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Quality of cultured eels as affected by pollution sources and risk assessment of dioxins and dioxin-like polychlorinated biphenyls

Hao Liu[1,2], Jianan Chen[1], Meng Dong[1], Jie Pang[2], Lei Qin[1] and Xuhui Huang[1*]

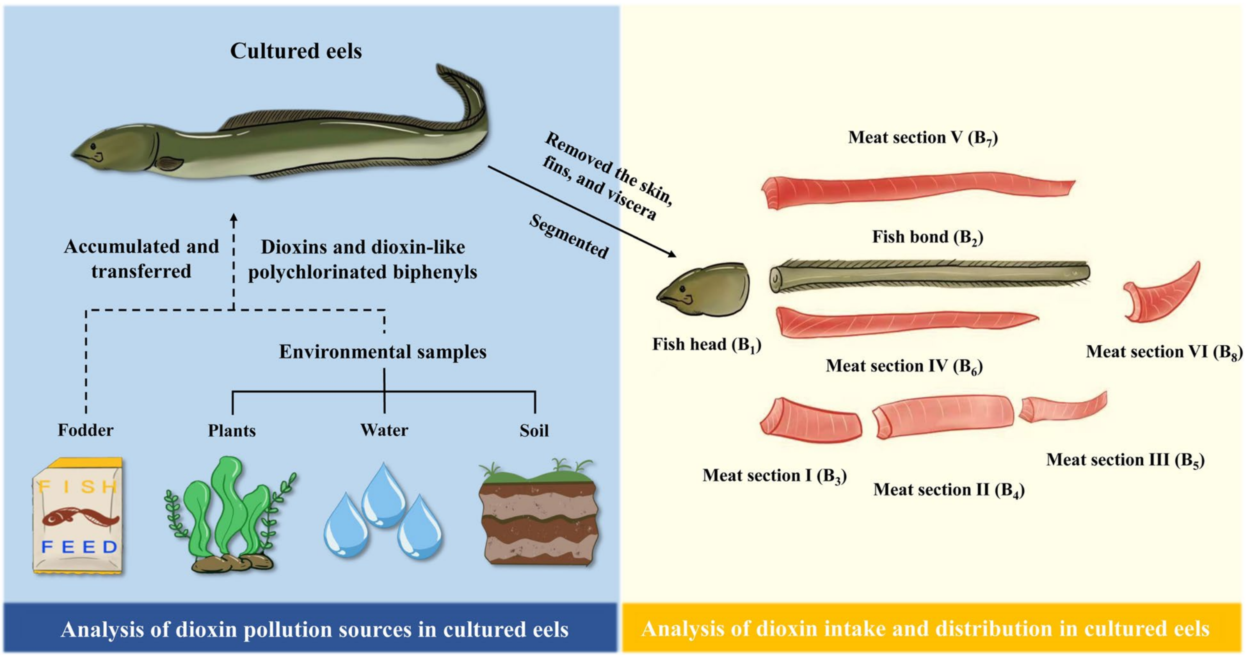
Abstract

The aim of this research was to determine the residues of dioxins and dioxin-like polychlorinated biphenyls in cultured eel and find out the source of pollution and the distribution pattern of eels. One hundred samples of eel, 4 fodder samples, and 12 environmental samples (water, plants, and soil) were collected from 4 cities and counties in Jiangxi Province, China. The contents of 17 kinds of dioxins (PCDD/Fs) and 12 kinds of dioxin-like polychlorinated biphenyls (dl-PCBs) were determined by high-resolution gas chromatography-tandem mass spectrometry, and the exposure risk was evaluated by using risk index. The total toxicity equivalence quantity (TEQ) of dioxin and dioxin-like polychlorinated biphenyls in eel and fodder samples collected in the study area were 0.65 ± 0.31 pg/g and 0.10 ± 0.02 pg/g, respectively. Dl-PCBs were the main dioxin pollution in eel and fodder samples. 2,3′,4,4′,5-pentachlorodiphenyl and 2,3,3′,4,4′-pentachlorobiphenyl were the main contributing monomers. The environmental samples were mainly polluted by polychlorinated dibenzo-p-dioxins (PCDDs), with the main contributing monomer being Octachlorodibenzodioxins (OCDD), while 3,3′,4,4′,5-pentachlorobiphenyl and 2,3,4,7,8-pentachlorodibenzofuran were the main toxic compounds in eel and fodder. The dioxin pollution of eels cultured in Jiangxi Province was mainly from fodder polluted via dl-PCBs. The meat segment VI (tail) exhibited a strong enrichment effect of polychlorinated benzofurans (PCDFs). It should be the key part for dioxins and dioxin-like polychlorinated biphenyls assessment. Further, the results were helpful to improve the edible safety of eel products and the efficiency of the risk assessment of dioxins and dioxin-like polychlorinated biphenyls in fish.

Keywords Eel, Dioxins, Dioxin-like polychlorinated biphenyls, Pollution sources, Risk index

*Correspondence:
Xuhui Huang
xuhuisos@dlpu.edu.cn
Full list of author information is available at the end of the article

Graphical Abstract



Introduction

Dioxins and dioxin-like polychlorinated biphenyls are a group of planar aromatic compounds substituted by polychlorinated, including polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and dioxin-like polychlorinated biphenyls (dl-PCBs). They are inevitable harmful by-products of industrial and thermal treatment processes which commonly found in water and soil (Hu et al. 2014; Liu & Liu 2009; Tang et al. 2018). They are classified as the first group of persistent organic pollutants (POPs) that must first be controlled (Zhang & Chen 2019), and highly potent carcinogens (McGregor et al. 1998). Due to their lipophilicity, they tend to enrich in animal epidermal tissue and eventually enter the human body through the food chain (Fechner et al. 2022; Geeraerts & Belpaire 2010; González & Domingo 2021; James & Kleinow 2014). As a result, they pose a significant risk to food safety and human health (Fiolet et al. 2022; Larsen 2006; Stadion et al. 2022; VoPham et al. 2022; Yim et al. 2022).

Animal foods, such as fish, meat, eggs, and dairy products, are more likely to be enriched by strong fat-soluble dioxins due to their high-fat content (Chang et al. 2012; Li et al. 2007; Zhang et al. 2021). The EU, Japan, and other regions have developed limits and standards for dioxin-like substances in food, while China lacks such standards. In the EU, Japan, extensive assessment of pollution status of dioxin-like substances in local animal-derived foods and the dietary intake of residents has been carried out (Shelepchikov et al. 2019; The United States, 2010). It was found that the content of dioxin in fish (especially fish oil, liver, and other parts with high-fat content) was much higher than that of other animal-derived food (Baars et al. 2004; Fattore et al. 2006; Marin et al. 2011; Sirot et al. 2012). Eel is the main economic fish in the world. China ranks first in the world in eel production, with a production of 234,000 tons in 2019, mainly distributed in Guangdong, Fujian, Jiangxi, and other places. Despite the significance of eel in the economy, there are few studies of dioxin-like substances in eel, and most of them focus on the characteristic distribution of dioxin species in eel (Blanchet-Letrouvé et al. 2014; Byer et al. 2013; Squadrone et al. 2015; Stadion et al. 2022; Zacs et al. 2013). Therefore, it is urgent to evaluate the pollution exposure of dioxin-like substances in the aquaculture system, determine the pollution source and enrichment, and find out the control measures of dioxin-like substances enrichment in aquaculture and production process.

In this paper, 17 kinds of PCDD/Fs and 12 kinds of dl-PCBs were systematically monitored and analyzed in the eel culturing process. The eel farms in 4 cities in Jiangxi Province including water, soil, and plants were comprehensively evaluated for dioxins and dioxin-like polychlorinated biphenyls contamination. The current level, composition characteristics, and distribution of dioxin-like pollutants in eels, as well as the exposure level of dioxin-like substances in the human daily diet were assessed. It was expected to provide the basic data and technical support for the management department to carry out regional dioxin-like substance control.

Materials and methods

Materials and reagents

Toluene, methanol, dichloromethane, ethanol, ether, ethyl acetate, acetone, n-hexane, isooctane, n-nonane were chromatographic grade and obtained from American Spectrum Chemical Company. Anhydrous sodium sulfate concentrated sulfuric acid, sodium hydroxide, florisilica, and silica gel were analytical grade and purchased from Aladdin Company, Shanghai, China. Alkaline alumina, sodium oxalate, and silver nitrate were analytically pure and purchased from Sigma, St. Louis, Missouri, USA. EPA23, EPA1613, P48-W-ES, P48-RS standard samples (> 95%) were bought from Wellington Laboratories, Guelph, Ontario, Canada.

Sample collection and preparation

The eel farms in 4 cities in Jiangxi Province were randomly selected as the investigating and survey area. According to the principle of uniform distribution and multi-point collection, 4 batches of samples were collected from each farm in the investigating area at different time periods, with 40–50 samples per batch. A total of 16 batches of eel samples were collected (752 samples in total). At the same time, 4 batches of fodder and environmental samples (water, plant, and soil samples) corresponding to eel samples at different time were collected as well. Samples from different farms were labeled farms-1 to farms-4. At the same time, according to the sample type, the obtained samples were labeled with names such as eel, fold, water, plant, and soil.

The eel samples collected were divided into two groups, Group A and Group B, for dioxins and dioxin-like polychlorinated biphenyls enrichment in eel experiment and dioxins and dioxin-like polychlorinated biphenyls enrichment in different tissue of eel experiment. In Group A, the eels collected from the same farm were cut and homogenized together for further detection. In Group B, the skin, fins, and viscera of the eels were removed before being segmented into eight parts, including fish head (B_1), fish bone (B_2), meat section I (B_3), meat section II (B_4), meat section III (B_5), meat section IV (B_6), meat section V (B_7), and meat section VI (B_8). Among them, the meat segments I–VI correspond to the chest, front end of the abdomen, back end of the abdomen, both sides of the spine, back, and tail of the eels. Each sample was homogenized separately and freeze-dried to a constant weight using a freeze dryer before testing.

Twenty liters of water for eel culturing with a depth of 0 to 15 cm was collected in stainless steel buckets at four sampling points of eel samples and stored in glass bottles covered with aluminum foil. For soil samples, 1 kg of fishpond soil was collected at each eel sample collection point using a clean stainless-steel shovel. Additionally, 0.5 kg of plants in the eel culture area were collected as well. All samples were stored separately in stainless steel containers covered with aluminum foil for further analysis.

Instrumental analysis

DFS high-resolution gas chromatograph-high resolution dual-focus magnetic mass spectrometer (HRGC-HRMS, ThermoScientific, Waltham, Massachusetts, USA) was used for 17 PCDD/Fs and 12 dl-PCBs analysis. The column used for separation was DB-5 (0.25 mm × 0.25 μ m × 60 m, Waters, Shanghai, China). The carrier gas was high-purity helium (99.9999%). The gas flow rate was set to 1.0 mL/min. The temperature of the sample inlet is set at 280 °C. The single sample injection volume was set to 1 μL and was used without splitting. The chromatographic column was kept at 140 °C for 1 min, and then increased to 200 °C at the rate of 20 $°C \cdot min^{-1}$ for 2 min. The temperature was then increased to 310 °C at the rate of 5 $°C \cdot min^{-1}$ for 1 min.

Mass spectrometry conditions were set as follows: the temperature of the electron ionization source and transmission line were set at 260 °C and 290 °C, respectively. The ionization energy was 35 eV. The acceleration voltage was 5000 V with a resolution more than 10,000. The scanning mode was set to the selected ion monitor (SIM) mode.

Toxic equivalent calculation

According to the regulations of the World Health Organization (WHO), the formula for calculating the toxic equivalent quantity (TEQ) of dioxins was as follows:

$$TEQ_i = TEF_i \times C_i \tag{1}$$

Where TEQ_i was the toxic equivalent concentration of dioxin monomer in the sample, pg TEQ/g. TEF_i was the toxic equivalent factor of dioxin monomer. C_i was the mass concentration of dioxin monomer in the sample, pg/g.

Quality assurance and quality control

The recovery of the ^{37}Cl sampling internal standard was 73–91%. The recovery of the ^{13}C internal standard was 59–108%. The recovery of the target compound in the blank spiking experiment was 94~109%. All of them met the quality control requirements. The detection limits of PCDD/Fs for eel, fodder, water, plant, and soil samples were 0.0331-90.5 ng/g, 0.056-17 ng/g, 0-4.1 ng/L, 0.22-97 ng/g, and 0.16-24 ng/g, respectively. The detection limits of dl-PCBs were 0.0522-296 ng/g, 0.0068-33 ng/g, 0-0.203 ng/L, 0.0067-71 ng/g, and 0.00132-19.2 ng/g, respectively.

Exposure risk assessment

According to the assessment method of FAO/WHO Joint Meeting of Pesticide Residues Experts (JMPR), the exposure risk was expressed by the percentage of exposure in ADI or ARfD (%ADI or %ARfD) as the risk index.

$$\text{Chronic assessment} : \%ADI = \text{Daily exposure}/ADI * 100 \quad (2)$$

$$\text{Acute assessment} : \%ARfD = \text{Daily exposure}/ARfD * 100 \quad (3)$$

When %ADI or %ARfD < 100, it indicates that the long-term and short-term exposure levels of the population were acceptable. On the contrary, it indicates that there were risks and risk management measures should be implemented.

Statistical analysis

The test results were recorded and saved by Excel 2010. The statistical analysis was conducted through the descriptive statistical analysis function of SPSS 21.0 software. The p value < 0.05 in the obtained results was regarded as a statistically significant difference.

Results and discussion

Analysis of concentration and toxicity equivalent of dioxins in eel culture system

The accumulated concentrations and toxic equivalent of dioxins in eel, fodder, and surrounding environmental samples were shown in Table 1. The accumulation of dl-PCBs in eel and fodder was much higher than that of PCDD/Fs (Mikolajczyk et al. 2020; Nøstbakken et al. 2021). The total concentration of dioxin-like polychlorinated biphenyls in the water samples was 17.74–24.26 pg/g, which was the lowest among eel, fodder, water, plant, and soil samples. The concentration of PCDD/Fs in the water sample was 6.05-11.68 pg/g, accounting for 34.1–48.1% of the total PCDD/Fs and dl-PCBs. This indicated that the accumulation of dioxin-like polychlorinated biphenyls in the water was approximately equal. A similar trend was also observed in the plant samples. The total

Table 1 Accumulation concentration and toxicity equivalent (pg/g) of dioxins and dioxin-like polychlorinated biphenyls in eel culture system

Sampling points	Samples	Concentration		Toxic equivalent	
		PCDD/Fs	PCDD/Fs & dl-PCBs	PCDD/Fs	PCDD/Fs & dl-PCBs
farm-1	eel	19.49 ± 0.97^b	511.49 ± 25.57^b	0.37 ± 0.02^b	0.72 ± 0.04^b
	fodder	7.89 ± 0.39^b	27.95 ± 1.40^c	0.05 ± 0.00^c	0.09 ± 0.00^d
	water	6.81 ± 0.34^b	18.04 ± 0.90^c	0.48 ± 0.02^b	0.51 ± 0.03^{bc}
	plant	13.84 ± 0.69^b	28.41 ± 1.42^c	0.33 ± 0.02^{bc}	0.41 ± 0.02^c
	soil	5553.32 ± 277.67^a	5557.86 ± 277.89^a	6.72 ± 0.34^a	6.74 ± 0.34^a
farm-2	eel	1.69 ± 0.08^b	201.61 ± 10.08^b	0.13 ± 0.01^c	0.33 ± 0.02^{bc}
	fodder	1.43 ± 0.07^b	72.1 ± 3.61^b	0.03 ± 0.00^c	0.1 ± 0.01^c
	water	11.68 ± 0.58^b	24.26 ± 1.21^b	0.52 ± 0.03^b	0.54 ± 0.03^b
	plant	7.14 ± 0.36^b	23.02 ± 1.15^b	0.3 ± 0.02^{bc}	0.34 ± 0.02^{bc}
	soil	7741.39 ± 387.07^a	7743.53 ± 387.18^a	8.55 ± 0.43^a	8.57 ± 0.43^a
farm-3	eel	30.11 ± 1.51^b	616.56 ± 30.83^b	0.54 ± 0.03^b	1.05 ± 0.05^b
	fodder	1.51 ± 0.08^b	86.76 ± 4.34^b	0.03 ± 0.00^b	0.12 ± 0.01^c
	water	6.05 ± 0.30^b	17.74 ± 0.89^b	0.56 ± 0.03^b	0.59 ± 0.03^{bc}
	plant	49.45 ± 2.47^b	73.14 ± 3.66^b	0.35 ± 0.02^b	0.43 ± 0.02^{bc}
	soil	$15,044.76 \pm 752.24^a$	$15,046.51 \pm 752.33^a$	15.74 ± 0.79^a	15.75 ± 0.79^a
farm-4	eel	4.38 ± 0.22^b	351.57 ± 17.58^b	0.15 ± 0.01^{cd}	0.5 ± 0.03^c
	fodder	1.55 ± 0.08^b	128.91 ± 6.45^c	0.01 ± 0.00^d	0.07 ± 0.00^e
	water	8.94 ± 0.45^b	18.81 ± 0.94^c	0.72 ± 0.04^b	0.74 ± 0.04^b
	plant	6.9 ± 0.35^b	45.5 ± 2.28^c	0.17 ± 0.01^c	0.25 ± 0.01^d
	soil	2626.08 ± 131.30^a	2626.21 ± 131.31^a	3.19 ± 0.16^a	3.2 ± 0.16^a

The experimental results are expressed with mean ± standard deviation, and the values in the same column are marked with [a], [b], [c], [d], and [e] to represent the significant difference among different samples in the same sampling points ($p < 0.05$)

concentration of dioxins in soil samples was 2626.21-15046.51 pg/g. The concentration of PCDD/Fs accounted for more than 99.9% of dioxin pollution in soil.

The levels of dioxin-like pollution of the same type of samples varied between different regions. This was due to the regional differences in the environmental pollution sources of dioxin. The variation in the composition of fodder and the pollution differences of the culture environment (water, plant, and soil) collectively influenced the absorption and metabolism of various pollutant monomers between eel samples (Authority, E.F.S. 2010; Karl et al. 2010; Zhao et al. 2020). Since China has not yet formulated the limit standards for dioxin-like compounds in food and fodder, the assessment and judgment were done by referring to the EU limit standards Commission Regulation (EC) No 1881/2006 (food), Commission Regulation EU NO 1259/2011 (food), Commission Regulation EU NO 1067/2013 (food), and Commission Regulation EU NO 277/2012 (fodder). The test results obtained for eel were lower than the EU standard limit (4.0 pg TEQ/g fresh weight and 12.0 pg TEQ/g fresh weight).

Distribution characteristics of dioxin in eel culture system

The proportions of different dioxins in eel, fodder, water, plant, and soil were used to indicate their distribution characteristics, shown in Fig. 1a. It can be seen that the distribution of dioxins in eel samples was mainly due to dl-PCBs. The main contributing monomers were 2,3',4,4',5-pentachlorodiphenyl (PCB 118) and 2,3,3',4,4'-pentachlorobiphenyl (PCB 105). The distribution characteristics of dioxin pollution in eel showed geographical, due to different pollution levels and main toxic contribution monomers (Alcock et al. 1998; Knutzen et al. 2003; Mikolajczyk et al. 2020; Van den Dungen et al. 2016). The composition of dioxin-like substances in fodder samples was similar to that in eel samples, which indicates that the exposure of eel to dioxins is closely related to its fodder. When comparing different environmental samples, it can be found that the concentration of PCDD/Fs in soil was much higher than dl-PCBs. The main contributing monomer was octachlorodibenzodioxin (OCDD) (99.44%). It could be the direct dioxin pollution source in eel and other environmental samples. The concentration of PCDD/Fs in water and plants was approximately the same as that of dl-PCBs. In addition, the main contribution monomers of dioxins in water and plants were different. In plants, OCDD (35.57%), 3,3',4,4'-tetrachlorobiphenyl (PCB 77) (26.64%) and PCB 118 (11.41%) were the main contributors, while in water, PCB 118 (28.74%), OCDD (20.42%) and PCB 77 (11.78%) were the dominant contributors. Among them, OCDD was the main pollutant in the environmental samples (Liu & Liu 2009; Liu et al. 2016). High-chlorine substituted dioxin monomer was more inclined to accumulate and transferred from the external environment. In general, the dioxin pollution in eel and fodder samples was mainly due to dl-PCBs, while that in environmental samples was PCDDs.

Figure 1b shows the percentage distribution of toxic equivalent of dioxin-like substances in eel, fodder, water, plant, and soil samples. The main toxic contribution

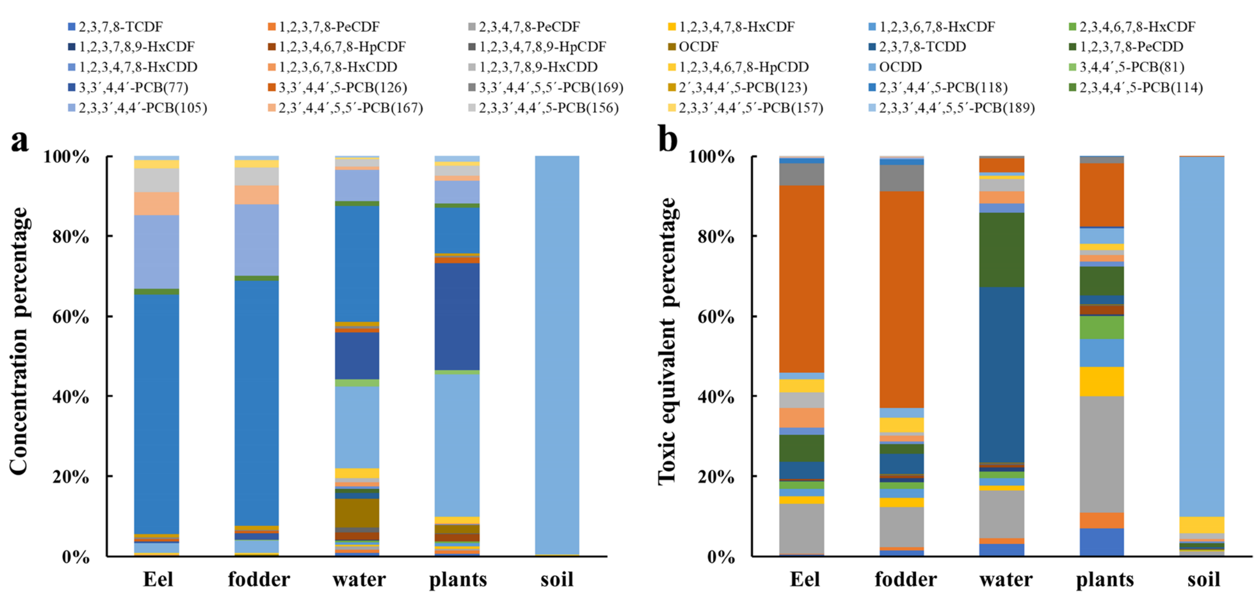


Fig. 1 Distribution proportion of dioxins and dioxin-like polychlorinated biphenyls in eel, fodder, and environmental samples (water, plants, and soil). **a** is the concentration distribution proportion, **b** is the distribution ratio of toxic equivalent

monomers of dioxin-like substances in different samples varied. The compounds 3,3′,4,4′,5-pentachlorobiphenyl (PCB 126) and 2,3,4,7,8-pentachlorodibenzofuran (2,3,4,7,8-PeCDF) were the main toxic contributing monomers in eel and fodder. They accounted for 46.79% and 12.56% in eel, respectively, and 53.97% and 9.95% in fodder, respectively. In water, 2,3,7,8-tetrachlorodibenzofuran (2,3,7,8-TCDD), 1,2,3,7,8-pentachlorodibenzofuran (1,2,3,7,8-PeCDD) and 2,3,4,7,8-PeCDF were the main toxic contributing monomers, while 2,3,4,7,8-PeCDF and PCB 126 were dominant more in plants. Besides, OCDD was the most toxic monomer of PCDD/Fs in soil (89.90%).

Analysis of dioxin pollution sources in eel culture system

Principal component analysis (PCA) and correlation analysis were conducted for dioxin-like substances in eel, fodder, water, plant, surrounding soil, and other samples collected in the investigated region, and the results are shown in Fig. 2. It can be seen from Fig. 2 that various samples can be effectively distinguished by PCA. From the results in Fig. 2d, there was a great correlation between dioxin-like substances in eel and dioxin-like substances in fodder. Besides, other environmental samples were also related to each other. Some studies have shown that dioxins were mainly transmitted and accumulated in the food chain through

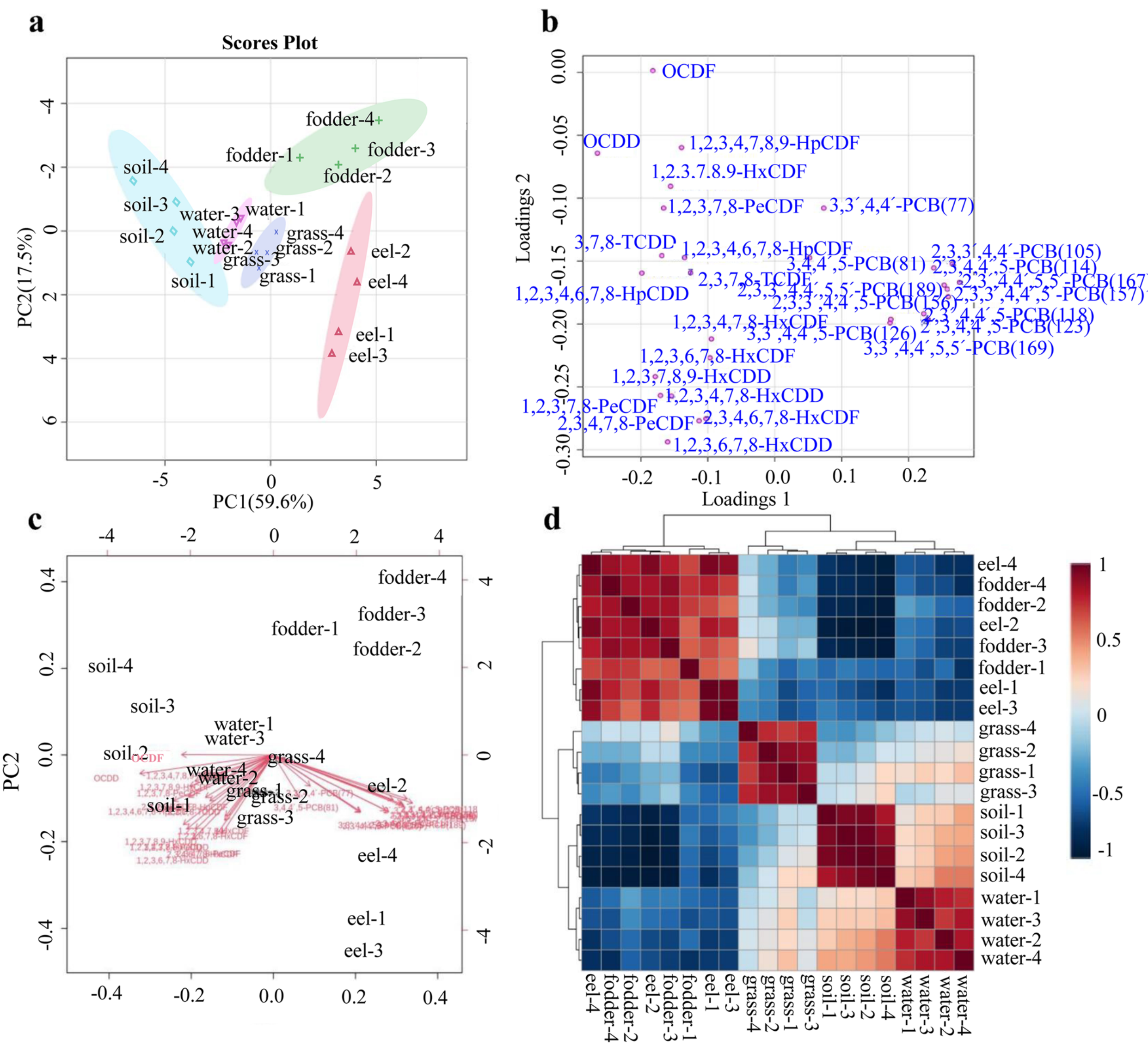


Fig. 2 Cluster analysis of dioxins and dioxin-like polychlorinated biphenyls in eel, fodder, and environmental samples (water, plant, and soil). **a** is the PCA diagram, **b** is the load diagram, **c** is the double-label diagram, **d** is the correlation diagram

diet (CONTAM et al. 2018; James & Kleinow 2014). In addition, there was a correlation and interaction between soil and water in the environment. They may be the main source of dioxin-like substances to be transferred to plant samples.

Concentration and distribution of dioxins and dioxin-like PCBs in eel

The eel samples collected were divided into meat section I, meat section II, meat section III, meat section IV, meat section V, meat section VI, skin, fin, and viscera. As showed in Tables 1 and 2, the concentration sum of PCDD/Fs in eight parts of the eel was significantly lower than that in the whole eel homogenate sample. It showed a decrease of 49.94–94.83% compared to the entire eel homogenate sample that retained the skin and viscera. It indicated that pollutants such as PCDD/Fs in eel were mainly concentrated in the viscera, skin, and fins. Removing the skin and viscera before eating eel meat can reduce the total TEQ of dioxin-like substances by 10.40–49.07% (27.73% on average). It can greatly reduce the exposure risk of dioxin and dioxin-like polychlorinated biphenyls and other pollutants in eel. The total concentration of PCDD/Fs and dl-PCBs in the B_1 was the lowest at 199.42 pg/g, while the concentration of PCDD/Fs was 2.30 pg/g. The total concentrations of PCDD/Fs and dl-PCBs in B_2 and B_8 were 358.86 pg/g and 330.08 pg/g, respectively. The total concentrations of PCDD/Fs and dl-PCBs in B_4-B_7 were all higher than the other parts. In addition to skin, fins, and viscera, dioxin-like substances were mainly concentrated in the located in the middle part of the eel.

As shown in Fig. 3, the concentration of dioxin-like substances in different eel parts was different. B_1 had poor enrichment for most dl-PCBs but had strong enrichment for 3,4,4',5-tetrachlorobiphenyl (PCB 81). B_2 was more inclined to enrich PCDDs and dl-PCBs organic pollutants. The contents of 2,3,7,8-TCDD, 1,2,3,7,8-PeCDD, and 1,2,3,6,7,8-Hexachlorodibenzo-*p*-dioxin in B_2 were significant. By comparing the distribution differences of various dioxins in the B_3-B_8, it can be found that except for B_3 and B_5, other meat segments showed strong enrichment of dl-PCBs. Group B_3 was the first segment below the head. Its trend of enrichment of PCBs was similar to that of the head. It can be concluded that when dl-PCBs were metabolized in eel, its distribution was likely to be transported from the head to the tail. In addition, it can be found that B_8 was located at the tail of the eel and had a strong enrichment effect for PCDFs organic pollutants. However, the content of PCDDs organic pollutants was lower than in other meat segments. It indicated that PCDDs organic pollutants tended to concentrate in the middle part of the eel.

Exposure risk assessment

In addition to the environmental samples, a total of 100 eel samples from major eel-producing areas in Jiangxi Province were assessed. The total TEQ of PCDD/Fs and dl-PCBs were 0.2–1 pg TEQ/g. According to the recommendation of FAO/WHO, the monthly intake tolerance (PTMI), the weekly tolerance (TWI), and the daily tolerance (TDI) of dioxins were 70 pg (TEQ)/(kg·month), 14 pg (TEQ)/(kg·week), and 1–4 pg (TEQ)/(kg·day), respectively. As the dietary guidelines for Chinese residents, adults were recommended to take 40–75 g of aquatic products daily, while children were recommended to take 50–75 g of meat, poultry, and fish per day. According to the 2021 fishery yearbook, the per capita intake of fish products in China was 25.3 kg, with an average of about 69.32 g per person per day. According to the maximum daily intake limit of 4 pg (TEQ)/(kg·day) for adults (60 kg) and children (13.1 kg), if adults consume 70 g of eel meat per day, the total intake of dioxins was 29.17% ADI, lower than 100%. It was non-toxic to adults. If adults consume

Table 2 Concentrations of dioxins and dioxin-like polychlorinated biphenyls in different parts of eel (pg/g)

Samples	Concentration		Toxic equivalent	
	PCDD/Fs	PCDD/Fs & dl-PCBs	PCDD/Fs	PCDD/Fs & dl-PCBs
B_1	2.30 ± 1.66^a	199.42 ± 100.01^b	0.11 ± 0.05^a	0.29 ± 0.10^c
B_2	2.47 ± 1.52^a	358.86 ± 190.41^{ab}	0.13 ± 0.05^a	0.41 ± 0.10^{ab}
B_3	2.93 ± 2.09^a	372.66 ± 157.13^a	0.14 ± 0.05^a	0.45 ± 0.09^{ab}
B_4	2.75 ± 1.74^a	436.76 ± 202.78^a	0.12 ± 0.04^a	0.47 ± 0.11^a
B_5	3.13 ± 1.58^a	401.33 ± 155.53^a	0.13 ± 0.02^a	0.45 ± 0.07^{ab}
B_6	2.79 ± 1.69^a	415.19 ± 167.75^a	0.13 ± 0.02^a	0.47 ± 0.07^a
B_7	2.82 ± 1.60^a	417.74 ± 172.76^a	0.14 ± 0.02^a	0.47 ± 0.05^a
B_8	2.61 ± 1.35^a	330.08 ± 75.79^{ab}	0.11 ± 0.03^a	0.37 ± 0.02^b

The experimental results are expressed with mean ± standard deviation, and the values in the same column are marked with ^{a}, ^{b}, and ^{c} to represent the significant difference between different samples ($p < 0.05$). B_1-B_8 represents fish head, fishbones, meat sections I-VI, respectively

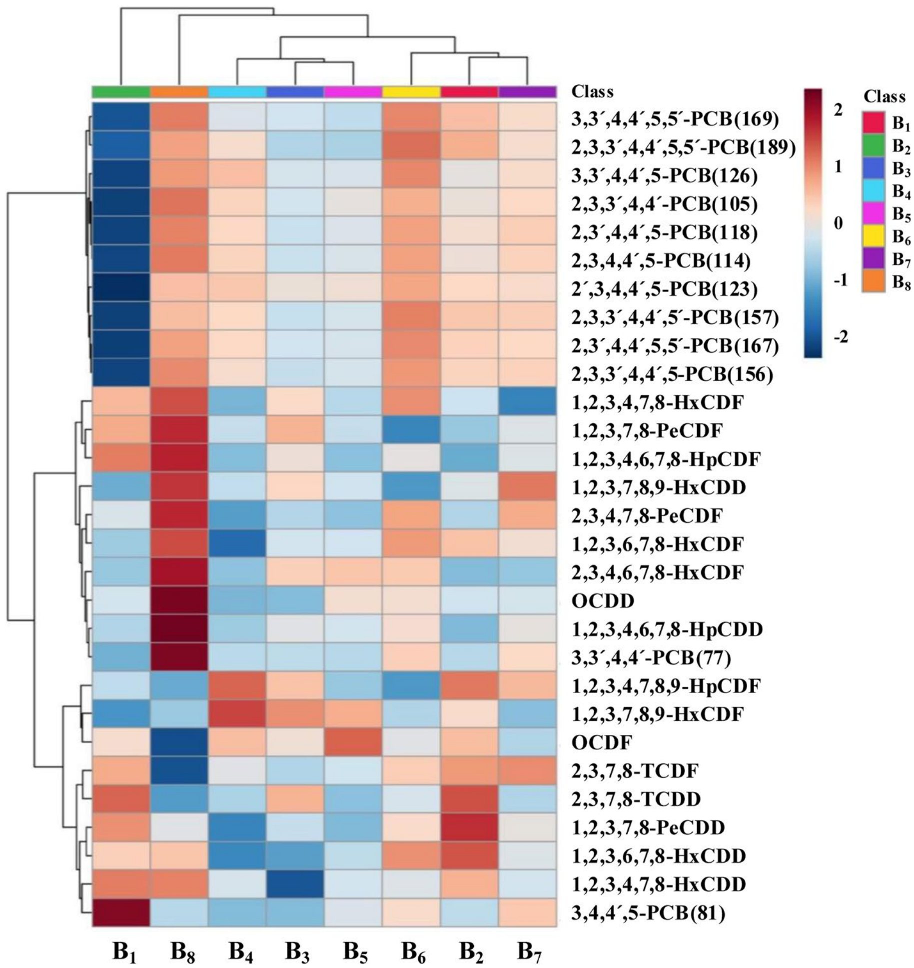


Fig. 3 Thermographic analysis of dioxins and dioxin-like polychlorinated biphenyls in different parts of eel

more than 240 g of eel meat per day, there was a chronic risk. In the case of children, according to the maximum daily intake limit of 4 pg (TEQ)/(kg·day) for children (13.1 kg), if their daily intake of eel meat and meat was 70 g, the total intake of dioxins was 133.59% ADI, higher than 100%. It was toxic to children. If the TEQ of dioxin-like substances was reduced by 27.73%, the total amount of dioxin-like substances consumed by children eating 70 g of eel meat per day was 96.54% ADI, lower than 100%, which was still at a safe level for children.

Developed countries and regions such as the European Union and Singapore have accurately limited the content of dioxins in food and animal fodder. The European Union has established the maximum TEQ of PCDD/Fs in eel and fish fodder at 4.0 pg/g fresh weight and 2.25 pg/g respectively, while the maximum TEQ of PCDD/Fs and dl-PCBs were 12.0 pg/g fresh weight and 7.0 pg/g, respectively. However, there are no limit standards for dioxin-like substances in food in China. It is urged to set the limit standards for dioxin-like substances in aquatic products in China. According to the requirements of the limit standard GB 5009.205-2013, the actual environmental pollution background, and the consumption pattern differences in China, it is suggested that the maximum TEQ of dioxin-like substances in eel be set at 10.0 pg/g (China Environmental Standard, 2017a, b, c; China National Standard, 2017a, b). Moreover, the detection system of dioxin-like substances in fodder should be developed to form a scientific and reasonable limit standard that is suitable for Chinese Nationals and to protect the public health. These results provided an important basis for risk prevention and control and government supervision.

Conclusion

Through the targeted detection of 17 dioxin components, the relationship between culture environment and dioxin enrichment in eel and the distribution of dioxin in different tissues of eel were analyzed. The dioxin pollution of eel was mainly caused by dl-PCBs.

The main contributing monomers were PCB 118 and PCB 105. The dioxin pollution of eel mainly originated from the fodder. It is important to strengthen the safety and supervision of fodder. Dl-PCBs could be transported from head to tail during the metabolism process of the eel. Meat segment VI (tail) had a strong enrichment effect on PCDFs organic pollutants. It should be the key part for dioxin risk analysis. The eel and fodder samples collected in this research did not exceed the EU limit standard. The aquaculture water and surrounding plants also met the standards. However, the toxic equivalent of surrounding soil was high. The emission control of dioxin-like substances in industrial incineration waste and the protection of the surrounding environments need to strengthen. The evaluation results of the dietary exposure risk index indicated that the normal consumption of eel meat was generally at a relatively safe level according to the recommended dosage of dietary guidelines for Chinese residents. Nevertheless, it is still necessary to formulate the limited standards of dioxin-like substances in aquatic products in China and strengthen the quality and safety management of the fodder and the environment in aquaculture.

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Authors' contributions
Conceptualization, X.-H.H.; methodology, H.L., and X.-H.H.; validation, H.L., J.-N.C., and M.D.; formal analysis, H.L. J.-N.C., and M.D.; investigation, H.L., J.-N.C., and M.D.; resources, X.-H.H., J.P., and L.Q.; data curation, H.L.; writing—original draft preparation, H.L.; writing—review and editing, H.L., and X.-H.H.; supervision, X.-H.H., J.P., and L.Q.; project administration, X.-H.H., J.P., and L.Q.; funding acquisition, X.-H.H. All authors have read and agreed to the published version of the manuscript.

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Availability of data and materials
The data used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no conflict of interests.

Author details
[1]SKL of Marine Food Processing & Safety Control, National Engineering Research Center of Seafood, Collaborative Innovation Center of Seafood Deep Processing, Dalian Technology Innovation Center for Chinese Prepared Food, School of Food Science and Technology, Dalian Polytechnic University, Dalian 116034, China. [2]College of Food Science, Fujian Agriculture and Forestry University, Fuzhou 350002, China.

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