Rev Environ Sci Biotechnol (2021) 20:75–142
https://doi.org/10.1007/s11157-020-09557-7

REVIEW PAPER

Plant uptake, translocation and metabolism of PBDEs in plants of food and feed industry: A review

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Received: 7 August 2020 / Accepted: 17 October 2020 / Published online: 9 November 2020

Abstract Polybrominated diphenyl ethers (PBDEs) have widely been used for decades as flame retardants in a variety of products like plastics for building insulation, upholstered furniture, electrical appliances, vehicles, aircrafts, polyurethane foams, textiles, cable insulation, appliance plugs and various technical plastics in concentrations of 5–30%. However, PBDEs also act as endocrine disrupters, neurotoxins, and negatively affect fertility. In 2001, worldwide consumption of technically relevant penta-BDEs was still estimated at 7500 tons, octa-BDEs at 3790 tons, and deca-BDE at 56,100 tons, but 50–60% of this total volume are discharged into the environment via sewage sludge and its agricultural use alone. In addition, soils are ubiquitously contaminated by the gaseous or particle-bound transport of PBDEs, which today has its main source in highly contaminated electronic waste recycling sites. The emitted PBDEs enter the food chain via uptake by the plants' roots and shoots. However, uptake and intrinsic transport behaviour strongly depend on crop specifics and various soil parameters. The relevant exposure and transformation pathways, transport-relevant soil and plant characteristics and both root concentration factors (RCF) and transfer factors (TF) as derivable parameters are addressed and quantified in this review. Finally, a simple predictive model for quantification of RCF and TF based on log K_{OW} values and the organic content of the soil/lipid content of the plants is also presented.

Keywords Plant uptake · Translocation · Root concentration factor · PBDE · Shoot concentration factor · Food industry

1 Application of PBDE and environmental relevance

Polybrominated diphenyl ethers (PBDEs) were used as flame retardants for decades in multiple products like building insulations, upholstered furniture, electrical devices, vehicles and aircrafts, polyurethane foams, textiles, cable insulations, device plugs, and a large number of technical plastics (ABS, HIPS, PBT, PAP) in concentrations of 5–30% (European Chemicals Bureau ECB 2003; Freudenschuß et al. 2008; Han et al. 2017). Even though 209 congeners of PBDEs exist, there were only three technical mixtures of PBDEs of commercial interest, named

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pentabromodiphenyl ether (penta-BDEs), octabromodiphenyl ether (octa-BDEs), and perbrominated diphenyl ether (deca-BDE). The global demand (EU demand) of penta-BDEs, octa-BDEs, and deca-BDE in 2001 was about 7500 tons (EU: 150 tons), 3790 tons (EU: 610 tons), and 56,100 tons (EU: 7600 tons), respectively (BSEF Bromine Science and Environmental Forum 2003). In 2003–2006 the annual consumption of BDE-209 reached 30,000 tons (China), 9600 tons (EU), 5000–10,000 tons (Northern America), and 1600 tons (Japan) (ECHA European Chemicals Agency 2015).

Besides their endocrine-disrupting properties, neurotoxicity, and negative impacts on fertility, the use of these PBDE mixtures was strictly regulated by the Stockholm Convention of 2001 due to their high degree of bromination and their classification as persistent organic pollutants (POPs). As acute toxicity of PBDEs declines by increasing degree of bromination (Sun et al. 2020), penta-BDEs and octa-BDEs were firstly banned in 2004, and deca-BDE was finally restricted in March 2019. At present, the use of deca-BDE is severely restricted to the production of spare parts of cars, trucks, and aeronautic vehicles (European Commission EC 2017).

As high-volume chemicals used in multiple applications and due to their both gaseous and particulate-based atmospheric transport, PBDEs are ubiquitous, but mainly detectable in soil and dust samples of China, where 70% of the global e-waste as the main source of PBDEs are recycled (Stone 2009), and in waste water treatment sludges as the second main source (Venkatesan and Halden 2014). At these e-waste recycling sites the highest BDE-209 concentration levels ever listed were described by Han et al. (2017), namely 6.3–12,194.6 ng g DM^{-1} at a ratio of 64.2–89.6% of the total PBDE ($\sum$PBDE). At levels of 2720–4250 ng g DM^{-1} of $\sum$PBDE at a BDE-209 ratio of 35–82% and at $\sum$PBDE levels up to 2000 ng g DM^{-1} similar concentration levels were previously described (Leung et al. 2007; Zhang et al. 2015). Moreover, the currently highest $\sum$PBDE levels in soil were quantified as 8.70–18,451 ng g DM^{-1} by Xu et al. (2019) at a production site for plastic parts in electrical industry in Changzhou. The same study revealed the currently highest measured dust concentrations of PBDEs with 7240–10,469 ng g DM^{-1} in an industrial environment, while concentrations of even 180–370,000 ng g DM^{-1} and 270–110,000 ng g DM^{-1} were detected in house dust and office dust samples in the UK (Tao et al. 2016).

The study of Hale et al. (2012) focused on the BDE-209 levels in sludges of waste water treatment plants (WWTPs) of 75 US WWTPs. It was detected at an average concentration of 2310 ng g DM^{-1} with a top level of 15,500 ng g DM^{-1} at a WWTP in Chicago. A similar study at 15 Hessian WWTPs revealed $\sum$PBDE levels of 85.5–5856 ng g DM^{-1} in aerated sludges and 140.84–14,816 ng g DM^{-1} in excess sludges (Leisewitz et al. 2003), but record setting levels of 2.5 w% were observed in sewage sludge of an industrial wastewater treatment plant in Turkey (Demirtepe and Imamoglu 2019). The annual input of PBDEs into the US environment in 2001 was quantified as 47.9–60.1 tons, where 24.0–36.0 tons per year were set free by agricultural use of sewage sludges (Venkatesan and Halden 2014).

As WWTP sludges are used as fertilizers in agriculture PBDE contaminations in the environment are not restricted to hotspots like e-waste sites and are finally ubiquitous due to the gaseous and particulate-based transport of PBDEs. Consequently, soil samples were positively tested towards PBDE contaminations in grassland and forest soils of the UK and Norway ($\sum$PBDE: 65–12,000 pg g DM^{-1}, (Hassanin et al. 2004), Western Austria ($\sum$PBDE: 10.4–2744 pg g DM^{-1}, (Freudenschuß et al. 2010), Germany (BDE-47: $<$ 27–505 pg g DM^{-1}, BDE-209: $<$ 156–461 pg g DM^{-1}, (Dreyer et al. 2018), and Artic ($\sum$12PBDEs ex BDE-209: 120 pg g DM^{-1}, (Dreyer et al. 2018); $\sum$PBDE: 1.7–416 pg g DM^{-1}, (Zhu et al. 2015).

In consequence of the restrictions in use of PBDEs, alternative brominated flame retardants like hexabromobenzene, pentabromotoluene, 1,2-bis(2,4,6-tribromophenoxy)ethane, decabromo diphenyl ethane, or chlorinated ones as Dechlorane Plus were introduced in the past decades. Their annual global production was about 100–180 kilotons in 2008 (Law et al. 2013). As these alternatives show similar degrees of bromination, high persistency and bioaccumulation potentials are expected (Liagkouridis et al. 2015; Zhu et al. 2018). A ubiquitous presence of these compounds was already proven by She et al. (2013).

2 Physical characteristics and their effect on transport pathways and plant uptake

PBDEs cover diphenyl ethers with a wide range of 2–10 bromo substituents. Hence, PBDEs reveal a large range of molar masses (328–959 g mol^{-1}), heterogeneous lipophilicity (log K_{OW} = 6–10), and volatility (log K_{OA} = 9–16; (She et al. 2013; Zhu et al. 2018) as well. Therefore, BDE congener specific transport and plant uptake mechanisms (soil–air–plant vs. soil–soil moisture–root–plant) strongly differ and depend on compound physical parameters (vapor pressure, K_{OW} value, K_{OA} value, Henry coefficient, air to plant distribution coefficient), meteorological parameters (temperature, wind velocity, rainfall, temporal rainfall distribution, deposition kinetics of gaseous BDEs, deposition kinetics of particulate BDEs), long range transport, plant specific characteristics (species, lipid content, carbohydrate content, fiber content, leaf morphology, non-lipid plant parts, bark consistency), and rhizosphere parameters (Klinčić et al. 2020; Yogui et al. 2011; Zhao et al. 2009; Zhu et al. 2015). Under aspects of transport, low brominated BDEs (Br_2–Br_3) are mainly and medium brominated BDEs (Br_4–Br_5), depending on the study, are minorly to dominantly distributed as gaseous compounds (BDE-15: 100%; BDE-28: 35–60%), while transmission and deposition of higher brominated congeners (Br_6–Br_{10}) are obligatorily characterized by adsorption of BDEs on a particulate phase (Dreyer et al. 2018; Gao et al. 2019; Yogui et al. 2011; Zhao et al. 2009; Zhu et al. 2020). Due to the lower-range transport of the particulate phase, spectrum and concentrations of BDEs in soil and plant samples taken out of densely populated regions are more or less in agreement with the BDE emission spectrum, while the spectrum of detected PBDEs in sparsely populated regions is dominated by low brominated congeners like BDE-47 (51.2%) and BDE-99 (17.8%; Zhao et al. 2009). The reduced ratio of high brominated BDEs in the PBDE pattern of soil samples was also shown by Han et al. (2017), where the ratio of BDE-209 declined from originally 64.2–89.6% of the $\sum$PBDE at the e-waste site to 10.4–35.8% at a rural sampling site nearby. Additionally, a significant concentration gradient of $\sum$PBDE from both densely populated to sparsely populated regions and from emission sites to adjacent regions can be observed. Similar results were observed in plant tissue samples of *Ligustrum lucidum Ait* (Graziani et al. 2019). Concentration levels in dust samples of 19 PBDEs were reported by Zhu et al. (2018) in China in the range of 4.33–71,000 ng g DM^{-1} at an average of 2590 ng g DM^{-1}. Further referenced PBDE levels in dust were in the range of 227–160,000 ng g DM^{-1} (South China; Wang et al. 2010), 6300–82,200 ng g DM^{-1} (East China; Ma et al. 2009), 320–290,000 ng g DM^{-1} (Thailand; Muenhor et al. 2010), 311–19,700 ng g DM^{-1} (USA; Schreder and La Guardia 2014), and 72–89,000 ng g DM^{-1} (UK; Harrad et al. 2010). Record setting levels of 180–370,000 ng g DM^{-1} were presented by Tao et al. (2016) in housing dust samples. Commonly, all studies revealed domination of BDE-209 ratio in the PBDE spectrum detected in dust and soil samples, i.e. BDE-209: 69.2%, BDE-196: 4.49%, BDE-47: 4.40%, other BDEs: $< 3.00\%$ as shown by Zhu et al. (2018). Even BDE-209 ratios of 90% (Zhu et al. 2020) and 93.2–99.6% were reported (Tao et al. 2016).

Due to the high molar mass and the lipophilicity of high brominated BDEs, plant uptake by the soil–soil moisture–root–plant pathway is of low relevance and restricted to low and medium brominated BDEs (Br_2–Br_5) like BDE-47, BDE-99 and BDE-100 (Klinčić et al. 2020; Mueller et al. 2006). Nevertheless, high brominated BDEs (Br_7–Br_{10}) like BDE-209 are detected in multiple plant samples, strengthening the hypothesis of adsorptive plant/shoot—uptake via the atmospheric pathway, even though BDE-209 revealed a low ratio of 0.1% of the total atmospheric PBDE pattern (Li et al. 2015b) due to high deposition rates of 120–137,000 pg PBDE m^{-2} d^{-1} (Zhan et al. 2019). Single studies delivered hints for intrinsic transport of BDE-209 in plants (Chow et al. 2015; Vrkoslavová et al. 2010; Zhao et al. 2017b). However, differentiation between intrinsic BDE-209 and BDE-209 adsorbed at the outer side of the roots/plant tissue is sophisticated. Plant availability of BDE-209 was quantified as 0.3–0.5% of the initial concentration set in the experimental setup of Wu et al. (2018b), i.e. 99.5–99.7% of BDE-209 are solely adsorbed on soil matrix or the outer side of the roots. Hence, atmospheric uptake of high brominated BDEs is the dominant pathway (Gao et al. 2019).

3 Human exposure to PBDE contaminations and uptake

Despite atmospheric PBDE plant uptake and subsequent use of plants as food, human PBDE uptake is dominated by inhalation of both gaseous and particulate PBDEs. The relevance of both pathways strongly depends on the contamination of the cultivation area and the place of residence, i.e. they are of low relevance in case of low contaminated regions, but might get highly relevant in case of contaminated regions next to industrial sites. Studies of Hites and Sjödin et al., scoping on the atmospheric ΣPBDE levels, revealed concentrations of 5.27–301 pg m^{-3} in ambient air and 0.08–67 ng m^{-3} at indoor air, but increased levels of up to 312.1 ng BDE-209 m^{-3} at a Swedish e-waste recycling site (Hites 2004; Sjödin et al. 2001). Average BDE-209 levels of 0.13 ng m^{-3} (gaseous BDE-209) and 140 ng m^{-3} (particulate BDE-209) were detected in 14 Chinese air samples of a wide spectrum of locations, pointing out the high relevance of inhalative human uptake in China (Li et al. 2015a). Here, the daily human uptake of BDE-209 was calculated as 570 ng d^{-1} (food), 3000 ng d^{-1} (respiration), and 69 ng d^{-1} (dust uptake), i.e. 84% of the daily uptake takes place by gaseous and particulate PBDE uptake, but is clearly dominated by particulate uptake (Fraser et al. 2009; Johnson-Restrepo and Kannan 2009; Klinčić et al. 2020; Lorber 2008; Schecter et al. 2006; Stapleton et al. 2008; Wu et al. 2007). At a ratio of 16%, uptake by food is the second dominant pathway.

At lower ambient PBDE levels dietary intake gets the dominant pathway, especially in case of high lipid content (European Food Safety Authority EFSA 2011; Martellini et al. 2016). Therefore, dietary intake is of high relevance for strategies in reduction of human PBDE uptake.

4 Detoxification mechanisms of PBDEs

4.1 Transformation of PBDE in soil and sediments

Transformation behavior of PBDEs in soil and sediments strongly depends on the degree of bromination and the concentration of oxygen, organic matter and microorganisms in these compartments as well. In general, low brominated compounds tend to be degraded under aerobic conditions, while high brominated compounds are mainly degraded under anaerobic conditions (Zhu et al. 2014c). This correlation was previously described in degradation of chlorinated compounds (Han et al. 2017; Pimviriyakul et al. 2020; Reineke et al. 2002). PBDEs are either mineralized by stepwise debromination or detoxified by hydroxylation or methoxylation reactions in the rhizosphere. Hence, Han et al. (2017) observed the formation of hydroxylated (OH-PBDE) and methoxylated (MeO-PBDE) transformation products of BDE-209 and other PBDEs in soil samples under aerobic conditions at levels of 1–22 ng g^{-1} DM ($\sum$OH-PBDE) and 0.04–0.3 ng g^{-1} DM ($\sum$MeO-PBDE). Hydroxylated transformation products were also observed for hydrophilic PBDEs like BDE-3 (Yao et al. 2020) or BDE-47 (Wang et al. 2019a).

Bacterial debromination of PBDEs in soil and sediments was shown by different authors (Chen et al. 2015, 2017; Farzana et al. 2019b; Hale et al. 2012; Wang et al. 2020; Zhao et al. 2017b; Zhu et al. 2014b, c). Transformation intermediates of BDE-153 (Br_6) were analyzed by Zhu et al. in eight different sediments revealing formation of lower brominated transformation products (Br_1–Br_6) under anaerobic conditions and, contrarily, negligible transformation under aerobic conditions (Zhu et al. 2014b). A second study by these authors focusing on BDE-47 and BDE-209 quantified conversion rates as 92–93.4% (BDE-47) and less than 5% (BDE-209) under anaerobic conditions at initial concentrations of 5000 ng g^{-1} DM, underlining the poor biodegradability of high brominated BDEs (Zhu et al. 2014c). Nevertheless, bacterial species of the genera *Achromobacter, Burkholderia, Dehalobacter, Dehalococcoides, Dehalogenimonas, Geobacter, Microbacterium, Rhodococcus, Sphingomonas*, and *Sulfurospirillum* are known for PBDE degradation potentials (Chen et al. 2015, 2017; Deng et al. 2016; Wang et al. 2019a; Yu et al. 2020; Zhu et al. 2014b).

4.2 Transformation of PBDE in the gas phase

Transformation of PBDEs by atmospheric reactions was also observed by multiple authors. Exemplarily, Ueno et al. detected OH-PBDEs in different Canadian abiotic surface waters, fresh snow and rainfall samples (Ueno et al. 2008). The authors suggested photolytic transformation of atmospheric PBDEs (gaseous and particulate) to their corresponding OH-PBDEs and subsequent transformations to lower brominated congeners. Kuch et al. (2005) observed the ring closure to the corresponding dibenzofurans and hydrodebromination to less brominated transformation products as the dominant reactions during UV exposure of PBDEs.

4.3 Transformation of PBDE in plants

Intrinsic PBDEs can be transformed by debromination, hydroxylation and methoxylation reactions mainly in the shoots of the plants as well, similar to microbial transformation reactions in soil and sediments. In the study of Huang et al. (2010) 19 different plants were initially spiked with BDE-209 via the soil phase. As transformation products lower brominated BDEs (Br_2–Br_9) and five different OH-BDEs/MeO-BDEs were detected in the plant tissue. However, the concentration of microorganisms in the soil phase increased in parallel, particularly complicating the interpretation of the results. The ratio of Br_2-BDEs up to Br_5-BDEs in the plant tissue was elevated in comparison to the soil (7.3–21.1% vs. 6.5–12.2%), and hydroxylation/methoxylation products were solely detected in the plant tissues, from which the authors concluded that, besides soil based microbial debromination reactions, an additional transformative turnover of PBDEs in the plant tissue took place. Further studies showed similar interpretations (Deng et al. 2016; Hu et al. 2020; Xu et al. 2016). This conclusion was also verified by Wang et al. (2012) focusing on transformation of BDE-28 and BDE-47 in maize. Potential microbial as well as adsorptive aspects were excluded by hydroponic cultivation. Under these conditions, BDE-47 (Br_4) was transformed in the root phase dominantly to 6-MeO-BDE-47 (275 ng g^{-1} DM), followed by 5-MeO-BDE-47 (40 ng g^{-1} DM), $\sum Br_2$-BDEs (23 ng g^{-1} DM), $\sum Br_3$-BDEs (20 ng g^{-1} DM), and minor amounts of two unknown hydroxylated BDEs (8 ng g^{-1} DM) during the first 48–96 h after exposure. However, the total content of PBDEs and brominated intermediates was lower than the initial concentration by a factor of 2–3 and further declined with experimental progress, i.e. BDE-47 was mineralized. Similar results were also observed for BDE-28 (Br_3). Thus, the parallel presence of debromination, hydroxylation and methoxylation was demonstrated. Furthermore, these reactions mainly took place in the plants' stems and shoots and were of minor relevance in the root fraction. Similar conclusions were also drawn by Pan et al. (Pan et al. 2016) for transformation of BDE-99 in rice, wheat, and soy plants in hydroponic cultivation, where O-methylation was again the dominant transformation mechanism. The level of the reverse reaction of x-MeO-BDE-99 to x-HO-BDE-99 (x = 5, 6) was 1–2 log units lower.

Debromination behavior of PBDEs in plants and quantification of corresponding congeners as intermediates were particularly demonstrated by She et al. (2013) for rice (conversion of BDE-209), by Zhao et al. (2012) for maize (conversion of BDE-28, BDE-47, and BDE-99) and for *Scirpus validus* by Zhao et al. (2017b). The detected intermediates represented only a minority of the initial PBDE levels. Thus, supported by microbial biotransformation processes, PBDEs were mainly mineralized.

In contrast, various studies showed almost unchanged concentrations of PBDEs over the total test period or comparable PBDE patterns both in soil and plant tissues due to negligible or low metabolism of PBDEs in soil and roots (Venkatesan and Halden 2014; Yang et al. 2008). In agreement with the former issues, Chen et al. postulated the high relevance of the established rhizosphere in degradation of PBDEs (Chen et al. 2015).

In summary, PBDEs in plants are transformed by debromination, hydroxylation and methoxylation reactions. However, plant uptake and transformation behavior strongly depend on the plant species and the established microbial consortium in the rhizosphere.

5 Soil–root transport: RCF and TF value

5.1 RCF value of PBDEs

Besides the atmospheric pathway, uptake of low brominated and, thus, hydrophilic PBDE congeners may also take place by the soil–soil moisture–root pathway. This pathway was exemplarily proven by Zhao et al. in maize (2012), where a clear concentration gradient of low brominated PBDEs was observed over the height of the plant. Contrarily, high brominated PBDE show low mobility in root based PBDE uptake due to the high lipophilicity of these compounds. The mobility as core aspect of PBDE plant uptake was clearly shown by Freudenschuß et al.

(2008) and Cheng et al. (2014) in soil samples, where concentration of low brominated congeners increased by soil depth, but decreased in case of high brominated compounds.

Even more, high brominated PBDEs are strongly adsorbed to soil particles or the outer root phase. In case of BDE-209 only 0.3–0.5% of the concentration present in soil is available to plants (Wu et al. 2018b). Hence, this pathway is of low relevance but still present as shown by BDE-209 levels 3.5–6 times higher in living roots of different plants than in non-living samples (Chow et al. 2017) or by small-scale soil based BDE gradients within the root zone (Száková et al. 2019). BDE-209 uptake by roots even might be the dominant pathway at high soil contamination levels or hydroponic cultivation (Zhang et al. 2015). This statement was clearly evidenced by greenhouse experiments of Huang et al. (Huang et al. 2010). Here, BDE-209 levels of plants were examined during parallel cultivation in either non-contaminated or contaminated soil. Levels reached 5.2–10.4 ng g DM^{-1} of BDE-209 in six different plant species cultivated in non-contaminated soil, which was less than 5% of the BDE-209 concentrations detected in the same species cultivated under contaminated conditions, i.e. more than 95% of BDE-209 contamination in plants could be attributed to plant uptake and intrinsic plant transport. Both processes were shown to be coupled to plant transpiration by Zhao et al. (2012). Hot as well as dry weather conditions, which increase plant transpiration, may thus be connected to elevated PBDE levels in shoots and leaves of the plants.

To increase comparability of PBDE uptake and intrinsic transport, both the root concentration factor (RCF) and the translocation factor (TF) were introduced in literature and correlated to the log K_{OW} value of PBDEs. As a conclusion and in difference to PCBs, there is a strong negative correlation of the log K_{OW} value and the RCF, i.e. higher RCF values were detected in case of lower brominated PBDEs and, therefore, compounds with lower log K_{OW} values than in case of higher log K_{OW} values (Zhang et al. 2015). In detail, the plant specific RCF of BDE-209 was up to ten times lower than the RCF of BDE-28 (Han et al. 2017; She et al. 2013; Zhang et al. 2015). This effect may be explained both by the lack of water solubility and, therefore, restricted root uptake with the soil moisture phase, and the strong adsorption of higher brominated PBDE on the soil phase. Furthermore, a serious inhibition of PBDE uptake was observed in case of high concentration levels (Pier et al. 2002).

In difference, a positive correlation of the log K_{ow} value with both the RCF and the TF was observed for maize with increasing height of the plants solely in case of the low brominated BDE-15, BDE-28, and BDE-47 (Wang et al. 2011c; Zhao et al. 2012). This effect was explained by PBDE concentrating caused by plant transpiration and, therefore, increasing water losses in the shoots of the plants.

5.2 RCF value of plants for bioremediation

The plant ability of PBDE accumulation at high RCFs is technically used in phytoremediation processes. Radish, green squash, and *S. validus* were previously described in PBDE phytoremediation of Br_5-BDEs (radish, green squash) and Br_4-BDEs to Br_7-BDEs (*S. validus*) at RCFs of even 1 or higher. RCFs of nearly 0.1 were achieved in case of lipophilic BDE-206 and BDE-207 in this study (Zhao et al. 2017b). High phytoremediation potentials, further enhanced by inoculation of the rhizosphere with *Bacillus cereus* JP12, were also described for *Sedum alfredii* as a herb, and for *Festuca arundinacea* as a grass (Lu and Zhang 2014). Initial concentrations of 4870 ng g^{-1} DM of BDE-209 were diminished by a factor of 15 reaching final levels of 320 ng g^{-1} DM within 120 days. In general, with exception of these plants for phytoremediation, RCFs of clearly less than 1 and a negative correlation of RCF and log K_{OW} values might be expected.

5.3 Effect of solubilizers

Plant availability and, therefore, plant uptake of adsorbed PBDEs might be enhanced in presence of native plant extracts or by injection of artificial solubilizers into the soil phase. Solubilization efficiencies of BDE-209 by different solubilizers were analyzed by Zhao et al. (2017a). Here, the cationic solubility promotor cetyltrimethylammonium bromide (CTAB), sodium dodecyl sulfate (SDS) as anionic solubility promotor, and both Tween 80 and β-cyclodextrin as non-ionic solubilizers were tested either as sole compounds or in mixture with each other. While the addition of the solubilizers did not lead to negative effects on plant growth, enhanced plant uptake of BDE-209 was only observed in case of CTAB, SDS, or Tween 80, but not for β-cyclodextrin. This finding is contradicted by the study of Li et al. (2018a), which investigated the elimination of BDE-209 by planting amaranth (*Amaranthus hypochondriacus*) with the optional additional inoculation of the soil samples with a mycelium or 0–1.2 w% of β-cyclodextrin. While the BDE-209 levels in the control sample solely planted with amaranth smoothly declined from 2200 ng g^{-1} DM to 2100 ng g^{-1} DM during the test period, elimination was enhanced by application of the mycelium (1600 ng g^{-1} DM) and also boosted in presence of β-cyclodextrin (750 ng g^{-1} DM). Similar results were reported by Li et al. (2018b) in case of BDE-209 soil contaminations with *Solanum nigrum* as planting and optional application of mycorrhizal fungi *Funneliformis mosseae* or *Rhizophagus intraradices*, where initial BDE-209 levels (4750 ng g^{-1} DM) strongly declined to final levels of 2250 ng g^{-1} DM during operation time.

The same tendency—but with clearly more relevance for practice—was reflected by a study of Li et al. (2019c) that examined the effect of extracts from wheat straw or pig manure on BDE-47 uptake in wheat plants. Here, uptake increased by a factor of 3.1 (wheat straw) and 1.9 (pig manure). The addition of a solubilizer without pronounced surfactant properties that simply increases the organic content of the soil leads to a contrary effect. In this case an increased accumulation of PBDEs in the soil phase and a reduced plant uptake efficiency was observed (Cheng et al. 2014; Xiang et al. 2019b).

5.4 Additional parameter affecting the log K_{OW}–RCFs correlation

As listed before, both positive and negative correlations between log K_{OW} and RCFs were observed. Potential explanatory approaches therefore refer to plant species specifics during accumulation and translocation of PBDEs, to differences in physical and chemical soil properties (see Sect. 6), variations of several orders of magnitude in pollutant concentrations, and the simultaneous, but hardly distinguishable, soil–air–plant uptake pathway. Especially the duration of the growth period of the cultivated plants (Gao et al. 2019; She et al. 2013) and the organic soil content (see Sects. 6, 7) showed considerable impact on PBDE uptake. Particularly high RCF levels up to 30,000 were observed in case of hydroponic cultivation approaches due to the high lipophilicity of the PBDEs and parallel absence of lipophilic soil matter (Pan et al. 2016).

5.5 TF values of PBDE

Following uptake, intrinsic PBDE transport via the plant specific water transport systems takes place. The concentration ratio of PBDE levels in the shoots to the levels in the roots is referred to as translocation factor (TF). A general statement about the correlation of log K_{OW} and TF values is not appropriate, since no clear positive or negative correlation was found. The TF value depends on species specifics, the lipid content of the shoots, the plant age, the distance of the plant tissue from the root plexus, as well as numerous other parameters, which are partly insufficiently determined. According to Zhang et al. the PBDE concentration in the soil phase is of particular relevance (Zhang et al. 2015). Examining rice plant samples, the authors observed a negative correlation of log K_{OW} and TF values at low concentration levels ($\sum$PBDE = 130 ng g^{-1} DM), but this correlation turned to positive in case of high PBDE levels ($\sum$PBDE = 2000 ng g^{-1} DM). A clear quantification of the TF values is further complicated by the simultaneous soil–air–plant exposure pathway, potentially falsifying the detected concentrations. In principle, a negative correlation may be assumed, i.e. with increasing degree of bromination and therefore increasing log K_{OW} values a decreasing mobility and thus an accumulation of PBDEs in the root area is expected. Hence, stem and shoots show significant lower contamination levels and relevance of atmospheric PBDE uptake significantly increases (Zhao et al. 2012). The bioaccumulation and translocation behavior of PBDEs in plants is not conclusively clarified and depends on numerous, partially insufficiently determined parameters.

In summary, it can be stated that RCF and TF values in plants—besides species specifics—depend on multiple parameters like organic content and heavy metal content in the soil. The effect of various soil parameters on PBDE uptake is examined in more detail in the following section. The phenotypic effect of uptake or translocation of PBDEs is often not yet understood, i.e. bioaccumulation and translocation behavior of

PBDEs in plants is not conclusively clarified and needs further investigations.

6 Factors of PBDE plant uptake

Various studies have looked at the physico-chemical properties of soils and the substance-specific properties of PBDEs with regard to plant uptake and biodegradation behavior. For dispersion, PBDE specifics (vapor pressure, K_{OW} value, air–water distribution K_{AW} value, air–plant distribution K_{AP} value), environmental factors (temperature, wind speed, amount of rain, temporal rain distribution, kinetics of gas deposition, kinetics of particle-bound deposition), plant properties (species, lipid content, leaf morphology, ratio of non-lipid plant parts, thickness of the bark, sugar content, fiber content), as well as the presence of an active rhizosphere are commonly of high relevance. For bioavailability and thus biodegradability of PBDEs pH value and soil composition are of particular importance (Yogui et al. 2011; Zhao et al. 2009; Zhu et al. 2015). In detail, relevant parameters are:

6.1 Excretion of plant solubilizers

In order to prevent potentially toxic or inhibitory accumulation of PBDEs, some plants pursue the strategy of excreting easily metabolizable intermediates as solubilizers into the rhizosphere that facilitate microbial biodegradation of PBDEs (Zhao et al. 2017b). According to the authors, such compounds could be amino acids, organic acids, sugars and exoenzymes to improve the bioavailability and thus the microbial degradability of BDE-209. However, the authors did not provide direct evidence for this hypothesis. The proof was finally provided by Farzana et al. (2019b), where addition of 620 mg L^{-1} of hexose both enhanced microbial debromination of BDE-99 to Br_2-BDEs and Br_3-BDEs in soil and uptake of PBDEs into *Kandelia obovate*.

6.2 Plant specifics

Behavior of PBDE plant uptake is fundamentally plant-specific and particularly defined by plant morphology. Exemplarily, Zhao et al. (2009) found that the wax layer of bay leaves leads to an increased uptake of both particulate-bound and gaseously transported PBDEs. A similar correlation between the age dependent lipid content of leaf and the atmospheric PBDE exposure was also established by Gao et al. (2019). Zhu et al (2020) quantified the accumulation of Br_3-BDEs to Br_{10}-BDEs in the wax layer of wheat to 29–93% of the total plant uptake.

In case of the soil–soil moisture–plant pathway a strong plant-specific accumulation of PBDEs in the plant tissue was observed by Huang et al. (2010). In pot experiments with six different plant species and an initial concentration of 4700 ng g^{-1} DM of BDE-209, soil levels declined by 12.1–38.5% after 60 days of cultivation, while plant levels specifically increased, i.e. PBDE levels reached 1822 ng $plant^{-1}$ as lowest level in alfalfa and 10,933 ng $plant^{-1}$ as the highest level in maize. Formation of plant eluates to enhance formation of the microbial microflora, biodegradation, as well as detoxification of PBDEs in the soil phase was postulated for single plant species by Wang et al. (2014).

6.3 Rhizosphere and mycorrhiza

The release of plant eluates is part of the symbiosis between the plant and the mycorrhizal fungi promoting the plant's uptake of nutrients and growth of microorganisms in the mycorrhizal area. The positive effects on biodegradation and detoxification were proven by Eggerstedt-Lehmann (2005) for petroleum-derived hydrocarbons and by Li et al. (2018a, b) for amaranth and black nightshade by application of mycorrhizal fungi *Funneliformis mosseae* or *Rhizophagus intraradices*. Compared to reference plants without fungi an increased depletion of 4750 ng g^{-1} DM to 2250 ng g^{-1} DM of BDE-209 was observed. Similar results were presented by Feng et al. (2019).

6.4 Specific root and leaf surface

The lipophilicity of PBDEs mainly evokes adsorption and accumulation of soil based PBDEs at the outer root surface. A potential connection between increased inner root accumulation of PBDEs and high specific root surface was postulated by Wang et al. (2014), but no final proof could be provided. The final evidence was provided for the radish *Raphanus sativus* L. by Yang et al. (2017) and for lettuce, radish and taro by Wang et al. (2016a, b) for BDE-209.

Additionally, this evidence was provided by Tian et al. (2012) for atmospheric transport and plant uptake by the leaf surface. Quantification of Br_2-BDE to Br_{10}-BDE in both pine needles and eucalyptus leaves and the dust particles adsorbed on them revealed $\sum$PBDE levels higher by a factor of 2.3 in the needles (148 ng g^{-1} DM) than the leaves (64.1 ng g^{-1} DM), even though both plants have comparable lipid contents in their foliage (pine: 82 mg g^{-1} DM; eucalyptus: 77 mg g^{-1} DM). However, this factor is reflected in the specific surface area of the foliage (pine: 17.2 m^2 kg^{-1}; eucalyptus: 5.8 m^2 kg^{-1}).

6.5 Lipid content

The lipid content of a plant, especially the root, has a strong impact on PBDE uptake characteristics and has been evaluated for various mosses and lichens as well as rice (Huang et al. 2010; She et al. 2013; Yogui et al. 2011). Huang et al. and recently Jian et al. (2020) found a direct correlation between the lipid content and both RCF value and TF value analyzing 6 and 11 plants of different lipid content, respectively (see Fig. 1), i.e. a higher lipid content leads to a lower intrinsic PBDE mobility and thus to a negative correlation with the TF value. According to additional atmospheric transport, Tian et al. pointed out the influence of the specific surface of the foliage (Tian et al. 2012).

6.6 Organic content of the soil

Similar to the lipid content of plants, increasing organic content of the soil evokes higher PBDE accumulation in the soil phase and thus reduced PBDE plant uptake (Cheng et al. 2014; Xiang et al. 2018; Zhao et al. 2017b; Zhu et al. 2014a, 2018). In case of sediments in mangroves, BDE-209 reached levels of 25 ng g^{-1} DM and 200 ng g^{-1} DM in the sediments at 7% and 20% of organic content, respectively (Zhu et al. 2014a). Similar results were observed for BDE-47 by Xiang et al. (2018, 2019a), where plant uptake in carrots was reduced by 31.5–69.8% by addition of 1–4 w% of swine manure to the soil fraction. Compared to the initial soil concentration of 384.5 ng g^{-1} DM the final BDE-47 level in soil without addition of organic matter was 121.1 ng g^{-1} DM and was increased to 268.4 ng g^{-1} DM at a 4% pig manure content. In parallel, PBDE biodegradation in soil increased by 8.6–28.5% (Xiang et al. 2018). Finally, Cheng et al. (2014) differentiated between TOC and DOC content and observed a clear improvement in adsorption of PBDEs in the soil matrix at higher TOC levels, whereas no effect was detected when increasing DOC levels. Due to enhanced biodegradation of PBDEs as co-substrate in the soil phase, both lower brominated congeners and lower total concentrations are therefore absorbed by the plants (Zhao et al. 2017b). This result was again validated for hydrophilic BDE-47 in presence of formiate, acetate, lactate, succinate, pyruvate, methanol or ethanol (Pan et al. 2020) and for hydrophilic BDE-209 after addition of pyrene (Li et al. 2020b).

6.7 Biochar

The admixture of pure or metal doped biochar to the soil phase strongly increased TOC levels and therefore affected PBDE uptake as investigated for Pak Choi (*Brassica chinensis*) by Wu et al. (2018a). BDE-209 and $\sum$PBDE plant uptake were reduced by 240–270 ng g^{-1} DM or a factor of 2.5–2.7. In contrast, both adsorption and plant uptake of BDE-153 were slightly increased by 5% in hydroponic culture (Jia et al. 2019), but this effect may have been caused by the high moisture content of the biochar.

6.8 Sewage sludge

In addition to liquid manure as agricultural fertilizer, the land application of sewage sludge is an important disposal method worldwide and allows substitution of mineral fertilizers. As sewage sludge reveals a high TOC content and enhanced contaminations with PBDEs or their detoxification and degradation products (Vrkoslavová et al. 2010), sewage sludge is a dominant exposure pathway. Until 2001, the annual environmental PBDE input in the USA was quantified as 47.9–60.1 tons, where 24.0–36.0 tons were associated with sewage sludge disposal (Venkatesan and Halden 2014). Hence, soil concentration levels and plant uptake of especially lipophilic PBDEs like BDE-209 considerably increased in the range of 840–3900 ng g^{-1} DM $\sum$PBDE during sewage sludge application (Huang et al. 2010; Law et al. 2006; Sellström et al. 2005). Corresponding soil levels after sewage sludge disposal reached more than

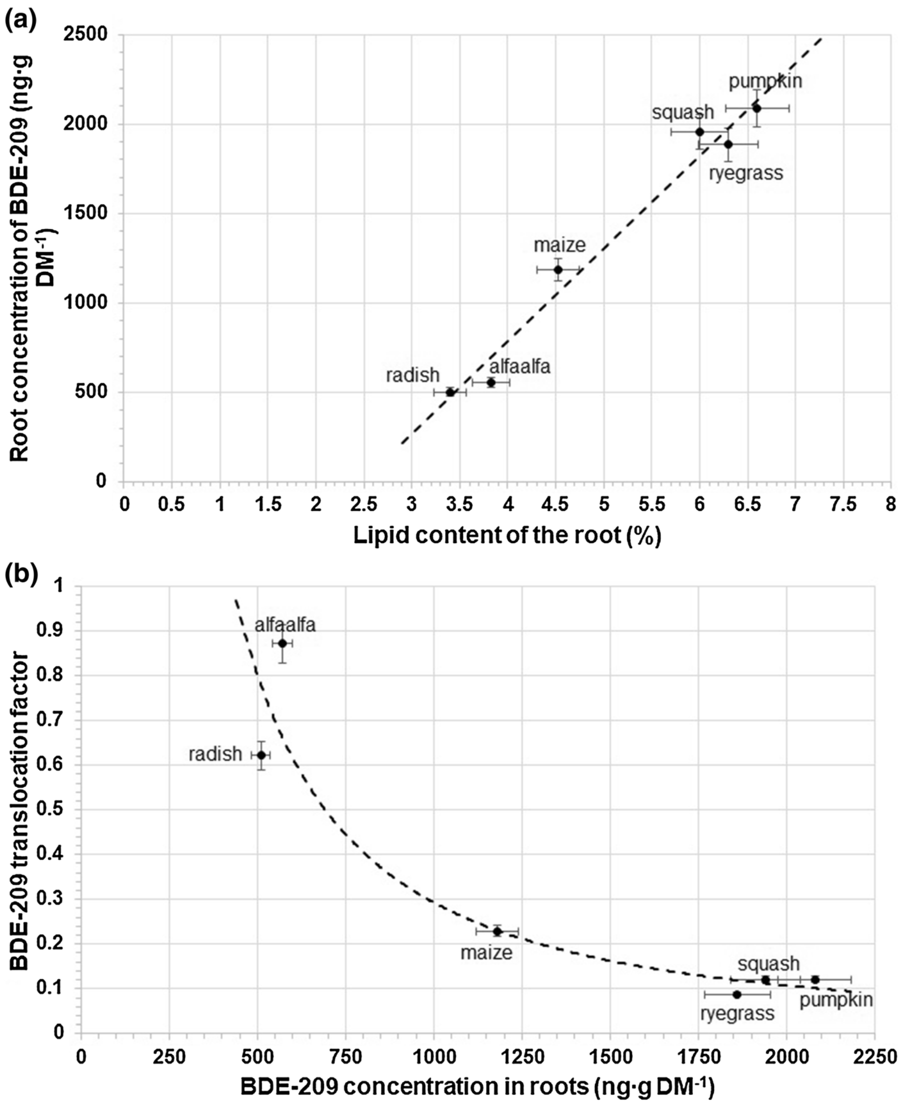

Fig. 1 **a** Correlation of BDE-209 concentration in roots and corresponding root lipid content (based on Huang et al. 2010). **b** Correlation of translocation factors and BDE-209 concentration in roots (based on Huang et al. 2010)

20,000 ng g^{-1} DM $\sum$PBDE considering pre-contamination of the soil. Increases by 568 ng g^{-1} DM and 400 ng g^{-1} DM were observed for $\sum Br_5$-BDE and BDE-209 in another study (Vrkoslavová et al. 2010). Published PBDE levels in different sewage sludge samples are summarized in Table 1. Similar to lipid levels, a negative correlation between BDE-209 uptake and organic content, implemented by sewage sludge output, was observed (Li et al. 2015b). Moreover, BDE-209 soil levels declined by less than 5% during a 3-year test period as shown in Fig. 2 (Venkatesan and Halden 2014; Zhu et al. 2014c).

6.9 Compost and digestate

In addition to sewage sludge and liquid manure, compost and digestate are important materials for soil improvement. Due to the relatively low TF values and preceding RCF values of the plant educts (leaves, green waste, fruit and food residues), the PBDE load of compost and digestates is rather low as confirmed by various studies. In composts of Bavaria, Sweden and Switzerland median PBDE concentrations of 12 ng g^{-1} DM, 2–21.6 ng g^{-1} DM and 10 ng g^{-1} DM were measured, respectively (Amundsen et al.

Table 1 PBDE levels in sewage sludge samples in ng g^{-1} DM

Location	No. of sites	BDE	Sludge type	Concentration	Source
Northeast America	48	$\sum Br_5$	Excess sludge	Up to 1530	Hale et al. (2012)
Western America	No data	$\sum Br_5$	Excess sludge	Up to 2120	Hale et al. (2012)
Hesse	15	∑PBDE	Activated sludge	85.5–5856	Leisewitz et al. (2003)
Hesse	15	∑PBDE	Excess sludge	140.84–14,816	Leisewitz et al. (2003)
USA	110	∑PBDE	Excess sludge	Up to 9400[a]	Venkatesan and Halden (2014)
		BDE-206		Up to 4350	
		BDE-207		Up to 3530	
		BDE-209		Up to 17,100	
		Ø BDE-209		5360	
Turkey	4	∑PBDE	Dewatered sludge sample	$44.0–2.46 \times 10^7$	Demirtepe and Imamoglu (2019)
		BDE-209		$66.9–2.46 \times 10^7$	
Baden-Wuerttemberg	22	∑PBDE	Dewatered sludge sample	77.7–338.4	Kuch et al. (2001)

[a] Based on average values

2005; Brändli 2006; Marb et al. 2003). A broadly based study of biocompost, green waste compost and digestates in Baden-Wuerttemberg showed comparable median concentrations of 13 ng g^{-1} DM, 5.4 ng g^{-1} DM, and 13.7 ng g^{-1} DM and confirmed the low relevance of both materials as PBDE source (Kuch et al. 2007).

6.10 Soil humidity

Due to the lipophilic character of PBDEs, soil moisture also plays an important role in the plant uptake or atmospheric losses of PBDEs. High soil moisture effectively prevents evaporation of BDEs as well as plant uptake (Wu et al. 2018a). Correspondingly, a longer PBDE load may be expected at wet locations.

6.11 Plastic particles

The partition coefficients of PBDEs towards various plastics are several orders of magnitude higher than those towards sewage sludge or soil (Teuten et al. 2007). Therefore, the hypothetical potential of soil remediation by injection of plastic particles was positively investigated. Due to the lack in biodegradability and spread of microplastics, however, this approach is not applicable.

6.12 Other additives

Additional additives like graphene, TiO_2, Al_2O_3, Ag, and carbon nanotubes were considered as relevant for BDE-209 uptake in spinach, pumpkin, cucumber, corn and water spinach by Wu et al. (2018b). Indeed, an increased plant uptake was observed for all of these additives. Despite the desorbing effect of these additives in soil, the bioavailability of BDE-209 in aqueous phase was between 0.3 and 0.5% of the initial concentration, i.e. 99.5–99.7% of the BDE concentration remained adsorbed to the soil matrix or external plant tissues.

Uptake of BDE-153 by lettuce in presence of the borosilicate mineral tourmaline and soluble humic acids was tested by Wang et al. (2017). In both cases an increased accumulation in both roots and shoots was observed. Whether this effect also occurs in other crops is still unclear. In case of the humic acids, a weak surfactant effect was expected due to their structure. A combination of bentonite and sodium persulfate as oxidizing agent was tested regarding to the bioavailability and eliminability of a mixture of 10 PBDEs (Br_3–Br_{10}) in soil. While bentonite proved to be particularly positive in immobilization of heavy metals as co-contamination, sodium persulphate enhanced bioavailability of PBDEs by in-situ oxidation. Negatively, bacterial density was sharply reduced with a recovery over 90 days (Ma et al. 2020).

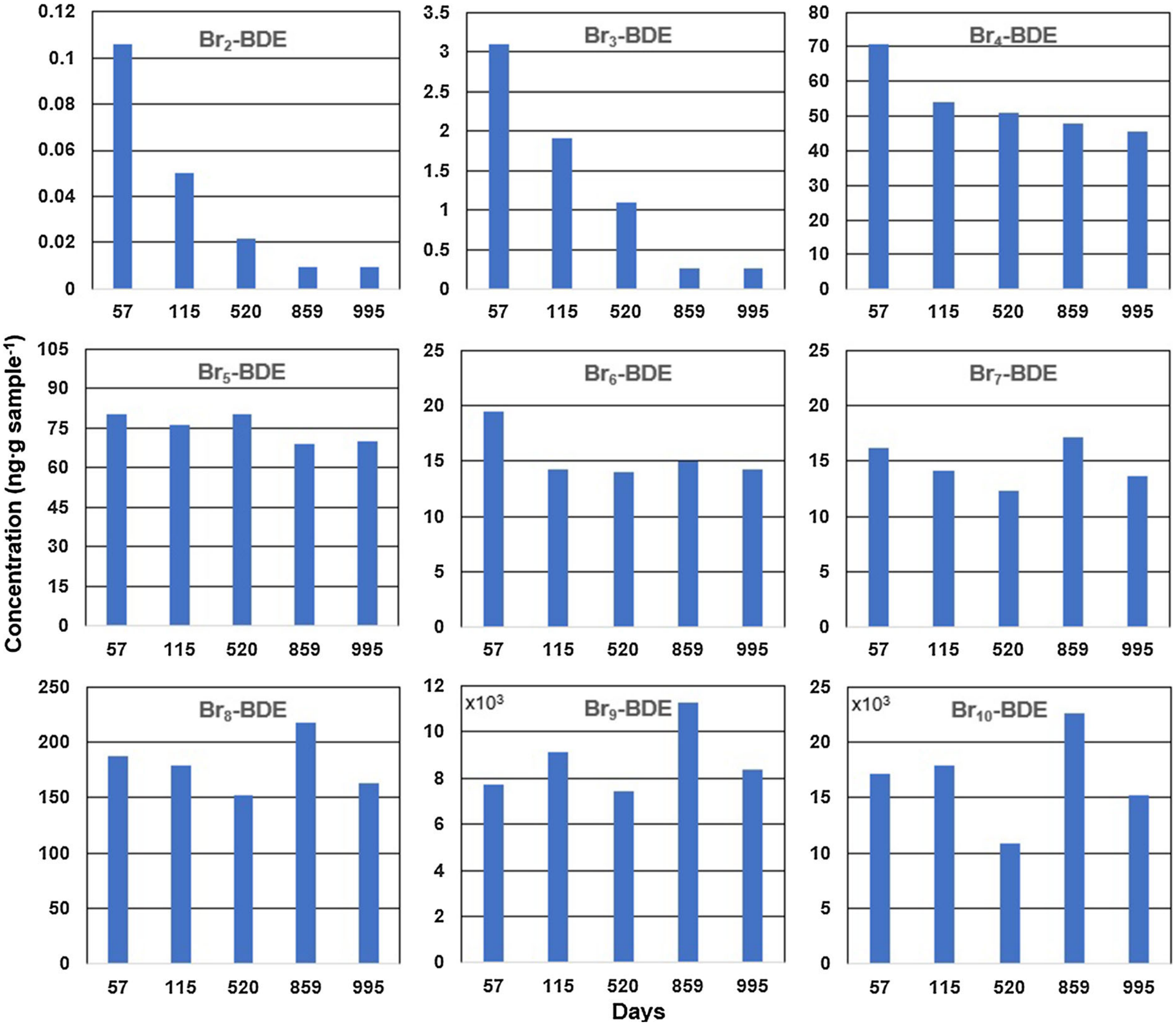

Fig. 2 Concentration of BDEs in sewage sludge/soil mixtures over 3 years after fertilization measure (based on Venkatesan and Halden 2014; simplified)

6.13 Solubilizers

The addition of surfactant-active additives leads to a reduction in the binding strength of highly halogenated PBDEs in particular to the soil matrix or the outer plant tissue, whereby both mobility of PBDEs in soil matrix and plant uptake are enhanced. While this is a desirable effect for phytoremediation, this approach is not applicable to plants for food production. For details on the use of solubilizers see Sect. 5.3 and Binelli et al. (2007).

6.14 Macro- and trace elements

Macro- und trace elements appear to be essential for the development of the microflora in the rhizosphere as well as for plant growth, but further differentiation is required in case of elimination and uptake of PBDEs.

In case of nitrate as additive an intensified desorption and biodegradation of BDE-99 was observed (Yan et al. 2017). Starting from an initial concentration of 770 ng g DM^{-1} BDE-99, turnovers of BDE-99 and corresponding intermediates increased by 66% and 63% since nitrate appears to be an alternative electron acceptor increasing microbial turnover in the soil phase. Hence, a residual concentration of 310 instead of 710 ng g DM^{-1} BDE-99 was determined.

In contrast to the expectation of a positive effect of an adequate trace element supply on microflora and microbial biodegradation behavior of PBDEs, Zhu et al. (2018) observed neither a positive nor a negative influence on PBDE uptake or PBDE degradation in plants affected by various macro- and trace elements (Si, Ca, Fe, Al, S, K, Ti, P, Mg, Na, Mn, Zn, Cl, As, Cu, Cr, Ni). As expected, microbial inhibition of BDE mineralization occurred at higher concentrations of trace elements, i.e.—30% for BDE-3 at 400 mg Cu kg DM^{-1} (Yao et al. 2020). For the sake of completeness, it should be noted that to date the potentially positive influence of trace elements on the microbial turnover of PBDEs was not addressed in a scientific study and therefore awaits final evaluation.

6.15 Heavy metals

In comparison to reference soil, Wu et al. (2018a) described a reduction in plant uptake of BDE-209 by almost 20% in pot cultures with Pak Choi plants (*Brassica chinensis*) in presence of Ni/Fe nanoparticles, whereas the uptake of $\sum$PBDEs increased by approx. 85% in the opposite direction. The iron content of the soil was increased from approx. 120 mg kg DM^{-1} to approx. 350 mg kg DM^{-1} by addition of these particles, while the nickel content was not quantified. The higher PBDE uptake was justified by chemical debromination of BDE-209 and enhanced mobilization, uptake and transport of Br_8- to Br_{10}-BDEs in the roots and shoots of the plants. This changed uptake behavior was also reflected in a higher translocation factor of 4.2 compared to < 0.02 for Br_8-BDEs. This result should be critically appraised due to a drop of translocation factors of Br_9-BDEs, BDE-209 and $\sum$PBDE by 60%, 45% and 75%, respectively. In contrast, BDE-47 plant uptake was positively influenced by iron addition as described by Pi et al. (plant uptake: 24.76% instead of less than 1.5%) (Pi et al. 2017).

Unlike the addition of iron, Lu et al. (2013) observed a reduction of BDE-209 uptake up to 50% by pumpkins (1180 ng g DM^{-1} vs. 2370 ng g DM^{-1} in roots) after addition of 300 mg Cu kg DM^{-1} to the soil. At further increasing levels inhibitory effects on microbial mineralization of PBDEs in soil were observed (Yao et al. 2020). At levels up to 1950 mg Pb kg DM^{-1} plant uptake of BDE-209 was reduced by a factor of 2.9–3.7 by tall fescue (*Festuca arundinaceae;* Chen et al. 2019). While no effect on BDE-209 uptake was observed for black nightshade at cadmium levels up to 14,800 ng g DM^{-1} (Li et al. 2018b), enhanced BDE-209 uptake was shown for amaranth (*Amaranthus hypochondriacus* L.; Li et al. 2020a).

In summary, a positive effect seems to result from the presence of essential heavy metals such as iron and copper at adequate concentrations, while non-essential heavy metals at non-toxic levels seem to have no effect on PBDE degradation. A direct effect on PBDE uptake into the plant is also not expected due to the ionic character of the heavy metals as opposed to the highly lipophilic PBDEs.

7 Predictive mathematical models

Due to the broad spectrum of plants used for food production, phytoremediation and eco-indication, efforts are being made to develop sensitive predictive models based on simple chemical conditions and input variables in order to be able to determine the exposure of potential food plants in advance. These mathematical models require input parameters like distribution equilibria, fat content, organic matter and soil–water concentration, PBDE concentration to varying degrees for a predictive statement about the RCF value, SCF value (shoot concentration factor) or the TF value.

Exemplarily, the model of Li et al. (2019b) allows a prediction of the RCF and the SCF based on the input parameter log K_{OW} and lipid content. The derived linear equation defined for the RCF value enable a good correlation between the modelled and the detected values, but did not differentiate intrinsic against externally adsorbed PBDE. Moreover, the model strongly failed in prediction of the SCF values that deviate by up to 2 decades from the real situation. A similar range was also reported by Collins et al. (2010). Even though dealing with the insecticide chlorpyrifos, the model of Hwang et al. (2017) showed a deviation of 25.3–58.2% for chlorpyrifos in case of lettuce, although the model is greatly simplified by the choice of the plant, as there is no need to differentiate between TF and SCR values.

Briggs et al. (1982) showed a significant decrease in BCF levels and thus RCF values of PBDEs starting at a log K_{OW} value of approx. 6.5 (corresponds to a log BCF value of approx. 4.6 or a molar mass of approx. 500–600 Da) after elimination of externally adsorbed congeners (see Fig. 3). This chart corresponds to Bintein's bilinear model (Bintein et al. 1993), which was confirmed by Meylan et al. (1999) for 610 non-ionic pollutants. This negative correlation at high log K_{OW} values and thus high lipophilicity bases on three restrictions of lipophilic compounds as follows:

1. *Kinetic of the state of equilibrium* The higher the lipophilicity of a pollutant, the longer it takes to achieve the state of equilibrium between two phases or compartments. The life span of annual crops might be too short to establish an equilibrium between soil and root or root and shoot (Nendza 1991).
2. *Solubility* Water solubility decreases by increasing lipophilicity and highly lipophilic substances preferentially adsorb on particles or surfaces. For absorptive root uptake of contaminants, however, both phase transition from soil to liquid phase and from liquid to intrinsic roots without adsorptive elimination on the tissue is required (Briggs et al. 1982; Nendza 1991).
3. *Membrane permeability and cellular transport mechanisms* The cellular uptake of pollutants through the cell membrane takes place by passive permeation (Briggs et al. 1982). The membrane permeability and thus bioavailability of contaminants is concisely described by Lipinski´s 'Law of 5', stating out low absorption or membrane permeability at:

   (a) log K_{OW} value > 5
   (b) molar mass > 500
   (c) more than 5 hydrogen bond donors (well represented by the sum of OH and NH bonds)
   (d) more than 10 ($= 2 \cdot 5$) hydrogen bond acceptors (simplified assumed by the sum of Ns and Os in the molecule).

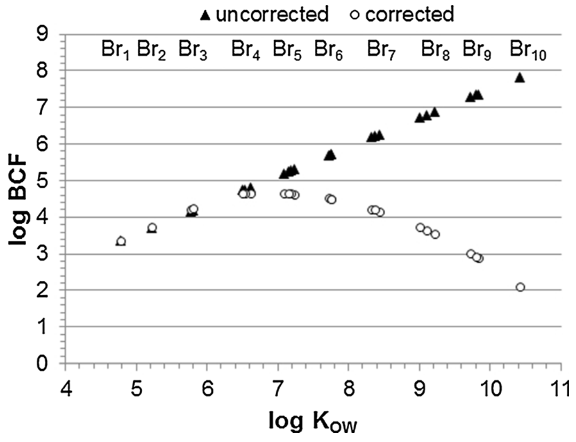

Fig. 3 Correlation of log K_{OW} and log BCF of 25 environmental relevant BDEs (− 3, − 7, − 17, − 28, − 30, − 47, − 49, − 66, − 85, − 99, − 100, − 123, − 153, − 154, − 155, − 183, − 184, − 191, − 197, − 201, − 202, − 206, − 207, − 208, − 209) using simple mathematical models with/without correction

In fact, requirements (a) and (b) are fulfilled in case of the PBDE correlation, where (b) is already met in case of Br_4- to Br_5-BDEs. However, Yan et al. points out that permeability of contaminants might be affected by co-transport phenomena of biomolecules like amino acids (Yang and Hinner 2015).

Taking plant-specific uptake characteristics of individual BDEs into account, critical analysis of the data of Sect. 8 reveals maximum RCF values for technical and economical relevant BDE-47 and BDE-99, but RCF values drop again at higher molar masses. In contrast, RCF levels of the isomer BDE-100 are consistently 2–40 times lower than those of BDE-99, which could be explained by a slightly lower log K_{OW} value of BDE-100 (7.08 vs. 7.18). The generally higher contamination of plants by BDE-209 than by the two former BDE congeners is caused by up to two decades higher soil contamination levels of BDE-209.

A critical evaluation of the literature data of Sect. 8, taking into account plant-specific uptake characteristics for individual BDEs, shows that a maximum RCF value actually occurs for the comparatively frequently analysed BDE-47 and BDE-99, which drops again at higher molar masses. In contrast, RCF values for the congener BDE-100 are consistently 2–40 times lower than those for BDE-99 despite the same molar mass, which can be explained by a slightly lower log KOW value (7.08 vs. 7.18). The generally higher exposure of plants to BDE-209 in absolute concentrations than to the two BDE congeners formerly mentioned is due to the up to 2 decades higher soil contamination with BDE-209.

A comparable correlation between log K_{OW} and TF value was observed for the comparatively polar pollutant classes of *O*-methylcarbamoyloximes and

Table 2 Lichens, mosses, grasses, herbs and flowers

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Lichens								
Lichens (*Usnea antarctica*)	BDE-15, -28, -47, -99, -100	–	–	192–220	–	–	–	Yogui et al. (2011)
Lichens (*Usnea aurantiacoatra*)		–	–	139–262	–	–	–	
Lichens (*Xanthoria parietina*)	BDE-17	–	–	0.003–0.015	–	–	–	Vitali et al. (2019)
	BDE-28	–	–	0.004–0.015	–	–	–	
	BDE-47	–	–	0.033–0.176	–	–	–	
	BDE-49	–	–	0.007–0.021	–	–	–	
	BDE-66	–	–	0.005–0.017	–	–	–	
	BDE-71	–	–	0.001–0.013	–	–	–	
	BDE-77	–	–	0.004–0.012	–	–	–	
	BDE-85	–	–	0.002–0.021	–	–	–	
	BDE-99	–	–	0.032–0.181	–	–	–	
	BDE-100	–	–	0.011–0.056	–	–	–	
	BDE-119	–	–	0.001–0.012	–	–	–	
	BDE-138	–	–	0.002–0.014	–	–	–	
	BDE-153	–	–	0.014–0.034	–	–	–	
	BDE-154	–	–	0.008–0.023	–	–	–	
	BDE-156	–	–	0.001–0.011	–	–	–	
Mosses								
Sickle moss (*Sanionia uncinata*)	BDE-15, -28, -47, -99, -100	–	–	818–1022	–	–	–	Yogui et al. (2011)
Tortula moss (*Syntrichia princeps*)		–	–	718	–	–	–	
Moss (*Brachythecium* sp.)		–	–	276	–	–	–	
Stringy moss (*Drepanocladus aduncus*)	ΣPBDE	0.00–0.42	–	0.04–0.5	–	26.2	–	Zhu et al. (2015)
Red-stemmed feathermoss (*Pleurozium schreberi*)	BDE-28	–	–	0.003–0.053	–	–	–	Kosior et al. (2015)
	BDE-47	–	–	0.058–0.273	–	–	–	
	BDE-66	–	–	0.005–0.128	–	–	–	
	BDE-85	–	–	0.001–0.017	–	–	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-99	–	–	0.048–0.496	–	–	–	
	BDE-100	–	–	0.011–0.089	–	–	–	
	BDE-153	–	–	0.009–0.187	–	–	–	
	BDE-154	–	–	0.008–0.059	–	–	–	
	BDE-183	–	–	0.013–1.134	–	–	–	
	BDE-209	–	–	0.992–148.2	–	–	–	
	∑PBDE	–	–	1.3–149.8	–	–	–	
Red-stemmed feathermoss (*Pleurozium schreberi,* after 90 days, non-contaminated site)	BDE-28	–	–	0.004–0.030	–	–	–	Kosior et al. (2017)
	BDE-47	–	–	0.041–0.340	–	–	–	
	BDE-66	–	–	0.022–0.151	–	–	–	
	BDE-85	–	–	0.007–0.090	–	–	–	
	BDE-99	–	–	0.034–0.416	–	–	–	
	BDE-100	–	–	0.017–0.099	–	–	–	
	BDE-153	–	–	0.013–0.090	–	–	–	
	BDE-154	–	–	0.014–0.098	–	–	–	
	BDE-183	–	–	0.035–0.308	–	–	–	
	BDE-209	–	–	1.59–13.8	–	–	–	
	ΣPBDE	–	–	1.87–15.4	–	–	–	
Red-stemmed feathermoss (*Pleurozium schreberi,* after 90 days, contaminated site)	BDE-28	–	–	0.005–0.092	–	–	–	Kosior et al. (2017)
	BDE-47	–	–	0.051–0.582	–	–	–	
	BDE-66	–	–	0.019–0.255	–	–	–	
	BDE-85	–	–	0.010–0.128	–	–	–	
	BDE-99	–	–	0.040–0.585	–	–	–	
	BDE-100	–	–	0.019–0.284	–	–	–	
	BDE-153	–	–	0.015–0.249	–	–	–	
	BDE-154	–	–	0.026–0.429	–	–	–	
	BDE-183	–	–	0.042–2.94	–	–	–	
	BDE-209	–	–	2.43–58.2	–	–	–	
	ΣPBDE	–	–	2.78–63.6	–	–	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Red-stemmed feathermoss (*Pleurozium schreberi,* after 90 days, non-contaminated site)	BDE-28	–	–	5.1–5.2 × 10^{-3}	–	–	–	Kosior et al. (2017)
	BDE-47	–	–	0.045–0.048	–	–	–	
	BDE-66	–	–	0.006–0.011	–	–	–	
	BDE-85	–	–	0.005–0.008	–	–	–	
	BDE-99	–	–	0.035–0.037	–	–	–	
	BDE-100	–	–	0.006–0.010	–	–	–	
	BDE-153	–	–	0.007–0.010	–	–	–	
	BDE-154	–	–	0.008–0.011	–	–	–	
	BDE-183	–	–	0.026–0.040	–	–	–	
	BDE-209	–	–	0.458–0.913	–	–	–	
	ΣPBDE	–	–	0.61–1.09	–	–	–	
Various mosses	ΣPBDE	0.19–0.26	–	0.09–0.22	–	0.34–1.14	–	Corsolini et al. (2019)
Reeds								
Burma reed (*Neyraudia reynaudiana*)	BDE-28	15.0–62.0	–	1.1–17.1	–	0.07–0.28		Wang et al. (2011b)
	BDE-47	14.5–44.6	–	1.7–15.4	–	0.12–0.35		
	BDE-100	11.0–28.8	–	0.8–13.8	–	0.07–0.48		
	BDE-99	8.2–25.6	–	0.9–11.5	–	0.11–0.45		
	BDE-154	7.8–25.4	–	0.8–23.6	–	0.10–0.93		
	BDE-153	5.8–27.4	–	0.6–9.4	–	0.10–0.34		
	BDE-183	7.5–40.0	–	0.8–11.0	–	0.11–0.28		
	BDE-209	66.7–284	–	0.6–128	–	0.01–0.45		
	ΣPBDE	151–533	–	12.5–217	–	0.08–0.41		
Reed (*Phragmites australis,* after 5 months)	∑Mono-BDE	0.40^{b}	21.8^{b}	13.6^{b}	53.9^{b}	33.7^{b}	0.62^{b}	Chow et al. (2017)
	∑Di-BDE	0.21^{b}	5.60^{b}	1.42^{b}	27.3^{b}	6.91^{b}	0.25^{b}	
	∑Tri-BDE	0.18^{b}	0.00^{b}	0.00^{b}	0.00^{b}	0.00^{b}	–	
	∑Tetra-BDE	0.43^{b}	0.52^{b}	0.35^{b}	1.22^{b}	0.82^{b}	0.67^{b}	
	∑Penta-BDE	0.64^{b}	1.81^{b}	0.20^{b}	2.85^{b}	0.32^{d}	0.11^{b}	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	∑Hexa-BDE	0.04^{b}	0.00^{b}	0.00^{b}	0.00^{b}	0.00^{b}	–	
	∑Hepta-BDE	0.00^{b}	0.00^{b}	2.08^{b}	–	–	–	
	∑Octa-BDE	0.05^{b}	0.00^{b}	2.31^{b}	0.00^{b}	46.1^{b}	–	
	∑Nona-BDE	0.22^{b}	5.64^{b}	1.58^{b}	25.6^{b}	7.20^{b}	0.28^{b}	
	BDE-209	6.95	92.2	3.11	13.3	0.45	0.034	
Reed (*Phragmites australis,* after 5 months)	∑Mono-BDE	7.16^{b}	–	–	–	–	–	Chow et al. (2017)
	∑Di-BDE	3.27^{b}	–	–	–	–	–	
	∑Tri-BDE	2.70^{b}	–	–	–	–	–	
	∑Tetra-BDE	6.99^{b}	–	–	–	–	–	
	∑Penta-BDE	23.7^{b}	–	–	–	–	–	
	∑Hexa-BDE	0.00^{b}	–	–	–	–	–	
	∑Hepta-BDE	2.40^{b}	–	–	–	–	–	
	∑Octa-BDE	9.75^{b}	–	–	–	–	–	
	∑Nona-BDE	19.5^{b}	–	–	–	–	–	
	BDE-209	87	529	38.9	6.09	0.45	0.073	
Reed (*Phragmites australis*, after 60 days)	BDE-209	2919–3029	56.1–69.9	5.6–8.8	0.02	< 0.01	0.08–0.16	Deng et al. (2016)
	∑PBDE	2952–3069	97.7–108.5	27.2–45.6	0.03–0.04	0.01–0.02	0.25–0.47	
Reed (*Phragmites australis Cav. Trin.*)	∑Mono-∑Nona-BDE							Zhou et al. (2019)
	BDE-209	3.85–11.9	6.39–19.75^{b}	–	1.66	0.89–1.44	0.53–0.85	
	∑PBDE	85.2–318.7	17.89–66.93	–	0.21	0.13–0.15	0.63–0.74	
		99–307	50^{b}	25–40^{b}	0.16–0.5	0.08–0.4	0.5–0.8	
Sedges and grasses								
Italian ryegrass (*Lolium multiflorum* L.)	BDE-209	3757–4168	1785–1972	167–188	0.47–0.48	0.04–0.05	0.09–0.10	Huang et al. (2010)
Italian ryegrass (*Lolium multiflorum* L.)	BDE-3	2.2–6	n.d	–	–	–	–	Huang et al. (2011)
	BDE-7	0.8–1.3	n.d	–	–	–	–	
	BDE-17	0.9–9	0.5–4.7	–	0.52–0.56	–	–	
	BDE-28	2.1–7	2.4–10.1	–	1.14–1.44	–	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-49	6–11.5	4.7–4.7	–	0.41–0.78	–	–	
	BDE-47	6.1–64.5	7.1–31.2	–	0.48–1.16	–	–	
	BDE-66	11.6–32	2–18.3	–	0.17–0.57	–	–	
	BDE-100	4.3–10.5	1.2–8.1	–	0.28–0.77	–	–	
	BDE-99	19–100.7	10.7–118.3	–	0.56–1.17	–	–	
	BDE-85	11.7–19.4	8.1–9.2	–	0.47–0.69	–	–	
	BDE-154	5–10.5	3.1–6.8	–	0.62–0.65	–	–	
	BDE-153	4.3–18.8	2.3–10.4	–	0.53–0.55	–	–	
	BDE-156	1–1.2	n.d	–	–	–	–	
	BDE-183	3.9–42.1	1.5–15.1	–	0.36–0.38	–	–	
	BDE-191	12.4–60.2	13.6–34.4	–	0.57–1.10	–	–	
	BDE-197	9.2–11.1	2.1–5.3	–	0.23–0.48	–	–	
	BDE-196	2.8–15.4	1.6–3.9	–	0.25–0.57	–	–	
	BDE-208	14.8–41.8	0.9–1.5	–	0.04–0.06	–	–	
	BDE-207	3.5–47.3	0.8–5.1	–	0.11–0.23	–	–	
	BDE-206	2.2–39.5	0.5–7.2	–	0.18–0.23	–	–	
	BDE-209	61.7–515.1	23.2–63.3	–	0.12–0.38	–	–	
	$\sum$PBDE	204.4–1014.7	104–316.2	–	0.31–0.51	–	0.26–0.62	
Italian ryegrass (*Lolium multiflorum* L.)	BDE-209	1563–1963	1462–1626	48.9–55.7	0.75–1.04	–	0.03–0.03	Wang et al. (2011a)
	BDE-206	125.5–147.5	96.9–110.5	9.3–9.9	0.66–0.88	–	0.09–0.10	
	BDE-207	212.5–257.5	58.5–73	11.7–12.4	0.28–0.28	–	0.16–0.21	
	BDE-208	91.8–99.4	116.4–122.8	73.1–81.9	1.17–1.34	–	0.63–0.67	
	BDE-196	21.4–52.8	50.9–52.3	6.1–34.3	0.99–2.38	–	0.12–0.67	
	BDE-197	5.5–22.8	44–47.3	15–15.2	2.07–8	–	0.32–0.35	
	BDE-191	39.9–45.1	12.4–74.9	–	0.27–1.88	–	–	
	BDE-183	–	21.3–44.8	76.3–106.9	–	–	2.39–3.58	
	BDE-138	–	–	36.9–45.5	–	–	–	
	BDE-156	–	24.5–52.8	77.1–157.9	–	–	2.99–3.15	
	BDE-153	–	–	28.6–29.7	–	–	–	
	BDE-154	–	27.5–42.4	n.d.–14.7	–	–	n.d.–0.35	
	BDE-126	–	n.d.–21.7	–	–	–	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-85	–	–	2.3–5.6	–	–	–	
	BDE-99	–	–	5.3–5.5	–	–	–	
	BDE-100	–	n.d.–6.3	n.d.–6.1	–	–	n.d.–0.97	
	BDE-77	–	n.d.–4.3	3.2–6.9	–	–	n.d.–1.61	
	BDE-66	22.4–23.2	3.2–5.8	4.8–6.3	0.14–0.25	–	1.09–1.50	
	BDE-47	–	4.8–12.8	3.1–6.6	–	–	0.24–1.38	
	BDE-71	–	1.2–14.4	–	–	–	–	
	BDE-49	–	–	5.6–14.4	–	–	–	
	BDE-28	9.2–10.6	7.8–10.7	2.2–3.7	0.74–1.16	–	0.28–0.35	
	BDE-17	–	3.1–4.5	2.8–4.4	–	–	0.62–1.42	
	BDE-15	20.1–27.1	0.7–1	1.1–5.4	0.03–0.04	–	1.57–5.40	
	BDE-7	2.5–3	8.9–12	3.5–6.1	3.56–4	–	0.29–0.69	
English ryegrass (*Lolium perenne* L., after 90 days)	BDE-209	242–3171	< 25	–	–	–	–	He et al. (2015)
English ryegrass (*Lolium perenne* L., after 60 days)	BDE-209	346.3	87.7–167.2	n.d	0.25–0.48	–	–	Feng et al. (2019)
		3127	360.5–544.4	n.d.–19.1	0.12–0.17	n.d.–0.01	n.d.–0.05	
Sooty sedge (*Carex misandra*)	ΣPBDE	0.00–0.42	–	0.05–0.11	–	18.8	–	Zhu et al. (2015)
Alpine hair grass (*Deschampsia alpina*)	ΣPBDE	0.00–0.42	–	0.07–0.08	–	44.3	–	Zhu et al. (2015)
Softstem bulrush (*Scirpus validus*)	BDE-209	1720–1840	280–360	0–70	0.088–0.195	–	0.194–0.387	Zhao et al. (2017b)
Softstem bulrush (*Scirpus validus,* after 60 days)	BDE-209	2919–3029	127.6–174.2	15.6–17.6	0.04–0.06	0.01	0.09–0.14	Deng et al. (2016)
	∑PBDE	2952–3069	203.9–243.1	44.6–46.8	0.07–0.08	0.01–0.02	0.18–0.23	
Great bulrush (*Schoenoplectus tabernaemontani,* after 60 days)	∑BDEs	2914.9	223.5	45.7	0.077		0.2	Deng et al. (2016)
	Deca-BDE	2801.5	150.9	16.6	0.054		0.11	
	Nona-BDEs	88						
	Octa-BDEs	23.3						
Nile grass (*Cyperus papyrus,* after 60 days)	BDE-209	2919–3029	74.0–101	5.1–6.7	0.02–0.03	< 0.01	0.05–0.09	Deng et al. (2016)

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	∑PBDE	2952–3069	130.8–153.6	22.1–28.3	0.04–0.05	0.01	0.14–0.22	
Bottle grass (*Setaria viridi*)	BDE-15	3.55		1.38		0.39		Wang et al. (2015)
	BDE-28	7.15		0.58		0.08		
	BDE-47	49.52		2.79		0.06		
	BDE-99	79.68		3.04		0.04		
	BDE-100	9.69		0.39		0.04		
	BDE-153	23.31		1.14		0.05		
	BDE-154	9.83		0.38		0.04		
	BDE-183	18.47		0.52		0.03		
	BDE-203	3.69		0.36		0.1		
	BDE-206	16.82		0.89		0.05		
	BDE-207	53.98		4.18		0.08		
	BDE-208	3.34		0.32		0.1		
	BDE-209	1994.44		39.12		0.02		
	ΣPBDE	2273.47		52.06		0.02		
Tall fescue (*Festuca arundinacea,* after 90 days)	BDE-209	279–3870	< 25	–	–	–	–	He et al. (2015)
Tall fescue (*Festuca arundinaceae*)	BDE-209	9300–9600	900–3400^b	190–460^b	0.10–0.36	0.02–0.05	0.14–0.21	Chen et al. (2019)
		48,600–49,100	2100–6100^b	360–770^b	0.04–0.13	0.01–0.02	0.11–0.17	
Late juncellus (*Juncellus serotinus* Rottboell)	∑Br$_1$-Br$_9$-BDE	3.85–11.9	10.66–32.96	–	2.77	1.46–1.91	0.53–0.69	Zhou et al. (2019)
	BDE-209	85.2–318.7	22.15–82.86	–	0.26	0.09–0.20	0.35–0.76	
	∑PBDE	99–307	70^b	25–50^b	0.23–0.7	0.08–0.5	0.36–0.71	
Ferns								
Eagle fern (*Pteridium aquilinum* var. *latiusculum*)	BDE-10	3.42	–	0.1	–	0.03	–	Yang et al. (2008)
	BDE-7	1.93	–	0.2	–	0.1	–	
	BDE-11	217.84	–	4.3	–	0.02	–	
	BDE-8	317.2	–	–	–	–	–	
	BDE-12 + 13	18.96	–	–	–	–	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-15	104.21	–	1.5	–	0.01	–	
	BDE-30	0.94	–	0.5	–	0.53	–	
	BDE-32	53.54	–	0.9	–	0.02	–	
	BDE-17 + 25	374.55	–	–	–	–	–	
	BDE-28 + 33	1021.26	–	8.8	–	0.01	–	
	BDE-35	54.47	–	0.8	–	0.01	–	
	BDE-37	188.13	–	3	–	0.02	–	
	BDE-75	120.51	–	10.9	–	0.09	–	
	BDE-49	1763.35	–	7.6	–	0	–	
	BDE-71	138.15	–	–	–	–	–	
	BDE-47	5349.07	–	32.5	–	0.01	–	
	BDE-66	2121.24	–	13.6	–	0.01	–	
	BDE-77	112.55	–	3.8	–	0.03	–	
	BDE-100	229.25	–	5.6	–	0.02	–	
	BDE-119	176.45	–	1.8	–	0.01	–	
	BDE-99	5469.37	–	25.2	–	0	–	
	BDE-116	1294.18	–	1.2	–	0	–	
	BDE-118	947.2	–	3.3	–	0	–	
	BDE-85	299.8	–	3.7	–	0.01	–	
	BDE126 + 155	267.45	–	–	–	–	–	
	BDE-154	219.7	–	0.4	–	0	–	
	BDE-153	849.96	–	0.3	–	0	–	
	BDE-138	132.3	–	1.8	–	0.01	–	
	BDE-166	147.25	–	0.4	–	0	–	
	BDE-183	180.17	–	1.7	–	0.01	–	
	BDE-181	7.62	–	5.6	–	0.73	–	
	BDE-190	8.77	–	0.1	–	0.01	–	
	BDE-209	3288.06	–	3.94	–	0	–	
	ΣPBDE	25,478.84	–	143.54	–	0.01	–	
Spider fern (*Pteridium multifida* Poir)	BDE-10	3.42	–	–	–	–	–	Yang et al. (2008)
	BDE-7	1.93	–	–	–	–	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-11	217.84	–	4.4	–	0.02	–	
	BDE-8	317.2	–	–	–	–	–	
	BDE-12 + 13	18.96	–	–	–	–	–	
	BDE-15	104.21	–	1.5	–	0.01	–	
	BDE-30	0.94	–	0.1	–	0.11	–	
	BDE-32	53.54	–	2	–	0.04	–	
	BDE-17 + 25	374.55	–	0.4	–	0	–	
	BDE-28 + 33	1021.26	–	0.9	–	0	–	
	BDE-35	54.47	–	1	–	0.02	–	
	BDE-37	188.13	–	3.6	–	0.02	–	
	BDE-75	120.51	–	8.5	–	0.07	–	
	BDE-49	1763.35	–	10	–	0.01	–	
	BDE-71	138.15	–	–	–	–	–	
	BDE-47	5349.07	–	33.4	–	0.01	–	
	BDE-66	2121.24	–	12.2	–	0.01	–	
	BDE-77	112.55	–	0.9	–	0.01	–	
	BDE-100	229.25	–	6.1	–	0.03	–	
	BDE-119	176.45	–	0.7	–	0	–	
	BDE-99	5469.37	–	16.7	–	0	–	
	BDE-116	1294.18	–	–	–	–	–	
	BDE-118	947.2	–	3.6	–	0	–	
	BDE-85	299.8	–	2.2	–	0.01	–	
	BDE126 + 155	267.45	–	1.2	–	0	–	
	BDE-154	219.7	–	0.9	–	0	–	
	BDE-153	849.96	–	0.8	–	0	–	
	BDE-138	132.3	–	0.3	–	0	–	
	BDE-166	147.25	–	–	–	–	–	
	BDE-183	180.17	–	0.2	–	0	–	
	BDE-181	7.62	–	0.7	–	0.09	–	
	BDE-190	8.77	–	1	–	0.11	–	
	BDE-209	3288.06	–	2.85	–	0	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	ΣPBDE	25,478.84	–	116.15	–	0	–	
Flowers								
Mountain avens (*Dryas octopetala*)	ΣPBDE	0.00–0.42	–	0.04–0.05	–	7.93	–	Zhu et al. (2015)
Arctic bell-heather (*Cassiope tetragona*)	ΣPBDE	0.00–0.42	–	0.04–0.12	–	8.13	–	Zhu et al. (2015)
Tufted saxifrage (*Saxifraga cespitosa*)	ΣPBDE	0.00–0.42	–	0.04	–	2.41	–	Zhu et al. (2015)
Japanese dock (*Rumex japonicus* Houtt.)	BDE-10	3.42	–	–	–	–	–	Yang et al. (2008)
	BDE-7	1.93	–	–	–	–	–	
	BDE-11	217.84	–	1.2	–	0.01	–	
	BDE-8	317.2	–	–	–	–	–	
	BDE-12 + 13	18.96	–	–	–	–	–	
	BDE-15	104.21	–	0.9	–	0.01	–	
	BDE-30	0.94	–	–	–	–	–	
	BDE-32	53.54	–	0.6	–	0.01	–	
	BDE-17 + 25	374.55	–	7.8	–	0.02	–	
	BDE-28 + 33	1021.26	–	1.7	–	0	–	
	BDE-35	54.47	–	0.6	–	0.01	–	
	BDE-37	188.13	–	2.2	–	0.01	–	
	BDE-75	120.51	–	12.2	–	0.1	–	
	BDE-49	1763.35	–	22.5	–	0.01	–	
	BDE-71	138.15	–	n.b	–	–	–	
	BDE-47	5349.07	–	47.8	–	0.01	–	
	BDE-66	2121.24	–	28.4	–	0.01	–	
	BDE-77	112.55	–	2.4	–	0.02	–	
	BDE-100	229.25	–	19.6	–	0.09	–	
	BDE-119	176.45	–	n.b	–	–	–	
	BDE-99	5469.37	–	58.7	–	0.01	–	
	BDE-116	1294.18	–	n.b	–	–	–	
	BDE-118	947.2	–	15.2	–	0.02	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-85	299.8	–	13.2	–	0.04	–	
	BDE126 + 155	267.45	–	n.b	–	–	–	
	BDE-154	219.7	–	3.5	–	0.02	–	
	BDE-153	849.96	–	17.6	–	0.02	–	
	BDE-138	132.3	–	6.4	–	0.05	–	
	BDE-166	147.25	–	n.b	–	–	–	
	BDE-183	180.17	–	0.3	–	0	–	
	BDE-181	7.62	–	n.b	–	–	–	
	BDE-190	8.77	–	0.1	–	0.01	–	
	BDE-209	3288.06	–	14.83	–	0	–	
	ΣPBDE	25,478.84	–	277.73	–	0.01	–	
Eastern daisy fleabane (*Erigeron annuus* L. Pers.)	BDE-10	3.42	–	1	–	0.29	–	Yang et al. (2008)
	BDE-7	1.93	–	n.b	–	–	–	
	BDE-11	217.84	–	31	–	0.14	–	
	BDE-8	317.2	–	n.b	–	–	–	
	BDE-12 + 13	18.96	–	2	–	0.11	–	
	BDE-15	104.21	–	10	–	0.1	–	
	BDE-30	0.94	–	1	–	1.06	–	
	BDE-32	53.54	–	2	–	0.04	–	
	BDE-17 + 25	374.55	–	11	–	0.03	–	
	BDE-28 + 33	1021.26	–	17	–	0.02	–	
	BDE-35	54.47	–	2	–	0.04	–	
	BDE-37	188.13	–	5	–	0.03	–	
	BDE-75	120.51	–	36	–	0.3	–	
	BDE-49	1763.35	–	16	–	0.01	–	
	BDE-71	138.15	–	n.b	–	–	–	
	BDE-47	5349.07	–	57	–	0.01	–	
	BDE-66	2121.24	–	20	–	0.01	–	
	BDE-77	112.55	–	2	–	0.02	–	
	BDE-100	229.25	–	11	–	0.05	–	
	BDE-119	176.45	–	n.b	–	–	–	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-99	5469.37	–	46	–	0.01	–	
	BDE-116	1294.18	–	n.b	–	–	–	
	BDE-118	947.2	–	7	–	0.01	–	
	BDE-85	299.8	–	6	–	0.02	–	
	BDE126 + 155	267.45	–	1	–	0	–	
	BDE-154	219.7	–	3	–	0.01	–	
	BDE-153	849.96	–	11	–	0.01	–	
	BDE-138	132.3	–	47	–	0.36	–	
	BDE-166	147.25	–	n.b	–	–	–	
	BDE-183	180.17	–	9	–	0.05	–	
	BDE-181	7.62	–	n.b	–	–	–	
	BDE-190	8.77	–	n.b	–	–	–	
	BDE-209	3288.06	–	15	–	0	–	
	ΣPBDE	25,478.84	–	326	–	0.01	–	
European centaury (*Centaurium erythraea*)	∑BDEs			0.001–0.001				Brudzińska-Kosior et al. (2015)
	BDE-209			0.001–0.002				
Chinese milkvetch (*Astragalus sinicus*, after 90 days)	BDE-209	343–3968	< 25	–	–	–	–	He et al. (2015)
Hance (*Sedum alfredii*)	BDE-209	2500^{b}	25,000^{b}	5000–38,000^{b}	10.1	1.9–15.1	0.2–1.5	Wang et al. (2019b)
		4800^{b}	22,000^{b}	4000–35,000^{b}	4.4	0.8–7	0.18–1.6	
		8100^{b}	28,000^{b}	6000–37,000^{b}	2.8	0.6–3.7	0.21–1.3	
		13,500^{b}	36,000^{b}	7000–42,000^{b}	2.4	0.5–2.8	0.19–1.2	
		21,200^{b}	90,000^{b}	16,000–81,000^{b}	4.6	0.8–4.2	0.18–0.9	
Various flowering plants	BDE-15, -28, -47, -99, -100	–	–	328	–	–	–	Yogui et al. (2011)
Herbs								
Alligator weed (*Alternanthera philoxeroides*, after 60 days)	BDE-209	2919–3029	71.4–99.4	10.2–11.8	0.02–0.03	< 0.01	0.10–0.17	Deng et al. (2016)
	∑PBDE	2952–3069	130.8–170.0	33.8–35.0	0.04–0.06	0.01	0.20–0.27	

Table 2 continued

Plant species (lichens, mosses, grasses, herbs, flowers)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Calamus (*Acorus calamus,* after 60 days)	BDE-200	2919–3029	230.0–242.4	10.0–11.8	0.08	< 0.01	0.04–0.05	Deng et al. (2016)
	$\sum$PBDE	2952–3069	306.6–328.0	27.1–34.1	0.10–0.11	0.01	0.08–0.11	
Nightshade (*Solanum nigrum*)	BDE-47	139.4	10.4	1.1–13.2	0.07	0.02		Vrkoslavová et al. (2010)
	ΣPenta-BDE	568	15.4	–	0.03	–		
	BDE-99	166.3	n.d	0.7–1.0	–	0.005		
	BDE-100	28.7	n.d	0.4–14.0	–	0.02		
	BDE-209	400.3	n.d	n.d	–	–		
Nightshade (*Solanum nigrum*, after 35 days)	BDE-209	2250–4500^{b}	800–1550^{b}	450–700^{b}	0.19–0.69^{b}	0.11–0.22^{b}	0.31–0.56^{b}	Li et al. (2018b)
	$\sum$Di-BDE	0–400^{b}	100–250^{b}	900–1600^{b}	0.63–0.83^{b}	3.0–4.8^{b}	3.6–9.0^{b}	
	$\sum$Tri-BDE	0–180^{b}	–	–	–	–	–	
	$\sum$Tetra-BDE	–	100–200^{b}	800–1400^{b}	–	–	6.0–9.3^{b}	
	$\sum$Penta-BDE	–	–	100^{b}	–	–	–	
	$\sum$Hexa-BDE	–	100–150^{b}	900–1500^{b}	–	–	6.0–10^{b}	
	$\sum$Hepta-BDE	–	50–100^{b}	350–500^{b}	–	–	3.5–10^{b}	
	$\sum$Octa-BDE	–	100–250^{b}	600–900^{b}	–	–	3.0–6.7^{b}	
	$\sum$Nona-BDE	300–2000^{b}	150–350^{b}	550–850^{b}	0.18–0.83^{b}	0.37–2.8^{b}	1.8–3.7^{b}	

n.d. not detected

[a] All data related to grams of lipid

[b] Read from charts

Table 3 Mangrove trees

Plant species (mangrove trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Black mangrove (*Aegiceras corniculatum*, after 15 months)	BDE-47	487	2500^{d}	ca. 90^{d}	ca. 5.1		ca. 0.036	Chen et al. (2017)
	BDE-7	25.5	101	6.96	3.96		0.069	
	BDE-17	50.3	236.2	10.7	4.7		0.045	
	BDE-28	5.24	12.5	2.54	2.4		0.203	
Black mangrove (*Aegiceras corniculatum*, after 9 months)	∑BDE-7, -17, -28	42–61	442–559	1.4–13.8	7.18–13.1		0.017–0.03	Chen et al. (2015)
	BDE-47	2100–2700	12,826–16,422	108–1469	4.79–7.81		0.045–0.055	
	BDE-209	46,500–50,000	22,484–26,605	153–753	0.49–0.62		0.011–0.015	
Black mangrove (*Aegiceras corniculatum*)	∑PBDE	–	–	$1.28^{d,c}$	–	3.3^{d}	–	Qiu et al. (2019)
Black mangrove (*Aegiceras corniculatum*, after 24 months)	BDE-209	$6400–15,000^{d}$	57.1	$1.06–9.07^{b}$	2.38	0.04–0.38	0.02–0.16	Farzana et al. (2019a)
	ΣHepta-BDE	–	338	$31.9–84.5^{b}$	0.12	0.01–0.03	0.68–1.52	
	ΣNona-BDE	383–2747	–	–	–	–	–	
Black mangrove (*Aegiceras corniculatum* Linn. Blanco)	ΣBr_1-Br_9-BDE	5.72–12.9	–	–	2.72	1.39–5.14	0.51–1.89	Zhou et al. (2019)
	BDE-209	28.1–361.7	–	–	0.58	0.19–0.85	0.32–1.47	
	ΣPBDE	33–327	130^{d}	$50–180^{d}$	0.40–3.94	0.15–5.45	0.38–1.38	
Black mangrove (*Avicennia corniculatum*, after 12 months)	BDE-7	–	101	6.96	–	–	0.07	Chen et al. (2017)
	BDE-17	–	236.2	10.7	–	–	0.05	
	BDE-28	–	12.5	2.54	–	–	0.2	
	BDE-47	2080	4.78	0.42	< 0.01	< 0.01	0.09	
White mangrove (*Avicennia marina*, after 15 months)	BDE-7	34.7	134	10.2	3.9		0.076	Chen et al. (2017)

Table 3 continued

Plant species (mangrove trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-17	73.2	267	21.8	3.6		0.082	
	BDE-28	7.46	29.4	3.62	3.9		0.123	
	BDE-47	322	3300[d]	140[d]	10.2[d]		0.042	
White mangrove (*Avicennia marina*, after 10 months	BDE-47	15.1	16.7	3.51	1.11	–	0.21	Zhu et al. (2014c)
	BDE-28	0.3	–	0.41	–	–	–	
	BDE-17	5.28	18.2	1.54	3.45	–	0.08	
	BDE-15	–	–	–	–	–	–	
	BDE-8	–	–	0.29	–	–	–	
	BDE-7/4	0.69	4.48	0.36	6.49	–	0.08	
	BDE-47	400	391	57.8	1.01	–	0.15	
	BDE-28	9.15	35.1	5.68	3.9	–	0.16	
	BDE-17	89.4	320	22.9	3.81	–	0.07	
	BDE-15	5.72	29.6	1.09	5.23	–	0.04	
	BDE-8	9.7	52.6	2.47	5.5	–	0.05	
	BDE-7/4	18	101	3.21	5.82	–	0.03	
	BDE-209	186	–	–	–	–	–	
	BDE-209	4726	–	–	–	–	–	
White mangrove (*Avicennia marina*, after 24 months)	BDE-209	6400–15,000[d]	18	3.44–10.3[b]	0.75	0.14–0.43	0.19–0.57	Farzana et al. (2019a)
	ΣHepta-BDE	–	251	29.4–118[b]	0.09	0.01–0.04	0.49–1.01	
	ΣNona-BDE	383–2747	–	–	–	–	–	
White mangrove (*Avicennia marina*)	BDE 28	–	–	–	2.18	–	1.05[e]	Hu et al. (2020)
	BDE 47	–	–	–	0.52	–	3.12[e]	
	BDE 66	–	–	–	0.68	–	4.52[e]	
	BDE 99	–	–	–	0.42	–	1.10[e]	
	BDE 100	–	–	–	0.42	–	2.35[e]	
	BDE 153	–	–	–	0.45	–	0.52[e]	
	BDE 154	–	–	–	1.28	–	3.19[e]	

Table 3 continued

Plant species (mangrove trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE 183	–	–	–	0.18	–	3.01^{e}	
	BDE 196	–	–	–	–	–	–	
	BDE 197	–	–	–	1.32	–	0.96^{e}	
	BDE 202	–	–	–	–	–	–	
	BDE 203	–	–	–	–	–	–	
	BDE 206	–	–	–	0.16	–	0.95^{e}	
	BDE 207	–	–	–	0.18	–	1.05^{e}	
	BDE 208	–	–	–	0.23	–	1.01^{e}	
	BDE 209	–	–	–	0.01	–	0.71^{e}	
	ΣPBDE	62.0–70.5	1.06–3.43	0.59–2.49^{b}	–	–	–	
White mangrove (*Avicennia marina*, after 12 months)	BDE-7	–	134	10.2	–	–	0.08	Chen et al. (2017)
	BDE-17	–	267	21.8	–	–	0.08	
	BDE-28	–	29.4	3.62	–	–	0.12	
	BDE-47	2080	5.62	0.5	< 0.01	< 0.01	0.09	
White mangrove (*Avicennia marina*)	ΣBr$_1$-Br$_9$-BDE	0.40–1.90	–	0.60–0.80	–	0.35–1.75	–	Chai et al. (2019)
	BDE-209	2.10–65.3	–	179.5–239	–	3.4–98.1	–	
	∑PBDE	2.50–67.2	–	180–240	–	0.35–98.1	–	
Large-leafed orange mangrove (*Bruguiera gymnorrhiza*)	∑PBDE	–	–	0.64^{d,c}	–	4.6^{d}	–	Qiu et al. (2019)
Upriver orange mangrove (*Bruguiera sexangula*)	∑PBDE	–	–	0.51^{d,c}	–	2.8^{d}	–	Qiu et al. (2019)
Upriver orange mangrove (*Bruguiera sexangula*)	BDE 28	–	–	–	1.7	–	1.29^{e}	Hu et al. (2020)
	BDE 47	–	–	–	0.05	–	8.28^{e}	
	BDE 66	–	–	–	0.74	–	8.34^{e}	
	BDE 99	–	–	–	0.24	–	4.83^{e}	
	BDE 100	–	–	–	0.31	–	9.81^{e}	
	BDE 153	–	–	–	0.33	–	4.18^{e}	
	BDE 154	–	–	–	2.31	–	7.07^{e}	

Table 3 continued

Plant species (mangrove trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE 183	–	–	–	0.13	–	6.97^{e}	
	BDE 196	–	–	–	0.6	–	0.91^{e}	
	BDE 197	–	–	–	0.61	–	0.98^{e}	
	BDE 202	–	–	–	–	–	–	
	BDE 203	–	–	–	0.36	–	0.92^{e}	
	BDE 206	–	–	–	0.15	–	1.14^{e}	
	BDE 207	–	–	–	0.18	–	1.12^{e}	
	BDE 208	–	–	–	0.27	–	1.14^{e}	
	BDE 209	–	–	–	0.02	–	1.33^{e}	
	ΣPBDE	59.8–119	1.13–5.40	0.20–7.75^{b}	–	–	–	
Milky mangrove (*Excoecaria agallocha*, after 8 months)	BDE-47	–	30–170^{d}	18–128^{d,b}	–	–	0.22–3.62^{d,b}	Pi et al. (2017)
	BDE-99	–	14–46^{d}	8–95^{d,b}	–	–	0.26–5.94^{d,b}	
	BDE-100	–	4–11.6^{d}	2.2–24.8^{d,b}	–	–	0.26–6.20^{d,b}	
	BDE-153	–	0.9–1.8^{d}	0.5–10^{d,b}	–	–	0.56–9.09^{d,b}	
	BDE-154	–	1–2.1^{d}	0.4–8.6^{d,b}	–	–	0.36–7.82^{d,b}	
	BDE-209	–	17–40^{d}	17–137^{d,b}	–	–	0.65–8.06^{d,b}	
Narrow-leaved kandelia (*Kandelia candel*)	∑PBDE	–	–	0.65^{d,c}	–	1.6^{d}	–	Qiu et al. (2019)
Water pen mangrove (*Kandelia obovata*, after 12 months)	BDE-47	61.9	46.8	15.2–37.1^{b}	0.756	0.245–0.599	0.324–0.793^{b}	Farzana et al. (2017)
	BDE-99	392	345	2.60–51.7^{b}	0.881	0.007–0.132	0.008–0.150^{b}	
	∑PBDE	71.3	77.2	7.50–37.1^{b}	1.08	0.105–0.520	0.097–0.481^{b}	
Water pen mangrove (*Kandelia obovata*, after 12 weeks)	BDE-47	11	31	9.60–17.8^{b}	2.82	0.873–1.62	0.310–0.574^{b}	Farzana et al. (2017)
	BDE-196	18	1.6	–	0.089	–	–	
	BDE-203	13.5	0.9	–	0.067	–	–	
	BDE-206	1589	70.2	–	0.044	–	–	
	BDE-207	811	42.8	–	0.053	–	–	
	BDE-209	45,283	21,902	353–487^{b}	0.484	0.008–0.013	0.016–0.026^{b}	
	∑PBDE	2462	149	10.8–20.5^{b}	0.06	0.004–0.008	0.073–0.138^{b}	

Table 3 continued

Plant species (mangrove trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Water pen mangrove (*Kandelia obovata*, after 24 months)	BDE-209	6400–15,000^{d}	6.3	0.67–3.71^{b}	0.26	0.03–0.15	0.11–0.59	Farzana et al. (2019a)
	ΣHepta-BDE	–	63.6	14.9–63.6^{b}	0.04	0.02	0.89–1.93	
	ΣNona-BDE	383–2747	–	–	–	–	–	
Water pen mangrove (*Kandelia obovata,* after 8 months)	BDE-47	–	18–140^{d}	13–114^{d,b}	–	–	0.04–6.38^{d,b}	Pi et al. (2017)
	BDE-99	–	6–33^{d}	6–24^{d,b}	–	–	0.18–3.17^{d,b}	
	BDE-100	–	1.2–18.6^{d}	1–4.4^{d,b}	–	–	0.08–2.83^{d,b}	
	BDE-153	–	1–5.6^{d}	1–3.7^{d,b}	–	–	0.23–4.02^{d,b}	
	BDE-154	–	0.8–3^{d}	0.5–3.1^{d,b}	–	–	0.33–3.88^{d,b}	
	BDE-209	–	21–45^{d}	21–158^{d,b}	–	–	1.73–7.52^{d,b}	
Water pen mangrove (*Kandelia obovata*)	BDE 28	–	–	–	1.61	–	1.37^{e}	Hu et al. (2020)
	BDE 47	–	–	–	0.02	–	8.62^{e}	
	BDE 66	–	–	–	0.21	–	5.41^{e}	
	BDE 99	–	–	–	0.18	–	0.18^{e}	
	BDE 100	–	–	–	0.5	–	3.21^{e}	
	BDE 153	–	–	–	–	–	1.00^{e}	
	BDE 154	–	–	–	0.74	–	1.45^{e}	
	BDE 183	–	–	–	0.13	–	3.07^{e}	
	BDE 196	–	–	–	0.39	–	1.07^{e}	
	BDE 197	–	–	–	1.88	–	1.01^{e}	
	BDE 202	–	–	–	–	–	–	
	BDE 203	–	–	–	1.54	–	0.98^{e}	
	BDE 206	–	–	–	0.21	–	0.97^{e}	
	BDE 207	–	–	–	0.24	–	0.99^{e}	
	BDE 208	–	–	–	0.31	–	0.99^{e}	
	BDE 209	–	–	–	0.02	–	0.72^{e}	
	ΣPBDE	46.4–74.8	1.10–4.29	1.15–2.90^{b}	–	–	–	

Table 3 continued

Plant species (mangrove trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Water pen mangrove (*Kandelia obovata,* after 6 months)	BDE-28	0.5^{d}	0.5–0.9^{d}	–	1.0–1.8^{d}	–	–	Li et al. (2020b)
	BDE-47	0.6–0.8^{d}	1.5–3.8^{d}	–	2.5–4.75^{d}	–	–	
	BDE-99	0.2^{d}	0.6–0.9^{d}	–	3.0–4.5^{d}	–	–	
	BDE-100	0.3–0.4^{d}	3.2–10.3^{d}	–	10.7–25.8^{d}	–	–	
	BDE-153	0.3^{d}	1.5–3.9^{d}	–	5.0–13^{d}	–	–	
	BDE-154	0.3^{d}	4.8–7.3^{d}	–	16.0–24.3^{d}	–	–	
	BDE-183	0.6–0.8^{d}	1.0–2.0^{d}	–	1.7–2.5^{d}	–	–	
	BDE-209	20,175–22,320	5400–5500^{d}	–	0.24–0.28^{d}	–	–	
Water pen mangrove (*Kandelia obovata,* after *9* months)	BDE-209	18,655–21,415	5600–6800^{d}	–	^{d} 0.26–0.37^{d}	–	–	Li et al. (2020b)
Water pen mangrove (*Kandelia obovate*)	$\sum$Br$_1$-Br$_9$-BDE	5.72–12.9	0.55–12.51	–	0.97	0.74–1.09	0.76–1.12	Zhou et al. (2019)
	BDE-209	28.1–361.7	7.87–101.28	–	0.28	0.10–0.55	0.37–2.01	
	$\sum$PBDE	33–327	60^{d}	25–120^{d}	0.18–1.82	0.08–3.64	0.42–2.00	
Water pen mangrove (*Kandelia obovate*)	Di-BDEs	–	43.2–50	72.6–76.2	–	–	1.52–1.68	Farzana et al. (2019b)
	Tri-BDEs	4.5–5.3	22.4–27.1	3.6–8.5	4.96–5.13	0.69–1.88	0.13–0.38	
	Tetra-BDEs	62.4–76	142.6–191.7	71.3–91.2	2.28–2.52	0.94–1.46	0.37–0.64	
	BDE-99	100.8–127.6	670.2–879.8	147.6–237.2	3.61–8.47	1.28–1.42	0.17–0.35	
White-flowered black mangrove (*Lumnitzera racemosa*)	$\sum$PBDE	–	–	0.61^{d,c}	–	0.15^{d}	–	Qiu et al. (2019)
Tall-stilt mangrove (*Rhizophora apiculata*)	$\sum$PBDE	–	–	0.56^{d,c}	–	1.2^{d}	–	Qiu et al. (2019)
Red mangrove (*Rhizophora stylosa*)	$\sum$PBDE	–	–	0.52^{d,c}	–	2.4^{d}	–	Qiu et al. (2019)
Sonneratia mangrove (*Sonneratia apetala* Buch, Ham)	$\sum$Br$_1$-Br$_9$-BDE	3.85–12.9	–	–	1.15–3.9	0.94–4.84	0.35–2.79	Zhou et al. (2019)
	BDE-209	28.1–361.7	–	–	0.5–0.53	0.13–0.71	0.28–1.33	
	$\sum$PBDE	33–327	100–120^{d}	30–150^{d}	0.33–3.64	0.09–4.55	0.3–1.25	

Table 3 continued

Plant species (mangrove trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. Root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Mangrove apple (*Sonneratia caseolaris L. Engler*)	$\sum$Br$_1$-Br$_9$-BDE	3.85–12.9	–	–	1.59–3.51	1.14–6.33	0.72–1.87	Zhou et al. (2019)
	BDE-209	28.1–361.7	–	–	0.21–0.45	0.10–0.83	0.15–2.33	
	$\sum$PBDE	33–327	50–100^{d}	10–175^{d}	0.16–3.03	0.03–5.30	0.20–2.00	
Mangrove apple (*Sonneratia caseolaris*)	$\sum$Br$_1$-Br$_9$-BDE	0.40–3.90	–	1.20–3.30	–	0.59–4.75	–	Chai et al. (2019)
	BDE-209	18.2–1987.6	–	322.8–595.7	–	0.16–28.9	–	
	$\sum$PBDE	18.6–1991.5	–	324–599	–	0.16–28.9	–	
Mangrove apple (*Sonneratia caseolaris*)	$\sum$PBDE	–	–	0.80^{d,c}	–	9.7^{d}	–	Qiu et al. (2019)
Hainan sonneratia (*Sonneratia hainanensis*)	$\sum$PBDE	–	–	0.86$^{d\ c}$	–	6.3^{d}	–	Qiu et al. (2019)
Various mangrove plants (*Aegiceras corniculatum*, *Sonneratia hainanensis*, *Sonneratia caseolaris*, *Kandelia candel*, *Bruguiera gymnorrhiza*, *Bruguiera sexangula*, *Rhizophora stylosa*, *Rhizophora apiculata*, *Lumnitzera racemosa*)	BDE-28	0.011–0.050	0.033–0.243	0.014–0.546^{b}	–	8.4^{d}	–	Qiu et al. (2019)
	BDE-35	0.001–0.060	0.002–0.030	0.001–0.220^{b}	–	2.6^{d}	–	
	BDE-47	0.008–0.665	0.024–0.849	0.008–0.277^{b}	–	4.2^{d}	–	
	BDE-77	0.005–0.134	0.001–0.223	0.002–0.721^{b}	–	7.1^{d}	–	
	BDE-99	0.002–0.059	0.018–0.796	0.005–0.148^{b}	–	8.9^{d}	–	
	BDE-100	0.005–0.125	0.003–0.065	0.005–0.141^{b}	–	2.5^{d}	–	
	BDE-153	0.004–0.035	0.011–0.054	0.005–0.209^{b}	–	3.5^{d}	–	
	BDE-154	0.002–0.067	0.012–0.075	0.005–0.121^{b}	–	5^{d}	–	
	BDE-183	0.006–0.267	0.005–0.058	0.005–0.240^{b}	–	4.1^{d}	–	
	BDE-209	0.003–2.18	0.005–0.231	0.004–0.318^{b}	–	6.5^{d}	–	
	$\sum$PBDE	0.083–2.93	0.189–1.99	0.150–1.81^{b}	–	–	–	

[a] All data related to grams of lipid

[b] Above-ground plant parts

[c] Whole plant incl. roots

[d] Read from charts

[e] C_{stem}/c_{root}

Table 4 Forest and ornamental trees

Plant species (trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. bark (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{bark}}{c_{root}}$	Source
Coniferous trees (pine, fir, spruce)	ΣPBDE	–	–	2.12–190[a]	–	–	–	Salamova and Hites (2013)
Weymoth pine (*Pinus strobus*)	ΣPBDE	–	–	0.989–15.1	–	–	–	Salamova and Hites (2010)
	BDE-47	–	–	0.225–2.69	–	–	–	
	BDE-99	–	–	0.368–3.86	–	–	–	
	BDE-100	–	–	0.103–1.01	–	–	–	
	BDE-209	–	–	0.103–5.14	–	–	–	
Japanese black pine (*Pinus thunbergii*)	BDE-209	1.17–5.42[b]	1.60–4.55[b]	0.40–5.95[b]	0.33–2.99	0.07–3.18	0.25–1.31	Wen et al. (2019)
Butterfly tree (*Bauhinia purpurea* Linn), white champaca (*Michelia alba* DC.), Chinese banyan (*Ficus microcarpa* var. *pusillifolia*)	BDE-28	–	–	–	–	0.50–100[b]	–	Ding et al. (2014)
	BDE-47	–	–	–	–	0.25–50[b]	–	
	BDE-99	–	–	–	–	0.13–79[b]	–	
	BDE-100	–	–	–	–	0.13–79[b]	–	
	BDE-153	–	–	–	–	0.50–792[b]	–	
	BDE-154	–	–	–	–	0.13–79[b]	–	
	BDE-183	–	–	–	–	0.05–32[b]	–	
	BDE-209	–	–	–	–	0.05–2.0[b]	–	
Willow (*Salix* L.)	BDE-28	0.004–0.105	–	0.015–0.063	–	1.04–2.18[c]	–	Chen et al. (2020)
	BDE-47	n.d.–0.095	–	0.005–0.061	–	0.54–1.50[c]	–	
	BDE-99	n.d.–0.219	–	n.d.–0.018	–	1.26–1.30[c]	–	
	BDE-100	n.d.–0.100	–	n.d.–0.019	–	–	–	
	BDE-153	n.d.–0.089	–	n.d	–	–	–	
	BDE-154	n.d.–0.110	–	n.d	–	–	–	
	BDE-183	n.d.–0.246	–	n.d	–	–	–	
	BDE-209	0.505–64.3	–	0.169–5.96	–	0.12–0.81[c]	–	

Table 4 continued

Plant species (trees)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. bark (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{bark}}{c_{root}}$	Source
	ΣHepta-BDE	0.024–0.197	–	0.028–0.082	–	0.22–1.56[c]	–	
	ΣOkta-BDE	1.25–13.3	–	0.490–1.73	–	0.12–0.83[c]	–	
Magnolie (*Magnolia grandiflora*)	ΣPBDE	36.4–5393.72	–	9.3–266[b]	–	0.05–0.26	–	Gao et al. (2019)
Echte Trauerweide (*Salix babylonica*)	ΣPBDE	36.4–5393.72	–	5.8–179[b]	–	0.03–0.16	–	Gao et al. (2019)
Urwaldmammutbaum (*Metasequoia glyptostroboides*)	ΣPBDE	36.4–5393.72	–	6.7–145[b]	–	0.03–0.18	–	Gao et al. (2019)
Himalaya-Zeder (Cedrus deodara)	ΣPBDE	36.4–5393.72	–	9.0–259[b]	–	0.05–0.25	–	Gao et al. (2019)
Glanzliguster (Ligustrum lucidum Ait.)	BDE-28	–	–	n.d.–0.002	–	–	–	Graziani et al. (2019)
	BDE-47	–	–	0.118–0.162	–	–	–	
	BDE-99	–	–	0.043–0.059	–	–	–	
	BDE-100	–	–	0.008–0.04	–	–	–	
	BDE-153	–	–	0.004	–	–	–	
	BDE-154	–	–	n.d.–0.003	–	–	–	
	BDE-183	–	–	0.01–0.026	–	–	–	
	ΣPBDE	–	–	0.272–0.411	–	–	–	

n.d. not detected

[a] All data related to grams of lipid

[b] Read from charts

[c] C_{bark}/C_{soil}

substituted phenylureas in barley by Briggs et al. (1982). The authors showed that this correlation presupposes sufficient water solubility of the pollutants within the intrinsic mass transport system and is therefore only applicable to polar and moderately lipophilic pollutants. However, no correlation was found between the uptake of the pollutant by the roots and the transfer behavior within the plant. It was postulated that the existing membrane barriers in the roots cannot be described by simple partition coefficients. The literature data presented in Sect. 8 suggest that plant specifics may have an additional influence which further complicates or even prevents a correlation between SCF and RCF or log KOW value. Due to the inadequate recording of these plant-specific parameters, it is not possible to make a reliable predictive statement on the PBDE levels occurring in plants.

8 RCF and TF values for specific crops

The plant specific root concentration factors (RCF) and translocation factors (TF) compiled from previous literature data were summarized and grouped in the Tables 2, 3, 4 and 5 as follows: Lichens, mosses,

Table 5 Crops for food production

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Cereals								
Rice	ΣPBDE	21.2–9316.8	4.5–126.8	3.6–58.3				Han et al. (2017)
	BDE-28	–	–	–	–	–	0.18–0.32	
	BDE-47	–	–	–	–	–	0.16–0.30	
	BDE-66	–	–	–	–	–	0.16–0.27	
	BDE-99	–	–	–	–	–	0.15–0.26	
	BDE-100	–	–	–	–	–	0.13–0.28	
	BDE-153	–	–	–	–	–	0.12–0.24	
	BDE-154	–	–	–	–	–	0.11–0.23	
	BDE-183	–	–	–	–	–	0.08–0.10	
	BDE-209	–	–	–	–	–	0.07–0.09	
Asian rice (*Oryza sativa* L. ssp. *Indica*)	∑PBDE	110–120	23–28	1.6–3.3	0.20–0.23	–	0.07–0.12	Zhang et al. (2015)
	∑PBDE	1100–1400	160–350	16–33	0.15–0.25	–	0.09–0.10	Wang et al. (2011b)
Rice	∑PBDE	15.6	–	14.5	–	–	0.93	She et al. (2013)
Asian rice (*Oryza sativa*)	BDE-28	0.17–0.27	–	0.05–0.07	–	0.16–0.30	–	
	BDE-47	1.28–1.65	–	0.31–0.46	–	0.16–0.31	–	
	BDE-66	0.24–0.37	–	0.06–0.10	–	0.14–0.27	–	
	BDE-99	0.97–2.27	–	0.13–0.27	–	0.07–0.20	–	
	BDE-100	0.19–0.54	–	0.03–0.05	–	0.07–0.17	–	
	BDE-153	0.51–1.04	–	0.01–0.03	–	0.01–0.03	–	
	BDE-154	0.30–0.65	–	0.01–0.03	–	0.02–0.07	–	
	BDE-183	0.93–1.14	–	0.06–0.07	–	0.04–0.06	–	
	BDE-209	15.6–29.8	–	0.58–0.83	–	0.02–0.04	–	
	∑PBDE	31.2–51.6	–	1.30–2.47	–	–	–	
Asian rice (*Oryza sativa*, after 60 days)	∑PBDE	2914.9	444.8	102.6	0.153	–	0.23	Deng et al. (2016)
	BDE-209	2801.5	368	62.8	0.131	–	0.17	
	ΣNona-BDE	88	–	–	–	–	–	
	ΣOcta-BDE	23.3	–	–	–	–	–	
Asian rice (*Oryza sativa* L. cv.)								Chow et al. (2015)

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Fengmeizhan	BDE-209	38.4–49.9	14.4–16	0.24–0.29	0.38–0.32	–	0.017–0.018	
Hefengzhan	BDE-209	31.7–44.4	14.9–18.4	0.29–0.35	0.47–0.41	–	0.019–0.019	
Guangyinzhan	BDE-209	32.6–48.0	14.9–16.8	0.25–0.3	0.46–0.35	–	0.017–0.018	
Asian rice (*Oryza sativa* L.)	ΣPBDE	ca. 75	ca. 8.9	ca. 3.5	0.12	–	0.39	Wang et al. (2014)
Asian rice (*Oryza sativa* L cv. Hefengzhan, after 5 months)	BDE-209	8.83	101	4.27–27.2	11.4	0.50–3.08	0.043–0.27	Chow et al. (2017)
	∑Mono-BDE	1.29^{b}	31.2^{b}	$12.2–129^{b}$	24.1^{b}	$9.41–100^{b}$	$0.39–4.14^{b}$	
	∑Di-BDE	1.04^{b}	12.2^{b}	$2.72–15.1^{b}$	11.7^{b}	$2.62–14.6^{b}$	$0.22–1.25^{b}$	
	∑Tri-BDE	0.64^{b}	–	$0–5.78^{b}$	–	$0–8.9^{b}$	–	
	∑Tetra-BDE	1.68^{b}	1.50^{b}	$0.45–6.90^{b}$	0.89^{b}	$0.27–4.1^{b}$	$0.30–4.60^{b}$	
	∑Penta-BDE	1.79^{b}	1.74^{b}	$0–4.01^{b}$	0.98^{b}	$0–2.2^{b}$	$0–2.30^{b}$	
	∑Hexa-BDE	–	–	$0–2.28^{b}$	–	–	–	
	∑Hepta-BDE	1.14^{b}	3.35^{b}	$0–7.69^{b}$	2.93^{b}	$0.00–6.7^{b}$	$0–2.30^{b}$	
	∑Octa-BDE	0.12^{b}	4.95^{b}	$1.83–11.4^{b}$	42.9^{b}	$15.8–98.7^{b}$	$0.37–2.30^{b}$	
	∑Nona-BDE	1.14^{b}	16.3^{b}	$4.01–12.5^{b}$	14.3^{b}	$3.52–11.0^{b}$	$0.25–0.77^{b}$	
	BDE-209	84.4	698	39.3–78.4	8.27	0.47–0.93	0.056–0.112	Chow et al. (2017)
	∑Mono-BDE	42.6^{b}	–	–	–	–	–	
	∑Di-BDE	11.2^{b}	–	–	–	–	–	
	∑Tri-BDE	8.0^{b}	–	–	–	–	–	
	∑Tetra-BDE	19.0^{b}	–	–	–	–	–	
	∑Penta-BDE	24.8^{b}	–	–	–	–	–	
	∑Hexa-BDE	–	–	–	–	–	–	
	∑Hepta-BDE	21.2^{b}	–	–	–	–	–	
	∑Octa-BDE	19.6^{b}	–	–	–	–	–	
	∑Nona-BDE	30.1^{b}	–	–	–	–	–	
Asian rice (*Oryza sativa* L. cv. Huanghuazhan, after 90 days)	BDE-209	229–3195	< 25	–	–	–	–	He et al. (2015)
Asian rice (*Oryza sativa* L. cv. Xiushui 134, after 90 days)	BDE-209	186–3457	< 25	–	–	–	–	He et al. (2015)
Long-grained rice (*Oryza sativa indica* HHZ, after 120 days)	BDE-1	–	–	$^{b}0^{d}$	–	–	–	Zhao et al. (2020)

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-2	–	–	$^{b}0^{d}$	–	–	–	
	BDE-3	–	–	$^{b}0^{d}$	–	–	–	
	BDE-7	–	–	$^{b}0^{d}$	–	–	–	
	BDE-10	–	–	$^{b}0^{d}$	–	–	–	
	BDE-11/8	–	–	$^{b}0^{d}$	–	–	–	
	BDE-12/13	–	–	$^{b}0^{d}$	–	–	–	
	BDE-15	–	–	$^{b}0^{d}$	–	–	–	
	BDE-17/25	–	–	$^{b}0^{d}$	–	–	–	
	BDE-30	–	–	$^{b}0^{d}$	–	–	–	
	BDE-32	–	–	$^{b}0^{d}$	–	–	–	
	BDE-33/28	–	–	$^{b}0^{d}$	–	–	–	
	BDE-35	–	–	$^{b}0^{d}$	–	–	–	
	BDE-37	–	–	$^{b}0^{d}$	–	–	–	
	BDE-47	–	–	$^{b}0^{d}$	–	–	–	
	BDE-49	–	–	$^{b}0^{d}$	–	–	–	
	BDE-66	–	–	$^{b}0^{d}$	–	–	–	
	BDE-75	–	–	$^{b}0^{d}$	–	–	–	
	BDE-99	–	–	$^{b}0^{d}$	–	–	–	
	BDE-100	–	–	$^{b}0^{d}$	–	–	–	
	BDE-126	–	–	$^{b}10^{d}$	–	–	–	
	BDE-181	–	–	$^{b}0^{d}$	–	–	–	
	BDE-183	–	–	$^{b}0^{d}$	–	–	–	
	BDE-203	–	–	$^{b}0^{d}$	–	–	–	
	BDE-206	–	–	$^{b}0^{d}$	–	–	–	
	BDE-209	2125	–	$^{b}400^{d}$	1.25	0.19–0.35	0.29	
	∑PBDE	–	–	421.8^{d}	–	–	–	
Long-grained rice (*Oryza sativa indica* YD1, after 120 days)	BDE-1	–	–	$^{b}6^{d}$	–	–	–	Zhao et al. (2020)
	BDE-2	–	–	$^{b}6^{d}$	–	–	–	
	BDE-3	–	–	$^{b}8^{d}$	–	–	–	
	BDE-7	–	–	$^{b}28^{d}$	–	–	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-10	–	–	$^{b}20^{d}$	–	–	–	
	BDE-11/8	–	–	$^{b}12^{d}$	–	–	–	
	BDE-12/13	–	–	$^{b}30^{d}$	–	–	–	
	BDE-15	–	–	$^{b}24^{d}$	–	–	–	
	BDE-17/25	–	–	$^{b}0^{d}$	–	–	–	
	BDE-30	–	–	$^{b}2^{d}$	–	–	–	
	BDE-32	–	–	$^{b}8^{d}$	–	–	–	
	BDE-33/28	–	–	$^{b}2^{d}$	–	–	–	
	BDE-35	–	–	$^{b}0^{d}$	–	–	–	
	BDE-37	–	–	$^{b}0^{d}$	–	–	–	
	BDE-47	–	–	$^{b}4^{d}$	–	–	–	
	BDE-49	–	–	$^{b}0^{d}$	–	–	–	
	BDE-66	–	–	$^{b}0^{d}$	–	–	–	
	BDE-75	–	–	$^{b}2^{d}$	–	–	–	
	BDE-99	–	–	$^{b}2^{d}$	–	–	–	
	BDE-100	–	–	$^{b}0^{d}$	–	–	–	
	BDE-126	–	–	$^{b}32^{d}$	–	–	–	
	BDE-181	–	–	$^{b}0^{d}$	–	–	–	
	BDE-183	–	–	$^{b}22^{d}$	–	–	–	
	BDE-203	–	–	$^{b}68^{d}$	–	–	–	
	BDE-206	–	–	$^{b}6^{d}$	–	–	–	
	BDE-209	2028	–	$^{b}140^{d}$	0.39	0.16–0.23	0.62	
	$\sum$PBDE	–	–	454.2^{d}	–	–	–	
Short-grained rice (*Oryza sativa japonica* NJ3, after 120 dadys)	BDE-1	–	–	$^{b}10^{d}$	–	–	–	Zhao et al. (2020)
	BDE-2	–	–	$^{b}10^{d}$	–	–	–	
	BDE-3	–	–	$^{b}10^{d}$	–	–	–	
	BDE-7	–	–	$^{b}24^{d}$	–	–	–	
	BDE-10	–	–	$^{b}20^{d}$	–	–	–	
	BDE-11/8	–	–	$^{b}14^{d}$	–	–	–	
	BDE-12/13	–	–	$^{b}24^{d}$	–	–	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-15	–	–	$^{b}24^{d}$	–	–	–	
	BDE-17/25	–	–	$^{b}4^{d}$	–	–	–	
	BDE-30	–	–	$^{b}1^{d}$	–	–	–	
	BDE-32	–	–	$^{b}4^{d}$	–	–	–	
	BDE-33/28	–	–	$^{b}2^{d}$	–	–	–	
	BDE-35	–	–	$^{b}2^{d}$	–	–	–	
	BDE-37	–	–	$^{b}2^{d}$	–	–	–	
	BDE-47	–	–	$^{b}28^{d}$	–	–	–	
	BDE-49	–	–	$^{b}0^{d}$	–	–	–	
	BDE-66	–	–	$^{b}24^{d}$	–	–	–	
	BDE-75	–	–	$^{b}4^{d}$	–	–	–	
	BDE-99	–	–	$^{b}0^{d}$	–	–	–	
	BDE-100	–	–	$^{b}0^{d}$	–	–	–	
	BDE-126	–	–	$^{b}150^{d}$	–	–	–	
	BDE-181	–	–	$^{b}64^{d}$	–	–	–	
	BDE-183	–	–	$^{b}30^{d}$	–	–	–	
	BDE-203	–	–	$^{b}12^{d}$	–	–	–	
	BDE-206	–	–	$^{b}0^{d}$	–	–	–	
	BDE-209	1870	–	$^{b}486^{d}$	0.22	0.2–0.36	0.98	
	∑PBDE	–	–	967.0^{d}	–	–	–	
Asian rice (*Oryza sativa* L., after 120 days)	BDE-209	346.3	n.d	n.d	–	–	–	Feng et al. (2019)
		3127	58.7–90.6	n.d	0.02–0.03	–	–	
Asian rice (*Oryza sativa* L.)	BDE-209	2919–3029.2	332.1403.9	58.0–67.6	0.11–0.14	0.02	0.14–0.20	Deng et al. (2016)
	∑PBDE	2953–3069.4	414–475.6	83.2–122	0.13–0.16	0.03–0.04	0.17–0.29	
Asian rice (*Oryza sativa* L.)	BDE-28	64.6	1.37	0.221–0.669	0.02	0.003–0.01	0.16–0.49	Wu et al. (2019)
	BDE-47	160	20.1	0.953–6.27	0.13	0.006–0.04	0.05–0.31	
	BDE-66	55	5.08	0.393–3.82	0.09	0.007–0.07	0.08–0.75	
	BDE-99	282	3.22	0.287–3.26	0.01	0.001–0.01	0.09–1.01	
	BDE-100	34.8	1.6	0.11–2.28	0.05	0.003–0.07	0.07–1.43	
	BDE-138	19.7	2.58	0.04–0.224	0.13	0.002–0.01	0.02–0.09	
	BDE-153	163	2.67	0.367–2.51	0.02	0.002–0.02	0.14–0.94	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-154	77.9	2.63	0.169–0.324	0.03	0.002–0.004	0.06–0.12	
	BDE-196	101	2.88	0.1–0.36	0.03	0.001–0.004	0.03–0.13	
	BDE-197	149	1.71	0.168–0.645	0.01	0.001–0.004	0.10–0.38	
	BDE-203	93.9	2.76	0.108–0.369	0.03	0.001–0.004	0.04–0.13	
	BDE-206	166	1.44	0.169–0.825	0.01	0.001–0.005	0.12–0.57	
	BDE-207	278	1.74	0.166–0.791	0.01	0.001–0.003	0.10–0.45	
	BDE-208	142	0.94	0.083–0.407	0.01	0.001–0.003	0.09–0.43	
	BDE-209	2949	54.9	4.27–28.7	0.02	0.001–0.010	0.08–0.52	
	∑PBDEs	4735	105	8.31–51.4	0.02	0.002–0.011	0.08–0.49	
Maize (*Zea mays*, after 28 days)	BDE-206	50–90	30	1	0.38–0.5	0.01–0.02	0.03–0.04	Navarro et al. (2017)
	BDE-207	40–70	30	1.0–2.0	0.5–0.67	0.02–0.03	0.03–0.06	
	BDE-209	1610–3310	470–1120	Oct-40	0.25–0.32	0.01	0.03–0.04	
Maize (*Zea mays* L., after 25 days)	BDE-209	420^{e}	–	10.7–28.4^{c}	–	0.025–0.068^{e}	–	Wu et al. (2018b)
Maize (*Zea mays* L. cv. Nongda 108)	BDE-209	3467–3758	1128–1247	253–285	0.32–0.33	0.07–0.08	0.22–0.23	Huang et al. (2010)
Maize (*Zea mays* L. cv. Zhengdan 1)	BDE-28	20.54	–	0.462	–	0.022	0.056	
	BDE-47	15.5	–	0.373	–	0.024	0.039	
	BDE-99	4.76	–	0.018	–	0.004	0.02	
Maize (*Zea mays* L. cv. Nongda 108)	BDE-3	02-Apr	n.d	–	–	–	–	Huang et al. (2011)
	BDE-7	0.5–1.3	n.d	–	–	–	–	
	BDE-17	0.5–7.9	4.8–5.6	–	0.71–9.60	–	–	
	BDE-28	2.4–9.8	1.3–9.9	–	0.54–1.01	–	–	
	BDE-49	5.1–9.3	6.2–6.2	–	0.67–1.22	–	–	
	BDE-47	8.9–47.8	9.9–36.4	–	0.76–1.11	–	–	
	BDE-66	10.4–41	1.5–18.2	–	0.14–0.44	–	–	
	BDE-100	7.2–9.9	1.4–7.4	–	0.19–0.75	–	–	
	BDE-99	11.2–88.2	8.3–67.1	–	0.74–0.76	–	–	
	BDE-85	11–18.8	6.3–12	–	0.57–0.64	–	–	
	BDE-154	6.1–8.7	2.4–6.4	–	0.39–0.74	–	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-153	3.3–13.2	4.1–10.9	–	0.83–1.24	–	–	
	BDE-156	0.8–1	n.d	–	–	–	–	
	BDE-183	5–38.7	1.1–12.3	–	0.22–0.32	–	–	
	BDE-191	11.9–53.9	15.3–42	–	0.78–1.29	–	–	
	BDE-197	8–12.8	4–4.5	–	0.35–0.50	–	–	
	BDE-196	2.1–9.1	1.3–3.4	–	0.37–0.62	–	–	
	BDE-208	3.8–28.3	1–1.2	–	0.04–0.26	–	–	
	BDE-207	5.1–46.8	1.4–7.2	–	0.15–0.27	–	–	
	BDE-206	3.4–45.4	3.2–11.2	–	0.25–0.94	–	–	
	BDE-209	65.6–505.9	18.5–85.1	–	0.17–0.28	–	–	
	∑PBDE	197.4–951.3	110.2–305.4	–	0.32–0.56	–	0.30–0.59	
Maize (*Zea mays* L.)	ΣPBDE	50^b	4^b	2.2^b	0.08	–	0.55	Wang et al. (2014)
Maize (*Zea mays* L., after 97 days)	BDE-28	–	–	–	0.52^b	–	0.51^b	Fan et al. (2020)
	BDE-47	–	–	–	0.12^b	–	8.2^b	
	BDE-66	–	–	–	–	–	–	
	BDE-85	–	–	–	–	–	–	
	BDE-99	–	–	–	0.14^b	–	4.8^b	
	BDE-100	–	–	–	0.21^b	–	10.8^b	
	BDE-153	–	–	–	0.07	–	3.9^b	
	BDE-154	–	–	–	0.2^b	–	2.7^b	
	BDE-183	–	–	–	–	–	–	
	BDE-196	–	–	–	–	–	–	
	BDE-197	–	–	–	–	–	–	
	BDE-203	–	–	–	–	–	–	
	BDE-206	–	–	–	–	–	–	
	BDE-207	–	–	–	–	–	–	
	BDE-208	–	–	–	–	–	–	
	BDE-209	320^b	29^b	n.d.–12^b	0.09^b	–	0.03^b	
	∑de-BDE	46^b	3.5^b	n.d.–7^b	–	–	–	
Wheat (*Triticum aestivum* L.)	BDE-209	0.47–3.27	3.08–6.32	0.21–3.66	1.94–6.69	–	0.07–0.58	Li et al. (2015b)

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Wheat (*Triticum aestivum* L., after 4.5 months)	BDE-47	–	–	$< 0.00004^{d}$	–	–	–	Gottschall et al. (2017)
	BDE-99	3.4	–	$< 0.0001^{d}$	–	–	–	
	BDE-100	0.62	–	$< 0.00007^{d}$	–	–	–	
	BDE-153	0.3	–	$< 0.0004^{d}$	–	–	–	
	BDE-154	0.26	–	$< 0.00005^{d}$	–	–	–	
	BDE-183	0.07	–	$< 0.0003^{d}$	–	–	–	
	BDE-209	16.8	–	$< 0.0006^{d}$	–	–	–	
Sorghum (*Sorghum bicolor* L. Moench)	BDE-10	3.42	–	n.b	–	–	–	Yang et al. (2008)
	BDE-7	1.93	–	n.b	–	–	–	
	BDE-11	217.84	–	2	–	0.01	–	
	BDE-8	317.2	–	2	–	0.01	–	
	BDE-12 + 13	18.96	–	n.b	–	–	–	
	BDE-15	104.21	–	n.b	–	–	–	
	BDE-30	0.94	–	n.b	–	–	–	
	BDE-32	53.54	–	n.b	–	–	–	
	BDE-17 + 25	374.55	–	3	–	0.01	–	
	BDE-28 + 33	1021.26	–	7	–	0.01	–	
	BDE-35	54.47	–	n.b	–	–	–	
	BDE-37	188.13	–	2	–	0.01	–	
	BDE-75	120.51	–	8	–	0.07	–	
	BDE-49	1763.35	–	7	–	0	–	
	BDE-71	138.15	–	n.b	–	–	–	
	BDE-47	5349.07	–	42	–	0.01	–	
	BDE-66	2121.24	–	10	–	0	–	
	BDE-77	112.55	–	1	–	0.01	–	
	BDE-100	229.25	–	8	–	0.03	–	
	BDE-119	176.45	–	n.b	–	–	–	
	BDE-99	5469.37	–	43	–	0.01	–	
	BDE-116	1294.18	–	n.b	–	–	–	
	BDE-118	947.2	–	3	–	0	–	
	BDE-85	299.8	–	5	–	0.02	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE126 + 155	267.45	–	1	–	0	–	
	BDE-154	219.7	–	2	–	0.01	–	
	BDE-153	849.96	–	6	–	0.01	–	
	BDE-138	132.3	–	2	–	0.02	–	
	BDE-166	147.25	–	n.b	–	–	–	
	BDE-183	180.17	–	4	–	0.02	–	
	BDE-181	7.62	–	1	–	0.13	–	
	BDE-190	8.77	–	n.b	–	–	–	
	BDE-209	3288.06	–	2.51	–	0	–	
	ΣPBDE	25,478.84	–	161.51	–	0.01	–	
Prince-of-Wales feather (*Amaranthus hypochondriacus* L., after 65 days)	BDE-209	750–1650^{b}	94–1320^{b}	50–96^{b}	0.12–0.80^{b}	0.03–0.11^{b}	0.04–0.96^{b}	Li et al. (2018a)
Prince-of-Wales feather (*Amaranthus hypochondriacus* L., after 60 days)	BDE-209	1250–2100	1300–2050	50–355^{b}	0.81–1.64	0.03–0.27	0.04–0.23	Li et al. (2019a)
	ΣBr$_1$-Br$_9$-BDE	–	300–2700^{b}	45–100^{b}			0.04–0.15	
Prince-of-Wales feather (*Amaranthus hypochondriacus* L., after 60 days)	BDE-209	2440–3730	880–1460^{b}	210–430^{b}	0.25–0.47^{b}	0.064–0.17^{b}	0.16–0.41^{b}	Li et al. (2020a)
Leafy vegetable								
Pak-choi (*Brassica chinensis*)	BDE-209	8700	440	290	0.05	–	0.66	Wu et al. (2018a)
	BDE-28	0.3–1.1	–	1.4	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	1.2	–	–	–	
	BDE-100	0.2–1.4	–	0.4	–	–	–	
	BDE-99	0.2–1.8	–	0.4	–	–	–	
	BDE-154	0.2–1.1	–	0.4	–	–	–	
	BDE-153	0.3–2.1	–	n.b	–	–	–	
	BDE-183	0.5–3.0	–	0.4	–	–	–	
	BDE-209	12.9–44.9	–	4.2	–	0.092	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	ΣPBDE	17.0–51.7	–	8.3	–	0.174	–	
Pak-choi (*Brassica campestris* L. ssp. *pakchoi*, after 60 days)	∑BDEs	72.17–98.6	9.2	33.9	0.09–0.13	0.34–0.47	3.68	Wang et al. (2016a, b)
	BDE-28	0.66	0.27	–	0.41	–	–	
	BDE-47	4.27	1.58	–	0.37	–	–	
	BDE-99	0.36	0.55	–	1.52	–	–	
	BDE-100	3.24	0.1	–	0.03	–	–	
	BDE-154	0.45	0.21	–	0.47	–	–	
	BDE-153	0.76	0.16	–	0.21	–	–	
	BDE-183	0.73	0.36	–	0.49	–	–	
	BDE-209	61.7	5.55	–	0.09	–	–	
Romaine lettuce (*Lactuca sativa* L. var. *romana* Gars)	BDE-28	0.3–1.1	–	0.8	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	1.7	–	–	–	
	BDE-100	0.2–1.4	–	0.6	–	–	–	
	BDE-99	0.2–1.8	–	0.7	–	–	–	
	BDE-154	0.2–1.1	–	0.6	–	–	–	
	BDE-153	0.3–2.1	–	0.6	–	–	–	
	BDE-183	0.5–3.0	–	0.7	–	–	–	
	BDE-209	12.9–44.9	–	4.9	–	0.124	–	
	ΣPBDE	17.0–51.7	–	10.7	–	0.206	–	
Romaine lettuce (*Lactuca sativa* L. var. *longifolia* Lam.)	BDE-28	0.3–1.1	–	2	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	2.7	–	–	–	
	BDE-100	0.2–1.4	–	0.9	–	–	–	
	BDE-99	0.2–1.8	–	1.2	–	–	–	
	BDE-154	0.2–1.1	–	0.9	–	–	–	
	BDE-153	0.3–2.1	–	0.9	–	–	–	
	BDE-183	0.5–3.0	–	1	–	–	–	
	BDE-209	12.9–44.9	–	8.4	–	0.234	–	
	ΣPBDE	17.0–51.7	–	17.8	–	0.478	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Lettuce (*Lactuca sativa*, after 60 days)	∑PBDE	8.30–35.20	1.2	24.7	0.03–0.14	0.70–2.98	20.58	Wang et al. (2016a, b)
	BDE-28	0.42	0.08	–	0.2	–	–	
	BDE-47	2.15	0.13	–	0.06	–	–	
	BDE-99	0.18	0.06	–	0.33	–	–	
	BDE-100	1.31	0.01	–	0.01	–	–	
	BDE-154	0.25	0.02	–	0.06	–	–	
	BDE-153	0.39	0.02	–	0.04	–	–	
	BDE-183	0.5	0.02	–	0.03	–	–	
	BDE-209	30	1.5	–	0.05	–	–	
Lettuce (*Lactuca sativa* L.)	ΣPBDE	40^{b}	3.3^{b}	2^{b}	0.08	–	0.61	Wang et al. (2014)
Butterhead lettuce (*Lactuca sativa* L. var. *capitata* L, after 60 days)	∑PBDE	351.1	10.66	18^{b}	0.03	–	1.7^{b}	Wang et al. (2016a, b)
	BDE-28	0.1	0.26	–	2.63	–	–	
	BDE-47	0.42	1.68	–	3.99	–	–	
	BDE-99	0.51	0.69	–	1.36	–	–	
	BDE-100	0.36	0.27	–	0.74	–	–	
	BDE-154	0.2	0.47	–	2.37	–	–	
	BDE-153	0.92	0.18	–	0.2	–	–	
	BDE-183	0.59	0.14	–	0.24	–	–	
	BDE-209	348	6.96	–	0.02	–	–	
Spinach (*Spinacia oleracea*, after 28 days)	BDE-17	0.01	–	n.d.–0.01^{c}	–	2.28–3.08	–	Navarro et al. (2017) and Wu et al. (2018b)
	BDE-28	0.01	–	n.d.–0.01^{c}	–	–	–	
	BDE-47	0.06–0.15	–	0.13–0.21^{c}	–	1.02–2.12	–	
	BDE-66	n.d	–	n.d	–	–	–	
	BDE-85	0.01	–	n.d	–	–	–	
	BDE-99	0.17–0.31	–	0.06–0.27^{c}	–	0.27–0.93	–	
	BDE-100	0.04–0.06	–	n.d.–0.02^{c}	–	0.26–0.45	–	
	BDE-138	n.d	–	n.d	–	–	–	
	BDE-153	0.09–0.12	–	0.01–0.05^{c}	–	0.06–0.51	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-154	0.08	–	0.02[c]	–	0.22–0.24	–	
	BDE-183	0.15–0.22	–	n.d.–0.07[c]	–	0.37	–	
	BDE-184	0.03	–	n.d	–	–	–	
	BDE-191	0.03–0.05	–	n.d	–	–	–	
	BDE-196	0.26–0.31	–	n.d	–	–	–	
	BDE-197	0.47–0.56	–	n.d	–	–	–	
	BDE-206	0.43–0.45	–	n.d	–	–	–	
	BDE-207	0.47–0.60	–	n.d	–	–	–	
	BDE-209	5.63–8.07	–	–	–	–	–	
	ΣPBDE	8.56–10.4	–	0.27–0.48[c]	–	–	–	
Spinat (*Spinacia oleracea* L.), nach 25 Tagen	BDE-209	420[e]	–	10.9–35.1[c]	–	0.026–0.084[e]	–	Wu et al. (2018b)
Hill Gynura (*Gynura cusimbua* D. Don S. Moore)	ΣPBDE	3.83	1.1[b]	1.2[b]	0.29	–	1.09	Wang et al. (2014)
Chinese spinach (*Ipomoea aquatica* Forsk)	ΣPBDE	15[b]	2.8[b]	2.2[b]	0.19	–	0.79	Wang et al. (2014)
Chinese spinach (*Ipomoea aquatica* Forsk, after 25 days)	BDE-209	420[e]	–	6.03–37.1[c]	–	0.014–0.088[e]	–	Wu et al. (2018b)
Broccoli (*Brassica oleracea* L. var. *botrytis*, after 60 days)	∑PBDE	17.6–39.79	9.2	24.2	0.23–0.52	0.62–1.38	2.63	Wang et al. (2016a, b)
	BDE-28	0.25	0.43	–	1.7	–	–	
	BDE-47	1.59	1.84	–	1.16	–	–	
	BDE-99	0.17	0.61	–	3.59	–	–	
	BDE-100	0.86	0.14	–	0.16	–	–	
	BDE-154	0.19	0.1	–	0.54	–	–	
	BDE-153	0.3	0.14	–	0.46	–	–	
	BDE-183	0.23	0.26	–	1.13	–	–	
	BDE-209	36.2	5.79	–	0.16	–	–	
Sweet potato vine (*Ipomoea batatas* L., after 28 days, pot test)	ΣPBDE	0.68	–	12.3–19.36	–	18.1–18.5	–	Yang et al. (2018)
	BDE-209	0.6123	–	11.54–16.61	–	18.8–27.1	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-207	0.0387	–	0.332–1.384	–	8.6–35.8	–	
	BDE-206	0.0208	–	0.369–1.208	–	17.7–58.1	–	
	BDE-197	0.0025	–	0.012–0.068	–	4.9–26.9	–	
	BDE-196	0.0018	–	0.015–0.060	–	8.0–32.7	–	
	BDE-191	0.0001	–	n.d.–0.004	–	n.d.–56.9	–	
	BDE-184	0.0001	–	0.001–0.002	–	18.1–28.5	–	
	BDE-183	0.0024	–	0.014	–	5.7	–	
	BDE-154	0.0001	–	0.001–0.002	–	9.0–14.2	–	
	BDE-153	0.0005	–	0.002–0.004	–	4.1–7.8	–	
	BDE-100	–	–	n.d.–0.001	–	–	–	
	BDE-99	0.0001	–	0.002–0.004	–	14.2–27.1	–	
	BDE-47	0.0003	–	0.002–0.009	–	7.1–31.7	–	
Sweet potato vine (*Ipomoea batatas* L., after 28 days (field test)	BDE-183	< 0.01	–	0.02	–	–	–	Yang et al. (2018)
	BDE-196	< 0.01	–	0.06	–	–	–	
	BDE-197	< 0.01	–	0.08	–	–	–	
	BDE-206	0.02	–	1.2	–	60	–	
	BDE-207	0.04	–	1.37	–	34.3	–	
	BDE-209	0.61	–	321.6	–	527	–	
Sweet potato vine (*Ipomoea batatas* L., after 60 days)	$\sum$BDEs	19.83	9.96	30^{b}	0.5	–	3.0^{b}	Wang et al. (2016a, b)
	BDE-28	0.18	0.66	–	3.68	–	–	
	BDE-47	1.23	4.69	–	3.81	–	–	
	BDE-99	0.16	1.14	–	7.15	–	–	
	BDE-100	0.59	0.21	–	0.35	–	–	
	BDE-154	0.24	0.2	–	0.85	–	–	
	BDE-153	0.26	0.17	–	0.64	–	–	
	BDE-183	0.67	0.08	–	0.12	–	–	
	BDE-209	16.5	2.81	–	0.17	–	–	
Chinese kale (*Brassica alboglabra* L.)	BDE-28	0.3–1.1	–	1.6	–	–	–	Wang et al. (2011b)

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-47	0.5–1.8	–	2	–	–	–	
	BDE-100	0.2–1.4	–	0.6	–	–	–	
	BDE-99	0.2–1.8	–	0.8	–	–	–	
	BDE-154	0.2–1.1	–	0.7	–	–	–	
	BDE-153	0.3–2.1	–	0.3	–	–	–	
	BDE-183	0.5–3.0	–	0.5	–	–	–	
	BDE-209	12.9–44.9	–	13.4	–	0.298	–	
	ΣPBDE	17.0–51.7	–	19.9	–	0.417	–	
Chinese kale (*Brassica alboglabra* L. H. Bailey, after 60 days)	∑PBDE	19.0–27.58	4.84	27.1	0.18–0.25	0.98–1.42	5.6	Wang et al. (2016a, b)
	BDE-28	0.21	0.27	–	1.28	–	–	
	BDE-47	1.46	1.94	–	1.33	–	–	
	BDE-99	0.18	0.72	–	3.98	–	–	
	BDE-100	0.8	0.14	–	0.17	–	–	
	BDE-154	0.19	0.19	–	1.01	–	–	
	BDE-153	0.29	0.13	–	0.44	–	–	
	BDE-183	0.25	0.07	–	0.27	–	–	
	BDE-209	24.2	2.18	–	0.09	–	–	
Cabbage (*Brassica oleracea* var. *capitata*, after 60 days)	∑PBDE	126–281.74	168.1	162.1	0.60–1.33	0.58–1.28	0.96	Wang et al. (2016a, b)
	BDE-28	0.28	0.52	–	1.84	–	–	
	BDE-47	1.79	2.43	–	1.36	–	–	
	BDE-99	0.06	0.95	–	15.87	–	–	
	BDE-100	0.86	0.16	–	0.19	–	–	
	BDE-154	0.61	2.29	–	3.75	–	–	
	BDE-153	1.15	5.21	–	4.53	–	–	
	BDE-183	4.99	6.99	–	1.4	–	–	
	BDE-209	272	87.04	–	0.32	–	–	
Chinese cabbage (*Brassica pekinensis,* after 60 days)	∑PBDE	24.2–28.1	11.6	9.7	0.41–0.48	0.35–0.40	0.84	Wang et al. (2016a, b)
	BDE-28	0.5	0.3	–	0.6	–	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-47	3.32	1.29	–	0.39	–	–	
	BDE-99	0.38	0.35	–	0.92	–	–	
	BDE-100	1.84	0.07	–	0.04	–	–	
	BDE-154	0.41	0.11	–	0.27	–	–	
	BDE-153	0.66	0.11	–	0.17	–	–	
	BDE-183	0.49	0.19	–	0.39	–	–	
	BDE-209	20.5	8.61	–	0.42	–	–	
Root vegetables								
Radish (*Raphanus sativus* L.)	BDE-28	0.3–1.1	–	0.4	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	0.4	–	–	–	
	BDE-100	0.2–1.4	–	n.b	–	–	–	
	BDE-99	0.2–1.8	–	0.3	–	–	–	
	BDE-154	0.2–1.1	–	n.b	–	–	–	
	BDE-153	0.3–2.1	–	0.4	–	–	–	
	BDE-183	0.5–3.0	–	n.b	–	–	–	
	BDE-209	12.9–44.9	–	0.6	–	0.029	–	
	ΣPBDE	17.0–51.7	–	2.1	–	0.082	–	
Radish (*Raphanus sativus* L.)	BDE-209	2967–3179	488–539	301–340	0.16–0.17	0.10–0.11	0.62–0.63	Huang et al. (2010)
Radish (*Raphanus sativus* L., after 60 days)	$\sum$PBDE	10.73–25.3	1	24.2	0.04–0.09	0.96–2.26	24.2	Wang et al. (2016a, b)
	BDE-28	0.2	0.14	–	0.71	–	–	
	BDE-47	1.49	0.16	–	0.11	–	–	
	BDE-99	0.22	0.09	–	0.41	–	–	
	BDE-100	0.69	0.01	–	0.02	–	–	
	BDE-154	0.25	0.01	–	0.04	–	–	
	BDE-153	0.32	0.02	–	0.05	–	–	
	BDE-183	0.43	0.01	–	0.03	–	–	
	BDE-209	21.7	0.65	–	0.03	–	–	
White radish (*Raphanus sativus,* after 10 days)	BDE-3	4800	90–430	–	0.02–0.09	–	–	Yang et al. (2017)

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
Radish (*Raphanus sativus* L. red cherriette F1)	DE-71 (commercial mixture of Br_5-BDEs(mainly BDE-47, -99, -100)	4.2–32	1–1.2	0.75–1	0.04–0.24	–	0.75–0.83	Mueller et al. (2006)
Carrot (*Daucus carota* L.)	BDE-28	0.3–1.1	–	0.5	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	0.7	–	–	–	
	BDE-100	0.2–1.4	–	0.3	–	–	–	
	BDE-99	0.2–1.8	–	0.4	–	–	–	
	BDE-154	0.2–1.1	–	0.3	–	–	–	
	BDE-153	0.3–2.1	–	0.3	–	–	–	
	BDE-183	0.5–3.0	–	0.3	–	–	–	
	BDE-209	12.9–44.9	–	5.1	–	0.113	–	
	ΣPBDE	17.0–51.7	–	7.8	–	0.164	–	
Carrot (*Daucus carota* L., after 90 days)	BDE-47	121.1–268.4	ca. 47–225	ca. 20–96	ca. 0.18–1.86	–	ca. 0.4–0.429	Xiang et al. (2018)
Carrot (*Daucus carota* L., after 90 days)	BDE-4	0.50–1.00^b	–	–	–	–	–	Xiang et al. (2019a)
	BDE-15	1.10–1.20^b	–	–	–	–	–	
	BDE-17	0.80–0.90^b	–	–	–	–	–	
	BDE-28	1.90–6.90^b	–	–	–	–	–	
	BDE-47	66–268^b	46–230^b	24–100^b	0.19–1.96^b	0.09–0.82^b	0.29–0.61^b	
	BDE-209	1.90–9.80^b	–	–	–	–	–	
Carrot (*Daucus carota* L., after 90 days)	BDE-4	0–0.68^b	–	–	–	–	–	Xiang et al. (2019b)
	BDE-15	0–1.35^b	–	–	–	–	–	
	BDE-17	0–0.97^b	–	–	–	–	–	
	BDE-28	3.1–9.3^b	–	–	–	–	–	
	BDE-47	50–125^b	66–228^b	5–100^b	0.80–1.82^b	0.10–0.80^b	0.08–0.44^b	
Taro (*Colocasia esculenta* L. Schott)	BDE-28	0.3–1.1	–	0.3	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	0.4	–	–	–	
	BDE-100	0.2–1.4	–	0.3	–	–	–	
	BDE-99	0.2–1.8	–	0.3	–	–	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/ shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-154	0.2–1.1	–	0.3	–	–	–	
	BDE-153	0.3–2.1	–	0.3	–	–	–	
	BDE-183	0.5–3.0	–	0.4	–	–	–	
	BDE-209	12.9–44.9	–	4.9	–	0.266	–	
	ΣPBDE	17.0–51.7	–	7.2	–	0.329	–	
Taro (*Colocasia esculenta L. Schott,* after 60 days)	BDE-209	2919–3029.2	124.1–135.1	11.5–12.1	0.04–0.05	< 0.01	0.09–0.10	(Deng et al. 2016)
	∑PBDE	2953–3069.4	189.6–232.2	56–62.8	0.06–0.08	0.02	0.24–0.33	
Taro (*Colocasia esculenta* L. Schott, after 60 days)	∑BDEs	76.80–86.88	1.2	31.5	0.01–0.02	0.36–0.41	26.25	Wang et al. (2016a, b)
	BDE-28	0.8	0.08	–	0.1	–	–	
	BDE-47	3.88	0.04	–	0.01	–	–	
	BDE-99	0.37	0.03	–	0.07	–	–	
	BDE-100	2.11	0.02	–	0.01	–	–	
	BDE-154	0.59	0.02	–	0.04	–	–	
	BDE-153	0.69	0.03	–	0.04	–	–	
	BDE-183	0.76	0.02	–	0.03	–	–	
	BDE-209	67.6	1.35	–	0.02	–	–	
Taro (*Colocasia esculenta* L. Schott)	ΣPBDE	45^{b}	13^{b}	0.88	0.29	–	0.07	Wang et al. (2014)
Shallot (*Allium ascalonicum* L.)	BDE-28	0.3–1.1	–	1	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	1.5	–	–	–	
	BDE-100	0.2–1.4	–	0.5	–	–	–	
	BDE-99	0.2–1.8	–	0.8	–	–	–	
	BDE-154	0.2–1.1	–	0.5	–	–	–	
	BDE-153	0.3–2.1	–	0.6	–	–	–	
	BDE-183	0.5–3.0	–	0.6	–	–	–	
	BDE-209	12.9–44.9	–	4.4	–	0.098	–	
	ΣPBDE	17.0–51.7	–	9.9	–	0.207	–	
Welsh onion (*Allium fistulosum*, after 60 days)	∑BDEs	7.55–15.31	11.6	29	0.76–1.54	1.89–3.84	2.5	Wang et al. (2016a, b)
	BDE-28	0.3	0.48	–	1.61	–	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-47	1.73	3.79	–	2.19	–	–	
	BDE-99	0.18	2.36	–	13.1	–	–	
	BDE-100	0.88	0.29	–	0.33	–	–	
	BDE-154	0.18	0.31	–	1.71	–	–	
	BDE-153	0.29	0.22	–	0.77	–	–	
	BDE-183	0.25	0.12	–	0.49	–	–	
	BDE-209	11.5	3.34	–	0.29	–	–	
Celery (*Apium graveolens*, after 60 days)	∑BDEs	13.99–16.8	17.4	38.7	1.04–1.24	2.30–2.77	2.22	Wang et al. (2016a, b)
	BDE-28	0.31	2.43	–	7.83	–	–	
	BDE-47	1.66	7.75	–	4.67	–	–	
	BDE-99	0.18	2.08	–	11.56	–	–	
	BDE-100	0.95	0.35	–	0.37	–	–	
	BDE-154	0.19	0.31	–	1.65	–	–	
	BDE-153	0.32	0.27	–	0.85	–	–	
	BDE-183	0.28	0.13	–	0.45	–	–	
	BDE-209	10.1	4.44	–	0.44	–	–	
Sweet potato (*Ipomoea batatas* L.)	ΣPBDE	735	4^{b}	2.2^{b}	0.01	–	0.55	Wang et al. (2014)
Legumes								
Pea (*Pisum sativum* L.)	BDE-28	0.3–1.1	–	1.7	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	1.7	–	–	–	
	BDE-100	0.2–1.4	–	0.6	–	–	–	
	BDE-99	0.2–1.8	–	0.7	–	–	–	
	BDE-154	0.2–1.1	–	0.5	–	–	–	
	BDE-153	0.3–2.1	–	0.6	–	–	–	
	BDE-183	0.5–3.0	–	–	–	–	–	
	BDE-209	12.9–44.9	–	3.9	–	0.09	–	
	ΣPBDE	17.0–51.7	–	9.7	–	0.21	–	
Pea (*Pisum sativum* L., after 60 days)	∑BDEs	77.1–104.18	14.14	33.9	0.13–0.18	0.33–0.44	2.42	Wang et al. (2016a, b)

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-28	0.5	0.66	–	1.32	–	–	
	BDE-47	2.79	2.85	–	1.02	–	–	
	BDE-99	0.31	1.1	–	3.56	–	–	
	BDE-100	1.75	0.23	–	0.13	–	–	
	BDE-154	0.51	0.29	–	0.57	–	–	
	BDE-153	0.65	0.15	–	0.23	–	–	
	BDE-183	0.87	0.15	–	0.17	–	–	
	BDE-209	96.8	8.71	–	0.09	–	–	
Alfalfa (*Medicago sativa* L. cv. Chaoren)	BDE-209	3878–4336	538–595	461–520	0.14	0.12	0.86–0.87	Huang et al. (2010)
Alfalfa (*Medicago sativa* L., after 90 days)	BDE-209	310–3165	< 25	–	–	–	–	He et al. (2015)
Peanut (*Arachis hypogaea* L.)	BDE-15	0.67	–	0.68	–	1.01	–	Wang et al. (2015)
	BDE-28	0.29	–	0.41	–	1.41	–	
	BDE-47	1.12	–	1.13	–	1.01	–	
	BDE-100	0.84	–	0.37	–	0.44	–	
	BDE-99	1	–	1.66	–	1.66	–	
	BDE-154	0.32	–	0.4	–	1.25	–	
	BDE-153	0.59	–	0.73	–	1.24	–	
	BDE-183	0.24	–	n.d	–	–	–	
	BDE-203	0.12	–	n.d	–	–	–	
	BDE-208	0.12	–	n.d	–	–	–	
	BDE-207	1.48	–	n.d	–	–	–	
	BDE-206	0.25	–	n.d	–	–	–	
	BDE-209	162.43	–	16.28	–	0.1	–	
	ΣPBDE	115.81	–	21.66	–	0.19	–	
Peanut (*Arachis hypogaea* L.)	ΣPBDE	4[b]	0.97[b]	1.6[b]	0.24	–	1.65	Wang et al. (2014)
Peanut (*Arachis hypogaea* Linn., after 105 days)	BDE-28	–	–	–	1[b]	–	0.32[b]	Fan et al. (2020)
	BDE-47	–	–	–	0.21[b]	–	0.27[b]	
	BDE-66	–	–	–	–	–	–	
	BDE-85	–	–	–	–	–	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-99	–	–	–	0.29^{b}	–	0.19^{b}	
	BDE-100	–	–	–	1.3^{b}	–	0.19^{b}	
	BDE-153	–	–	–	0.29^{b}	–	0.35^{b}	
	BDE-154	–	–	–	0.53^{b}	–	0.21^{b}	
	BDE-183	–	–	–	–	–	–	
	BDE-196	–	–	–	–	–	–	
	BDE-197	–	–	–	–	–	–	
	BDE-203	–	–	–	–	–	–	
	BDE-206	–	–	–	–	–	–	
	BDE-207	–	–	–	–	–	–	
	BDE-208	–	–	–	–	–	–	
	BDE-209	450^{b}	57^{b}	0–132^{b}	0.13^{b}	–	2.29^{b}	
	$\sum$de-BDE	32^{b}	5.5^{b}	0–4.4^{b}	–	–	–	
Cowpea (*Vigna unguiculata* L. Walp)	ΣPBDE	20^{b}	2^{b}	3.2^{b}	0.1	–	1.6	Wang et al. (2014)
Cucurbits								
Zucchini (*Cucurbita pepo* ssp. *pepo* cv. Lvjinli)	BDE-209	3221–3583	1849–2044	212–239	0.57	0.06–0.07	0.11–0.12	Huang et al. (2010)
Zucchini (*Cucurbita pepo* ssp. *pepo* cv. Cuiyu-2)	4076–4710	1948–2193	231–261	0.46–0.48	0.05–0.06	0.12		Huang et al. (2010)
Zucchini (*Cucurbita pepo* ssp. *pepo* cv. Lvjinli)	BDE-3	2.5–5.8	n.d	–	–	–	–	Huang et al. (2011)
	BDE-7	1–1.7	n.d	–	–	–	–	
	BDE-17	0.8–8	1.2–6.2	–	0.78–1.50	–	–	
	BDE-28	1.5–12.2	7.1–7.1	–	0.58–4.73	–	–	
	BDE-49	4–15.3	0.4–5.9	–	0.10–0.39	–	–	
	BDE-47	5.9–58.1	9–66.1	–	1.14–1.53	–	–	
	BDE-66	13.8–37.8	1.1–23.4	–	0.08–0.62	–	–	
	BDE-100	4.4–8.6	1.5–7	–	0.34–0.81	–	–	
	BDE-99	8.6–82.7	10.2–83.4	–	1.01–1.19	–	–	
	BDE-85	15.4–20.5	7.2–14.1	–	0.47–0.69	–	–	
	BDE-154	7.5–9.7	3.8–6.6	–	0.51–0.68	–	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-153	3.5–15.5	0.4–13.1	–	0.11–0.85	–	–	
	BDE-156	1–1.2	n.d	–	–	–	–	
	BDE-183	4.5–40.8	1.2–10.6	–	0.26–0.27	–	–	
	BDE-191	18.9–58.8	16–31.5	–	0.54–0.85	–	–	
	BDE-197	6.4–10.6	3.6–5.1	–	0.48–0.56	–	–	
	BDE-196	1.3–10.5	2.1–6	–	0.57–1.62	–	–	
	BDE-208	1.1–37.7	0.1–1.8	–	0.05–0.09	–	–	
	BDE-207	2.3–48.9	0.6–4.6	–	0.09–0.26	–	–	
	BDE-206	1.8–44.1	1.3–5.3	–	0.12–0.72	–	–	
	BDE-209	69.7–525.4	35.1–110.4	–	0.21–0.50	–	–	
	∑PBDE	201–997.4	132.2–347.7	–	0.35–0.66	–	0.21–0.5	
Pumpkin (after 60 days)	BDE-138	–	1.8–10.1	0.03–7.2	–	–	0.015–0.80	Lu et al. (2013)
	BDE-183	–	3.3–16.9	0.02–4.0	–	–	0.005–0.25	
	BDE-191	–	8.2–30.9	0.06–12.1	–	–	0.007–0.45	
	BDE-196	–	14.8–42.8	0.03–23.0	–	–	0.002–0.61	
	BDE-197	–	5.3–25.3	0.04–10.6	–	–	0.008–0.45	
	BDE-206	–	135–227	1.43–30.4	–	–	0.009–0.15	
	BDE-207	–	55.2–93.0	1.28–47.8	–	–	0.023–0.58	
	BDE-208	–	31.9–75.9	0.20–14.4	–	–	0.006–0.19	
	BDE-209	4743–4850	1164–2354	5.63–342	0.25–0.49	0.001–0.071	0.004–0.20	
Pumpkin (*Cucurbita moschata, after 25 days*)	BDE-209	420^{e}	–	11.4–47.4^{c}	–	0.027–0.113^{e}	–	Wu et al. (2018b)
Pumpkin (*Cucurbita pepo* L., after 90 days)	BDE-209	261–3995	< 25	–	–	–	–	He et al. (2015)
Yellow zucchini (*Cucurbita pepo* L.)	DE-71 (commercial mixture of Br_5-BDEs (mainly BDE-47, -99, -100)	3.4–32	2.2–2.5	4	0.08–0.22	–	1.6–1.8	Mueller et al. (2006)
Cucumber (*Cucumis sativus* L., after 25 days)	BDE-209	420^{e}	–	7.65–39.1^{c}	–	0.018–0.093^{e}	–	Wu et al. (2018b)
Others								
Tobacco (*Nicotiana tabacum*)	BDE-47	139.4	0.5	38.5–61.6	0.004	0.29	–	Vrkoslavová et al. (2010)
	ΣPenta-BDE	568	n.d	68.4	–	0.12	–	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-99	166.3	n.d	10.5–22.6	–	0.12	–	
	BDE-100	28.7	n.d	4.5–7.3.0	–	0.23	–	
	BDE-209	400.3	n.d	n.d.–116.8	–	0.04	–	
Crown daisy (*Chrysanthemum coronarium* L.)	BDE-28	0.3–1.1	–	2.4	–	–	–	Wang et al. (2011b)
	BDE-47	0.5–1.8	–	2	–	–	–	
	BDE-100	0.2–1.4	–	0.6	–	–	–	
	BDE-99	0.2–1.8	–	0.8	–	–	–	
	BDE-154	0.2–1.1	–	0.6	–	–	–	
	BDE-153	0.3–2.1	–	0.6	–	–	–	
	BDE-183	0.5–3.0	–	0.8	–	–	–	
	BDE-209	12.9–44.9	–	5.3	–	0.145	–	
	ΣPBDE	17.0–51.7	–	13	–	0.313	–	
Crown daisy (*Chrysanthemum coronarium* L., after 60 days)	∑PBDE	97.6–108.93	87.1	29	0.80–0.89	0.27–0.30	0.33	Wang et al. (2015, 2016a, b)
	BDE-28	0.6	1.61	–	2.69	–	–	
	BDE-47	3.02	4.05	–	1.34	–	–	
	BDE-99	0.28	1.65	–	5.89	–	–	
	BDE-100	1.72	0.26	–	0.15	–	–	
	BDE-154	0.49	0.43	–	0.88	–	–	
	BDE-153	0.56	0.27	–	0.48	–	–	
	BDE-183	0.26	0.14	–	0.52	–	–	
	BDE-209	102	79.56	–	0.78	–	–	
Aubergine (*Solanum melongena* L.)	ΣPBDE	620^{b}	5.9^{b}	5.69	0.01	–	0.96	Wang et al. (2014)
Tomato (*Solanum lycopersicum* L., after 6 months)	BDE-17	n.d	n.d.–0.01	0.01	3.00–8.00	0.49–2.36	1	Navarro et al. (2017)
	BDE-28	n.d.–0.01	0.01–0.04	0.01–0.03	3.21–33.3	1.94–16.7	0.25–3.00	
	BDE-47	0.12–0.23	0.27–0.36	0.31–0.49	1.77–2.64	1.60–2.48	0.86–1.81	
	BDE-66	0.01	n.d.–0.01	n.d	0.03–3.20	0.03–0.12	–	
	BDE-99	0.22–0.54	0.37–0.55	0.06–0.17	1.58–2.93	0.23–0.66	0.12–0.41	
	BDE-100	0.05–0.08	0.04–0.07	0.02–0.06	0.97–1.31	0.39–1.14	0.29–1.00	

Table 5 continued

Plant species (for food production)	PBDE	Conc. soil (ng g DM^{-1})	Conc. root (ng g DM^{-1})	Conc. plant/shoot (ng g DM^{-1})	$\frac{c_{root}}{c_{soil}}$	$\frac{c_{plant}}{c_{soil}}$	$\frac{c_{shoot}}{c_{root}}$	Source
	BDE-153	0.07–0.10	0.01–0.04	n.d.–0.01	0.28–0.52	0.07–0.10	0.25–1.00	
	BDE-154	0.06–0.07	0.01–0.04	n.d.–0.11	0.22–0.59	0.01–4.47	0.25–1.00	
	BDE-183	0.14–0.28	0.06–0.07	n.d.–0.02	0.39–1.16	0.02–0.21	0.14	
	BDE-184	0.02–0.03	n.d.–0.01	n.d	0.21	–	–	
	BDE-191	0.02–0.03	n.d	n.d	–	–	–	
	BDE-196	0.20–0.25	n.d.–0.03	n.d.–0.04	0.22	0.03–0.16	0.67	
	BDE-197	0.12–0.31	n.d.–0.03	n.d.–0.02	0.19	0.09–0.11	0.67	
	BDE-206	0.57–0.89	n.d.–0.13	n.d.–0.58	0.2	0.02–0.80	0.08–1.00	
	BDE-207	0.60–1.05	n.d.–0.16	n.d.–0.50	0.27	0.03–0.62	0.06–0.69	
	BDE-209	6.54–10.5	n.d.–2.92	n.d.–10.4	0.34	0.03–1.58	0.03–1.63	
	ΣPBDE	8.99–13.0	0.88–4.26	0.002–11.6	–	–	–	

n.d. not detected

[a] All data related to grams of lipid

[b] Read from charts

[c] Whole plant incl. roots

[d] Solely grains

[e] Related to the initial soil concentration

grasses, herbs and flowers (Table 2); Mangrove trees (Table 3); Forest trees and ornamental trees (Table 4); and crops for food production (Table 5). Data were partially derived from figures presented in literature.

9 Conclusions

PBDEs have been used as flame retardants in various products for decades. Despite legal restrictions, they are still released into the environment at high concentrations. Due to negative effects as endocrine disruptor, neurotoxicity and on reproductive capacity, knowledge of their accumulation in soil and, in particular, their uptake by plants for food production is of high relevance. PBDE plant uptake can take place both by the soil–air–plant tissue pathway and the soil–soil water–root–plant pathway. In former case, low brominated BDEs (Br_2-Br_5) predominantly occur in gaseous form, while high-brominated BDEs (Br_8-Br_{10}) are exclusively detected in particulate form. Accordingly, gaseous BDEs are almost present ubiquitously, while concentrations of particulate BDEs strongly decline with distance from the emission source.

Transport and plant uptake are strongly affected by physical and chemical properties of the BDEs (vapor pressure, octanol–water partition coefficient, air–water partition coefficient, air–plant partition coefficient), environmental factors (i.e. temperature, wind velocity, amount of rain, temporal rain distribution, gas deposition kinetics, particle-bound deposition kinetics), large-scale atmospheric transport processes, plant properties (i.e. species, lipid content, foliage morphology, non-lipid plant parts, bark thickness, sugar content, fiber content) as well as terrestrial rhizospheres. During atmospheric transport PBDEs are subject to UV-induced transformation processes like debromination, hydroxylation and ring closure to dibenzofurans. Due to the lipophilic character, PBDEs are characterized by an increased adsorption on lipophilic soil matrices and, thus, by a lack of mobility and low uptake via the soil–soil water–root–plant pathway. Hence, uptake and intrinsic transport is only expected for low brominated BDEs. Therefore, declining concentrations of PBDEs could be detected from soil via roots via shoots and fruit, i.e. both RCF and TF value are negatively correlated with the log K_{OW} value. Corresponding studies therefore showed a dominant human intake of PBDEs by respiration and inhalation of dust with 84%, while only 16% were correlated with dietary uptake.

The actual exposure of vegetarian foods to PBDEs depends on many parameters, where mineralization and detoxification mechanisms in both the soil matrix and the plant tissue significantly affect the resulting levels. The following parameters were identified as relevant for plant uptake behavior:

- The release of plant intermediates like amino acids, organic acids, sugars and exoenzymes, as occurs for example in symbiosis with rhizobia, both promotes microbial degradation of PBDEs in the soil matrix and PBDE plant uptake.
- Microbial degradation of PBDEs in soil and plant uptake are enhanced in presence of a rhizosphere.
- Atmospheric PBDE uptake is strongly influenced by the plant morphology and especially the lipid content of the shoots. PBDE levels rise with increasing lipid content.
- The PBDE plant uptake is promoted by an increase of the specific surface area of the roots or leaves.
- The lipid content of the plant can be directly correlated with the RCF value of the plant, i.e. high lipid contents in the plant roots lead to an increased PBDE uptake. In parallel, however, high root lipid levels evoke immobilization of PBDEs in the roots and thus a low TF value. Basically, the higher the plant's lipid content the higher the PBDE uptake and thus PBDE load in consumable parts of the plant and subsequent food products.
- PBDE immobilization and accumulation is promoted by increasing TOC levels in soil (e.g. through the introduction of compost, sewage sludge, digestates, biochar), i.e. PBDE plant uptake decreases with increasing TOC levels.
- There is no effect of increasing DOC levels on PBDE plant uptake due to the lack of solubility. However, terrestrial microbial biodegradation is supported.
- With PBDE loads of up to 2.5 w%, sewage sludge represents an important source of PBDEs causing a considerable increase in soil pollution. In contrast, the PBDE load of compost and digestates is low, i.e. soil pollution effects are negligible.
- High lipophilic alternate soil conditioners enforce immobilization and therefore reduced plant uptake of PBDEs.

- With increasing soil moisture, evaporative PBDE losses decrease on the one hand and immobilization of PBDEs increases on the other hand. Plant uptake thus decreases with increasing soil moisture.
- Ionic additives as well as nanoscale organic substances (i.e. graphite powder, carbon nanotubes) both increase mobilization and plant uptake of PBDEs due to surfactant effects and the particle size. The same effect is observed for solubilizers.
- Macroelements such as nitrate favor the terrestrial degradation of PBDEs through their function as an alternative electron acceptor, which indirectly reduces the plant's load.
- Regarding the low concentration levels, trace elements have no effect on PBDE plant uptake. However, microbial transformation of PBDEs in soil is enhanced and, thus, PBDE load is reduced.
- The presence of heavy metals at high levels indirectly enforces PBDE plant uptake due to the inhibition of the terrestrial microbial degradation.
- Predictive mathematical models exist, which allow a very good prediction of the RCF value with a minimum of input parameters. In contrast, the prediction of SCF and TF values is not appropriate due to the inadequate recording of plant-specific parameters.
- In accordance to Lipinski´s 'Law of 5′ Br_4- and Br_5-BDE congeners show the highest RCF levels, while high TF factors require higher polarity. Within the same isomers, even slight differences in lipophilicity significantly affect these levels.

10 Outlook

According to the poor biodegradability of PBDEs, questions concerning the accumulation of PBDEs in the food chain and inhalation exposure will continue to be relevant for future decades. Comparable problems as described for PBDEs could be expected for alternative brominated flame retardants such as hexabromobenzene, pentabromotoluene, 1,2-bis-(2,4,6-tribromophenoxy)ethane, decabromodiphenylethane or dechloran plus, since they also exhibit a high degree of bromination, high persistence and a high bioaccumulation potential.

Acknowledgements We would like to thank Lukas Lesmeister (DVGW, Karlsruhe), Melanie Mechler (Center of Agricultural Technology Augustenberg, Karlsruhe) and Prof. Karl-Heinrich Engesser (ISWA, Stuttgart) for their continuous support.

Funding Open Access funding enabled and organized by Projekt DEAL. This work was supported by the German Federal Environment Agency [acronym FLUORTRANSFER, grant number FKZ 3718 74 210 0; AZ: 91 007-2/82].

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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