



Dioxin-like contaminants (PCDD/Fs, PBDD/Fs, PXDD/Fs, PCBs, PCNs) & PBDEs in edible avian eggs other than chickens

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ARTICLE INFO

Keywords:

Poultry eggs
Food safety
Human exposure
Brominated dioxins
Environmental contaminants
Free-range

ABSTRACT

The occurrence of dioxin-like environmental contaminants, polybrominated diphenylethers (PBDEs) and polychlorinated biphenyls (PCBs) was investigated in eggs of eleven avian species excluding chickens. The majority were duck and quail eggs, but smaller numbers of goose, turkey, guinea-fowl, pheasant, pea-fowl, gull, ostrich, emu and rhea eggs from retail outlets were also analysed using high-resolution sector-field mass spectrometry. Polychlorinated/brominated dibenzo-*p*-dioxins/dibenzofurans (PCDD/Fs, PBDD/Fs), PCBs and PBDEs were measured in 104 samples. Mixed halogenated dioxins, furans, biphenyls (PXDD/Fs & PXBs), and polychlorinated naphthalenes (PCNs) were investigated in ~1/5th of samples. These environmental contaminants were detected in all species at lipid weight maxima of 26 pg TEQ/g, 465 ng/g NDL-PCBs and 227 ng/g PBDEs. Except for PCDD/Fs and PBDD/Fs (detected in 90% of samples), gull eggs showed highest contaminant levels. PBDD/F TEQ (max. 7.98 pg/g lipid) exceeded PCDD/F TEQ in 26% of duck eggs and elevated contaminant levels were recorded for other species. Different husbandry practices, access to soil and herbage under free-range conditions, seasonality and lower periodicity of egg laying may promote elevated contaminant levels. Dietary intakes of PCDD/F and PCB TEQ through consumption of duck eggs ranged from 0.04 to 0.44 pg TEQ/kg bw/week for adult consumers, and approximately doubled (0.08 – 0.94 pg TEQ/kg bw/week) when all measured DL-TEQ was included. Indicative intakes from eggs of other species were considerably higher, with corresponding values ranging from 0.44 to 5.3 and 0.51 to 6.2 pg TEQ/kg bw/week, respectively. Uniquely, the study provides baseline levels of emerging environmental contaminant occurrence and dietary exposure through eggs of hitherto unstudied avian species. The results emphasise the significance of non-regulated TEQ inputs. The doubling of TEQ intake through duck egg consumption when these emerging contaminants are included, suggests that the current limited focus on chlorinated congeners may provide an inadequate reflection of dietary exposure.

1. Introduction

The poultry industry is the largest of all livestock farming, with an economic value that is expected to grow to almost half a trillion dollars (\$493 billion) by 2026 (The poultry site, 2022). Egg production accounts for more than 50% of this value. The eggs of the domestic chicken, *Gallus domesticus*, account for the vast majority of this produce, but the eggs of other avian species contribute significantly to the total. The most popular of these are duck and quail (duck eggs account for up to 30% of eggs consumed in China and SE Asia – Sumarmono, 2019) but the eggs of other species such as goose and turkey are also commonly

retailed. Eggs of these other species are increasingly consumed in different parts of the world, either due to personal preferences, cultural significance (e.g., duck eggs in East and Southeast Asia are key ingredients of prized culinary products such as moon cakes in China and Thailand, or Balut in Vietnam) or due to the demands of physical fitness and sport (the perceived higher protein content in the eggs of some species, e.g., goose, turkey, are considered to be important for building and maintaining muscle mass). Additionally, in recent years, growing consumer interest has created a new demand for eggs of other species as evidenced by restaurant menus in large cities and the wider availability of these products. However the exact consumption rates of these eggs

This article is part of a special issue entitled: Food Analytics 4.0 and Environmental Health published in Environmental Research.

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<https://doi.org/10.1016/j.envres.2026.125959>

Received 5 February 2026; Received in revised form 24 September 2026; Accepted 16 October 2026

Available online 17 October 2026

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remain a knowledge gap.

Apart from ducks and quails, many of these avian species are farmed to a much lower extent than chickens. Additionally, the eggs of wild seabirds are also foraged as a food in a number of countries such as Canada, the United States, U.K., Norway, Denmark, Iceland, Russia, etc. (CAFF, 2008). In the UK, licensed pickers are allowed to harvest the eggs of common wild seabirds such as black-headed gulls. This practice must give due care to the requirements of the breeding season and welfare of the birds, and harvesting is only allowed for a few weeks during April and May. Similarly, by adhering to correct husbandry practices, breeding requirements and the welfare of the birds, the eggs of many farmed avian species are only available during a few months of the year. Eggs are available online and from specialist retailers, but the eggs of some species may also be sold to wholesalers, food markets and to more expensive restaurants (The Guardian, 2023).

Physiologically, the formation and composition of eggs in avian species is strongly dependent on the liver as this organ synthesises the lipids that are required for formation of the vitellus (egg yolk). These are transported in lipoprotein form (very low density lipoproteins and vitellogenins) by the plasma and deposited in the developing follicular sacs which form the vitellus (Leveille, 1969). Thus the size and functionality of the liver and the nutrients that it produces are key to the formation of the vitellus and the eggs. This is particularly important as the birds approach maturity and during the continuing cycle of egg production. This functionality of the liver as the main site of fatty acid synthesis is physiologically different to the dominant role that adipose tissue plays in mammalian lipogenesis (Shivaprasad and Jaap, 1977). The avian liver also performs another important function in common with other animal species – that of detoxification through the metabolism of a range of contaminants. The transfer of lipophilic contaminants from the liver to eggs is therefore an inevitable physiological reality. Herein lies a paradox, the same organ that provides the fundamental building blocks of the next generation also inadvertently transfers contaminants that are detrimental to the reproductive success and life of the offspring (Ferne et al., 2001; Thompson et al., 2006; Ottinger and Dean, 2022). This deposition of contaminants to avian eggs also affects consumers of the eggs, such as predatory wildlife species who may feed on the eggs of wild birds, and also humans, although the vast majority of this food is derived from farmed produce. Thus, the concentrations of a range of different contaminants are controlled in eggs in different countries with food safety regulations specifying maximum levels in some regions (European Commission, 2023). These include polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs), dioxin-like polychlorinated biphenyls (DL-PCBs), non-dioxin-like PCBs (NDL-PCBs) and perfluoroalkyl substances. However, related environmental contaminants such as polychlorinated naphthalenes (PCNs) and polybrominated diphenylethers (PBDEs) as listed by the Stockholm Convention are known to occur in avian eggs (Fernandes et al., 2010, Fernandes et al., 2017, 2023; Zacs et al., 2021; Godéré et al., 2024). Similarly, the occurrence of other dioxin-like contaminants (DL-contaminants) such as polybrominated dibenzo-*p*-dioxins/dibenzofurans (PBDD/Fs), polyhalogenated (Br/Cl) dibenzo-*p*-dioxins, dibenzofurans and biphenyls (PXDD/Fs and PXBs) in the eggs of domestic chickens and ducks has also been reported earlier (Dirks et al., 2024; Fernandes et al., 2011, 2014; Pajurek et al., 2019).

The adverse effects of human and animal exposure to these contaminants are well-known and include carcinogenicity, teratogenicity, neuro- and neuro-developmental toxicity, immunotoxicity, reproductive toxicity as well as a range of endocrine disrupting effects (Birnbaum et al., 2003; van den Berg et al., 2013). Regulatory control, whether on foods, animal feed or on environmental release, is a universal acknowledgement of the risk posed by exposure of these contaminants to human and animal health. The process of establishing the regulatory framework for some contaminants such as PCDD/Fs, PCBs and to some extent PBDEs (EFSA, 2026; Stockholm Convention, 2019) is dependent on evidential data on the occurrence of these contaminants in foods including eggs. This information is usually obtained through general

monitoring of food supplies but data on the occurrence of the other contaminants mentioned above are scarce and there is practically no information on the collective occurrence of these contaminants in the eggs of other avian species (other than some limited data on duck eggs). In some cases, reported occurrence data is a result of contamination incidents e.g., duck eggs from contaminated waters (Liu et al., 2015) or egg contamination from the processing of electronic wastes (Petrlík et al., 2022; Jeungsmarn et al., 2023). These reports are useful for highlighting potentially high and sustained exposure in contamination hot spots, but do not provide an indication of the occurrence levels in the general food supply.

The objective of this study was to investigate the occurrence of a wide range of food contaminants in the eggs of avian species (other than the domestic chicken) that are available to the general public. The study targeted duck eggs as these are the most commonly consumed after chicken eggs but also included quail eggs. Additionally, a small, exploratory number of egg samples of other species – goose, turkey, guinea-fowl, ostrich, rhea, pheasant, pea-fowl, gull and a single emu egg – that are known to be consumed and were available on retail sale, were included. The eggs of most of these species are rarely studied for the presence of toxic environmental contaminants and dietary exposure to consumers is not known. Additionally, unlike the vast majority of chickens eggs produced globally, many of the study species, e.g., ostrich, rhea, pheasant, emu, pea-fowl, etc., are normally raised outdoors in free-range conditions or were undomesticated as in the case of black headed gulls. This may be an important distinction from the dietary exposure point of view as outdoor raised species have been reported to show higher contamination levels than birds raised indoors (Roszko et al., 2014; Dervilly-Pinel et al., 2017; Pajurek et al., 2019; Piskorska-Pliszczynska et al., 2019). The study provides unique insights into the contamination of eggs from species that are available year-round as in the case of duck and quail or seasonally, as in the case of many of the other species. It also provides data on a unique set of contaminants – in addition to PCDD/Fs, PCBs and PBDEs which are more commonly measured, the study included PBDD/Fs in all samples and investigated the occurrence of PXDD/Fs, PXBs and PCNs in just under a fifth of the sample set. In addition to providing a baseline level of contaminant occurrence in these foods for the first time, the study also allowed dietary exposure to be estimated for specific populations who may consume these eggs. This consumption may be a result of personal preference, for gourmet reasons, or as part of health and fitness diets. Consumption may potentially be more regular in the case of those who farm and have easier access to the eggs of these species.

2. Materials and methods

2.1. Samples

104 samples of eggs of different avian species were collected, generally from retail outlets such as supermarkets, farm shops and specialist food stores throughout the UK. Although duck and quail eggs were available all year round, the eggs of the other species were only available during the breeding season, which was generally from late January to May, but extended to August for some species such as turkey. The number of individual eggs (in each analysed egg sample) collected per species, varied from between 18 and 36 in the case of the relatively small (8–12 g) quail eggs, to around a dozen for many of the other species (duck, goose, turkey, pheasant, peafowl, guinea fowl and gull), to only 1 and 2 in the case of the ratites - rhea and ostrich, whose eggs weigh approximately 600g and 1300g, respectively. Where multiple eggs were required to obtain the required sample mass, these were pooled and homogenised before analysis. The whole egg was used (i.e., not separated into yolk and albumen) for analysis and the lipid content was determined gravimetrically.

The numbers of samples analysed per species approximately reflect the market share and popularity of the products and are listed in Table 1

(additional information in Table S2) along with approximate egg weights. Thus, the majority of the samples were duck and quail eggs (seventy and ten respectively), with relatively small sample numbers for the other species (six in the case of goose, two to three for most other species, and a single sample of emu eggs). These limited sample numbers would provide an indication of contaminant levels rather than be representative of contamination in the eggs of these species. Apart from gulls, the scientific names listed in Table 1 represent the most popular species farmed in the UK and Europe, and reflect the species of eggs collected. As most of the egg samples were retail products, information on the exact species was not included in the original sample packaging.

2.2. Determinands

The following analytes were determined: Regulated contaminants (European Commission, 2017a) and those prioritised by the European Union Reference Laboratory (EURL, 2023; Fernandes et al., 2025) are highlighted in bold.

Dioxins - all 17, 2378-Cl substituted PCDD and PCDF congeners. DL-PCBs - IUPAC numbers 77, 81, 105, 114, 118, 123, 126, 156, 157, 167, 169, and 189.

NDL-PCBs - IUPAC numbers 18, 28, 31, 47, 49, 51, 52, 99, 101, 128, 138, 153, and 180.

PBDE congeners: IUPAC numbers BDE-17, 28/33, 47, 49, 66, 71, 77, 85, 99, 100, 119, 126, 138, 153, 154, 183 and 209.

PCN congeners - IUPAC numbers PCN-52/60, 53, 66/67, 64/68, 69, 71/72, 73, 74, & 75.

Brominated dioxins - 2,3,7-tri-BDD, 2,3,8-tri-BDF, and ten, 2,3,7,8-Br substituted tetra - hepta-brominated PBDD/F congeners (Fernandes et al., 2008).

Mixed halogenated dioxins and biphenyls (PXDD/F and PXBs) - 13, tri - hexa-halogenated PXDD/DFs and 6 coplanar and mono-ortho substituted biphenyls. (Fernandes et al., 2011).

PCDD/Fs, DL- and NDL-PCBs, PBDEs and PBDD/Fs were analysed in all 104 samples. PCNs, PXDD/Fs and PXBs were measured in a smaller sub-set of 19 of these samples.

2.3. Analytical methodology and quality of data

The multi-analyte method used for the extraction, purification and analysis of the egg samples for PCDD/Fs, PCBs, PBDEs and PBDD/Fs has been described in detail in earlier publications (Fernandes et al., 2004, 2008) and has been used extensively to analyse foods including eggs in several reported studies (Fernandes et al., 2008, 2009a, 2016, 2019, 2023). Similarly, the methodology for PCNs, PXDD/Fs and PXBs which

were determined in two separate methods has also been reported previously (Fernandes et al., 2010, 2011) and used to analyse foods and other farm related matrices in several studies (Fernandes et al., 2010, 2014, 2019, 2023). In general, the three methodologies are similar and to summarise: aliquots (equivalent to 3-5 g fat) of the egg samples were fortified with ^{13}C -labelled analogues of target compounds and exhaustively extracted using a n-hexane/dichloromethane mixed solvent. Planar (PCDD/Fs, PBDD/Fs, PXDD/Fs, PCNs and non-ortho substituted PCBs) analytes were fractionated from the non-planar PBDEs and ortho-substituted PCBs on activated carbon. In the case of PXDD/Fs and PXBs, a second fractionation was required in order to completely exclude PCBs and PBDEs (Fernandes et al., 2011). The fractionated extracts were concentrated and purified using adsorption chromatography on alumina. Measurement was carried out using high resolution gas chromatography-high resolution mass spectrometry (HRGC-HRMS) at a resolution of 10,000, except for the PXDD/Fs and PXBs for which 13,000–15,000 resolution was used.

The analytical methodologies were robustly validated for the analyses of foods including eggs, prior to sample analysis and validation parameters describing the performance of the methods have been reported earlier (Fernandes et al., 2004, 2008, 2010, 2011). The performance meets the criteria described in European regulations or in recommended guidance in the case of PBDEs (Fernandes et al., 2022a). The methodologies used for many of the contaminants (PCDD/Fs, DL-PCBs, NDL-PCBs, PBDEs and PBDD/Fs) were accredited to the ISO 17025 standard and equivalent criteria were used for PCNs and PXDD/Fs, as described earlier (Fernandes et al., 2010, 2011). This included the use of in-house reference materials and procedural blanks with every sample batch, which were evaluated for suitability prior to quantitation and reporting. Further quality assurance measures included the successful participation in international inter-comparison exercises on PCDD/Fs, PCBs and PBDEs in multiple tests conducted by the Norwegian Institute of Public Health and the EURL which showed good performance with achieved z-scores lying within ± 2 . Analytical recoveries based on the use of ^{13}C labelled surrogates were typically in the range of 50 to 110% for most analytes but lower (40 - 80%) for PCNs. Other method performance parameters such as the linearity of measurement, limit of quantitation (LOQ), precision, and measurement uncertainty (MU - expanded uncertainty with a coverage factor of 2) assessed during the project were similar to those reported earlier (Fernandes et al., 2008, 2010, 2011) with MU ranging from approximately 20% (at $\geq 10\times$ the LOQ) to around 200% at the LOQ. For all analytes, the procedure used for estimating the LOQ (below this level, the analyte was reported as "<") was as described by the current LOQ guidance (European Commission, 2017b) for analyses using isotope dilution, internal standardisation and the incorporation of the relevant batch procedural blank. The resulting LOQs were considerably better than those required for the regulated contaminants (European Commission, 2017a), and are generally better or at least equivalent, to those reported in the current literature for the other contaminants.

Individual concentrations of measured PCDD/F and DL-PCB congeners were converted to toxic equivalents (TEQs) using TEF₂₀₀₅ values (rather than TEF₂₀₂₂ as discussed below in the results section). Dietary exposure from weekly egg consumption was estimated conventionally as the product of contaminant concentration and the intake rate (amounts of eggs consumed in a week), divided by the bodyweight. Conventional statistical treatment was used to provide occurrence ranges, mean and median values in order to summarise the large amount of TEQ and other data, but the non-parametric Mann-Whitney U Test was used to assess significant differences between data sets. Additionally, associations between data for different contaminants was examined using the Pearson correlation coefficient which calculates the strength and direction of the linear relationship between the various contaminant data sets.

Table 1
Breakdown of the analysed avian egg samples.

Species		Number of samples	Approx. weight of single egg (g)
Common name	Scientific name of popular farmed species ^a		
Quail	<i>Coturnix japonica</i>	10	8 - 12
Pheasant	<i>Phasianus colchicus</i>	2	34
Black headed Gull	<i>Chroicocephalus ridibundus</i>	2	37.5
Guinea fowl	<i>Numida meleagris</i>	2	45
Duck	<i>Anas platyrhynchos</i>	70	65 & 75
	<i>domesticus</i> , <i>Cairina moschata</i>		
Turkey	<i>Meleagris gallopavo domesticus</i>	3	87
Peafowl	<i>Pavo cristatus</i>	2	90 - 120
Goose	<i>Anser anser</i>	6	145
Rhea	<i>Rhea americana albescens</i>	3	600
Emu	<i>Dromaius novaehollandiae</i>	1	600
Ostrich	<i>Struthio camelus</i>	3	1300

^a Excluding black headed gulls which are a wild species.

3. Results and discussion

The results of the egg analyses are presented as toxic equivalents (TEQs) for the dioxin-like contaminants or as summed concentrations for NDL-PCBs and PBDEs. The results are summarised by descriptive statistics in Table 2, as the volume of raw data is very large and has previously been reported (Food Standards Agency, 2017) to the sponsoring body. Ten of the seventy duck eggs were labelled as free-range (F. R.) and were therefore listed separately for comparison in Table 2. The toxic equivalency factors (TEFs) that are used for computing TEQs have recently been revised (Fitch et al., 2024), but this revision has not yet been updated in relevant regulatory limits and is not widely used, so the 2005 toxic equivalent factors (TEF₂₀₀₅ - van den Berg et al., 2006) were used. Initial examination of the effects of using TEF₂₀₂₂ on DL-PCBs and PCDD/Fs in this study indicate a TEQ reduction of around 49% (range; -6 to -70%) for DL-PCBs and approximately 20% (ranging from an increase by 34% to a reduction of 39%, see Table S1) for PCDD/Fs, compared to TEF₂₀₀₅. This TEF revision will clearly have implications for the assessment of dietary intakes and for the updating of maximum acceptable limits within existing regulations on PCDD/F and PCB levels in food and animal feed. These will also need to take into account, revision of the tolerable weekly intake of PCDD/Fs and PCBs (EFSA, 2026), which would ultimately require more sensitive analysis of foods. Toxic equivalents for the other dioxin-like, AhR active contaminants (PBDD/Fs in all samples and PXDD/Fs, PXBs and PCNs in a sub-set of samples) have also been summarised in Tables 2 and 3. These were calculated for the measured PBDD/F congeners using analogous

Table 3

Concentrations of dioxin-like contaminants in eggs of duck and other avian species. PCNs and PXDD/F + PXBs were measured in 19 samples. (Detection frequency – PCNs were detected in 100% of analysed samples; PXDD/Fs & PXBs in 95% of samples).

Dioxin-like Contaminant	Egg concentrations, TEQ ^{a,b,c} pg/g lipid					
	Range	Median	Mean	Range	Median	Mean
	Duck (N = 70)			Other species (goose, gull, peafowl, ^b ratites); N = 8		
PCDD/F	0.10 - 6.95	0.25	0.69	0.76 - 10.8	4.03	4.82
DL-PCB	0.04 - 1.77	0.13	0.25	0.22 - 16.3	1.13	2.62
PBDD/F	0.14 - 7.98	0.26	0.46	0.21 - 2.54	0.46	0.69
PCN	0.01 - 0.17	0.03	0.05	0.01 - 0.28	0.06	0.09
PXDD/F + PXB	0.07 - 0.46	0.14	0.18	0.11 - 0.76	0.23	0.35
Σ Measured TEQ	0.39 - 11.6	0.81	1.63	1.35 - 26.5	5.91	8.6

^a Toxic equivalent.

^b Includes Ostrich, Emu and Rhea.

^c PCN TEQ derived from 9 congeners; PXDD/F + PXB from 17 congeners.

PCDD/F TEFs as recommended by a WHO/UNEP panel and others (van den Berg et al., 2013; Fernandes and Falandysz, 2021). Relative Potency (REP) values for PXDD/Fs and PXBs were taken from the only study on

Table 2

Summary of PCDD/F, PCB, PBDD/F and PBDE concentrations in retailed eggs of various avian species (Detection frequency – PCDD/Fs, PCBs and PBDEs in 100% of samples; PBDD/Fs in 90% of samples).

Species (No. of samples)		TEQ ^{a,b} , pg/g lipid			Concentration ^b , ng/g lipid	
		PCDD/F	PCDD/F + PCB	^c PBDD/F	ΣNDL-PCBs	^d ΣPBDEs
Duck (60)	Range	0.1 - 6.95	0.16 - 8.56	0.14 - 7.98	0.17 - 16.3	0.4 - 12
	Median	0.26	0.41	0.26	0.57	1.01
	Mean	0.66	0.91	0.47	1.17	1.56
Duck- Free Range (10)	Range	0.13 - 4.05	0.17 - 4.79	0.15 - 1.12	0.14 - 24	0.51 - 1.69
	Median	0.23	0.35	0.29	0.57	1.08
	Mean	0.84	1.11	0.40	3.03	0.97
Quail (10)	Range	0.09 - 0.55	0.21 - 0.57	0.18 - 0.6	0.21 - 1.21	0.28 - 9.95
	Median	0.23	0.28	0.23	0.43	0.92
	Mean	0.28	0.33	0.30	0.51	1.82
Goose (6)	Range	0.76 - 10.8	0.98 - 11.8	0.25 - 1.42	1.35 - 9.38	1.22 - 9.8
	Median	3.60	4.91	0.47	5.33	1.90
	Mean	4.06	5.00	0.58	5.20	3.43
Turkey (3)	Range	0.77 - 4.4	1.0 - 5.18	0.23 - 0.35	1.48 - 2.25	1.51 - 2.27
	Median	1.08	1.49	0.25	1.50	1.63
	Mean	2.08	2.56	0.28	1.74	1.80
Guinea fowl (2)	Range	0.99 - 2.04	1.27 - 2.85	0.29 - 0.93	0.98 - 2.67	0.9 - 3.55
	Median	-	-	-	-	-
	Mean	1.52	2.06	0.61	1.83	2.23
Pheasant (2)	Range	1.34 - 3.29	1.71 - 3.98	0.36 - 0.59	0.89 - 4.22	1.09 - 2.55
	Median	-	-	-	-	-
	Mean	2.32	2.85	0.47	2.56	1.82
Pea-fowl (2)	Range	1.46 - 10.4	3.15 - 11.5	0.33 - 0.47	4.15 - 11.1	2.91 - 4.79
	Median	-	-	-	-	-
	Mean	5.95	7.34	0.40	7.62	3.85
Black-headed gull (2)	Range	6.61 - 8.43	22 - 23	1.98 - 2.54	447 - 465	177 - 227
	Median	-	-	-	-	-
	Mean	7.52	22.4	2.26	456	202
Rhea (3)	Range	2.62 - 6.4	3.05 - 6.64	0.21 - 0.61	1.07 - 3.05	2.5 - 3.6
	Median	2.95	3.20	0.46	1.21	3.28
	Mean	3.99	4.30	0.43	1.78	3.13
Ostrich (3)	Range	2.53 - 5.82	3.35 - 7.51	0.31 - 0.46	2.1 - 10.4	0.87 - 3.83
	Median	4.03	5.23	0.45	6.37	2.65
	Mean	4.13	5.36	0.41	6.29	2.45
Emu (1)	Concentration	6.35	8.1	0.5	3.13	4.91

^a TEQ - toxic equivalents.

^b Measurement uncertainty ranges from 20%, to 200% at LOQ.

^c TEQ from 10 congeners (see text).

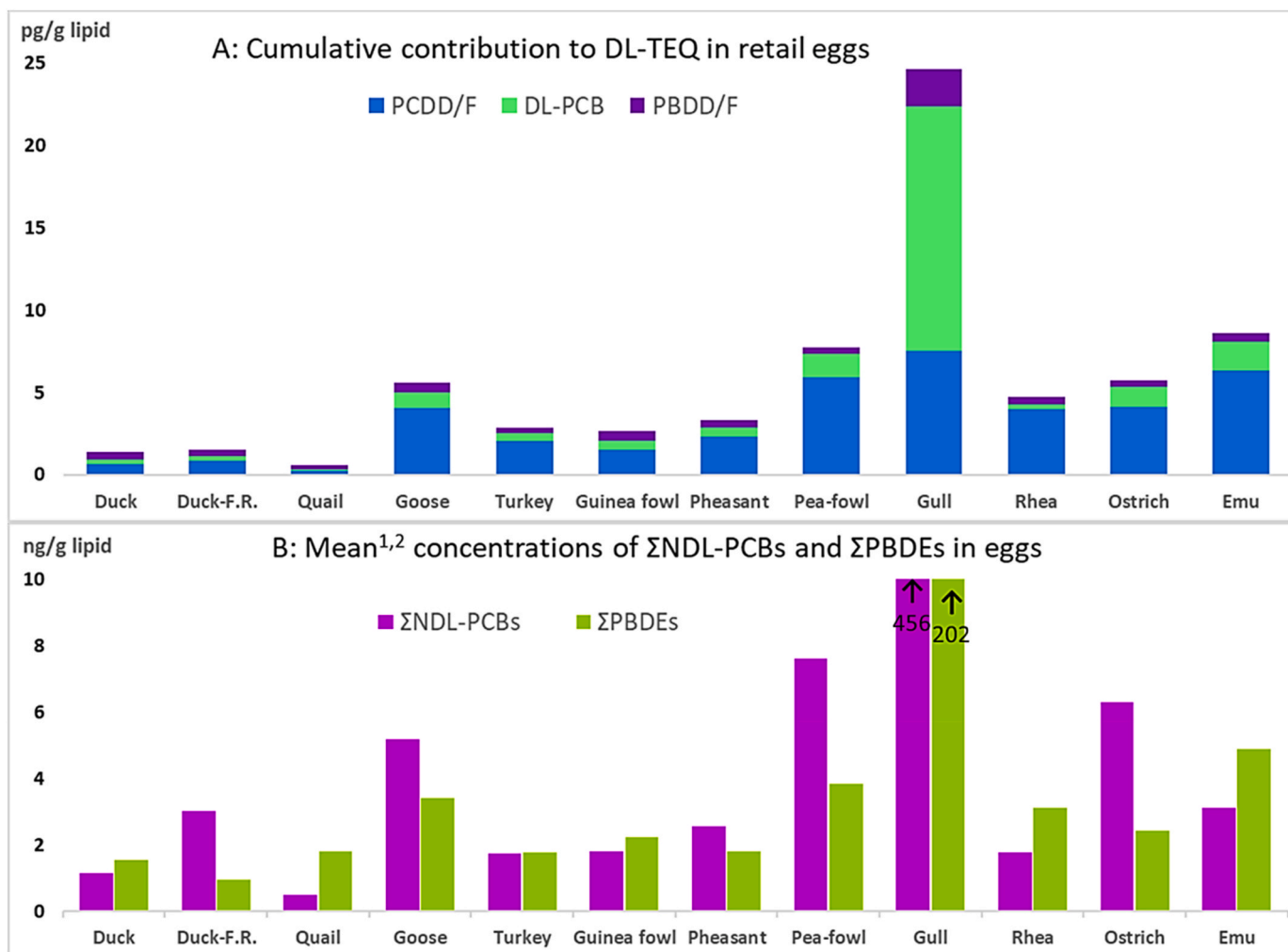
^d Sum of 17 congeners (see text).

these congeners in commonly consumed foods (Fernandes et al., 2014) based on earlier comprehensive reports on REPs for these compounds (Wall, 2012; Wall et al., 2015) which also reviewed the existing data with favourable comparison of the REP values. These REPs and those used for PCN congeners (Fernandes et al., 2022b, Table S3) have been widely used in human exposure studies over the last 15 years (Pratt et al., 2013; Fernandes et al., 2010, 2011, 2014, 2018, 2019, 2023; Falandysz and Fernandes, 2020; Zacs et al., 2021; Godéré et al., 2024). However, they are based on a smaller number of toxicological studies than PCDD/Fs and PCBs, and would benefit from further confirmatory studies.

3.1. PCDD/Fs, PCBs and PBDEs

Concentrations of the investigated contaminants varied among the avian egg species analysed. All major contaminant groups were detected, but burdens and congener patterns differed across species. PCDD/Fs and PCBs (DL-PCBs and NDL-PCBs) occurred in all egg samples with combined TEQ concentrations ranging from 0.16 pg TEQ/g lipid weight (lw) in a sample of duck eggs to 23 pg TEQ/g lw in a sample of black headed gull eggs. (Table 2). The lowest occurrence levels of all the investigated species were seen in quail eggs (range, 0.21 – 0.57 pg TEQ/g). In general, higher mean concentrations (4.3 to 22.4 pg TEQ/g lw)

occurred in the eggs of species that were less intensively reared such as peafowl and raites as well as in black headed gulls. Apart from the latter, which are effectively a wild species (scavengers and opportunistic feeders with a varied, omnivorous diet, including in the case of the present birds, a significant proportion of small aquatic species) and in which PCBs contributed on average, 65% of the combined PCDD/F and PCB TEQ, the eggs of all other species showed the opposite pattern, with an average of 72% contribution from PCDD/Fs (Fig. 1A). This was reflected in the NDL-PCB concentrations where the mean value for the gulls eggs (456 ng/g lipid) was two orders of magnitude greater than the concentrations in the eggs of most other species (range of mean values, 0.51 – 7.62 ng/g lipid). A very similar relationship was seen for summed PBDE concentrations, between the mean values for gull eggs and the eggs of the other species (202 ng/g lipid vs a range of mean values of 0.97 – 4.91 ng/g lipid, respectively). Across all samples, PBDE concentrations ranged from 0.3 to 227 ng/g fat (0.05 – 22.7 ng/g whole) for the sum of the measured PBDE congeners. The corresponding PBDE range for duck eggs was 0.4 – 12 ng/g fat (0.07 – 1.5 ng/g whole). The most frequent occurrence was seen for PBDE-47, 49, 66, 85, 99, 100, 153, 154, 183 and 209. BDE-209 generally showed the highest levels of occurrence across all species. The sum of the 18 measured PBDE congeners was on average 2% higher than the sum of the EC recommended PBDE congeners (European Commission Recommendation, 2014), as



¹ Concentrations in gull eggs (456 & 202 ng/g respectively for PBDEs and NDL-PCBs are off-scale. ² Concentrations for Emu are from a single sample

Fig. 1. Graphical summary of mean contaminant concentrations across retail avian eggs of various species

noted before for a range of foods including eggs (Fernandes et al., 2016). The relative occurrences of PBDEs and NDL-PCBs in the eggs of the various species studied are shown in Fig. 1B.

There is practically no comparable information on retail duck eggs apart from a report on official survey data from Poland (Piskorska-Pliszczynska et al., 2019) where the main focus was on chickens eggs but the eggs of duck, quail, goose and ostrich were also investigated. The reported PCDD/F and PCB TEQ range for duck eggs was 0.5 – 1.53 pg/g lipid with a mean value of 0.8 pg/g lipid. The TEQ occurrence ranges for the eggs of quail, goose and ostrich were 0.44 to 1.04 pg/g fat, 0.48 – 3.27 pg/g lipid and 0.85 – 74 pg/g lipid respectively, with mean values 0.55 pg/g lipid, 1.23 pg/g lipid and 10.9 pg/g lipid respectively (Piskorska-Pliszczynska et al., 2019). Data availability is only a little better for domestic chickens, for which there are a number of studies that investigate eggs from potentially contaminated scenarios, but relatively few recent studies that investigate the regular food supply or market basket data. A Canadian study reported combined PCDD/F and PCB TEQ of 0.089–12.8 pg/g lipid (median 0.34 pg/g) (Rawn et al., 2012), while sum NDL-PCBs ranged from 0.1 ng/g lipid to 9.33 ng/g lipid (median 0.495 ng/g lipid).

Similarly PCDD/F and PCB TEQ in chicken eggs (including battery caged, barn, organic and free-range) from Poland (Pajurek et al., 2019) ranged from 0.44 to 9.63 pg/g lipid with NDL-PCBs ranging from 0.08 to 9.58 ng/g lipid and PBDEs from 0.16 to 12 ng/g lipid. The highest values were seen in organic and free-range eggs. In contrast, chicken eggs from China showed a wider PCDD/F and PCB TEQ range from 0.71 to 37.4 pg/g lipid with a median of 2.04 pg/g lipid (Shen et al., 2017). The earlier mentioned study from Poland (Piskorska-Pliszczynska et al., 2019) reported TEQ values of 0.44 to 29.8 pg/g lipid for chicken eggs from battery cages, organic and free range husbandry. Reflecting the other contemporary study from Poland, higher TEQ values were seen in organic and free range birds (mean values of 1.57 and 1.6 pg/g lipid) compared to battery caged birds with a mean value of 0.78 pg/g lipid. However, a study from Italy (Ceci et al., 2026) showed similar mean levels of TEQ (PCDD/Fs and PCBs) and PBDEs from organic, barn and caged chicken eggs. The most recent UK total diet study showed that the egg group sample (a composite of 34 retail egg samples collected from 14 locations across the country) had a PCDD/F and PCB TEQ concentration of 0.46 pg/g lipid, 1.35 ng/g lipid of NDL-PCBs and 0.57 ng/g lipid of PBDEs.

3.2. Dioxin-like TEQ from other contaminants

PBDD/Fs were detected in 90% of all study samples, but the occurrence of individual PBDD and PBDF congeners varied. As noted for foods in general (Fernandes et al., 2009a, 2009b; Fernandes and Falandysz, 2021; Dirks et al., 2024), PBDF congeners were far more frequently detected compared to PBDDs. In particular, penta- and hexa-BDDs were not detected in the current study even when PBDF concentrations in the same sample were relatively high (e.g., 7.7 – 19 pg/g lipid). The resulting TEQ was thus mainly the result of PBDF occurrence and was quantitatively more significant ($p < 0.01$, Mann Whitney U test) than that of the PCN or PXDD/F plus PXB TEQ in the samples where this was measured ($n = 19$). PBDD/F TEQ concentrations ranged from 0.14 to 7.98 pg/g lipid across all duck eggs and 0.18 to 2.54 pg/g for the eggs of other species. The range for the duck eggs was strongly influenced by a couple of outlying data points, and the mean value of 0.46 pg TEQ/g lipid for all duck eggs was not very dissimilar to the mean values of the other species (0.53 pg/g lipid) which ranged from 0.28 to 0.61 pg/g lipid, apart from the black headed gull eggs at 2.26 pg/g lipid (Table 2). Both, mean and particularly, median PBDD/F TEQ values were comparable to PCDD/F TEQ for duck and quail eggs; in fact, median TEQ values were equal to or greater than PCDD/F TEQ (Table 2), but were comparatively lower in the eggs of other species. Relatively higher TEQ arising from PBDD/Fs (compared to PCDD/Fs) has also been reported (Zhang et al., 2024) in foods such as eggs and duck from China (mean

values of 0.64 compared to 0.41 pg TEQ/g lipid and 2.22 compared to 0.18 pg TEQ/g lipid, in eggs and duck respectively) as well as in foods from Italy, including chicken eggs (Diletti et al., 2020; Ceci et al., 2022). The study from Poland (Pajurek et al., 2019) on PCDD/Fs and PCBs in chicken eggs also measured PBDD/Fs with TEQ ranging from 0.05 to 0.57 pg TEQ/g lipid (PBDD/F concentrations were higher in barn eggs compared to organic or free-range).

PCN TEQ was relatively low across species ranging from 0.01 to 0.28 pg/g lipid (0.004 to 0.06 pg/g ww) but it was significantly higher than that previously reported for chicken eggs in the UK (max: 0.003 pg/g ww) or from Ireland, China and Latvia (max: 0.002 pg/g ww) (Fernandes et al., 2010, 2011; Li et al., 2022; Zacs et al., 2021). The TEQ was on average 2% (range 0.5 – 7%) of the PCDD/F TEQ, a proportion that was consistent with other studies which measured chicken eggs, but lower than that reported for foods from France (Godéré et al., 2024). Despite the very small number of PXDD/F and PXB congeners measured in this study as a proportion of the overall number of congeners of possible toxicological significance, the TEQ values (range, 0.07 to 0.46 pg/g lipid; mean 0.18 pg/g lipid in duck eggs and range 0.11 to 0.76 pg/g lipid; mean 0.35 pg/g lipid in the eggs of other species) were more significant ($p < 0.01$, Mann-Whitney U Test, $n = 19$) compared to PCNs (Table 3) and were on average, 8% (range 3–18%) of the corresponding PCDD/F TEQ, which is similar to that reported earlier for eggs (chicken, duck and gulls) from the UK (Fernandes et al., 2014). Reflecting the occurrence pattern for PBDD/Fs, PXDFs (as well as PXBs) were detected far more frequently than PXDDs.

3.3. Regulation and exposure

In addition to raising awareness and disseminating information on contaminant occurrence in foods, some countries and regional authorities take more robust measures to promote food safety by regulating contaminant occurrence. These regulations are gradually augmented or amended and refined as new knowledge emerges. Thus, the EU commission regulation on maximum limits of PCDD/F and DL-PCB TEQ was recently amended in 2023 (European Commission, 2023), i.e., from specifying limits for “Hen eggs and egg products” to a more inclusive “Poultry eggs and egg products except goose eggs”. The current study was conducted before the above amendment in 2022, so technically the data reported here would not be covered. However, if the maximum limits as applied to domestic chickens (“hens”) eggs had been applied, then 19 samples, including 3 duck, 4 goose, 3 ostrich, 3 rhea, 2 gull and one each of emu, peafowl, turkey and pheasant, showed toxic equivalent (TEQ) values that were above the regulated PCDD/F limit (2.5 pg/g fat) for chickens eggs. Of these, 12 samples also showed concentrations of combined PCDD/F and PCB TEQ that were above the corresponding regulated limit for chicken eggs (5 pg/g fat). Additionally, both gull egg samples showed indicator PCB levels that were greater than 400 ng/g fat, an order of magnitude above the regulated limit of 40 ng/g fat for chicken eggs.

Annual per capita egg consumption typically ranges from 175 chicken eggs on average in the UK, equivalent to approx. 3 eggs per week according to industry data (Egginfo, 2024), or six eggs per week in countries with traditionally higher consumption rates such as Japan (World Population Review, 2024) where they may be used in a variety of dishes e.g., containing ramen, noodles, rice and in pastries. This is equivalent to approximately 150 g to 300 g per week for average consumption, although higher rates of consumption of seven to twelve eggs per week, or approximately 350 to 600g, is not unusual. Poultry eggs are graded by size which varies even within the same species and clearly, also between species. Recipes for globally popular dishes such as an omelette also vary the amount of raw egg used, depending on the size of the eggs that are used. For the purposes of estimating dietary intake it was therefore more practical to use consumption by weight rather than by egg number. So, weekly portion sizes of 50 g (low intake, approximately $\leq$ one egg), 150 to 300 g (average intake, three to six eggs) and

600 g (high intake, or approximately a dozen eggs per week) were considered in order to provide a deterministic assessment. The TEQ intake of PCDD/Fs, PCBs and the other measured DL-contaminants through the consumption of these non-chicken eggs was estimated conservatively for adults, using the median contaminant concentration values as listed in Tables 2 and 3, and a bodyweight (bw) of 70 kgs. As mentioned earlier the concentration data were positively skewed (skewness range: 2.5 for PCDD/Fs to 7.3 for PBDD/Fs) so the use of the median values rather than the mean avoided overestimation of the average intake. The data in Table 4 shows a range of PCDD/F and PCB dietary intakes from 0.04 pg TEQ/kg bw/week for low rates of duck egg consumption (equivalent to one egg per week) to 0.44 pg TEQ/kg bw/week for high consumption, equivalent to 12 eggs per week. These TEQ intakes approximately doubled when the contribution from other DL-like contaminants was considered. Clearly, exposure estimates for the eggs of species with limited sample numbers would have greater uncertainty and the occasional or rare consumption of these eggs may not represent general population level exposure. An estimate of overall dietary exposure would require the additional contribution from the remainder of the weekly diet. Corresponding intake estimates for NDL-PCBs and PBDEs are also included in Table 4.

The data on PBDD/Fs, PCNs, PXDD/Fs and PXBs provides a unique insight into the occurrence of these contaminants in non-chicken eggs and the contribution that they make to the overall DL-TEQ. Not all TEQ contributing congeners were measured (due to the non-availability of standards) so the reported TEQ gives a partial view of occurrence and exposure. Based on reported occurrences in other terrestrially produced foods, the PBDD/Fs and PCNs congeners selected for measurement were likely to be among the major contributors to the corresponding PBDD/F and PCN TEQ. However, for PXDD/Fs and PXBs, the selection represents only a very small fraction of the potential TEQ. Currently, there is neither the information (REP values) nor the tools (standards) required to measure additional congeners and allow a better estimate of the extent of the underestimation based on the reported fraction. However, since the availability of standards limited the study to thirteen of the possible 337 PXDDs and 647 PXDFs with lateral (2,3,7,8- Br/Cl) substitution and six of the corresponding 62 (tetra-to hexa-substituted) PXB congeners with non-ortho, or mono-ortho substitution, it is reasonable to assume that the measured contribution is a gross underestimate.

3.4. Discussion

Although chickens eggs are by far the more popular and widely produced product, the eggs of other poultry species are known to be consumed in many parts of the world, either as part of the diet (e.g. among producers or where there is easy availability), as an occasional or seasonal delicacy (e.g. during festivals in Asian countries) or for other reasons as mentioned in section 1. The physiological inevitability of

avian egg contamination as mentioned earlier has been confirmed by many reports (Rawn et al., 2012; Roszko et al., 2014; Pajurek et al., 2019) leading to regulation in some countries or regions such as the EU. In the context of the current study, these regulations cover TEQ arising from PCDD/Fs and PCBs and the content of NDL-PCBs (European Commission, 2023). However they do not include TEQ for other DL-contaminants that are known to provoke the same biological effects as PCDD/Fs and PCBs (through very similar, if not the same, mechanisms), despite a recommendation that they should be included in the TEF scheme (van den Berg et al., 2006; van den Berg et al., 2013; Fernandes and Falandysz, 2021). It is clear from available studies (Pajurek et al., 2019; Diletti et al., 2020; Fernandes et al., 2023; Dirks et al., 2024), that the TEQ contribution can be substantial and in some studies on foods, this unregulated contribution has been reported to exceed the combined PCDD/F and PCB TEQ (Diletti et al., 2020; Ceci et al., 2022; Zhang et al., 2024). In the current study, this exceedance was seen in 29% of the duck and quail eggs for PBDD/F TEQ alone, but not in the eggs of other species. However, since regulatory limits under EU legislation are generally based on adequate occurrence data, any extension of the existing limits to cover other DL-contaminants would, on the basis of this limited set of results as well as similar data reported for hen eggs, require a revision of existing limits.

The PBDD/F TEQ reported in this study is a partial value as not all 2,3,7,8-Br substituted congeners were measured (at the time of analysis, analytical standards for some congeners were not commercially available). As reviewed in other literature on PBDD/F occurrence in foods (Fernandes and Falandysz, 2021), not all PBDD congeners are detectable in food samples and in particular, the penta- and hexa-BDD congeners were not detected in any sample in this study despite LOQs being as low as 0.04 - 0.09 pg/g fat in some cases. As the REP values for these undetected congeners are relatively high, there is always a baseline contribution to the resulting upper bound TEQ values for PBDD/Fs. In this study, the average contribution from these undetected congeners was 0.11 pg/g fat. On the other hand, detected congeners such as the 2, 3,7-T₃BDD and 2,3,8-T₃BDF which provoke relatively potent responses in assays (e.g., REPs of 0.05 and 0.02 respectively – Wall et al., 2015) are not included in the proposed TEQ scheme for PBDD/Fs (van den Berg et al., 2013). Given that the partial contribution of PBDD/Fs to the cumulative TEQ from PCDD/Fs and PCBs is significant in some foods (e.g., in the present study and also in Diletti et al., 2020; Ceci et al., 2022; Zhang et al., 2024), a considered and realistic approach for the inclusion of PBDD/Fs (and other DL-contaminants) in the DL-TEQ scheme should be established.

Chronologically, PCDD/Fs and PCBs were measured first, so the selection of a smaller number of 19 samples for PXDD/F, PXB and PCN analysis was based on elevated PCDD/F and PCB TEQs. However, in retrospect this did not appear to be the most effective criteria for selection because there was poor correlation between the combined TEQ

Table 4
Dietary intake based on median contaminant concentrations for duck eggs and eggs of four other avian species.

Contaminant	Adult Intake - pg TEQ/kg bw/week							
	Duck Eggs				Other Eggs (goose, gull, peafowl, ratites)			
	Low	Average range	High		Low	Average range	high	
^a Consumption rate →								
PCDD/F & PCB TEQ	0.04	0.11	0.22	0.44	0.44	1.33	2.66	5.31
^b All measured DL-TEQ	0.08	0.23	0.47	0.94	0.51	1.54	3.09	6.17
Adult Intake - ng/kg bw/week								
NDL-PCBs	0.06	0.17	0.33	0.66	0.44	1.31	2.61	5.23
Sum PBDEs	0.10	0.29	0.58	1.17	0.29	0.88	1.76	3.51

^a Weekly consumption; Low, equivalent to 50g, average range, 150 – 300g, high, 600g.

^b Includes PCDD/Fs, DL-PCBs, PBDD/Fs, PCNs, PXBs and PXDD/Fs.

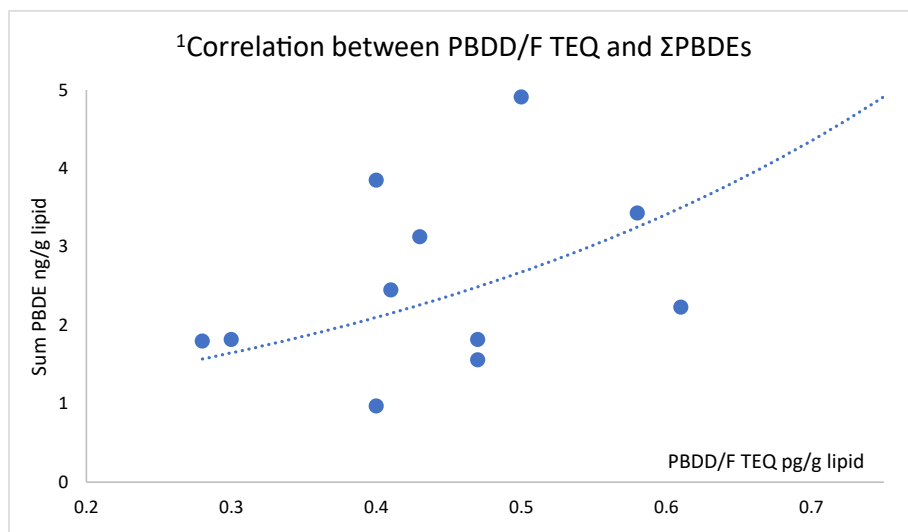
^c Based on 70 Kg adult bodyweight (bw).

of PCDD/Fs and PCBs and the individual TEQ occurrences of the other measured contaminants (apart from the gull eggs that generally showed elevated levels of all measured contaminants). This was evident for the PBDD/Fs in duck and quail eggs where elevated levels occurred almost exclusively (96%) in samples where the PCDD/F and PCB TEQs were low, i.e., below the median TEQ value. So the dominance of PBDD/F TEQ in almost 30% of the samples suggests that different sources affect the contamination of retail eggs. An indication of this is seen in the poor correlation of PBDD/F and PCDD/F occurrence ($r = 0.27$) in the eggs although they are both the products of sub-optimal combustion. PBDD/Fs are known to also originate as by-products in technical PBDEs and other BFR products such as tetrabromobisphenol A, bromophenols, 1,2-bis (tribromophenoxy) ethane and perhaps more pertinently, small quantities have been reported to form during the production of bromine containing agricultural chemicals such as Bromoxynil, Profenofos, Bromophos, etc. which are reported to yield small quantities of PBDD/Fs (Lee et al., 1986; Hanari et al., 2006; Ren et al., 2011; Fernandes and Falandysz, 2021). Unlike studies on other foods (Fernandes et al., 2009a; Ceci et al., 2022) which found poor association between PBDE and PBDF occurrence, this study showed good correlation ($r = 0.8$, $N = 104$) between these contaminants (Pearson correlation (r) of 0.8 which improved to 0.98 when the data was stratified to use mean egg concentrations [$N = 11$] for the different species) as shown in Fig. 2.

A feature of the current study was the difference in contamination levels between the more widely produced duck and quail eggs compared to the other species. The limited number of egg samples of these other species introduces uncertainty to the analysis of the data and provides indicative comparisons, but in general terms, the mean and median values for these other species were higher. So, while the differences in contaminant concentrations were not significant between duck and quail for summed Br-plus Cl-TEQ or sum of PBDEs ($p > 0.05$ in both cases, Mann-Whitney test) they were markedly greater between duck/quail and the other species ($p < 0.01$, for both, TEQ and PBDEs, using mean egg concentrations for the eleven different species). Husbandry practices used in the raising of the different species should be taken into account when considering these differences as well as the pathways that may facilitate higher contamination. In the UK, most quail and ducks and in some cases, turkeys, are reared in indoor farming systems (RSPCA, 2024). On the other hand, most of the other species (excluding black-headed gulls which are wild) are raised either in free-range conditions or the birds at least have access to soil. In these cases, grass, other herbage and insects (plus fish and amphibians in the case of gulls) also

supplement the diet. Additionally, birds will ingest soil particles either inadvertently or intentionally in order to break down larger dietary particles of food, grain, etc. in the crop, in order to aid digestion and facilitate the passage of food through the digestive system. This access to a less controlled dietary pathway has been noted in other studies (Waegeneers et al., 2009; Roszko et al., 2014) and may contribute to higher contaminant levels in farmed species that have access to soils (De Vries et al., 2006; Dervilly-Pinel et al., 2017; Pajurek et al., 2019). Commercial poultry feed is regulated for contaminants and studies that have measured PCDD/Fs, PCBs, PBDEs etc., in poultry feed in the UK (Fernandes et al., 2016, 2019, 2023), report low contamination levels. Another reason for the higher contaminant concentrations may relate to the differing physiological requirements of reproduction. In common with chickens, domestic species of ducks and quails have been bred to produce eggs more regularly, and particularly if the lighting of enclosures is adjusted (photo-stimulation) (Davis et al., 1993; Abd El-Hack et al., 2019). This is not the case for many of the other species where egg production is seasonal. As mentioned earlier, the eggs of some species are only available between late winter and early spring. Thus the transfer of fat and liver contaminants to the eggs that is seen in regular egg producers like domestic chickens, ducks and quails would occur at a considerably lower periodicity in the other species. This is because species like goose, turkey, peafowl, ratites, etc. lay two to three eggs a week, in order to produce a suitable sized clutch. Also, egg laying occurs mainly during the breeding season which varies between species. A possible consequence of this lower rate of egg production is potentially, contaminant build-up during the relatively longer latent periods which are then secreted at a higher rate to the eggs when laying re-commences in the following breeding season.

Much of the recent literature on human exposure through dietary intake of eggs relates only to chicken eggs and appears to focus on PCDD/Fs and DL-PCBs in contaminated products (Piskorska-Pliszczynska et al., 2016; Squadrone et al., 2015; Hoogenboom et al., 2016). However, where exposure was reported as part of the regular food supply, weekly dietary exposure (0.05 to 0.17 pg TEQ/kg bw) was very similar to that reported here for an average consumption rate of duck eggs (0.11 to 0.22 pg TEQ/kg bw) of approx. 3 – 6 eggs per week (Table 4). Apart from the more popular duck and quail eggs, there are likely to be considerably fewer individuals who consume the eggs of other species. As mentioned earlier, this consumption is likely to be occasional, influenced by availability during the breeding season and would apply to gourmets, farmers and egg producers and those who raise small numbers of birds either as



¹ Mean concentrations for different species. Data for black-headed gull eggs is off-scale due to elevated concentrations

Fig. 2. Correlation between PBDE and PBDD/F occurrence in retail avian eggs

¹ Mean concentrations for different species. Data for black-headed gull eggs is off-scale due to elevated concentrations.

pets or on small holdings for personal consumption. The considerably higher dietary exposure rates that result from the consumption of the eggs of these other species may thus impact specific populations. Practical consideration also suggests that it is unlikely that a significant number of individuals would consume, for example, 600g of ostrich or gull eggs in a week. However, this rate of consumption is possible at least, occasionally, for the specific groups mentioned above and represents a worst case exposure scenario based on the current data. In such cases, targeted consumer advice may be appropriate. It is worth reiterating that not all dioxin-like congeners within the measured contaminant classes were included so the actual DL-TEQ intake could be higher.

4. Conclusion

This study demonstrates the occurrence of a wide range of organic contaminants in the edible eggs of avian species other than chickens and provides unique data on the major known contributors to DL-TEQ, encompassing PCDD/Fs, PCBs and PBDD/Fs as well as PCNs, PXDD/Fs and PXBs in some samples. The contribution of TEQ from PBDD/Fs was comparable and sometimes higher than PCDD/F TEQ, particularly in duck eggs (max. 7.98 pg/g lipid) where in 26% of cases, it exceeded PCDD/F TEQ, but other contaminants occurred at elevated levels in most of the other species. In the sub-set of samples where all TEQ-contributing classes were measured, median concentrations showed that PCDD/Fs made the highest contribution to sum-TEQ at > 60%, followed by DL-PCBs at 16–20%, PBDD/Fs at 8–13%, PXDD/Fs and PXBs at 3–4% and PCNs at 1%. However, the contribution from the latter three classes of contaminants is underestimated as not all TEQ-contributing congeners were measured (in the cases of PXDD/Fs and PXBs, it is likely to be a gross underestimation). Additionally, the re-evaluation of TEFs (Fitch et al., 2024) for PCDD/Fs and PCBs is also likely to increase the TEQ contribution of these other contaminant classes. For organic and free-range reared species, different husbandry practices that include access to free-range conditions, specific breeding seasons and the lower periodicity of egg laying may contribute to higher body burdens and may promote higher levels of transfer to a smaller number of eggs compared to commercial ducks and quail species which are bred to lay more regularly.

Adult dietary intake of PCDD/F and PCB TEQ from average weekly consumption of approx. 3–6 duck eggs, estimated using median contaminant values, was not dissimilar to that of reported intakes from chicken eggs, but this approximately doubled to 0.47 pg TEQ/kg bw/week, when other DL-contaminants were included. The estimated intakes through consumption of the eggs of the other species (excluding quails which generally showed low levels of contamination) can only be considered as indicative because of the limited number of samples investigated for PXDD/Fs, PXBs and PCNs, but the corresponding intake from average consumption (using median contaminant values) was considerably higher at 2.66 and 3.09 pg TEQ/kg bw/week, respectively for PCDD/F plus PCB TEQ, and the combined TEQ from all measured DL-contaminants. Dietary exposure would likely be higher in those relatively few individuals who consumed the eggs of some species on more than an occasional basis. As all the eggs in this study originated from the UK, extrapolating contaminant intake to other countries and regions would require careful consideration of local egg contamination levels and also local consumption patterns.

A limitation that should be considered in the interpretation of the findings of this study involves the limited investigation into the additional TEQ contributions from PXDD/Fs, PXBs and PCNs. As a result of project funding considerations (and also the non-availability of a wider range of standards) only a limited number of samples could be included for these analyses. The estimates of dietary intake that are based on this data should therefore be considered indicative, but the universal detection of these contaminants should prompt further investigation, not only in the eggs of the studied species but also in the eggs of domestic chickens. Additionally, notwithstanding the limitation of low sample

numbers, the doubling of TEQ intakes when these emerging contaminants are included, suggests that the current regulatory focus, solely on PCDD/F and PCB TEQ, may be an insufficient safety measure. Thus, further monitoring of edible eggs for emerging DL-contaminants and risk assessment of the exposure to human populations is recommended in order to support extension of the current regulations.

CRedit authorship contribution statement

A.R. Fernandes: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Investigation, Formal analysis, Conceptualization. **M. Rose:** Writing – review & editing, Supervision, Resources. **F. Smith:** Writing – review & editing, Investigation, Formal analysis, Data curation. **D. Mortimer:** Writing – review & editing, Supervision, Conceptualization. **I. Lake:** Writing – review & editing, Visualization, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to the Food Standards Agency, UK for funding this work. The contribution of Sean Panton to the NDL-PCB and PCN measurements is much appreciated.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envres.2026.125959>.

References

- Abd El-Hack, M., Hurtado, C., Toro, D., Alagawany, M., Abdelfattah, E., Elnesr, S., 2019. Fertility and hatchability in duck eggs. *Worlds Poult. Sci. J.* 75 (4), 599–608.
- Birnbaum, L., Staskal, D., Diliberto, J., 2003. Health effects of PBDDs and PBDFs. *Environ. Int.* 29, 855–860.
- CAFF (Conservation of Arctic Flora and Fauna), 2008. In: Merkel, F., Barry, T. (Eds.), *Seabird Harvest in the Arctic*, CAFF Technical Report No. 16. Available at: https://library.arcticportal.org/468/1/CAFF_Technical_Report_No.16_---Seabird_Harvest_in_the_Arctic.pdf. Accessed: Oct 2025.
- Ceci, R., Diletti, G., Bellocchi, M., Chiumiento, F., D'Antonio, S., De Benedictis, A., Leva, M., Piritto, L., Scortichini, G., Fernandes, A.R., 2022. Brominated and chlorinated contaminants in food (PCDD/Fs, PCBs, PBDD/Fs PBDEs): simultaneous determination and occurrence in Italian produce. *Chemosphere* 288, 132445.
- Ceci, Roberta, D'Antonio, Silvia, De Benedictis, Alfonso, Di Bernardo, Giuseppe, Fernandes, Alwyn R., Leva, Manuela, Salini, Romolo, Scortichini, Giampiero, Tammara, Giulio, Diletti, Gianfranco, 2026. Chlorinated and brominated contaminants in Italian chicken eggs from different housing systems. *Food Control* 183, 111943. <https://doi.org/10.1016/j.foodcont.2025.111943>, 111943. <https://linkinghub.elsevier.com/retrieve/pii/S0956713525008126>.
- Davis, G., Parkhurst, C., Brake, J., 1993. Light intensity and sex ratio effects on egg production, egg quality characteristics, and fertility in breeder Pekin ducks. *Poult. Sci.* 72 (1), 23–29.
- De Vries, M., Kwakkel, R.P., Kijlstra, A., 2006. Dioxins in organic eggs: a review. *NJAS-wagening. J. Life Sci.* 54 (2), 207–221.
- Dervilly-Pinel, G., Guérin, T., Minvielle, B., Travel, A., Normand, J., Bourin, M., Royer, E., Dubreil, E., Mompelat, S., Hommet, F., et al., 2017. Micropollutants and chemical residues in organic and conventional meat. *Food Chem.* 232, 218.
- Diletti, G., Ceci, R., De Benedictis, A., Leva, M., Migliorati, G., Piritto, L., Vairano, I., Fernandes, A.R., 2020. Polybrominated dibenzo-p-dioxins and furans (PBDD/Fs) in Italian food: occurrence and dietary exposure. *Sci. Total Environ.* 741, 139916.
- Dirks, C., Gerssen, A., Weide, Y., Meijer, T., Van der Weg, G., Van de Schans, M.G., Bovee, T.F., 2024. Brominated dioxins in egg, broiler, and feed additives: significance of bioassay-directed screening for identification of emerging risks in food. *Food* 13 (6), 931.
- EFSA (European Food Safety Authority), 2026. Update of the risk assessment on dioxins and dioxin-like PCBs in feed and food. *EFSA J.* 24, e10103.
- Egginfo, 2024. UK egg industry data. Egg consumption figures. available at: <http://www.egginfo.co.uk/egg-facts-and-figures/industry-information/data>. Accessed: Oct. 2025.

- EURL (European Union Reference Laboratory, 2023. Guidance Document on the Determination of Organobromine Contaminants. <https://eurl-pops.eu/working-groups/guidance-documents>. (Accessed October 2026). Available at: Accessed.
- European Commission, 2017a. Commission Regulation (EU) 2017/644 of 5 April 2017 laying down methods of sampling and analysis for the control of levels of dioxins, dioxin-like PCBs and non-dioxin-like PCBs in certain foodstuffs and repealing Regulation (EU) no 589/2014. Off. J. Eur. Union L 92/9, 6.4.2017.
- European Commission, 2017b. Guidance document on the estimation of LOD and LOQ for measurements in the field of contaminants in feed and food. Available at: <https://ec.europa.eu/jrc/en/publication/guidance-document-estimation-lod-and-loq-measurements-field-contaminants-feed-and-food>. Accessed: Oct. 2025.
- European Commission, 2023. COMMISSION REGULATION (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) no 1881/2006. Off. J. Eur. Union L119, 103–157.
- European Recommendation, 2014. Commission recommendation of 3 march 2014 on the monitoring of traces of brominated flame retardants in food. Off. J. Eur. Communities. L65/39.
- Falandysz, J., Fernandes, A., 2020. Compositional profiles, persistency and toxicity of polychlorinated naphthalene (PCN) congeners in edible cod liver products from 1972–2017. *Environ. Pol.* 260, 114035.
- Fernandes, A., Dicks, P., Mortimer, D., Gem, M., Smith, F., Driffield, M., White, S., Rose, M., 2008. Brominated and chlorinated dioxins, PCBs and brominated flame retardants in Scottish shellfish: methodology, occurrence and human dietary exposure. *Mol. Nutr. Food Res.* 52 (2), 238–249.
- Fernandes, A., Falandysz, J., 2021. Polybrominated dibenzo-p-dioxins and furans (PBDD/Fs): contamination in food, humans and dietary exposure. *Sci. Total Environ.* 761, 1431912.
- Fernandes, A., Mortimer, D., Dicks, P., Gem, M., Smith, F., Rose, M., 2009a. Brominated dioxins (PBDD/Fs), PBBs and PBDEs in Marine Shellfish in the UK. *Food Add. Contam* 26 (6), 918–927.
- Fernandes, A., Mortimer, D., Gem, M., Smith, F., Rose, M., Pantan, S., Carr, M., 2010. Polychlorinated Naphthalenes (PCNs): Congener specific analysis, occurrence in food and dietary exposure in the UK. *Environ. Sci. Technol.* 44, 3533–3538.
- Fernandes, A., Mortimer, D., Rose, M., Smith, F., Pantan, S., Garcia-Lopez, M., 2016. Bromine content and brominated flame retardants in food and animal feed in the UK. *Chemosphere* 150, 472–478.
- Fernandes, A., Mortimer, D., Wall, R., Bell, D., Rose, M., Carr, M., Pantan, S., Smith, F., 2014. Mixed halogenated Dioxins/Furans (PXDD/Fs) and biphenyls (PXBs) in food: occurrence and toxic equivalent exposure using specific relative potencies. *Environ. Int.* 73, 104–110.
- Fernandes, A., Rose, M., Mortimer, D., Carr, M., Pantan, S., Smith, F., 2011. Mixed Brominated/Chlorinated Dibenzo-p-Dioxins, dibenzofurans and biphenyls: simultaneous congener-selective determination in food. *J. Chromatogr. A* 1218, 9279–9287.
- Fernandes, A., Tlustos, C., Smith, F., Carr, M., Petch, R., Rose, M., 2009b. Polybrominated diphenylethers (PBDEs) & brominated dioxins (PBDD/Fs) in Irish food of animal origin. *Food Addit. Contam. B* 2 (1), 86–94.
- Fernandes, A., White, S., D'Silva, K., Rose, M., 2004. Simultaneous determination of PCDDs, PCDFs, PCBs and PBDEs in food. *Talanta* 63 (5), 1147–1155.
- Fernandes, Alwyn, Rose, Martin, Falandysz, Jerzy, 2017. Polychlorinated naphthalenes (PCNs) in food and humans. *Environment International* 104, 1–13. <https://doi.org/10.1016/j.envint.2017.02.015>. <https://linkinghub.elsevier.com/retrieve/pii/S016041201610352>.
- Fernandes, A.R., Kilanowicz, A., Stragierowicz, J., Klimczak, M., Falandysz, J., 2022b. The toxicological profile of polychlorinated naphthalenes (PCNs). *Sci. Total Environ.* 837, 155764.
- Fernandes, A.R., Lake, I., Dowding, A., Rose, M., Jones, N., Petch, R., Smith, F., Pantan, S., 2019. The potential of recycled materials used in agriculture to contaminate food through uptake by livestock. *Sci. Total Environ.* 667, 359–370.
- Fernandes, A.R., Lake, I.R., Dowding, A., Rose, M., Jones, N., Smith, F., Pantan, S., 2023. The transfer of environmental contaminants (brominated and chlorinated dioxins and biphenyls, PBDEs, HBCDDs, PCNs and PFAS) from recycled materials used for bedding to the eggs and tissues of chickens. *Sci. Total Environ.* 892, 164441.
- Fernandes, A.R., Mortimer, D., Holmes, M., Rose, M., Zhihua, L., Huang, X., Smith, F., Pantan, S., Marshall, L., 2018. Occurrence and spatial distribution of chemical contaminants in edible fish species collected from UK and proximate marine waters. *Environ. Int.* 114, 219–230.
- Fernandes, A.R., Schachtele, A., Malisch, R., Zwickel, T., Tschiggfrie, K., Falandysz, J., 2025. Prioritising relevant polychlorinated naphthalene (PCN) congeners for human dietary exposure studies. *Chemosphere* 370, 144044.
- Fernandes, A.R., Zwickel, T., Schachtele, A., 2022a. Ensuring the reliability of brominated flame retardant data on food and feed occurrence through harmonised analytical criteria and proficiency testing. *Chemosphere* 286, 131921.
- Fernie, K.J., Smits, J., Bortolotti, G., Bird, D., 2001. Reproduction success of American kestrels exposed to dietary polychlorinated biphenyls. *Environ. Toxicol. Chem.* 20 (4), 776–781.
- Fitch, S., Blanchette, A., Haws, L., Franke, K., Ring, C., DeVito, M., Wheeler, M., Walker, N., Birnbaum, L., Van Ede, K., Fernandes, E.A., 2024. Systematic update to the mammalian relative potency estimate database and development of best estimate TE factors for dioxin-like compounds. *Reg. Toxicol. Pharmacol.* 147, 105571.
- Food Standards Agency, 2017. Contaminants in duck and other speciality eggs. Report to the Food Standards Agency. Available at: <https://webarchive.nationalarchives.gov.uk/ukgwa/20220807015605mp/https://www.food.gov.uk/print/pdf/node/2661>. Accessed: September 2025.
- Godéré, M., Cariou, R., Padioleau, A., Vénisseau, A., Marchand, P., Vaccher, V., Le Bizec, B., Dervilly, G., 2024. Polychlorinated naphthalenes in foods from the French market: occurrence, dietary exposure, and evaluation of relative contributions to dioxin-like contaminants. *Environ. Sci. Technol.* 58 (3), 1721–1730.
- Hanari, N., Kannan, K., Miyake, Y., Okazawa, T., Kodavanti, P., Aldous, K., Yamashita, N., 2006. Occurrence of polybrominated biphenyls, polybrominated dibenzo-p-dioxins, and polybrominated dibenzofurans as impurities in commercial polybrominated diphenyl ether mixtures. *Environ. Sci. Technol.* 40, 4400–4405.
- Hoogenboom, R.L., Ten Dam, G., van Bruggen, M., Jeurissen, S., van Leeuwen, S., Theelen, R., Zeilmaker, M., 2016. Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) and biphenyls (PCBs) in home-produced eggs. *Chemosphere* 150, 311–319.
- Jeungsmarn, P., Boontongmai, T., Saetang, P., Petrlik, J., Jelinek, N., Bell, L., Grechko, V., Bubphachai, N., Thowsakul, C., Teebthaisong, A., 2023. Persistent organic pollutants (POPs) in the surroundings of electronic waste recycling sites in Chachoengsao Province, Thailand. *Matrix* 500, 1.
- Lee, A., Campbell, B., Kelly, W., 1986. Dioxin and Furan Contamination in the Manufacture of Halogenated Organic Chemicals. Technical report EPA600/2-86/101. Hazardous Waste Engineering Research Laboratory, USEPA, 1986.
- Leveille, G.A., 1969. In vitro hepatic lipogenesis in the hen and chick. *Comp. Biochem. Physiol.* 28, 431–435.
- Li, C., Zhang, L., Yang, Q., Wu, Y., Zheng, M., Yang, L., Lyu, B., et al., 2022. Comprehensive evaluation of dietary exposure and health risk of polychlorinated naphthalenes. *Environ. Sci. Technol.* 56 (9), 5520–5529.
- Liu, P.-Y., Chen, X.-R., Zhao, Y.-X., et al., 2015. Changes of polybrominated diphenyl ether concentrations in ducks with background exposure level and time. *Chemosphere* 118, 253–260.
- Ottinger, M.A., Dean, K.D., 2022. Actions of toxicants and endocrine disrupting chemicals in birds. In: *Sturkie's Avian Physiology*. Academic Press, pp. 1373–1404.
- Pajurek, M., Pietron, W., Maszewski, S., Mikolajczyk, S., Piskorska-Pliszczynska, J., 2019. Poultry eggs as a source of PCDD/Fs, PCBs, PBDEs and PBDD/Fs. *Chemosphere* 223, 651.
- Petrlik, J., Bell, L., DiGangi, J., Allo'o, S., Kuepou, G., Ochola, G., Grechko, V., Jelinek, N., Strakova, J., Skalsky, M., Drwiega, Y.I., 2022. Monitoring dioxins and PCBs in eggs as sensitive indicators for environmental pollution and global contaminated sites and recommendations for reducing and controlling releases and exposure. *Emerging Contam.* 8, 254–279.
- Piskorska-Pliszczynska, J., Struciński, P., Kan, C., 2019. Contaminants in eggs: dioxins/pbcs and other toxic substances and their possible health implications. In: “Chemical Hazards in Foods of Animal Origin”. Wageningen Academic Publishers, pp. 292–298.
- Piskorska-Pliszczynska, J., Struciński, P., Mikolajczyk, S., Maszewski, S., Rachubik, J., Pajurek, M., 2016. Pentachlorophenol from an old henhouse as a dioxin source in eggs and related human exposure. *Environ. Pol.* 208, 404–412.
- Pratt, I., Anderson, W., Crowley, D., Daly, S., Evans, R., Keane, D., Fernandes, A., Fitzgerald, M., Geary, M., Morrison, J., Reilly, A., Tlustos, C., 2013. Brominated and fluorinated organic pollutants in the breast milk of first-time Irish mothers: is there a relationship to levels in food? *Food Addit. Contam.* 30, 1788–1798.
- Rawn, D.F., Sadler, A., Quade, S., Sun, W., Kosarac, I., Hayward, S., Ryan, J., 2012. The impact of production type and region on polychlorinated biphenyl (PCB), polychlorinated dibenzo-p-dioxin and dibenzofuran (PCDD/F) concentrations in Canadian chicken egg yolks. *Chemosphere* 89 (8), 929–935.
- Ren, M., Peng, P., Cai, Y., Chen, D., Zhou, L., Chen, P., 2011. PBDD/F impurities in some commercial deca-BDE. *Environ. Pol.* 159, 1375–1380.
- Roszkó, M., Szymczyk, K., Jędrzejczak, R., 2014. Influence of hen breeding type on PCDD/F, PCB & PBDE levels in eggs. *Sci. Total Environ.* 487, 279.
- RSPCA, 2024. Duck farming – welfare of farmed ducks. Available at: <https://www.rspca.org.uk/adviceandwelfare/farm/ducks>. Accessed: Oct. 2025.
- Shen, H., Guan, R., Ding, G., Chen, Q., Lou, X., Chen, Z., Zhang, L., Xing, M., Han, J., Wu, Y., 2017. Polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs) and polychlorinated biphenyls (PCBs) in Zhejiang foods (2006–2015): market basket and polluted areas. *Sci. Total Environ.* 574, 120–127.
- Shivaprasad, H.L., Jaap, R.G., 1977. Egg and yolk production as influenced by liver weight, liver lipid and plasma lipid in three strains of small bodied chickens. *Poult. Sci.* 56 (5), 1384–1390.
- Squadrone, S., Brizio, P., Nespoli, R., Stella, C., Abete, M.C., 2015. Human dietary exposure and levels of PCDDs, PCDFs, DL-PCBs and ND-PCBs in free-range eggs close to a secondary aluminum smelter, Northern Italy. *Environ. Pol.* 206, 429–436.
- Stockholm Convention, 2019. All POPs listed in the Stockholm Convention. Available at: <http://www.pops.int/TheConvention/ThePOPs/AllPOPs/tabid/2509/Default.aspx>. Accessed: Oct. 2025.
- Sumarmono, J., 2019. Duck production for food security. In: *IOP Conference Series. Earth Environ. Sci.*, 372. IOP Publishing, 1.
- The Guardian, 2023. Series: the age of extinction: birds. Available at: <https://www.theguardian.com/environment/2023/may/03/ban-taking-threatened-black-headed-gull-eggs-for-uk-diners-says-rspb>.
- The poultry site, 2022. Report: global poultry market to grow to \$493.21 billion by 2026. Available at: <https://www.thepoultrysite.com/news/2022/06/global-poultry-market-to-grow-to-493-21-billion-by-2026-report>. Accessed: October 2025.
- Thompson, H., Fernandes, A., Rose, M., White, S., Blackburn, A., 2006. Possible chemical causes of skeletal deformities in grey heron nestlings (*Ardea cinerea*) in North Nottinghamshire, UK. *Chemosphere* 65 (3), 400–409.
- van den Berg, M., Birnbaum, L.S., Denison, M., De Vito, M., Farland, W., Feeley, M., et al., 2006. The 2005 world health organization Re-evaluation of human and mammalian toxic equivalency factors for dioxins and dioxin-like compounds. *Toxicol. Sci.* 93, 223–241.
- van den Berg, M., Denison, M.S., Brinbaum, L.S., DeVito, M., Fiedler, H., Falandysz, J., et al., 2013. Polybrominated dibenzo-p-dioxins (PBDDs), dibenzofurans (PBDFs) and

- biphenyls (PBBs) - inclusion in the toxicity equivalency factor concept for dioxin-like compounds. *Toxicol. Sci.* 133, 197–208.
- Waegeneers, N., De Steur, H., De Temmerman, L., Van Steenwinkel, S., Gellynck, X., Viaene, J., 2009. Transfer of soil contaminants to home-produced eggs and preventive measures to reduce contamination. *Sci. Total Environ.* 407 (15), 4438.
- Wall, R., 2012. Potency and Species Specificity of Aryl Hydrocarbon Receptor Ligands. University of Nottingham, UK. PhD thesis. <http://etheses.nottingham.ac.uk/2798/>.
- Wall, R., Fernandes, A., Rose, M., Rowlands, C., Bell, D., Mellor, I., 2015. Characterisation of chlorinated, brominated and mixed halogenated ligands as potent and as partial agonists of the aryl hydrocarbon receptor. *Environ. Int.* 76, 49–56.
- World Population Review, 2024. Egg consumption by country 2024. Available at: <https://worldpopulationreview.com/country-rankings/egg-consumption-by-country>. Accessed: August 2025.
- Zacs, D., Perkons, I., Pasecnaja, E., Bartkevics, V., 2021. Polychlorinated naphthalenes (PCNs) in food products in Latvia: Congener-Specific analysis, occurrence, and dietary exposure of the general population. *Chemosphere* 264, 128460.
- Zhang, L., Peng, P., Li, H., Liu, M.Y., Hu, J.F., 2024. Halogenated aromatic pollutants in routine animal-derived food of south China: occurrence, sources, and dietary intake risks. *Environ. Pol.* 350, 124002.