.scitotenv.2011.11.072

Subedi, B., Balakrishna, K., Sinha, R. K., Yamashita, N., Balasubramanian, V. G., & Kannan, K. (2015). Mass loading and removal of pharmaceuticals and personal care products, including psychoactive and illicit drugs and artificial sweeteners, in five sewage treatment plants in India. *Journal of Environmental Chemical Engineering, 3*(4), 2882–2891. doi:10.1016/j.jece.2015.09.031

Subedi, B., Lee, S., Moon, H. B., & Kannan, K. (2014). Emission of artificial sweeteners, select pharmaceuticals, and personal care products through sewage sludge from wastewater treatment plants in Korea. *Environment International, 68*, 33–40. doi:10.1016/j.envint.2014.03.006

Sun, C., Dudley, S., McGinnis, M., Trumble, J., & Gan, J. (2019). Acetaminophen detoxification in cucumber plants via induction of glutathione S-transferases. *Science of the Total Environment*, *649*, 431–439. doi:10.1016/j.scitotenv.2018.08.346

Sun, C., Dudley, S., Trumble, J., & Gan, J. (2018). Pharmaceutical and personal care products-induced stress symptoms and detoxification mechanisms in cucumber plants. *Environmental Pollution*, *234*, 39–47. doi:10.1016/j.envpol.2017.11.041

Sun, J., Wu, X., & Gan, J. (2015). Uptake and metabolism of phthalate esters by edible plants. *Environmental Science & Technology*, *49*(14), 8471–8478. doi:10.1021/acs.est.5b01233

Sun, P., Casteel, K., Dai, H., Wehmeyer, K. R., Kiel, B., & Federle, T. (2014). Distributions of polycyclic musk fragrance in wastewater treatment plant (WWTP) effluents and sludges in the United States. *Science of the Total Environment*, *493*, 1073–1078. doi:10.1016/j.scitotenv.2014.04.038

Tarpani, R. R. Z., & Azapagic, A. (2018). A methodology for estimating concentrations of pharmaceuticals and personal care products (PPCPs) in wastewater treatment plants and in freshwaters. *Science of the Total Environment*, *622-623*, 1417–1430. doi:10.1016/j.scitotenv.2017.12.059

Tasho, R. P., & Cho, J. Y. (2016). Veterinary antibiotics in animal waste, its distribution in soil and uptake by plants: A review. *Science of the Total Environment*, *563-564*(3), 366–376. doi:10.1016/j.scitotenv.2016.04.140

Teglia, C. M., Perez, F. A., Michlig, N., Repetti, M. R., Goicoechea, H. C., & Culzoni, M. J. (2019). Occurrence, distribution, and ecological risk of fluoroquinolones in rivers and wastewaters. *Environmental Toxicology and Chemistry*, *38*(10), 2305–2313. doi:10.1002/etc.4532

Tian, R., Zhang, R., Uddin, M., Qiao, X., Chen, J., & Gu, G. (2019). Uptake and metabolism of clarithromycin and sulfadiazine in lettuce. *Environmental Pollution*, *247*, 1134–1142. doi:10.1016/j.envpol.2019.02.009

Tran, N. H., Hoang, L., Nghiem, L. D., Nguyen, N. M. H., Ngo, H. H., Guo, W., Trinh, Q. T., Mai, N. H., Chen, H., Nguyen, D. D., Ta, T. T., & Gin, K. Y. H. (2019). Occurrence and risk assessment of multiple classes of antibiotics in urban canals and lakes in Hanoi, Vietnam. *Science of the Total Environment*, *692*, 157–174. doi:10.1016/j.scitotenv.2019.07.092

Veras, T. B., Luiz Ribeiro de Paiva, A., Duarte, M. M. M. B., Napoleão, D. C., & da Silva Pereira Cabral, J. J. (2019). Analysis of the presence of anti-inflammatories drugs in surface water: A case study in Beberibe river - PE, Brazil. *Chemosphere*, *222*, 961–969. doi:10.1016/j.chemosphere.2019.01.167

Verslycke, T., Mayfield, D. B., Tabony, J. A., Capdevielle, M., & Slezak, B. (2016). Human health risk assessment of triclosan in land-applied biosolids. *Environmental Toxicology and Chemistry*, *35*(9), 2358–2367. doi:10.1002/etc.3370

Wang, J., & Wang, S. (2016). Removal of pharmaceuticals and personal care products (PPCPs) from wastewater: A review. *Journal of Environmental Management*, *182*, 620–640. doi:10.1016/j.jenvman.2016.07.049

Wang, Z., Wang, X. Y., Tian, H., Wei, Q. H., Liu, B. S., Bao, G. M., Liao, M. L., Peng, J. L., Huang, X. Q., & Wang, L. Q. (2019). High through-put determination of 28 veterinary antibiotic residues in swine wastewater by one-step dispersive solid phase extraction sample cleanup coupled with ultra-performance liquid chromatography-tandem mass spectrometry. *Chemosphere*, *230*, 337–346. doi:10.1016/j.chemosphere.2019.05.047

Wu, C., Spongberg, A. L., Witter, J. D., Fang, M., & Czajkowski, K. P. (2010). Uptake of pharmaceutical and personal care products by soybean plants from soils applied with

biosolids and irrigated with contaminated water. *Environmental Science & Technology*, *44*(16), 6157–6161. doi:10.1021/es1011115

Wu, X., Conkle, J. L., Ernst, F., & Gan, J. (2014). Treated wastewater irrigation: Uptake of pharmaceutical and personal care products by common vegetables under field conditions. *Environmental Science & Technology*, *48*(19), 11286–11293. doi:10.1021/es502868k

Wu, X., Dodgen, L. K., Conkle, J. L., & Gan, J. (2015). Plant uptake of pharmaceutical and personal care products from recycled water and biosolids: A review. *Science of the Total Environment*, *536*, 655–666. doi:10.1016/j.scitotenv.2015.07.129

Wu, X., Ernst, F., Conkle, J. L., & Gan, J. (2013). Comparative uptake and translocation of pharmaceutical and personal care products (PPCPs) by common vegetables. *Environment International*, *60*, 15–22. doi:10.1016/j.envint.2013.07.015

Xie, H., Hao, H., Xu, N., Liang, X., Gao, D., Xu, Y., Gao, Y., Tao, H., & Wong, M. (2019). Pharmaceuticals and personal care products in water, sediments, aquatic organisms, and fish feeds in the Pearl River Delta: Occurrence, distribution, potential sources, and health risk assessment. *Science of the Total Environment*, *659*, 230–239. doi:10.1016/j.scitotenv.2018.12.222

Xu, J., Wu, L., & Chang, A. C. (2009). Degradation and adsorption of selected pharmaceuticals and personal care products (PPCPs) in agricultural soils. *Chemosphere*, *77*(10), 1299–1305. doi:10.1016/j.chemosphere.2009.09.063

Xu, Z., Li, X., Hu, X., & Yin, D. (2017). Distribution and relevance of iodinated X-ray contrast media and iodinated trihalomethanes in an aquatic environment. *Chemosphere*, *184*, 253–260. doi:10.1016/j.chemosphere.2017.05.048

Yamamoto, H., Nakamura, Y., Moriguchi, S., Nakamura, Y., Honda, Y., Tamura, I., Hirata, Y., Hayashi, A., & Sekizawa, J. (2009). Persistence and partitioning of eight selected pharmaceuticals in the aquatic environment: Laboratory photolysis, biodegradation, and sorption experiments. *Water Research*, *43*(2), 351–362. doi:10.1016/j.watres.2008.10.039

Yang, Y., Ok, Y. S., Kim, K. H., Kwon, E. E., & Tsang, Y. F. (2017). Occurrences and removal of pharmaceuticals and personal care products (PPCPs) in drinking water and water/sewage treatment plants: A review. *Science of the Total Environment*, *596-597*, 303–320. doi:10.1016/j.scitotenv.2017.04.102

Zeng, X., Sheng, G., Gui, H., Chen, D., Shao, W., & Fu, J. (2007). Preliminary study on the occurrence and distribution of polycyclic musks in a wastewater treatment plant in Guandong. *Chemosphere*, *69*(8), 1305–1311. doi:10.1016/j.chemosphere.2007.05.029

Zhang, C., Feng, Y., Liu, Y., Wang, Chang, H., Qing, Li, Z., Jun, Xue, J. & Ming, (2017). Uptake and translocation of organic pollutants in plants: A review. *Journal of Integrative Agriculture*, *16*(8), 1659–1668.(16)61590-3 doi:10.1016/S2095-3119(16)61590-3

Zhang, C., Xue, J., Cheng, D., Feng, Y., Liu, Y., Aly, H. M., & Li, Z. (2019). Uptake, translocation and distribution of three veterinary antibiotics in *Zea mays* L. *Environmental Pollution*, *250*, 47–57. doi:10.1016/j.envpol.2019.03.110

Zhang, M., & Zhu, L. (2009). Sorption of polycyclic aromatic hydrocarbons to carbohydrates and lipids of ryegrass root and implications for a sorption prediction model. *Environmental Science & Technology*, *43*(8), 2740–2745. doi:10.1021/es802808q

Zhang, Z., Wang, B., Yuan, H., Ma, R., Huang, J., Deng, S., Wang, Y., & Yu, G. (2016). Discharge inventory of pharmaceuticals and personal care products in Beijing. *Emerging Contaminants*, *2*(3), 148–156. doi:10.1016/j.emcon.2016.07.001

Zhao, F., Yang, L., Chen, L., Li, S., & Sun, L. (2019). Bioaccumulation of antibiotics in crops under long-term manure application: Occurrence, biomass response and human exposure. *Chemosphere*, *219*, 882–895. doi:10.1016/j.chemosphere.2018.12.076

Zheng, W., Wiles, K. N., Holm, N., Deppe, N. A., & Shipley, C. R. (2014). Uptake, translocation, and accumulation of pharmaceutical and hormone contaminants in vegetables. *ACS Symposium Series*, *1171*, 167–181. 10.1021/bk-2014-1171.ch009

Zhou, L. J., Ying, G. G., Liu, S., Zhang, R. Q., Lai, H. J., Chen, Z. F., & Pan, C. G. (2013). Excretion masses and environmental occurrence of antibiotics in typical swine and dairy cattle farms in China. *Science of the Total Environment*, *444*, 183–195. doi:10.1016/j.scitotenv.2012.11.087