Emerging Contaminants 11 (2025) 100567

Contents lists available at ScienceDirect

Emerging Contaminants

journal homepage: www.keaipublishing.com/en/journals/emerging-contaminants

Review of brominated flame retardants and polybrominated dibenzo-p-dioxins and dibenzofurans in eggs and contamination sources

Jindrich Petrlik [a,b], Lee Bell [a,c], Joseph DiGangi [a], Aileen Lucero [d], Gilbert Kuepouo [e], Griffins Ochieng Ochola [f], Nikola Jelinek [b], Miroslava Jopkova [b], Jana Pulkrabova [g], Tomas Gramblicka [g], Martin Skalsky [h], Yuyun Ismawati [i], Eric Akortia [j], Sam Adu-Kumi [k], Penchom Saetang [l], Thitikorn Boontongmai [l], Maria Carcamo [m], Bjorn Beeler [a], Peter Behnisch [n], Christine Herold [o], Hana Walaska [b,p], Roland Weber [o,*]

[a] International Pollutants Elimination Network (IPEN), Göteborg, Sweden
[b] Arnika – Toxics and Waste Programme, Seifertova 85, Prague, Czech Republic
[c] Toxics Free Australia (TFA), Perth, Australia
[d] EcoWaste Coalition, 78a Masigla Ext, Diliman, Quezon City, Metro Manila, Philippines
[e] Centre de Recherche et d'Education pour le Developpement (CREPD), Yaounde, Cameroon
[f] Centre for Environmental Justice and Development (CEJAD), Nairobi, Kenya
[g] University of Chemistry and Technology, Faculty of Food and Biochemical Technology Department of Food Analysis and Nutrition, Technicka 5, Prague 6, Czech Republic
[h] Arnika – Citizens Support Center, Seifertova 85, Prague, Czech Republic
[i] Nexus3 Foundation, Denpasar, 80223, Indonesia
[j] Ghana Atomic Energy Commission, National Nuclear Research Institute, Accra, Republic of Ghana
[k] Environment Youth Action Network, 19 Hamburger Street, Fafraha-Adenta, Accra, Republic of Ghana
[l] Ecological Alert and Recovery – Thailand (EARTH), Nonthaburi, Thailand
[m] La Red de Accion en Plaguicidas y sus Alternativas para America Latina, Montevideo, Uruguay
[n] BioDetection Systems BV (BDS), Science Park 406, 1098 XH, Amsterdam, the Netherlands
[o] POPs Environmental Consulting, D-73527, Schwäbisch Gmünd, Germany
[p] Forensic Laboratory of Biologically Active substances, Department of Chemistry of Natural Compounds, Faculty of Food and Biochemical Technology, University of Chemistry and Technology Prague, Technicka 5, 16628, Prague, Czech Republic

ARTICLE INFO

Article history:
Received 5 August 2025
Received in revised form
31 August 2025
Accepted 10 September 2025
Available online 11 September 2025

Keywords:
PBDD/PBDF
PBDE
HBCDD
Novel BFRs
Plastic
Free-range eggs
Stockholm convention

ABSTRACT

The data on the concentrations of brominated flame retardants (BFRs) and polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs) in eggs from free-range chickens were reviewed and compiled including assignment to major sources. The highest levels of polybrominated diphenyl ethers (PBDEs) and PBDD/Fs in pooled eggs from free-range chickens were detected at sites where e-waste was burned, near waste incineration, metallurgical facilities and at landfills/dumps. The PBDD/F pattern indicated that PBDEs and Tetrabromobisphenol A (TBBPA) are the major sources for PBDD/F contamination in the eggs. Dioxin bio-assays like the DR CALUX are useful to screen for total dioxin toxicity (PCDD/Fs, dl-PCB, PBDD/Fs and mixed polybrominated-polychlorinated dibenzo-p-dioxins/furans (PXDD/Fs)). The robust and cheap bioassay approach is currently the only method which also quantifies the dioxin-like toxicity of the complex group of PXDD/Fs where instrumental analysis cannot quantify the dioxin toxicity.

A major source of human exposure to BFRs is eggs from chickens that have pecked particles from e-waste plastics or other waste/products treated with BFRs. When chickens ingest plastic particles containing contaminants, the latter are transferred to their eggs. This is similar to what has been documented for sea birds. The BFRs listed as persistent organic pollutants (POP) with the highest level detected were PBDEs and hexabromocyclododecane (HBCDD). HBCDD is mainly contained in expanded and extruded polystyrene (EPS/XPS) which can be easily pecked by chickens. This was likely the reason for several HBCDD contaminated eggs above 1000 ng/g fat and up to 18,321 ng/g fat. EPS/XPS insulation which contain 90 % of all HBCDD formerly produced (~640,000 tonnes in ~42 million tonnes of EPS/XPS) is partly also used as insulation in henhouses and other parts of farms and private houses. Since

* Corresponding author.
E-mail address: roland.weber10@web.de (R. Weber).
Peer review under the responsibility of KeAi Communications Co., Ltd.

https://doi.org/10.1016/j.emcon.2025.100567

chickens like to peck at and eat the soft polymer, this can be a relevant exposure source. A wide range of novel BFRs (nBFR) were detected in chicken eggs. The nBFR with the highest levels and frequency detected was 1,2-Bis(2,4,6-tribromophenoxy)ethane (BTBPE). BTBPE was often found in eggs in the monitoring of the International Pollutants Elimination Network (IPEN) with levels frequently above 10 ng/kg fat and three samples above 100 ng/g fat, up to 221 ng/g fat. DBDPE was also frequently detected in eggs with a maximum concentration of 2077 ng/g fat at the sites where plastic waste is used as fuel in boilers/incinerators. Also, hexabromobenzene (HBBz) was frequently detected in eggs above 0.1 ng/g fat with highest level of 30.3 ng HBBz/g fat.

Recommendations for controlling BFR and PBDD/F exposure of chicken and eggs are provided including the listing of PBDD/F and PXDD/F in the Stockholm Convention, the better control of plastic containing BFRs including the prohibition of exports of e-waste and plastic wastes to developing countries, better control and environmentally sound management of ashes from waste incineration or metallurgical processes, the improvement of environmentally sound management of BFR containing plastic wastes, prevention of recycling POPs containing wastes, and the substitution of BFRs.

1. Introduction

Twenty-eight persistent organic pollutants (POPs) or groups of POPs have been newly listed in the Stockholm Convention since 2009, including 5 brominated flame retardants (BFRs). These BFRs are tetraBDE/pentaBDE (to restrict commercial PentaBDE), hexaBDE/heptaBDE (to restrict commercial OctaBDE), decaBDE, hexabromobiphenyl (HBB) and hexabromocycldodecane (HBCDD) [1–4]. These listed brominated flame retardants (BFRs), like many other halogenated flame retardants, elicit toxic effects including e.g. endocrine disruption, reproductive toxicity, neurodevelopmental impairment, damage to the immune system, as well as cancer [5–9]. Furthermore, polybrominated dibenzo-p-dioxins and dibenzofurans (PBDD/Fs) and brominated-chlorinated PXDD/Fs are currently being evaluated in the POP Review Committee and it was concluded that they meet the POP criteria [3,10], and might be listed in 2027.

For humans, one of the main exposure routes to POPs is food [11–13]. BFRs have been detected at different levels in food [14] and for Nigeria, a recent increase of PBDEs in foodstuff has been reported [15]. However, it needs to be stressed that for PBDEs, the release from products like flame retarded upholstered furniture, car seats or pillows and recycling of polyurethane foam have been associated with high exposure and extremely high PBDE levels in individual persons ,[16,17]. Direct contact with treated textiles and house dust can also lead to considerable exposure to HBCDD and PBDEs [18,19].

For chlorinated POPs, like polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) or polychlorinated biphenyls (PCBs), and fluorinated POPs, such as PFOS or PFOA, the consumption of chicken eggs can be a major exposure source, in particular, if eggs from free-range chickens living on soils contaminated with POPs are frequently consumed [13,20–22]. For POPs, the consumption of chicken/eggs is probably the most sensitive exposure pathway from contaminated soil to humans [13,21,23]. The Food and Agriculture Organization of the United Nations (FAO) highlighted that contaminated soil is a high risk for global food production [24]. Due to the high proportion of soil in the feed of free-range chickens and the transfer of POPs into the eggs, chicken eggs are ideal “active samplers” and indicators for POP-contaminated soils [20,23]. Eggs play an important role in human nutrition, as they are a relatively inexpensive and a rich food source of very high biological value. The daily animal protein requirement for the human body can be covered by eggs in the cheapest way and with the lowest environmental impact [25]. In relation to total exposure to PCDD/Fs and PCBs the average exposure via eggs is considered moderate, e.g. 6 % in Europe [26,27]. Exposure via eggs can be much higher for people in contaminated areas consuming eggs from their own chicken flocks and can become a major exposure pathway on contaminated sites. This has been demonstrated by the significantly elevated PCDD/F body burdens in populations living on PCDD/F-contaminated sites [28,29].

There are abundant data on PCDD/F and dl-PCB contamination of free-range eggs from the last two decades (e.g. Ref. [13,30–32]) and data has recently been reviewed [20]. However, data for PBDD/Fs, brominated POPs and other BFRs in eggs are less prominent, in particular since there are no regulatory limits for PBDD/Fs and POP-BFRs in food and such information has not been compiled in a review. However, PBDD/Fs have toxicities similar to those of the highly toxic PCDD/Fs and are therefore also of concern [33–36]. The WHO expert group suggestion is to use the TEFs of PCDD/Fs until specific TEFs might be assigned for PBDD/Fs [36]. It is estimated that the production and use of the 1.9 million tonnes of PBDEs (Abassi et al., 2019; [4]) resulted in approximate 1000 tonnes of PBDD/Fs in plastics in products like electrical and electronic equipment (EEE), vehicles and textiles [37]. A considerable share of BFR-containing products has been exported to developing countries and these products are still in use or in waste streams [38–42]. Such wastes are frequently burned in the open or in simple waste incinerators with associated additional formation and releases of PBDD/Fs and brominated-chlorinated PXDD/Fs with related contamination of the environment and risk for human exposure via food [20,43–45].

In this review we compiled information on the contamination of chicken eggs in a systematic manner in respect to listed brominated POPs, PBDD/Fs and novel BFRs (nBFRs). In addition to scientific literature, a major resource for this review are the studies of Arnika Association, a civil society organization based in the Czech Republic and the International Pollutants Elimination Network (IPEN; formerly International POPs Elimination Network), an international network of more than 600 public interest NGOs active in more than 120 countries (https://ipen.org/about) which has monitored POPs in eggs since the Stockholm Convention entered into force in 2004 and analysed more than 100 potential pollution sources [20,46], especially in developing countries where there are large gaps in POP monitoring data for polluted areas, food and human exposure.

2. Materials and methods

2.1. Compilation of information from global monitoring of the IPEN/Arnika POPs in eggs project

2.1.1. Sampling campaigns of eggs by Arnika and the IPEN

At the start of the Stockholm Convention, IPEN and Arnika, in cooperation with many public interest NGOs, started sampling of free-range chicken eggs in many developing countries and countries with economies in transition from five continents (Asia, Africa, Europe, North and South America). The sampling focused on different potentially contaminated sites influenced by waste management or unintentional POP sources identified in the Stockholm Convention. Their results were published in a range of reports focused on Armenia [47,48], Bosnia and Herzegovina, Montenegro, Serbia [49], Cameroon, Ghana [50], China ([51], Indonesia (Petrlik et al., 2020; [32,52]), Kazakhstan (Petrlik et al., 2016b), Kenya [53,54], Georgia [55], Moldova [56], Ukraine [57], Thailand [58], and sites specifically affected by waste incineration residues in Asia and Europe [59]. Normally between 2 and 6 eggs were pooled for analysis of one flock.

In total, the egg survey of IPEN included 209 pooled egg samples which were analysed for a range of POPs, for example organochlorine pesticides (OCPs), flame retardants as well as unintentionally produced POPs such as PCDD/Fs and dl-PCBs, hexachlorobenzene and others. This included 187 pooled egg samples from free-range chickens taken in the vicinity of various industrial/commercial sites, obsolete POPs stockpiles and dumpsites mainly, but not only, in developing countries and countries with economies in transition. In addition, 14 pooled egg samples from supermarkets in selected countries of the sampling campaigns were analysed as references and to evaluate the status of eggs from supermarkets in the countries. Additionally, eight egg samples were taken from remote areas where no particular POP contamination was expected. 114 samples were analysed for PBDEs and some other BFRs, and 41 also for PBDD/Fs. 150 were analysed for PCDD/Fs and dl-PCBs, 68 samples were analysed by DR CALUX, and most of them were summarized in a previous report [60].

The TEQ values for the PBDD/Fs were calculated according to the World Health Organization (WHO) recommendation for human and mammalian toxic equivalency factors (TEF) with recommendation to use the same as for PCDD/F congeners [36].

Eggs were collected into typical plastic egg packaging and were boiled for approximately 7 min. The homogenates from the edible parts of the eggs were used for the analyses in the laboratories.

2.1.2. Instrumental analysis

For the studies of IPEN/Arnika, the samples were analysed by gas chromatography and high resolution mass spectrometry (HRGC/HRMS) in ISO 17025 accredited laboratories with a resolution >10,000 using ^{13}C isotope labelled standards for quantification. PBDD/F analysis followed the European Union's methods for the control of levels of PCDD/Fs and dl-PCBs for levels in certain foodstuffs, as laid out in Commission Regulation (EU) No 252/2012 [61] and Commission Regulation (EU) 2017/644 [62]. Details of the method can be found there.

For brominated flame retardants 16 PBDE congeners, three HBCDD isomers, and six novel BFRs (nBFRs), including 1,2-bis(2,4,6-tribromophenoxy) ethane (BTBPE), decabromodiphenyl ethane (DBDPE), hexabromobenzene (HBBz), octabromo-1,3,3-trimethylphenyl-1-indan (OBIND), 2,3,4,5,6-pentabromoethyl benzene (PBEB), and pentabromotoluene (PBT), as well as tetrabromobisphenol A (TBBPA) were analysed in selected samples.

2.1.3. Details on extraction procedure for the isolation of BFRs are published elsewhere (Petrlik et al., 2022). Gas chromatography coupled to mass spectrometry with negative ion chemical ionization (GC-MS-NICI) for the analysis of selected BFRs

GC-MS analyses were performed using same GC-MS instrument operated in negative ion chemical ionization and selected ion monitoring (SIM) mode. The injection (2 μL) was done in cold pulsed splitless with injection pulse pressure 50 psi and splitless period 1.5 min. For the separation of targeted substances, a DB-XLB (15 m × 250 μm × 0.10 μm) capillary column was used. For each compound, one quantification and two confirmation ions (*m/z*) were monitored. The injection and oven temperature program is described elsewhere [63].

2.1.4. Ultra-high performance liquid chromatography coupled to tandem mass spectrometry with electrospray ionization (UHPLC-ESI-MS/MS) for the analysis of HBCDDs and TBBPA

LC-MS/MS analyses were performed using an Agilent 1290 Infinity II liquid chromatograph interfaced with an Agilent 6495 LC/MS triple quadrupole mass selective detector operated in electrospray ionization in negative mode and MRM mode. For each compound, one quantification and two confirmation MRM transition were monitored. Sample was injected in methanol (5 μL) on an Acquity UPLC BEH C18 (100 mm × 2.1 mm × 1.7 μm) column, which was used for separation of target substances. Temperature of the column was set on 40 °C. Mobile phases consisted of 5 mM ammonium acetate in deionized water (A) and 5 mM ammonium acetate in methanol (B). Total run time of analysis was 13 min.

2.2. Quality Assurance/Quality Control (QA/QC)

The procedural blanks were prepared and analysed with each batch of samples (instead of sample, same amount of deionized water was analysed) for the control of the background contamination by target compounds.

For the compensation of matrix effects as well as for the control of recovery of the entire procedure, internal standards (surrogates) were used. Those surrogates included isotopically labelled analogues of target compounds ($^{13}C_{12}$-PBDE 209, $^{13}C_{12}$-TBBPA and $^{13}C_{12}$-HBCDDs) and rare congeners of PBDEs (No. 37 and 77).

The methods for the determination of all target compounds were validated by the analyses of an artificially contaminated sample of eggs (pooled sample prepared from five individual eggs) and soil, each in six replicates. The artificial contamination concentrations in eggs were as follows: 2 ng/g lipid weight (lw). for PBDEs and nBFRs, 10 ng/g lw for HBCDDs and TBBPA. The method performance characteristics, i.e. limit of quantification (LOQ), recoveries (REC) and the values of repeatability expressed as relative standard deviation (RSD) for each group of target analytes, are summarized in Table 1. The LOQs are defined as the lowest calibration standard which provided the signal to noise ratio (S/N) > 10 for proper quantification.

Table 1
Method performance characteristics (LOQs, REC, RSD) for both matrices and all groups of target contaminants.

	Eggs		
	LOQ (μg/kg lipid weight)	REC (%)	RSD (%)
PBDEs	0.2–1.7	93–106	3–7
HBCDDs	4.2	108–112	8–9
TBBPA	4.2	111	8
nBFRs	0.2–3.3	102–115	7–13

2.3. Screening with bioassay

Seventy-one of the pooled egg samples were monitored for dioxin-like toxicity with DR CALUX® by the commercial laboratory of BioDetection Systems. Samples where the TEQs were higher than what could be explained by the PCDD/F and dioxin-like PCB data (published in the former review [20]) were additionally analysed for PBDD/Fs. Sample clean-up was performed including removing compounds causing false non-compliant results or compounds that may decrease the response, causing false compliant results, as required by the European Commission Regulation (EU) 2017/644 by sulfuric acid silica treatment to oxidize PAHs [62]. The details of the assay and the procedures are published elsewhere [64].

Many of the DR CALUX analysed egg sample results were summarized in a previous report [60].

2.4. Compilation of data from peer reviewed papers

Information was also gathered from the peer reviewed literature on POPs contaminated chicken eggs and sources of the related contamination. The review focusses on compiling information on eggs contaminated with POP-BFRs listed in the Stockholm Convention, major nBFRs and the POP-candidates PBDD/Fs and PXDD/F. For the literature search we used Google Scholar, Organohalogen Compounds database and ResearchGate with pertinent key words (eggs, chicken egg, duck eggs, PBDEs, HBCDD, BFRs, PBDD, PBDF, other BFR names and abbreviations, contaminated). Most the studies found in the scientific literature come from industrial countries and China with some studies from developing countries (e.g., Ref. [65–77]).

The major information on POP-BFR levels and all PBDD/F levels in eggs in developing countries was sourced from IPEN's screening surveys which were mainly carried out in developing countries. Some of the PBDD/F and BFR data are published for the first time in this review and an overview on the source of the data for the individual eggs are compiled in supporting information in Tables SI 1 to Table SI 5.

3. Results and discussion

3.1. Overall exposure of chickens/eggs to brominated POPs

For chickens, there may be several sources of exposure to POPs (Fig. 1). The major sources are: specific point sources on a farm (e.g., housing), soil, animal bedding (e.g., recycled materials) as well as feed (Fig. 1; see below). For free-range poultry around pollution sources the contamination of eggs is predominantly triggered by soil pollution [13,23,30].

3.1.1. Soil

Consumption of chicken and duck meat or eggs is probably the most sensitive exposure pathway for POPs from soil to humans [13,23]. Free-range laying hens and broilers ingest on average about 11 g and up to 30 g soil per day. The transfer rate from soil to eggs is 0.4–0.5 for the TEQ relevant tetra- and penta-chlorinated PCDD/Fs and PCBs [78,79]. Therefore, soil ingestion is suggested to be a predominant contamination pathway, which is a central factor in the risk assessment of POP exposure on livestock farms as well, especially in free-range systems [80]. In our previous review on PCDD/Fs and PCBs in eggs we have documented that around emission sources, soil ingestion is the most important exposure pathway for free-range poultry for these pollutants. More than 90 % of eggs from chickens living on these sites were above the European maximum residue limits [20]. For other POPs, studies on the transfer rates are rare. The transfer for ΣPBDE7 (triBDE to heptaBDEs) from soils to chicken eggs was calculated to be 0.28 on average (range of 0.15–0.4) [44]. For HBCDD the transfer rate has been determined to 0.23 [81]. These transfer rates are comparable to those the higher chlorinated PCDD/F congeners [78].

It needs to be noted that the average ingestion of soil strongly depends on the time chickens spend outside and the time spent outside is related to the size of the chicken flock [30]. Flocks with fewer than 500 hens spend 40 % or more of their time outdoors, while in farms with more than 10,000 hens the animals are outdoors less than 10 % of the time [30]. Therefore, small flocks of chickens on contaminated sites ingest particularly high levels of soil pollutants because they spend more time pecking outside [30]. Most of the IPEN samplings were on small flocks of less than 100 chickens spending much of the time outside and therefore had a high uptake of soil.

Besides direct ingestion of soil, the ingestion of soil organisms such as insects and earthworms may be an important route for the uptake of POPs from soil and related bioaccumulation in these animals [82]. Heavy metals and organic pollutants such as PBDEs, PCDD/Fs, and PCBs have been found to accumulate in earthworms ingesting contaminated soils [83,84]. Shang et al. found higher bioaccumulation potential in earthworms for PCBs and PBDEs compared to PCDD/Fs, and tetra-, penta- and hexa-halogenated PCDD/Fs homologs were more easily accumulated by earthworms than the lighter and heavier PCDD/F homologs.

Both routes of exposure (eggs and meat) need to be taken into account, when assessing the risk of human exposure or the likelihood of exceeding maximum levels based on the transfer of contaminants from soil to humans via chicken.

3.1.2. Chicken feed

Chicken feed may also be contaminated with POPs or other environmental contaminants [85]. Feed contaminated with PCDD/Fs and PCBs has triggered large feed and food crises, sometimes affecting thousands of farms [86]. Fish meal is one major source of POPs in chicken feed [87–89]. The high levels of PBDEs in eggs reported in the US PBDE food survey were most likely due to the presence of brominated POPs in fish meal [90] and also nBFRs are already present in fish meal frequently fed to chicken resulting in human exposure [89]. In addition, other feed can contain nBFRs [91,92].

Feed additives may also contain PBDEs and PBDD/Fs, which can contaminate chicken and eggs, as well as other livestock [93,94]

3.1.3. Water

Chickens consume approximately 1.77 g water per gram of food [95] which translates to approximately 200 ml/day. The POPs assessed in the current study (PBDD/Fs, PBDEs, HBCDD, and nBFRs) have a low water solubility and water consumption is not considered a relevant exposure pathway for these pollutants.

3.1.4. Bedding

For chickens, consumption of bedding materials has been reported at around 2 % and even 4 % of feed intake (referenced in Ref. [96]). The pressure for greater sustainability of resources and increasing costs of natural products have led to an increased use of recycled materials. However, recycled materials that are used for animal bedding can be a relevant source of contaminants for chickens [97]. For example, the selection of recycled wood is based on visual inspection which may not always be able to distinguish between chemically treated and untreated wood [96]. Brambilla et al. [98] examined bedding materials made from shavings of treated timber for their contamination with PCDD/Fs and pentachlorophenol (PCP). The concentration of PCDD/Fs and PCP in the

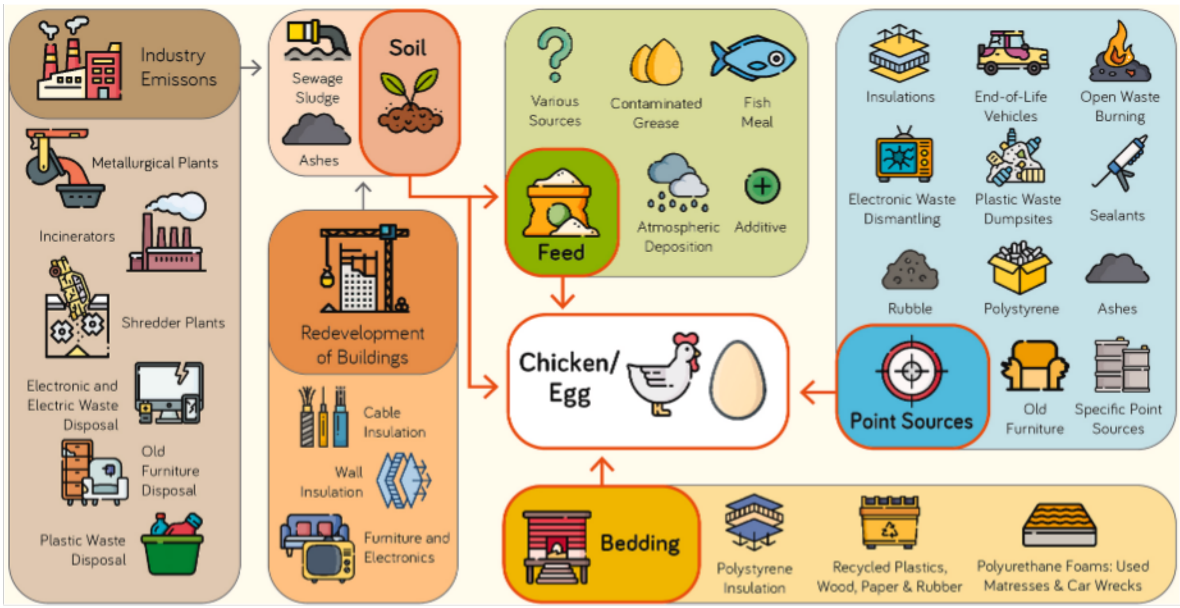

Fig. 1. Major exposure pathways of BFRs and PBDD/Fs to chicken/egg.

wood shavings was on average 50 pg WHO-TE/g and 15 μg PCP/g, respectively. Laying hens that lived on this bedding had accumulated PCDD/Fs. Their eggs were heavily contaminated with both PCDD/Fs (47 pg WHO-TE/g lw) and PCP (500 ng/g ww) [98].

Fernandes et al. [96] used recycled wood shavings, recycled cardboard, dried paper sludge and clean wood shavings to investigate the transfer of PCDD/Fs, PBDD/Fs, PCBs, polybrominated biphenyls (PBBs), PBDEs, HBCDD, polychlorinated naphthalenes (PCNs) and perfluoroalkyl and polyfluoroalkyl substances (PFASs) PFAS from recycled materials used for bedding to the eggs and tissues of chickens. The strongest evidence of uptake in that study was seen for some of the Σ13 non-dl-PCBs (for PCB-28, -81, 138, 153 and 180), for PBDEs and TEQ in the tissues and eggs of chickens raised on shredded cardboard [96]. Shredded cardboard contained 223 ng/g Σ17 PBDEs and dried paper sludge contained 420 ng/g Σ17 PBDEs. The use of these bedding materials resulted in elevated PBDEs levels in chicken eggs of 11 ng/g fat and 16 ng/g fat, respectively, compared to 0.43 ng/g fat when using clean wood shavings as bedding [96]. Similarly, these recycled materials contained HBCDD (43 and 55 ng/g, respectively) and resulted in slightly elevated levels of HBCDD in chicken eggs (both 0.4 ng/g fat) compared to 0.1 ng/fat when clean wood shavings were used [96]. For PBDEs, the transfer factors from bedding materials into the eggs increased with the bromine number, up to a maximum value for BDE-209. This relationship was reversed for PCDFs (and to some extent for PCDDs) with tetra- and penta-chlorinated congeners showing a greater tendency for selective uptake [96].

Studies indicate that animal beddings may be an overlooked source of food chain contamination. As the bedding is used in direct contact with livestock and then is applied on the pasture, into the soil, or as a feed for composting facilities, contaminants from animal beddings pose a risk of dermal, inhalation and oral exposure even beyond the period of use.

3.1.5. Point sources on farms and other hot spot areas where chickens are kept

For POP-BFRs, point sources on farms can be a relevant source for contamination of chickens. This includes insulation materials such as polyurethane foams and other polymers in buildings (See Fig. 1). For HBCD, the major use and source are expanded and extruded polystyrene (EPS/XPS) insulation materials. EPS and XPS are often used to insulate poultry houses [99] and are readily pecked by chickens [67,81]. Also PUR spray foam and flexible PUR foam, polyethylene and polypropylene used in buildings including farms have partly been treated with BFRs including PBDEs and nBFR substitutes [1,3,41].

Another source of BFRs may be end-of-life vehicles that sometimes remain at farmyards or classic cars sometimes stored in a barn. These cars can contain high levels of PBDEs or HBCDD and other BFRs [58,100].

Also stored electric and electronic equipment may be a source of PBDEs or other POPs plastic additives [101]. When waste electric and electronic equipment (WEEE) is stored and handled outdoors, polymer materials are subject to UV radiation, weathering and heat and to degradation through tearing, abrasion and crushing. Microplastics containing BFRs and other plastic additives will be released to the surrounding area [102]. Chicken can particularly pick small plastic pieces from crushed WEEE or other crushed BFR containing plastics. Microplastic ingestion by chicken is confirmed by a monitoring study of poultry manure [103]. In addition, POP-BFRs and other plastic additives evaporate from products/waste. POPs and many other BFRs are semi-volatile organic chemicals (SVOCs). SVOCs outgas from materials to which they have been added and release to the air increases steeply with temperature. SVOCs exist in air as vapours or are included in or sorbed on suspended particles. They can partition among the gas phase, airborne particles, settled dust, and available surfaces. Higher PBDE concentrations in air have been measured in source areas such as electronic recycling plants [104]. Gaseous and particle-bound SVOCs, that are suspended in the air, are transferred to plant surfaces and soils via wet or dry atmospheric deposition [105,106]. For less volatile components, such as PCDD/Fs and higher polybrominated PBDEs, particle-bound deposition was shown to be the dominating transfer mechanism [106]. PBDD/Fs have an even higher adsorptivity than PCDD/Fs and show higher PBDD/F-TEQ to PCDD/F-TEQ ratios than other food groups [107].

Pollutants are transferred from the air to plants very effectively.