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Fujita, Kentaro Inui, Hideyuki

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How does the Cucurbitaceae family take up organic pollutants (POPs, PAHs, and PPCPs)?

- 3 Kentaro Fujita (kentaro.fujita1221@gmail.com)¹, Hideyuki Inui (hinui@kobe-u.ac.jp)^{1,2,*}
- ¹Graduate School of Agricultural Science, Kobe University, 1-1 Rokkodaicho, Nada-ku, Kobe, Hyogo

5 657-8501, Japan

- ²Biosignal Research Center, Kobe University, 1-1 Rokkodaicho, Nada-ku, Kobe, Hyogo 657-8501,
 Japan
- 8 *Corresponding Author: Hideyuki Inui, Biosignal Research Center, Kobe University, 1-1 Rokkodaicho,
- 9 Nada-ku, Kobe, Hyogo 657-8501, Japan
- 10 E-mail: hinui@kobe-u.ac.jp, Telephone number: +81-78-803-5863
- 11

12 Abstract

13Crop contamination with organic pollutants is an important food safety concern. Since organic 14pollutants are highly toxic, human consumption of contaminated crops can harm human health. Thus, 15understanding the mechanisms of how organic pollutants are accumulated in crop plants can aid the 16development of strategies for safer crop production. It is well known that the Cucurbitaceae family 17accumulates organic pollutants in its fruits at high concentrations. Previous studies have described the 18organic pollutant-uptake mechanisms of the Cucurbitaceae family. However, an integrated 19understanding of organic pollutant uptake by Cucurbitaceae is still lacking. In this review, we discuss 20the uptake mechanisms from the perspective of plant molecular biology. We clearly show that major 21latex-like proteins identified from the Cucurbitaceae family play a crucial role in the uptake of organic 22pollutants. This is the first review to describe the mechanisms underlying the accumulation of organic 23pollutants in the Cucurbitaceae family across the entire uptake pathway.

24

25 KEYWORDS: crop contamination, Cucurbitaceae family, major latex-like proteins, organic pollutants

26

27 **1. Introduction**

28Organic pollutants are widely distributed in the world and contaminate the environment (Wania and 29MacKay 1996; Shen et al. 2013). Organic pollutants remain in the environment without degradation 30 because they have long half-lives (Mattina et al. 1999; Sarma et al. 2019). In agriculture, crop 31contamination with organic pollutants is a severe problem. If maximum residue limits are exceeded in 32crops, farmers must discard all of the crops cultivated on the same agricultural land. Thus, the 33 economic loss for farmers is enormous. Furthermore, organic pollutants show toxicity, such as 34carcinogenicity (Abdur Rehman et al. 2017) and neurotoxicity (Pessah et al. 2019; Shi et al. 2019) in 35human beings, and the intake of contaminated crops can lead to severe diseases. Therefore, crop 36 contamination is an urgent problem in recent crop production. In this review, we introduce three groups 37of organic pollutants involved in crop contamination: persistent organic pollutants (POPs), 38 polyaromatic hydrocarbons (PAHs), and pharmaceuticals and personal care products (PPCPs).

39 POPs include organochlorine insecticides (chlordane, dichlorodiphenyltrichloroethanes [DDTs], drins 40[aldrin, endrin, and dieldrin], and hexachlorocyclohexane [HCHs]); industrial materials 41(polychlorinated biphenyls [PCBs], polybrominated diphenyl ethers (PBDEs), and per- and 42polyfluoroalkyl substances [PFASs]); and unintentional products (polychlorinated dibenzo-*p*-dioxins 43[PCDDs] and polychlorinated dibenzofurans [PCDFs]). The use and production of POPs were strictly 44prohibited in 181 countries in 2020. In particular, large amount of organochlorine insecticides have 45been applied in agricultural land before they were banned from being use. For example, Japan 46 produced or imported about 44,467 t of DDT, 683 t of dieldrin, and 315,000 t of HCH (Namiki et al. 472018).

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PAHs, unlike POPs, are not intentionally produced and released to agricultural land. PAHs are mainly
generated from the biomass combustion (Shen et al. 2021). They are produced by incomplete straw
burning and biochar treatment used to promote plant growth in agricultural lands (Jenkins et al. 1996;
Fabbri et al. 2013). Since they are not easily degraded, the amount of PAHs in agricultural field is
increasing unknowingly.

53 PPCPs are new and emerging pollutants. They are released into wastewater after their use. After the 54 treatment, the reclaimed wastewaters are irrigated to agricultural lands in countries where freshwater 55 supply is limited (Pedersen et al. 2003; Miller et al. 2016). Some PPCPs are detected in irrigated water 56 and agricultural runoff and lands (Pedersen et al. 2003, 2005; Xu et al. 2009; Bourdat-Deschamps et 57 al. 2017). Consequently, carbamazepine, one of the PPCPs, is detected in the urine of people who eat 58 crops treated with the irrigated water (Paltiel et al. 2016).

Many crops with edible aerial parts (fruits, leaves, and stems) do not accumulate organic pollutants in
their aerial parts. However, high concentrations of organic pollutants are detected in the aerial parts of
the Cucurbitaceae family, such as cucumber (*Cucumis sativus*), melon (*C. melo*), pumpkin (*Cucurbita maxima*), squash (*C. pepo*), and zucchini (*C. pepo*) (Otani et al. 2007).

The purpose of this review is to discuss the uptake mechanisms of organic pollutants in the Cucurbitaceae family in four steps: (1) solubilization, (2) absorption, (3) translocation, and (4) transport, and show the crucial steps in their uptake. Since the amount of organic pollutants in the aerial parts of the Cucurbitaceae family shows that they are not or less metabolized in the plants, we mainly discuss the uptake of organic pollutants.

68 (1) Organic pollutants in the soil bind to soil organic matters (SOMs), and their bioavailability is low.

- 69 However, root exudates, especially organic acids, disrupt the linkage between SOMs and organic
- 70 pollutants and then solubilize organic pollutants.

(2) Solubilized organic pollutants are adsorbed to the roots, absorbed into the root cells, taken up into
 the root tissues, and localized in the root tissues depending on their physicochemical properties.

(3) Organic pollutants are translocated from the roots (inside the Casparian strip) into xylem vessels.

(4) The organic pollutants translocated into xylem vessels are transported to aerial parts by thecohesion force of water (Pockman et al. 1995; Chunfang et al. 1999).

76 We show that the translocation of organic pollutants from the roots to xylem vessels plays a crucial 77role in their uptake in the Cucurbitaceae family. Major latex-like proteins (MLPs) produced in the root 78cells bind to organic pollutants through their internal hydrophobic cavity and increase their solubility 79(Inui et al. 2013; Goto et al. 2019; Fujita et al. 2020b; Iwabuchi et al. 2020). MLP-organic pollutant 80 complexes are translocated into xylem vessels, and organic pollutants are transported to the aerial parts 81 (Goto et al. 2019). Consequently, contamination with organic pollutants occurs in the Cucurbitaceae 82 family. We discuss the organic pollutants contaminating agricultural land and their accumulation in 83 the Cucurbitaceae family. We show that the different accumulation levels of organic pollutants in their 84 aerial parts depend on their physicochemical properties, such as hydrophobicity and chemical structure. 85 Furthermore, we introduce a cultivation method for safer crop production. Finally, we conclude by 86 suggesting the need for necessary future research for a comprehensive understanding of the uptake of 87 organic pollutants in the Cucurbitaceae family. This is the first review to focus on organic pollutant 88 uptake from the perspective of plant molecular biology. This review leads to the development of new 89 techniques to produce safer crops and provide them in our daily diet.

90

91 **2.** Uptake mechanisms

92 **2.1. Solubilization**

The first step in the uptake of organic pollutants is their solubilization in the rhizosphere and the
increase in their bioavailability for plants. The bioconcentration factor (BCF) of PCDD/Fs in the aerial

-4-

95parts of C. pepo in soil culture is much lower than that in hydroponic culture (Inui et al. 2008, 2011). 96 This suggests that root exudates are necessary to release PCDD/Fs from the soil components. The 97roots exude sugars, organic acids, amino acids, secondary metabolites, carbohydrates, and proteins for 98 the uptake of nutrients and signal transduction between the roots (Walker et al. 2003; Preece and 99Peñuelas 2020; Wang et al. 2020). Particularly, organic acids contribute to the uptake of metal ions by 100 dissolving metal ions through chelation (Yang et al. 2001; Dakora and Phillips 2002; White and Kottler 1012002; White et al. 2003a, 2006; Luo et al. 2006; Chen et al. 2017). However, they have a secondary 102 influence on the rhizosphere. Organic acids disrupt the soil structure and humic organic compounds-103metal ions-mineral linkages (Yang et al. 2001; White and Kottler 2002; White et al. 2003a, 2006; Luo 104et al. 2006). Bioavailable $p_{p'}$ -DDT has a negative correlation with the amount of SOM (Luo et al. 1052006). DDX includes dichlorodiphenyldichloroethane (DDD) (o, p'-DDD and p, p'-DDD), 106 dichlorodiphenyldichloroethylene (DDE) (o,p'-DDE and p,p'-DDE), and DDT (o,p'-DDT and p,p'-107 DDT) (Meijer et al. 2001). Since soil organic carbon (SOC) binds to DDX in the rhizosphere, it 108decreases the mobility of DDT (Tao et al. 2004). Organic acids (acetic acid, succinic acid, l-aspartic 109 acid, malic acid, L-glutamic acid, salicylic acid, shikimic acid, isocitric acid, chorismic acid, sinapic 110acid, caffeic acid, p-hydroxybenzoic acid, gallic acid, tartaric acid, ferulic acid, protocatechuic acid, 111 *p*-coumaric acid, mugineic acid, oxalic acid, citric acid, and piscidic acid) release organic pollutants 112from the linkages, and then, organic pollutants are solubilized and taken up into the roots (Badri and 113Vivanco 2009).

Citric and oxalic acids were the candidates that promoted the bioavailability of organic pollutants in the rhizosphere through solubilization. These acids desorb PAHs (Subramaniam et al. 2004; Yoshihara et al. 2014), p,p'-DDE (White et al. 2003a), and p,p'-DDT (Luo et al. 2006). However, oxalic acid was not detected in the rhizosphere of *C. sativus* and *C. pepo*. Therefore, citric acid is a possible promoter of the bioavailability of organic pollutants in the root exudates of the Cucurbitaceae family (Wang et

119al. 2004). Citric acid promotes the accumulation of perylene (Yoshihara et al. 2014), PCBs (White et 120 al. 2006), and $p_{,p}$ '-DDE (White et al. 2003a) in the aerial parts of the Cucurbitaceae family. The amount of citric acid in the rhizosphere of C. sativus was higher than that of C. pepo, and the root 121122concentration factor (RCF) of p,p'-DDE of C. sativus was higher than that of C. pepo (Wang et al. 1232004). This clearly shows that the amount of citric acid correlates with the root uptake of organic 124pollutants. However, citric acid does not play a crucial role in the uptake of organic pollutants to the 125aerial parts because the BCF of $p_{,p}$ '-DDE in the aerial parts of C. pepo is much higher than that of C. 126sativus (Wang et al. 2004). Moreover, citric acid promotes the root uptake of p,p'-DDE in the non-127Cucurbitaceae family (White and Kottler 2002). These studies suggest that citric acid plays an 128important role in the solubilization of POPs and then uptake into roots, but the released amount from 129the Cucurbitaceae family tends to be lower than that from the non-Cucurbitaceae family. C. pepo root 130exudates increase the root uptake of PCBs in weeds (beggar's tick [Bidens cernua], lamb's quarter 131[Chenopodium album], wild carrot [Daucus carota], broad-leaved plantain [Plantago major], and 132curly dock [Rumex crispus]), and C. pepo (Ficko et al. 2011). Therefore, citric acid promotes the 133bioavailability and root uptake of organic pollutants from the rhizosphere, but it does not influence the 134accumulation of organic pollutants in the aerial parts of plants in the Cucurbitaceae family.

135

136 **2.2. Absorption**

Organic pollutants are transported from the root periphery to the vascular bundles. Figure 1 shows the typical dicot cross root structure. The outer surface is covered with epidermis with root hair cells. From the outer surface, the root is mainly divided into the epidermis, cortex, endodermis, pericycle, and vascular bundles (phloem and xylem vessels) (Banda et al. 2019). Compounds are transported to vascular bundles via any of these three pathways: apoplastic, symplastic, or transcellular (Ramakrishna and Barberon 2019). In the apoplastic pathway, compounds are transported by passive

143diffusion through the extracellular space in the cell wall, and their transport is blocked by the Casparian strip formed by lignin (Naseer et al. 2012). Since the plasma membrane at the Casparian strip attaches 144145to intercellular walls, it works as a diffusion barrier in endodermis (Roppolo et al. 2011). In the 146symplastic pathway, compounds are transported from cells to cells through plasmodesmata, which 147comprises cytoplasmic connections between adjacent cells from the epidermis to pericycle (Ma and 148 Peterson 2001). They depend on polarized influx and efflux or diffusion gradients through the plasma 149membrane, and their transport is blocked by suberin lamella (Barberon et al. 2016; Doblas et al. 2017). 150In the transcellular pathway, compounds are transported by crossing membranes of neighboring cells 151(Peterson and Enstone 1996; Li et al. 2017).

152Perylene, a hydrophobic organic pollutant, is passively diffused into the plasma membrane and 153transported intracellularly via plasmodesmata (Yamazaki et al. 2015). Surprisingly, the transport of 154perylene is not blocked by the Casparian strip and localized in the plasma membrane of the endodermis 155and pericycle. Thus, perylene is transported by the symplastic pathway through the plasma membrane. 156In addition, it has been suggested that non-ionic compounds such as hydrophobic organic pollutants 157are passively transported to vascular bundles through the cell membrane (Collins et al. 2006). However, 158the adsorption and absorption of organic pollutants in the root tissue are not different in C. pepo ssp. 159ovifera (low accumulator) and C. pepo ssp. pepo (high accumulator) (Yamazaki et al. 2015). Therefore, 160the absorption step does not influence the uptake of organic pollutants in the Cucurbitaceae family.

161

162 **2.3. Translocation**

The crucial factor for the uptake of organic pollutants in the Cucurbitaceae family is the translocation of organic pollutants into xylem vessels. Since perylene is localized in the endodermis and pericycle of both *C. pepo* ssp. *ovifera* and *C. pepo* ssp. *pepo*, their specific translocation mechanisms would underlie the uptake of organic pollutants in the Cucurbitaceae family (Yamazaki et al. 2015). 167 Chlordane and heptachlor *exo*-epoxide (HEPX) are transported from roots to aerial parts through 168 xylem vessels in *C. sativus* and *C. pepo* (Mattina et al. 2004). Xylem sap consists of water from the 169 roots, and it is difficult to solubilize hydrophobic organic pollutants. Since the solubilization ability of 170 xylem sap by protein deactivators is decreased, xylem sap from the Cucurbitaceae family is thought 171 to contain protein that has the ability to solubilize organic pollutants (Murano et al. 2010; Inui et al. 172 2013). This suggests that the protein in xylem sap binds to and solubilizes organic pollutants.

173The 17 kDa protein in xylem sap from several C. pepo cultivars has a positive correlation with the 174BCF of PCBs in aerial parts and is identified as a major latex-like protein (MLP) (Inui et al. 2013). 175They were first identified in opium poppy (Papaver somniferum) in 1985 (Nessler et al. 1985) and 176have been identified in the Cucurbitaceae family (C. sativus (Iwabuchi et al. 2020), C. moschata 177(Iwabuchi et al. 2020), fig leaf squash [Cucurbita ficifolia] (Iwabuchi et al. 2020), loofah [Luffa cylindrica] (Iwabuchi et al. 2020), C. melo (Aggelis et al. 1997), white-flowered gourd [Lagenaria 178siceraria] (Iwabuchi et al. 2020), and C. pepo (Inui et al. 2013; Goto et al. 2019)) and non-179180Cucurbitaceae family (Arabidopsis thaliana (Wu et al. 2008), cotton [Gossypium hirsutum] (Chen and 181Dai 2010), ginseng [Panax ginseng] (Choi et al. 2015), grapevine [Vitis vinifera] (Zhang et al. 2018), 182peach [Prunus persica] (Ruperti et al. 2002), and soybean [Glycine max] (Strömvik et al. 1999)). 183 MLPs have various biological functions, which include: disease resistance (Yang et al. 2015; Gai et 184al. 2018; Song et al. 2020), salt stress tolerance (Wang et al. 2016), leaf formation (Litholdo et al. 1852016), enzymatic activity (Lichman et al. 2020), and plant hormone response (Ruperti et al. 2002; Sun 186et al. 2010; Li et al. 2013; Zhang et al. 2018). The most striking structural feature of MLPs is the 187 internal hydrophobic cavity, which enables them to bind to hydrophobic compounds (Lytle et al. 2009; 188Fernandes et al. 2013; Choi et al. 2015). Recombinant MLPs from the Cucurbitaceae family bind to organic pollutants, such as 17β-estradiol (Goto et al. 2019), 4-hydroxy-2',3,3',4',5'-189 190pentachlorobiphenyl (4OH-PeCB106) (Inui et al. 2013), 4-t-octylphenol (Goto et al. 2019), dieldrin

(Goto et al. 2019; Fujita et al. 2020b), and pyrene (Fujita et al. 2020b). Therefore, organic pollutants
are solubilized in xylem sap through the binding of MLPs. Since *MLP* genes are mainly expressed in
the root (Goto et al. 2019), MLPs bind to organic pollutants in the plasma membrane of the endodermis
and pericycle. Finally, MLP-organic pollutant complexes are translocated into xylem vessels (Figure
2).

196

197 **2.4. Transport**

198 Translocated organic pollutants into xylem vessels are transported to aerial parts by water cohesion 199force (Pockman et al. 1995; Chunfang et al. 1999). Phloem vessels can also be the route. Xylem and 200 phloem sap are acidic and basic, respectively. Since MLPs bind to organic pollutants under an acidic 201condition, xylem vessels are an important route (Inui et al. 2013; Goto et al. 2019; Fujita et al. 2020b; 202Iwabuchi et al. 2020). Transported organic pollutants to aerial parts cause physiological changes in 203plants. p_{p} -DDE induces genes related to signal transduction, environmental stress, and 204photosynthesis in C. pepo (Chhikara et al. 2010). This suggests that p,p'-DDE in the soil induces stress 205in plants and inhibits physiological functions such as photosynthesis.

206There is a difference in the uptake ability of the Cucurbitaceae family. The concentrations of dieldrin 207and endrin in the shoots of C. pepo were two and three times higher than those in the shoots of L. 208cylindrica, respectively (Otani et al. 2007). The binding affinity of MLPs can explain this difference. 209 MLP from L. cylindrica does not bind to PeCB106, but MLP from C. pepo does (Inui et al. 2013; 210Iwabuchi et al. 2020). This suggests that the cavity of MLP from L. cylindrica is less hydrophobic, 211and the binding affinity of MLP to hydrophobic organic pollutants is relatively low. Hence, the uptake 212amount of organic pollutants in L. cylindrica is low. 213Previous studies have shown that cross-breeding influences the uptake amount of organic pollutants

214 (White 2010; Isleyen et al. 2013; Sugiyama et al. 2013, 2016). The concentrations of DDX and

215chlordane in F1 hybrids (C. pepo ssp. pepo \times C. pepo ssp. ovifera) were lower than those of C. pepo 216ssp. pepo parents, and those in F1 back-cross plants are in the middle between parents and F1 plants 217(White 2010; Isleyen et al. 2013; Sugiyama et al. 2013, 2016). These results suggest that a single gene 218or locus controls the uptake of organic pollutants following Mendelian segregation. This suggests that 219the gene expression level made a difference in their uptake ability. In contrast, a recent study proposes 220two hypotheses regarding the inheritance of uptake ability trait, and they are two or three different 221dominant gene models (Sugiyama et al. 2016). The candidate genes are MLP and zinc finger protein 222(ZFP) genes. ZFPs, like MLPs, play a crucial role in the uptake of organic pollutants in the 223Cucurbitaceae family (Inui et al. 2015). ZFPs function as transcription factors through the binding of 224the zinc finger motif to DNA. The expression level of ZFP genes in C. pepo ssp. pepo is higher than 225that in C. pepo ssp. ovifera, and the expression of CpZFP genes promotes the accumulation of 2263,3',4,4',5-pentachlorobiphenyl (PeCB126) in the aerial parts of transgenic tobacco (Nicotiana 227 tabacum) plants. These results suggest that CpZFPs bind to the promoter region of NtMLP genes and induce the expression of NtMLP genes. However, only a single MLP gene, FB7-4, has ever been 228229identified in N. tabacum (Neale et al. 1990). Thus, it is thought that ZFPs induce other genes 230responsible for the uptake of organic pollutants other than MLP genes.

231

232 **3.** Organic pollutants taken up by the Cucurbitaceae family

233 **3.1. DDX (Table 1.A)**

DDT was applied to control agricultural pests until it was prohibited owing to its toxicity (Lunney et al. 2004). However, DDT is still used to control malaria in several countries in Africa and Asia (Van Den Berg 2009). DDT is transformed to DDE by exposure to weathering, and DDE is the most abundant compound in DDX in the environment (Aislabie et al. 1997; Megharaj et al. 1997). DDT is directly transformed into DDD under aerobic condition (Corona-Cruz et al. 1999). In 2001, it was first

239confirmed that C. pepo accumulated a higher concentration of p,p'-DDE in their fruits compared with 240other plant families (White 2001; Lunney et al. 2004). In the Cucurbitaceae family, the genus 241Cucurbita accumulates DDX more than the genera Cucumis and Citrullus (White 2002; Gent et al. 2422007; Isleyen and Sevim 2012; Isleyen et al. 2012a; Namiki et al. 2013). Furthermore, C. pepo has a 243different uptake ability in their subspecies: C. pepo ssp. pepo accumulates higher concentrations of 244DDX in their aerial parts than C. pepo ssp. ovifera and texana (White 2002, 2010; White et al. 2003b, 2005; Isleyen et al. 2012b, 2013). The BCF value of C. pepo ssp. pepo in the stem is 11 times higher 245246than that of C. pepo ssp. texana (White et al. 2003b). Translocation factor from the roots to the stems 247of C. pepo ssp. pepo is 4.9 times higher than that of C. pepo ssp. ovifera (White et al. 2005). Thus, C. 248pepo ssp. pepo has efficient translocation mechanisms of DDX from roots to xylem vessels.

249

250 **3.2. Drins (Table 1.B)**

Drins consist of organochlorine insecticides aldrin, dieldrin, and endrin, and are registered as POPs 251252(Jorgenson 2001). Dieldrin is produced through the epoxidation of aldrin by soil bacteria and is a 253stereoisomer of endrin (Good and Ware 1969; Ferguson and Korte 1977). In the United States, aldrin 254and dieldrin were the second most applied pesticides in the 1960s, and the amount of aldrin applied in 255Iowa between 1961 and 1965 reached 5-6.6 million pounds (Jorgenson 2001). Since dieldrin had been 256applied to control agricultural pests, such as spotted cucumber beetle (*Diabrotica undecimpunctata*), 257before it was banned, a large amount of dieldrin remains in agricultural lands (Gladstone and Wong 2581977). Dieldrin has been detected in agricultural soils in Japan (Hashimoto 2005), Portugal (Gonçalves 259and Alpendurada 2005), the United States (Harner et al. 1999), and Switzerland (Hilber et al. 2008). 260Since 1965, the Cucurbitaceae family has accumulated dieldrin in their fruits (Lichtenstein and Schulz 2611965). Dieldrin and endrin were found to be accumulated at much higher concentrations in the Cucurbitaceae family than in other plant families (Alliaceae, Amaranthaceae, Apiaceae, Asteraceae, 262

263Brassicaceae, Chenopodiaceae, Euphorbiaceae, Fabaceae, Lamiaceae, Linaceae, Malvaceae, Pedaliaceae, Poaceae, Polygonaceae, Solanaceae, Tiliaceae) (Otani et al. 2007; Murano et al. 2010; 264265Saito et al. 2012; Namiki et al. 2013, 2018). Contamination with dieldrin in the Cucurbitaceae family 266is a severe problem in crop production and often occurs in Japan. The agricultural land in Tokyo is 267contaminated with dieldrin, and in C. sativus, maximum residue limit has been exceeded (Hashimoto 2682005). One of the reasons for the accumulation is the low maximum residue limit of dieldrin (0.02) 269ppm) compared with that of other POP-organochlorine insecticides (HCHs [0.2 ppm] and DDX [0.2 270ppm]). In addition, the chemical properties of dieldrin can be a factor for contamination: the half-life 271of dieldrin is longer than that of HCHs, and the $\log K_{ow}$ value of dieldrin is lower than that of DDX 272(Namiki et al. 2013). Thus, dieldrin is not readily degraded in soil and is not retained in the soil. Hence, 273the amount of dieldrin taken up into the roots is more than that of HCHs and DDX. Another reason is 274the binding affinity of MLPs to dieldrin. The BCF of bulky PCBs in the aerial parts of C. pepo is 275higher than that of planer PCBs (Matsuo et al. 2011). This suggests that compounds with a bulky 276structure fit into the hydrophobic cavity of MLPs. Since dieldrin is a bulky structure, the 3D structure 277of dieldrin may fit into the cavity of MLPs, and thus, the amount of dieldrin in the aerial parts of the 278Cucurbitaceae family is large. Consequently, maximum residue limit of dieldrin is often exceeded in 279crops.

280

281 **3.3.** Other POPs and their related organochlorine insecticides (Table 1.C)

HCH has been used as an insecticide, and commercial HCH is mainly a mixture of α -, β -, and γ -HCH isomers (Vijgen et al. 2011). Only γ -HCH, called Lindane, shows insecticidal activity, and 450,000 t of γ -HCH have been applied to agricultural land between 1950 and 2000 in the world (Vijgen et al. 2011). In particular, β -HCH is highly toxic to humans through the activation of estrogenic action (Steinmetz et al. 1996). Hence, HCH isomers (α , β , and γ) are registered as POPs (Vijgen et al. 2011). HCHs are also taken up by the Cucurbitaceae family, but their uptake, which is different with isomer,
has not been investigated (Namiki et al. 2013, 2015, 2018).

289Technical chlordane is a mixture of more than 140 compounds and has been applied as an insecticide 290and herbicide in the United States for agricultural and residential purpose (Dearth and Hites 1991; 291Mattina et al. 1999). The major components of technical chlordane include chlordane isomers (cis-292chlordane and trans-chlordane), trans-nonachlor, and heptachlor (Dearth and Hites 1991). Cis-293chlordane and trans-chlordane contain enantiomers: (-) cis-chlordane and (+) cis-chlordane, (-) trans-294chlordane, and (+) trans-chlordane (Mattina et al. 2002). It is known that chlordane and HEPX are detected in the C. pepo and C. melo cultivated in the United States (Mattina et al. 2000). C. pepo 295296accumulated the highest concentrations of chlordane in the edible aerial parts of all tested crops 297cultivated in the soil where chlordane was applied 38 years ago (Mattina et al. 2000). The amount of 298cis-chlordane taken up into the roots of C. pepo was higher than in trans-chlordane (Mattina et al. 2992002). Enantiomer fraction (EF) is used to understand enantioselectivity and is defined as the ratio of 300 (+) enantiomers in the sum of (-) and (+) enantiomers. EFs of chlordane isomers in the fruits of C. 301 pepo were higher than those in the roots (Mattina et al. 2002; White et al. 2002). In contrast, EFs in 302the fruits of C. sativus were lower than those in the roots (Mattina et al. 2002). From the roots to the 303 fruits of C. pepo, EF of cis-chlordane increased, but that of trans-chlordane decreased (White et al. 304 2002). Cis-chlordane is the dominant component in the roots, stems, and fruits of C. pepo ssp. pepo 305 and ovifera. From the roots to the fruits of C. pepo ssp. pepo and ovifera, EF of trans-chlordane 306 increased, while that of cis-chlordane decreased; (+) trans-chlordane and (-) cis-chlordane in the fruits 307 are more dominant than those in the roots (Isleyen et al. 2013). These results suggest that chlordane is 308 taken up and accumulates isomer- and enantiomer- selectively. These enantiomer selectivities can be 309 explained by the binding selectivity of MLPs because chlordane isomers are hydrophobic compounds.

310

311 **3.4. PCBs and PCDD/Fs (Table 1.D)**

312Polychlorinated organic pollutants, such as PCBs (Manz et al. 2001; Armitage et al. 2006; Zhang et al. 3132007) and PCDD/Fs (Jou et al. 2007; Shen et al. 2009; Deng et al. 2011), are detected in agricultural 314lands via waste emission and volatilization. The uptake of PCDD/Fs in the Cucurbitaceae family was 315investigated in 1994 (Hülster et al. 1994). The study showed, for the first time, that Cucurbita genus 316 accumulated organic pollutants from the roots to the fruits through the stem and denied the established 317theory that the evaporation of organic pollutants from the soil contaminated the fruits in the 318 Cucurbitaceae family. The Cucurbitaceae family, especially the Cucurbita genus, shows a higher 319 transpiration stream concentration factor of PCDD/Fs than other plant species, although RCF is 320 equivalent (Zhang et al. 2009). In addition, it is shown that PCBs are also accumulated from the roots 321via xylem vessels (Whitfield Åslund et al. 2008; Greenwood et al. 2011).

322It is notable that the hydrophobicity of PCB congeners does not correlate with their BCF, although the 323 hydrophobicity of PCDD/Fs congeners has a negative correlation with their BCF in C. pepo (Matsuo 324et al. 2011). Thus, the uptake of PCBs depends on factors other than hydrophobicity (Inui et al. 2011). 325PeCB congeners with chlorines at ortho-positions tend to be highly taken up (Matsuo et al. 2011). 326 Furthermore, in the four PeCB congeners accumulated in C. pepo, there were three PCB congeners 327 with chlorines at ortho-positions (2,2',3,5,6-PeCB [PeCB93], 2,2',3,5',6-PeCB [PeCB95], and 2,3,3',4,4'-PeCB [PeCB105]) (Whitfield Åslund et al. 2007). These results clearly show that the uptake 328329 of PCBs in C. pepo shows congener selectivity (Matsuo et al. 2011; Goto et al. 2019). The volume of 330 PCB congeners with chlorines at *ortho*-positions is bulky because they prevent the rotation of the C-331C bond between the rings (Fujita et al. 2020b). In contrast, the accumulation of tri-, tetra-, and 332hexachlorinated biphenyl (HxCB) congeners is not influenced by their bulkiness but by the number of 333 chlorines, hydrophobicity, and molecular weight (Greenwood et al. 2011). However, PeCB and HxCB

congeners with chlorines at *ortho*-positions are highly accumulated in *C. pepo* ssp. *pepo* (Matsuo et
al. 2011). Thus, further research is needed to clarify the accumulation mechanisms of PCB congeners.

337 **3.5. Others (Table 1.E)**

338PAHs show high hydrophobicity and are also accumulated in the aerial parts of the Cucurbitaceae 339 family (Mattina et al. 2006; Parrish et al. 2006). However, a comparison of the uptake ability of PAHs 340 between the Cucurbitaceae family and the non-Cucurbitaceae family has never been investigated. To date, the accumulation level of PAHs is thought to be equivalent to that of POPs. Pyrene, a PAH, show 341high hydrophobicity ($\log K_{ow}$, 5.2) (Miller et al. 1985) and is accumulated in C. pepo (Fujita et al. 342343 2020b). The same hypothesis that the BCF of POPs accumulated in C. pepo ssp. pepo is more than 344that in C. pepo ssp. ovifera and C. sativus is confirmed in case of PAHs such as anthracene, 345fluoranthene, and phenanthrene (Mattina et al. 2006). Therefore, the Cucurbitaceae family would 346 accumulate PAHs like POPs at higher concentrations than other plant families.

347PFASs have recently received attention owing to their persistence and toxicity (Brambilla et al. 2015). 348 The Cucurbitaceae family accumulates PFASs, such as polyfluoroalkyl phosphate diesters (Lee et al. 349 2014), perfluorocarboxylic acids (Lee et al. 2014), and 6:2 fluorotelomer sulfonic acid (Zhao et al. 3502019), but does not accumulate them at high concentrations compared with other plant families 351(Lechner and Knapp 2011; Felizeter et al. 2014; Zhao et al. 2018). The $\log K_{ow}$ values of PFASs, such 352as perfluorooctane sulfonate and perfluorooctanoic acid, are 5.26 and 4.59, respectively, and nearly 353equivalent to that of dieldrin ($\log K_{ow}$, 5.2) (Namiki et al. 2013; Milinovic et al. 2016). Since their 354translocation is not blocked by the Casparian strip, they are localized in the endodermis and pericycle (Yamazaki et al. 2015). Therefore, PFASs are targeted by MLPs for binding. However, PFASs have 355356 an alkyl chain, unlike other POPs.

rings (DDX and PCBs) or a naphthalene ring (drins) as a basic structure (Chakraborty and Das 2016). However, PFASs contain a long alkyl chain (Ghisi et al. 2019). Compounds binding MLPs from the Cucurbitaceae family usually contain ring structures, and compounds with a long chain have never been identified as MLP-binding compounds. Therefore, MLPs are thought to not bind PFASs.

The structures of PFASs are different from those of DDX, drins, and PCBs, which contain two benzene

362 Consequently, PFASs are not translocated into xylem vessels as MLP-PFAS complexes.

363 PPCPs include acetaminophen, caffeine, and carbamazepine. Carbamazepine is detected in the aerial 364 parts of C. sativus and C. pepo (Shenker et al. 2011; Knight et al. 2018). Sixteen PPCPs were tested 365in 17 PPCPs accumulated in the shoots of C. sativus (Sun et al. 2018). However, the Cucurbitaceae 366 family does not accumulate PPCPs at high concentrations compared with other plant families (Wu et 367al. 2013; Garvin et al. 2015). The uptake level (BCF and TSCF) of PPCPs was not higher in the 368 Cucurbitaceae family than in the non-Cucurbitaceae family, probably owing to the low hydrophobicity 369 of PPCPs, except for triclocarban, which shows a high hydrophobicity (Wu et al. 2013; Garvin et al. 370 2015). For example, the $\log K_{ow}$ values of carbamazepine and caffeine are 2.45 and -0.07, respectively 371(Shenker et al. 2011; Garvin et al. 2015). Therefore, PPCPs do not enter the inside of the Casparian 372strip, and consequently, MLPs do not bind PPCPs at a high affinity.

373

357

4. Approaches for safer crop production

Agricultural lands in the world are contaminated with organic pollutants, and farmers have to produce crops for food supply. It is essential to produce safer crops even in agricultural lands that are contaminated with organic pollutants. Recently, novel approaches to reduce crop contamination through the regulation of MLPs have been proposed for the treatment of agrochemicals: suppression of the expression of *MLP* genes and inhibition of the binding of MLPs to organic pollutants. Since the expression of *MLP* genes is influenced by environmental factors, such as temperature (Sun et al. 2010; 381Zhang et al. 2018; Inui et al. 2020), light period (Neale et al. 1990; Inui et al. 2020), drought (Sun et 382 al. 2010; Wang et al. 2016; Ma et al. 2017; Zhang and Shi 2018; Lv et al. 2020), and flood (Mustafa 383 et al. 2015), it suggests that the application of agrochemicals can control the expression of MLP genes. 384 The fungicide Daconil suppresses the expression of *MLP* genes in the roots and reduces the uptake of 385dieldrin and pyrene in C. pepo (Fujita et al. 2020a). In contrast, MLPs, which are identified in several 386 plants, bind various hydrophobic compounds (Lytle et al. 2009; Choi et al. 2015). Thus, agrochemicals 387that bind MLPs can inhibit the binding of MLPs to organic pollutants. The insecticide Colt containing 388 the MLP-binding compound, pyrifluquinazon, as an active ingredient, inhibits the binding of MLPs to 389 dieldrin and pyrene, and its application reduces the uptake of dieldrin and pyrene into C. pepo (Fujita 390 et al. 2020b). These studies contribute to safer crop production in agricultural lands contaminated with 391organic pollutants.

392Transgenic plants are powerful tools for the reduction of the uptake of organic pollutants in the 393 Cucurbitaceae family. Since recent studies have developed an efficient transformation method using 394hairy root culture, the transformation of the Cucurbitaceae family is easier than ever (Nanasato et al. 395 2013). LinA from Sphingomobium japonicum UT26 was identified as a dehydrogenase responsible 396 for the degradation of y-HCH (Imai et al. 1991). C. moschata expressing LinA accumulates and 397 degrades γ -HCH (Nanasato et al. 2016). To date, genes responsible for the degradation of organic 398 pollutants, such as PCBs (Kimbara et al. 1989) and PCDD/Fs (Habe et al. 2001; Miyauchi et al. 2008), 399 have been identified in microorganisms. Therefore, the Cucurbitaceae family that expresses these 400genes can help in the remediation of agricultural lands.

401 The soil type affects the accumulation of organic pollutants in the Cucurbitaceae family. The

- 402 cultivation in allophanic soils suppressed the accumulation of chlordecone in the fruits of *C. sativus*
- 403 because the clay fractal structure of the allophane traps chlordecone in the soil (Woignier et al. 2012;
- 404 Clostre et al. 2014). To date, the application of adsorbents was attempted to trap organic pollutants.

- 405 The wood chip charcoal decreased the concentration of dieldrin in the fruits of *C. sativus* (Saito et al.
- 406 2011). In addition, the active carbon showed the higher suppression effects on the accumulation of
- 407 dieldrin in the fruits of *C. sativus* (Hashimoto 2007; Saito et al. 2011) and decreased HEPX
- 408 concentrations in the fruits of *C. maxima* (Murano et al. 2009).
- 409 Grafting also controls the uptake of organic pollutants. Since grafting decreases the concentration of
- 410 dieldrin in *C. sativus* fruits on low accumulator rootstocks (Otani and Seike 2007), the concentrations
- 411 of organic pollutants in the scion (aerial parts) depend on the uptake ability in the rootstock (Otani and
- 412 Seike 2006, 2007; Hashimoto 2007; Isleyen and Sevim 2012). In Japan, 80% of C. sativus is cultivated
- 413 by grafting on the *Cucurbita* rootstock (Otani and Seike 2006). Thus, the selection of rootstock of low-
- 414 accumulator species is crucial for safer crop production.
- 415

416 **5.** Concluding remarks and future perspectives

417In this review, we discussed the specific uptake mechanisms of organic pollutants in the Cucurbitaceae 418family. Their uptake in plants occurs in four steps: (1) solubilization, (2) absorption, (3) translocation, and (4) transport. We showed that the translocation of organic pollutants plays a crucial role in their 419 420uptake in the Cucurbitaceae family. MLPs bind organic pollutants on the plasma membrane of the 421endodermis and pericycle in the roots, and MLP-organic pollutant complexes are translocated into 422xylem vessels. The solubilization of organic pollutants is promoted through the binding of MLPs, and solubilized organic pollutants in xylem sap are transported to the fruits (Figure 3). Therefore, the 423424Cucurbitaceae family accumulates hydrophobic organic pollutants such as organochlorine insecticides, 425PCBs, and PCDD/Fs. It is thought that MLPs tend to bind hydrophobic organic pollutants with a high 426affinity because MLPs have an internal hydrophobic cavity as their binding site. However, hydrophilic 427organic pollutants, such as PFASs with a short alkyl chain and PPCPs, are not accumulated at high 428concentrations in the Cucurbitaceae family compared with other plant families.

MLPs are a key factor for the uptake of organic pollutants in the Cucurbitaceae family. However, there
are still gaps in understanding their accumulation and biological functions. Thus, further research is
recommended owing to the following:

432 (1) MLPs are distributed in dicots and monocots. MLP genes in G. hirsutum (Yang et al. 2015), N.

433 *benthamiana* (Song et al. 2020), and sugar beet (*Beta vulgaris*) (Kloos et al. 2002; Oltmanns et al.

434 2006) are highly expressed in the roots like *C. pepo* (Goto et al. 2019). However, only MLPs from

the Cucurbitaceae family translocate organic pollutants from the roots into xylem vessels.

436 (2) Factors responsible for different uptake abilities in these subspecies have not been clarified. Since437 the localization of organic pollutants in the root tissues is not different among the subspecies, that

of MLPs can be different. For example, MLPs in *C. pepo* ssp. *ovifera* are not secreted from the
endodermis and pericycle, but those in *C. pepo* ssp. *pepo* are released and readily translocate into
xylem vessels. Thus, the investigation of the localization of MLPs in root tissues may lead to the

441 understanding of different uptake mechanisms in these subspecies.

(3) The translocation mechanisms of MLP-organic pollutant complexes from the roots to the xylem
vessel remain unclear. Thus, further research is necessary to clarify the translocation mechanisms
of MLPs. One possibility is the interaction of MLPs with other proteins. Several proteins have
been identified as interaction partners of MLPs, and it is possible that these proteins help to
translocate MLP-organic pollutant complexes into xylem vessels (Yang et al. 2015; Litholdo et al.
2016; Wang et al. 2016; Lv et al. 2020).

(4) Organic pollutants accumulated in the aerial parts are metabolized during uptake. However, few
studies focusing on metabolism are published (Chhikara et al. 2010; Zhai et al. 2011). As far as we
know, only the metabolites of heptachlor (Hayashi et al. 2018) and PFASs (Zhao et al. 2018, 2019)
have been investigated in the Cucurbitaceae family. Since PeCB126 is metabolized by mammalian
cytochrome P450 species, it is essential to identify the metabolites in plants because they can show

higher toxicity than parent compounds (Mise et al. 2016). This suggests that the currentcontamination assessment in crops underestimates the toxicity effects.

455This review clearly shows the uptake mechanism of organic pollutants in the Cucurbitaceae family. It 456is well known since the 1960s that the Cucurbitaceae family accumulates organic pollutants in their 457fruits. Subsequently, many studies have been performed to understand the mechanisms involved in 458their solubilization, absorption, translocation, and transport. In the last decade, MLPs have been 459identified as transporting factors for organic pollutants, and the crucial role of MLPs in crop 460 contamination by hydrophobic pollutants has been recognized. Clarification of the mechanisms 461involved in the translocation of organic pollutants by MLPs would lead to new approaches for safer 462crop production.

463

464 **Conflicts of interest**

We declare that we have no known competing financial interests or personal relationships that couldinfluence the work reported in this review.

467

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480

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- 1000
- 1001

1002 Figure legends

1003 Figure 1. Localization of organic pollutants in root cells.

- 1004 Organic pollutants bind to soil organic matter in the rhizosphere. Organic acids are released from the
- 1005 roots as root exudates and disrupt the linkage between soil organic matter and organic pollutants.
- 1006 Desorbed organic pollutants are solubilized, and their bioavailability is increased. Organic pollutants
- 1007 absorbed into the roots are diffused in the plasma membrane of the root cells and transported to the
- 1008 endodermis and pericycle through the plasmodesmata.
- 1009
- 1010 Figure 2. Translocation mechanisms of organic pollutants into xylem vessels through binding to major
- 1011 latex-like proteins.
- 1012 MLPs produced in the root cells bind to organic pollutants in the plasma membrane of the endodermis
- 1013 and pericycle. MLP-organic pollutant complexes are translocated into xylem vessels and transported
- 1014 to the aerial parts. As a result, contamination with organic pollutants occurs in the Cucurbitaceae
- 1015 family. Xv, xylem vessel Pe, pericycle; En, endodermis; Co, cortex; Ep. Epidermis.
- 1016
- 1017 Figure 3. Accumulation steps in the Cucurbitaceae family.



Figure 1



Figure 2



Accumulation mechanism in the Cucurbitaceae family

- 4. Transport of organic pollutants to the fruits
- 3. Translocation of organic pollutants into xylem vessels
- 2. Absorption of organic pollutants into the root cells
- 1. Solubilization of organic pollutants



Figure 3

1 Table 1. Organic pollutants taken up by the Cucurbitaceae family

2 (A) DDX

| Organic pollutant | $\log K_{\rm ow}$ | Plant species | Concentration | | Plant organ |
|-------------------|-----------------------|------------------------------|-------------------------|--------------------------------|--|
| | | | Soil | Plant | |
| DDD | 5.5 | Cucumber (Cucumis sativus) | <mark>0.003 µg/g</mark> | 6.46 μg/g (Shoot) | Shoot (Namiki et al. 2013) |
| | (Namiki et al. 2013) | Pumpkin (Cucurbita maxima) | <mark>0.003 µg/g</mark> | 9.15 μg/g (Shoot) | |
| | | Pumpkin (Cucurbita moschata) | <mark>0.003 µg/g</mark> | <mark>8.15 μg/g (Shoot)</mark> | |
| | | Zucchini (Cucurbita pepo) | <mark>0.003 µg/g</mark> | <mark>7.88 µg/g (Shoot)</mark> | |
| DDE | 5.7 | Cucumber (Cucumis sativus) | <mark>0.003 µg/g</mark> | 18.81 μg/g (Shoot) | Shoot (Namiki et al. 2013) |
| | (Namiki et al. 2013) | Pumpkin (Cucurbita maxima) | <mark>0.003 µg/g</mark> | 24.42 μg/g (Shoot) | |
| | | Pumpkin (Cucurbita moschata) | <mark>0.003 µg/g</mark> | 21.53 μg/g (Shoot) | |
| | | Zucchini (Cucurbita pepo) | <mark>0.003 µg/g</mark> | 21.40 μg/g (Shoot) | |
| <i>p,p</i> '-DDE | 6.96 | Cucumber (Cucumis sativus) | <mark>140 µg/g</mark> | 120 ng/g (Fruit) | Leaf (White 2002; Wang et al. 2004; Gent et al. 2007) |
| | (Sabljić et al. 1995) | | | (Gent et al. 2007) | Fruit (White 2002; Wang et al. 2004; Gent et al. 2007) |
| | | | | | Petiole(Gent et al. 2007) |
| | | | | | Stem (White 2002; Wang et al. 2004; Gent et al. 2007) |
| | | Melon (Cucumis melo) | 150–1200 ng/g | 10 ng/g (Fruit) | Leaf (White 2002) |
| | | | | | Fruit (White 2002) |
| | | | | | Stem (White 2002) |
| | | Squash (Cucurbita pepo) | <mark>180 ng/g</mark> | <mark>6.1 ng/g (Fruit)</mark> | Leaf (White 2002, 2010; Chhikara et al. 2010) |
| | | | | (Chhikara et al. 2010) | Fruit (White 2002, 2010; Chhikara et al. 2010) |
| | | | | | Stem (White 2002, 2010; Chhikara et al. 2010) |

| Pumpkin (Cucurbita maxima) | <mark>150–1200 ng/g</mark> | <mark>46 ng/g (Fruit)</mark> | Fruit (White 2001, 2002) |
|-------------------------------------|----------------------------|-------------------------------|---|
| | | (White 2002) | Leaf (White 2001, 2002; Peters et al. 2007) |
| | | | Stem (White 2001, 2002; Peters et al. 2007) |
| Pumpkin (Cucurbita pepo) | 478.4 ng/g | 400 ng/g (Leaf) | Leaf (Kelsey et al. 2006) |
| | | | Stem (Kelsey et al. 2006) |
| Watermelon (Citrullus lanatus) | <mark>610.21 ng/g</mark> | 0.49 μg/L (Xylem sap) | Xylem sap (Isleyen and Sevim 2012) |
| Zucchini (Cucurbita pepo) | <mark>180 ng/g</mark> | <mark>160 ng/g (Fruit)</mark> | Fruit (White 2001, 2010; White et al. 2003a, b, 2005, 2007; |
| | | (Chhikara et al. 2010) | Wang et al. 2004; Gent et al. 2007; Chhikara et al. 2010; |
| | | | Eevers et al. 2018) |
| | | | Leaf (White 2001, 2010; White et al. 2003b, 2005, 2007; |
| | | | Wang et al. 2004; Gent et al. 2007; Peters et al. 2007; |
| | | | Chhikara et al. 2010; Eevers et al. 2018) |
| | | | Petiole (Gent et al. 2007) |
| | | | Shoot (Namiki et al. 2013) |
| | | | Stem (White 2001, 2010; White et al. 2003b, 2005, 2007; |
| | | | Wang et al. 2004; Gent et al. 2007; Peters et al. 2007; |
| | | | Chhikara et al. 2010; Eevers et al. 2018) |
| | | | Xylem sap (Isleyen and Sevim 2012) |
| Pumpkin (<i>Cucurbita maxima</i>) | 3,700 ng/g | 4,262 ng/g (Shoot) | Shoot (Lunney et al. 2004) |
| | | (Lunney et al. 2004) | Stem (Denyes et al. 2016) |
| Squash (Cucurbita pepo) | 1,480 ng/g | > 4 ng/g (Leaf) | Fruit (Isleyen et al. 2012a) |
| | | (Isleyen et al. 2012a) | Leaf (Isleyen et al. 2012b, a) |
| | | | Stem (Isleyen et al. 2012b, a, 2013) |

DDX

| | | | Xylem sap (Isleyen et al. 2012b, a) |
|--------------------------------|-------------------------|----------------------|---|
| Watermelon (Citrullus lanatus) | <mark>1,670 ng/g</mark> | > 2 ng/g (Leaf) | Fruit (Isleyen et al. 2012a) |
| | | | Leaf (Isleyen et al. 2012a) |
| | | | Stem (Isleyen et al. 2012a) |
| | | | Xylem sap (Isleyen et al. 2012a) |
| Zucchini (Cucurbita pepo) | <mark>3,700 ng/g</mark> | 2,991 ng/g (Shoot) | Aerial parts (Mattina et al. 2006) |
| | | (Lunney et al. 2004) | Leaf (Isleyen et al. 2012b) |
| | | | Shoot (Lunney et al. 2004) |
| | | | Stem (Isleyen et al. 2012b, 2013) |
| | | | Xylem sap (Mattina et al. 2006; Isleyen et al. 2012b) |

3 DDD, dichlorodiphenyldichloroethane; DDE, dichlorodiphenyldichloroethylene; DDX, DDD, DDE, and DDT

4 (B) Drins

| Organic pollutant | $\log K_{\rm ow}$ | Plant species | Concentration | | Plant organ |
|-------------------|-----------------------|--------------------------------------|-------------------------|-------------------------------------|--|
| | | | Soil | Plant | |
| Aldrin | 6.5 | Cucumber (Cucumis sativus) | - | - | Fruit (Lichtenstein and Schulz 1965) |
| | (Shen and Wania 2005) | | | | |
| Dieldrin | 5.2 | Balsam pear (Momordica charantia) | <mark>594 μg/kg</mark> | > 100 μg/kg (Shoot) | Shoot (Otani et al. 2007) |
| | (Namiki et al. 2013) | Figleaf squash (Cucurbita ficifolia) | <mark>594 μg/kg</mark> | > 1000 µg/kg (Shoot) | |
| CI CI | | Loofah (Luffa cylindrica) | <mark>594 μg/kg</mark> | <mark>> 500 μg/kg (Shoot)</mark> | |
| | | White-flowered gourd | <mark>594 μg/kg</mark> | <mark>> 200 µg/kg (Shoot)</mark> | |
| | | (Lagenaria siceraria) | | | |
| | | White gourd (Benincasa hispida) | <mark>594 μg/kg</mark> | <mark>> 200 µg/kg (Shoot)</mark> | |
| | | Winter squash (Cucurbita maxima) | 594 μg/kg | <mark>> 900 μg/kg (Shoot)</mark> | |
| | | Cucumber (Cucumis sativus) | <mark>0.004 μg/g</mark> | 11.42 μg/g (Shoot) | Fruit (Lichtenstein and Schulz 1965; Hilber et al. 2008, |
| | | | | (Namiki et al. 2013) | 2009; Saito et al. 2011, 2012; Seike et al. 2012) |
| | | | | | Leaf (Saito et al. 2012) |
| | | | | | Shoot (Otani et al. 2007; Sakai et al. 2009; Murano et al. |
| | | | | | 2010; Namiki et al. 2013) |
| | | | | | Not mentioned (Hashimoto 2005) |
| | | Melon (Cucumis melo) | 594 μg/kg | > 200 μg/kg (Shoot) | Fruit (Hashimoto 2007; Saito et al. 2012) |
| | | | | (Otani et al. 2007) | Shoot(Otani et al. 2007) |
| | _ | Pumpkin (<i>Cucurbita maxima</i>) | <mark>0.004 µg/g</mark> | 14.64 μg/g (Shoot) | Fruit (Hashimoto 2007; Saito et al. 2012) |

| | | | | (Namiki et al. 2013) | Leaf (Saito et al. 2012) |
|--------|----------------------|--------------------------------------|-------------------------|-------------------------------------|---|
| | | | | | Shoot (Otani et al. 2007; Namiki et al. 2013) |
| | | Pumpkin (Cucurbita moschata) | <mark>0.004 μg/g</mark> | 15.00 μg/g (Shoot) | Shoot (Namiki et al. 2013) |
| | | Watermelon (Citrullus lanatus) | <mark>594 μg/kg</mark> | <mark>> 500 μg/kg (Shoot)</mark> | Fruit (Saito et al. 2012) |
| | | | | (Otani et al. 2007) | Shoot (Otani et al. 2007) |
| | | Zucchini (Cucurbita pepo) | 12.5 µmol/kg | 1.65 μM (Xylem sap) | Fruit (Hashimoto 2007; Saito et al. 2012) |
| | | | | (Fujita et al. 2020a) | Leaf (Saito et al. 2012) |
| | | | | | Shoot (Otani et al. 2007; Murano et al. 2010; Namiki et al. |
| | | | | | 2013, 2015) |
| | | | | | Xylem sap (Murano et al. 2010; Fujita et al. 2020a, b) |
| Endrin | 5.2 | Balsam pear (Momordica charantia) | <mark>58 µg/kg</mark> | <mark>> 5 μg/kg (Shoot)</mark> | Shoot (Otani et al. 2007) |
| | (Namiki et al. 2013) | Figleaf squash (Cucurbita ficifolia) | <mark>58 μg/kg</mark> | <mark>> 30 μg/kg (Shoot)</mark> | |
| CI CI | | Loofah (Luffa cylindrica) | <mark>58 μg/kg</mark> | <mark>> 20 μg/kg (Shoot)</mark> | |
| | | Melon (Cucumis melo) | <mark>58 μg/kg</mark> | > 10 μg/kg (Shoot) | |
| | | Watermelon (Citrullus lanatus) | <mark>58 μg/kg</mark> | <mark>> 50 μg/kg (Shoot)</mark> | |
| | | White-flowered gourd | <mark>58 µg/kg</mark> | <mark>> 20 μg/kg (Shoot)</mark> | |
| | | (Lagenaria siceraria) | | | |
| | | White gourd (Benincasa hispida) | <mark>58 µg/kg</mark> | <mark>> 20 μg/kg (Shoot)</mark> | |
| | | Winter squash (Cucurbita maxima) | <mark>58 µg/kg</mark> | <mark>> 70 μg/kg (Shoot)</mark> | |
| | | Cucumber (Cucumis sativus) | <mark>0.009 µg/g</mark> | 9.93 μg/g (Shoot) | Shoot (Otani et al. 2007; Namiki et al. 2013) |
| | | Pumpkin (Cucurbita maxima) | <mark>0.009 µg/g</mark> | <mark>13.84 µg/g (Shoot)</mark> | |
| | | Zucchini (Cucurbita pepo) | <mark>0.009 µg/g</mark> | 14.57 μg/g (Shoot) | |

| | | (Namiki et al. 2013) | |
|------------------------------|-------------------------|---------------------------------|----------------------------|
| Pumpkin (Cucurbita moschata) | <mark>0.009 µg/g</mark> | <mark>12.28 µg/g (Shoot)</mark> | Shoot (Namiki et al. 2013) |
| | | (Namiki et al. 2013) | |

5 -, not mentioned

6 (C) Other POPs and their related organochlorine insecticides.

| Organic pollutant | logK _{ow} | Plant species | Concentration | | Plant organ |
|--------------------|-----------------------|----------------------------|-------------------------|---------------------------|--|
| | | | Soil | Plant | |
| 1-Hydroxychlordene | 3.3 | Zucchini (Cucurbita pepo) | _ | - | Shoot (Hayashi et al. 2018) |
| | (Hayashi et al. 2018) | | | | |
| cis-Chlordane | 6.1 | Cucumber (Cucumis sativus) | (–) 670–1,160 ng/g | 27 ng/g (Leaf) | Fruit (Mattina et al. 2002, 2004; Hilber et al. 2008) |
| | (Shen and Wania 2005) | | (+) 782–1,406 ng/g | 29 ng/g (Leaf) | Leaf (Mattina et al. 2002, 2004) |
| | | | | (Mattina et al. 2002) | Stem (Mattina et al. 2002, 2004) |
| CI CI ĈI | | | | | Xylem sap (Mattina et al. 2004) |
| | | Pumpkin (Cucurbita maxima) | (−) 670–1,160 ng/g | 29 ng/g (Leaf) | Fruit (Mattina et al. 2002) |
| | | | (+) 782–1,406 ng/g | 34 ng/g (Leaf) | Leaf (Mattina et al. 2002) |
| | | | | (Mattina et al. 2002) | Stem (Mattina et al. 2002) |
| | | Squash (Cucurbita pepo) | - | - | Fruit (Isleyen et al. 2013) |
| | | | | | Stem (Isleyen et al. 2013) |
| | | Zucchini (Cucurbita pepo) | <mark>2,440 ng/g</mark> | 2,940 ng/g (Aerial parts) | Aerial parts (Mattina et al. 2006) |
| | | | | (Mattina et al. 2006) | Fruit (Mattina et al. 2002, 2004; White et al. 2002; Isleyen |
| | | | | | et al. 2013) |
| | | | | | Leaf (Mattina et al. 2002, 2004; White et al. 2002), |
| | | | | | Peel (White et al. 2002) |
| | | | | | Stem (Mattina et al. 2002, 2004; White et al. 2002; Isleyen |
| | | | | | et al. 2013) |

| | | | | | Xylem sap (Mattina et al. 2004, 2006) |
|-----------------|-----------------------|----------------------------|---------------------------------|--------------------------------|--|
| trans-Chlordane | 6.22 | Cucumber (Cucumis sativus) | <mark>(−) 665–1,207 ng/g</mark> | 24 ng/g (Leaf) | Fruit (Mattina et al. 2002, 2004) |
| | (Shen and Wania 2005) | | (+) 557–980 ng/g | 14 ng/g (Leaf) | Leaf (Mattina et al. 2002, 2004) |
| CI CI | | | | (Mattina et al. 2002) | Stem (Mattina et al. 2002, 2004) |
| | | | | | Xylem sap (Mattina et al. 2004) |
| | | Pumpkin (Cucurbita maxima) | <mark>(−) 665–1,207 ng/g</mark> | 26 ng/g (Leaf) | Fruit (Mattina et al. 2002) |
| | | | <mark>(+) 557–980 ng/g</mark> | 23 ng/g (Leaf) | Leaf (Mattina et al. 2002) |
| | | | | (Mattina et al. 2002) | Stem (Mattina et al. 2002) |
| | | Squash (Cucurbita pepo) | _ | _ | Fruit (Isleyen et al. 2013) |
| | | | | | Stem (Isleyen et al. 2013) |
| | | Zucchini (Cucurbita pepo) | <mark>2,150 ng/g</mark> | 2,037 ng/g (Aerial parts) | Aerial parts (Mattina et al. 2006) |
| | | | | (Mattina et al. 2006) | Fruit (Mattina et al. 2002, 2004; White et al. 2002; Isleyen |
| | | | | | et al. 2013) |
| | | | | | Leaf (Mattina et al. 2002, 2004; White et al. 2002), Peel |
| | | | | | (White et al. 2002) |
| | | | | | Stem (Mattina et al. 2002, 2004; White et al. 2002; Isleyen |
| | | | | | et al. 2013) |
| | | | | | Xylem sap (Mattina et al. 2004, 2006) |
| Chlordane | 6.06 | Cucumber (Cucumis sativus) | - | - | Leaf (Mattina et al. 2003) |
| | (Rodan et al. 1999) | Pumpkin (Cucurbita maxima) | l. | - | |
| ci ci ci | | Zucchini (Cucurbita pepo) | <mark>0.327 µg/g</mark> | <mark>0.612 µg/g (Leaf)</mark> | Fruit (Mattina et al. 2000) |
| | | | | (Mattina et al. 2000) | Leaf (Mattina et al. 2000, 2003) |
| | | | | | Stem (Mattina et al. 2000) |

| Chlordecone | 4.5 | Christophine (Sechium edule) | > 5,000 mg/kg | < 1,000 μg/kg (Fruit) | Fruit (Clostre et al. 2014) |
|---------------------|-----------------------|------------------------------|-------------------------|--|----------------------------------|
| | (Clostre et al. 2014) | Cucumber (Cucumis sativus) | > 5,000 mg/kg | <mark>> 10,000 µg/kg (Fruit)</mark> | Fruit (Clostre et al. 2014) |
| ci ci | | | | | Leaf (Clostre et al. 2014) |
| | | | | | Stem (Clostre et al. 2014) |
| | | Pumpkin (Cucurbita moschata) | > 5,000 mg/kg | <mark>> 30,000 µg/kg (Fruit)</mark> | Fruit (Clostre et al. 2014) |
| | | Zucchini (Cucurbita pepo) | - | <mark>.</mark> | Leaf (Clostre et al. 2014) |
| | | | | | Stem (Clostre et al. 2014) |
| Endosulfan | 4.8 | Zucchini (Cucurbita pepo) | - | - | Stem (Garvin et al. 2015) |
| | (Garvin et al. 2015) | | | | |
| | | | | | |
| α-НСН | 3.81 | Cucumber (Cucumis sativus) | <mark>0.008 µg/g</mark> | <mark>1.87 µg/g (Shoot)</mark> | Shoot (Namiki et al. 2013) |
| | (Namiki et al. 2013) | Pumpkin (Cucurbita maxima) | <mark>0.008 µg/g</mark> | 2.72 μg/g (Shoot) | |
| ci ⁿⁿ ci | | Pumpkin (Cucurbita moschata) | <mark>0.008 µg/g</mark> | 2.49 μg/g (Shoot) | |
| Ci | | Zucchini (Cucurbita pepo) | <mark>0.008 µg/g</mark> | 3.30 μg/g (Shoot) | |
| β-НСН | 3.8 | Cucumber (Cucumis sativus) | <mark>0.008 µg/g</mark> | 1.66 μg/g (Shoot) | Shoot (Namiki et al. 2013) |
| CI ANN CI | (Namiki et al. 2013) | Pumpkin (Cucurbita maxima) | <mark>0.008 µg/g</mark> | <mark>1.98 μg/g (Shoot)</mark> | |
| | | Pumpkin (Cucurbita moschata) | <mark>0.008 µg/g</mark> | 2.23 μg/g (Shoot) | |
| | | Zucchini (Cucurbita pepo) | <mark>0.008 µg/g</mark> | 3.22 μg/g (Shoot) | Shoot (Namiki et al. 2013, 2015) |
| | | | | (Namiki et al. 2013) | |
| ү-НСН | 3.7 | Cucumber (Cucumis sativus) | <mark>0.009 µg/g</mark> | 0.56 μg/g (Shoot) | Shoot (Namiki et al. 2013) |
| CI CI | (Namiki et al. 2013) | Pumpkin (Cucurbita maxima) | <mark>0.009 µg/g</mark> | 0.86 μg/g (Shoot) | |
| ci Ci | | Pumpkin (Cucurbita moschata) | <mark>0.009 µg/g</mark> | 0.76 μg/g (Shoot) | |

| | | Zucchini (Cucurbita pepo) | <mark>0.009 µg/g</mark> | <mark>1.00 μg/g (Shoot)</mark> | |
|------------|-----------------------|------------------------------|-------------------------|-------------------------------------|--|
| Heptachlor | 4.62 | Cucumber (Cucumis sativus) | <mark>19.8 mg/l</mark> | <mark>> 0.05 μg/g (Shoot)</mark> | Fruit (Lichtenstein and Schulz 1965) |
| | (Hayashi et al. 2018) | | (Hydroponics) | (Hayashi et al. 2010) | Shoot (Hayashi et al. 2010) |
| ci ci | | Pumpkin (Cucurbita maxima) | <mark>19.8 mg/l</mark> | 0.014 μg/g (Shoot) | Shoot (Hayashi et al. 2010) |
| Ci | | | (Hydroponics) | (Hayashi et al. 2010) | |
| | | Zucchini (Cucurbita pepo) | <mark>19.8 mg/l</mark> | 0.091 μg/g (Shoot) | Shoot (Hayashi et al. 2010, 2018) |
| | | | (Hydroponics) | (Hayashi et al. 2010) | |
| HEPX | 5 | Cucumber (Cucumis sativus) | <mark>0.001 µg/g</mark> | <mark>10.06 µg/g (Shoot)</mark> | Fruit (Lichtenstein and Schulz 1965; Hilber et al. 2008) |
| | (Namiki et al. 2013) | | | (Namiki et al. 2013) | Shoot (Namiki et al. 2013) |
| CI CI | | | | | Xylem sap (Mattina et al. 2004) |
| °O | | Pumpkin (Cucurbita maxima) | 0.001µg/g | <mark>13.29 µg/g (Shoot)</mark> | Shoot (Murano et al. 2009; Namiki et al. 2013) |
| | | | | (Namiki et al. 2013) | |
| | | Pumpkin (Cucurbita moschata) | <mark>0.001µg/g</mark> | <mark>12.99 µg/g</mark> | Shoot (Namiki et al. 2013) |
| | | Squash (Cucurbita pepo) | <mark>57.5 µg/kg</mark> | 0.550 mg/kg (Shoot) | Fruit (Sugiyama et al. 2013) |
| | | | | (Sugiyama et al. 2013) | Shoot (Sugiyama et al. 2013, 2016) |
| | | White-flowered gourd | <mark>≥ 0.14µg/g</mark> | <mark>> 1 μg/g</mark> | Vine (Campbell et al. 2009) |
| | | (Lagenaria siceraria) | | | |
| | | Zucchini (Cucurbita pepo) | 0.001µg/g | <mark>14.44 μg/g (Shoot)</mark> | Aerial parts (Mattina et al. 2006) |
| | | | | (Namiki et al. 2013) | Shoot (Namiki et al. 2013; Hayashi et al. 2018) |
| | | | | | Xylem sap (Mattina et al. 2004, 2006) |
| | 6.35 | Cucumber (Cucumis sativus) | 638–1,175 ng/g | 23 ng/g (Leaf) | Fruit (Mattina et al. 2002) |
| | (Maruya et al. 2009) | | | (Mattina et al. 2002) | Leaf (Mattina et al. 2002) |
| | | | | | Stem (Mattina et al. 2002) |

| trans-Nonachlor | | | | Xylem sap (Mattina et al. 2004) |
|-----------------|----------------------------|-----------------------------|-------------------------|--|
| | Pumpkin (Cucurbita maxima) | <mark>638–1,175 ng/g</mark> | 18 ng/g (Leaf) | Fruit (Mattina et al. 2002) |
| | | | | Leaf (Mattina et al. 2002) |
| CI | | | | Stem (Mattina et al. 2002) |
| | Squash (Cucurbita pepo) | _ | - | Fruit (Isleyen et al. 2013) |
| | | | | Stem (Isleyen et al. 2013) |
| | Zucchini (Cucurbita pepo) | <mark>1,080 ng/g</mark> | 515 ng/g (Aerial parts) | Aerial parts (Mattina et al. 2006) |
| | | | (Mattina et al. 2006) | Fruit (Mattina et al. 2002, 2004; White et al. 2002; Isleyen |
| | | | | et al. 2013) |
| | | | | Leaf (Mattina et al. 2002, 2004; White et al. 2002) |
| | | | | Peel (White et al. 2002) |
| | | | | Stem (Mattina et al. 2002, 2004; White et al. 2002; Isleyen |
| | | | | et al. 2013) |
| | | | | Xylem sap (Mattina et al. 2004, 2006) |

7 HCH, hexachlorocyclohexane; HEPX, Heptachlor *exo*-epoxide; -, not mentioned

8

9 (D) PCBs, PCDDs, and PCDFs

| Organic pollutant | logK _{ow} | Plant species | Concentration | | Plant organ |
|-------------------|---------------------------|----------------------------|--------------------------------|---------------------------------|---|
| | | | Soil | Plant | - |
| PCBs | 4.09-8.18 | Cucumber (Cucumis sativus) | <mark>105 µg/g</mark> | > 5 μg/g (Leaf) | Fruit (White et al. 2006) |
| | (Hawker and Connell 1988) | | | | Leaf (White et al. 2006) |
| (CI)m (CI)n | | | | | Stem (White et al. 2006) |
| | | Pumpkin (Cucurbita maxima) | <mark>105 µg/g</mark> | <mark>> 5 μg/g (Leaf)</mark> | Leaf (Whitfield Åslund et al. 2007) |
| | | | | (White et al. 2006) | Leaf and petiole (Low et al. 2011) |
| | | | | | Petiole (Whitfield Åslund et al. 2007) |
| | | | | | Shoot (Ficko et al. 2011; Greenwood et al. |
| | | | | | 2011; Denyes et al. 2012) |
| | | | | | Stem (Whitfield Åslund et al. 2007, 2008; |
| | | | | | Low et al. 2011) |
| | | | | | Xylem sap (Greenwood et al. 2011) |
| | | Zucchini (Cucurbita pepo) | <mark>5,100 ng - TEQ/kg</mark> | > 40 pg-TEQ/g (Aerial parts) | Aerial parts (Inui et al. 2008, 2011; Matsuo et |
| | | | | (Inui et al. 2008) | al. 2011) |
| | | | | | Fruit (White et al. 2006) |
| | | | | | Leaf (White et al. 2006; Goto et al. 2019) |
| | | | | | Stem (White et al. 2006; Goto et al. 2019) |
| | | | | | Xylem sap (Goto et al. 2019) |
| PCDD/Fs | 3.68-8.75 | Cucumber (Cucumis sativus) | <mark>148 ng - TEQ/kg</mark> | 21.0 ng - TEQ/kg (Fruit) | Fruit (Hülster et al. 1994) |
| | (Govers et al. 1996) | | | (Hülster et al. 1994) | Leaf (Hülster et al. 1994) |

| | | | | Shoot (Zhang et al. 2009) |
|--|----------------------------|--------------------------------|------------------------------|---|
| | Pumpkin (Cucurbita maxima) | 148 ng - TEQ/kg | 3.1 ng - TEQ/kg (Fruit) | Fruit (Hülster et al. 1994) |
| (• · ym | | | (Hülster et al. 1994) | Leaf (Hülster et al. 1994) |
| ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~ | | | | Shoot (Zhang et al. 2009) |
| (CI)m (CI)m | Zucchini (Cucurbita pepo) | <mark>5,100 ng - TEQ/kg</mark> | > 40 pg-TEQ/g (Aerial parts) | Aerial parts (Inui et al. 2008, 2011; Matsuo et |
| | | | (Inui et al. 2008) | al. 2011) |
| | | | | Fruit (Hülster et al. 1994) |
| | | | | Leaf (Hülster et al. 1994) |
| | | | | Shoot (Zhang et al. 2009) |

10 PCBs, polychlorinated biphenyls; PCDDs, polychlorinated dibenzo-*p*-dioxins; PCDFs, polychlorinated dibenzofurans; TEQ, toxic equivalent

11 (E) Others

| Organic pollutant | $\log K_{\rm ow}$ | Plant specie | Concentration | | Plant organ |
|---|-----------------------|----------------------------|-------------------------|---------------------------------|------------------------------------|
| | | | Soil | Plant | |
| Anthracene | 4.54 | Zucchini (Cucurbita pepo) | 178 ng/g | 15.0 ng/g (Aerial parts) | Aerial parts (Mattina et al. 2006) |
| | (Miller et al. 1985) | | | | Xylem sap (Mattina et al. 2006) |
| Caffeine | -0.07 | Zucchini (Cucurbita pepo) | - | | Shoot (Garvin et al. 2015) |
| | (Garvin et al. 2015) | | | | |
| Carbamazepine | 2.45 | Cucumber (Cucumis sativus) | <mark>13.98 µg/L</mark> | <mark>25.6 μg/kg (Fruit)</mark> | Fruit (Shenker et al. 2011) |
| H ₂ N O | (Shenker et al. 2011) | | | | Leaf (Shenker et al. 2011) |
| | | | | | Stem (Shenker et al. 2011) |
| | | Zucchini (Cucurbita pepo) | 20 mg/kg | <mark>> 80 mg/kg</mark> | Leaf (Knight et al. 2018) |
| N-EtFOSA | 6.71 | Pumpkin (Cucurbita maxima) | - | | Shoot (Zhao et al. 2018) |
| 0 F F F F F F F F HN S F F F F F F F 0 F F F F F F F F F | (Zhao et al. 2018) | | | | |
| Fluoranthene | 5.22 | Zucchini (Cucurbita pepo) | <mark>3,970 ng/g</mark> | 161 ng/g (Aerial parts) | Aerial parts (Mattina et al. 2006) |
| | (Miller et al. 1985) | | | | Xylem sap (Mattina et al. 2006) |
| 6:2 FTSA | 4.44 | Pumpkin (Cucurbita maxima) | 1 | 4 | Shoot (Zhao et al. 2019) |
| F F F F F F O F F F F F F S H H H H H H H H F F F F F F F S I O O O O O I O O I O O I O O I O O I O O O I O O O O I O O O O O O O O O O O O O | (Zhao et al. 2019) | | | | |

| HBCD | 4.78 | Pumpkin (Cucurbita maxima) | 100 ng/mL | > 3 ng/g (Leaf) | Leaf (Hou et al. 2017) |
|--|-----------------------|----------------------------|------------------------|--|--|
| Br Br | (Hou et al. 2017) | | (Hydroponics) | | Stem (Hou et al. 2017) |
| Br Br Br | | | | | |
| PBDEs | 4.31-8.35 | Zucchini (Cucurbita pepo) | 75 μg/kg | <mark>> 4 μg/kg</mark> | Shoot (Mueller et al. 2006) |
| | (Li et al. 2008) | | | | |
| Pentachloroaniline | 5.08 | Cucumber (Cucumis sativus) | 0.2 mg/kg | < 0.01 mg/kg | Fruit (Hilber et al. 2008) |
| CICI | (de Wolf et al. 1994) | | | | |
| | | | | | |
| Perylene | 6.5 | Zucchini (Cucurbita pepo) | 1.25 mmol/kg | 3.81 nM (Xylem sap) | Stem (Yoshihara et al. 2014) |
| | (Miller et al. 1985) | | | (Fujita et al. 2020a) | Xylem sap (Fujita et al. 2020a) |
| PFOA | 5.30 | Cucumber (Cucumis sativus) | <mark>805 µg/kg</mark> | 23.8 μg/kg (Peeled edible | Peeled edible parts (Lechner and Knapp |
| | (Zhao et al. 2019) | | | parts) | 2011) |
| Г Г Г Г Г Г Г ÒH | | | | | Peel (Lechner and Knapp 2011) |
| PFOS | 6.43 | Cucumber (Cucumis sativus) | <mark>556 µg/kg</mark> | <mark>1.3 µg/kg (Peeled edible parts)</mark> | Peeled edible parts (Lechner and Knapp |
| F F F F F F F O F F F F F F F H H F H H H H H H H H F H H H H | (Zhao et al. 2019) | | | | 2011) |
| FFFFFFF | | | | | Peel (Lechner and Knapp 2011) |
| Phenanthrene | 4.6 | Zucchini (Cucurbita pepo) | 1,661 ng/g | 193 ng/g (Aerial parts) | Aerial parts (Mattina et al. 2006) |
| | (Miller et al. 1985) | | | | Xylem sap (Mattina et al. 2006) |

| Pyrene | 5.2 | Zucchini (Cucurbita pepo) | 1.25 mmol/kg | 0.74 μM (Xylem sap) | Aerial parts (Mattina et al. 2006) |
|---------------------|----------------------|---|--------------------------|------------------------------|---|
| | (Miller et al. 1985) | | | (Fujita et al. 2020a) | Xylem sap (Mattina et al. 2006; Fujita et al. |
| | | | | | 2020a, b; Inui et al. 2020) |
| Triclocarban | 3.5 | Zucchini (Cucurbita pepo) | | | Stem (Garvin et al. 2015) |
| | (Snyder et al. 2010) | | | | |
| ^(a) PAHs | - | Cucumber (Cucumis sativus) | <mark>36,300 ng/g</mark> | 0.124 μg (Leaf) | Leaf (Parrish et al. 2006) |
| | | Squash (Cucurbita pepo) | <mark>36,300 ng/g</mark> | <mark>0.631 µg (Leaf)</mark> | Stem (Parrish et al. 2006) |
| | | Zucchini (Cucurbita pepo) | <mark>36,300 ng/g</mark> | 1.13 µg (Leaf) | |
| PFAAs | - | ^(b) Pumpkin (not mentioned) | - | | Flower (Lee et al. 2014) |
| | | | | | Fruit (Lee et al. 2014) |
| | | | | | Leaf (Lee et al. 2014) |
| | | | | | Stalk (Lee et al. 2014) |
| | | ^(c) Zucchini (<i>Cucurbita pepo</i>) | - | | Edible parts (Felizeter et al. 2014) |
| | | | | | Leaf (Felizeter et al. 2014) |
| | | | | | Stem (Felizeter et al. 2014) |
| PPCPs | - | Cucumber (Cucumis sativus) | - | - | ^(d) Leaf/stem (Wu et al. 2013) |
| | | | | | ^(e) Shoot (Sun et al. 2018) |

12 N-EtFOSA, N-ethyl perfluorooctane sulfonamide; 6:2 FTSA, 6:2 fluorotelomer sulfonic acid; HBCD, hexabromocyclododecane; PBDEs, polybrominated

- 13 diphenyl ethers; PFOA, perfluorooctanoic acid PFOS, perfluorooctanesulfonic acid; PAHs, polycyclic aromatic hydrocarbons; PFAAs, perfluoroalkyl acids;
- 14 PPCPs, pharmaceutical and personal care products; -, not mentioned

- 15 ^(a)PAHs include phenanthrene, anthracene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene,
- 16 dibenz[a,h]anthracene, indeno[1,2,3-cd]pyrene, and benzo[g,h,i]perylene
- 17 (b)4:2 diPAP (polyfluoroalkyl phosphate diester), 6:2 diPAP, 8:2 diPAP, perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), PFOA,
- 18 perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), and perfluoroundecanoic acid (PFUnA) were detected in flowers, fruits, leaves, and stalks.
- 19 6:2/8:2 diPAP was detected in flowers, fruits, and stalks. 10:2 diPAP was detected in fruits and stalks. Perfluoropentanoic acid (PFPeA) was detected in
- 20 flowers, fruits, and leaves.
- 21 (c)PFBA (perfluorobutanoic acid), PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnA (perfluoroundecanoic acid), PFDoA (perfluorododecanoic acid),
- 22 PFTrA (perfluorotridecanoic acid), PFTeA (perfluorotetradecanoic acid), PFBS (perfluorobutane sulfonic acid), PFHxS (perfluorohexane sulfonic acid), and
- 23 PFOS were detected.
- 24 ^(d)Caffeine, meprobamate, primidone, sulfamethoxazole, atenolol, trimethoprim, DEET, carbamazepine, dilantin, diuron, naproxen, diazepam, fluoxetine,
- 25 atorvastatin, ibuprofen, gemfibrozil, triclosan, and triclocarban were detected.
- 26 (e)Caffeine, meprobamate, primidone, sulfamethoxazole, atenolol, trimethoprim, carbamazepine, dilantin, diazepam, atorvastatin, naproxen, ibuprofen,
- 27 gemfibrozil, triclosan, diclofenac, and triclocarban were detected.
- 28