

Trace element content and health risk assessment of main aquaculture products in Northeast China

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Abstract

This study used ICP-MS (inductively coupled plasma mass spectrometry) to analyze 22 trace elements' safety and content of main freshwater aquaculture products in Northeast China, comparing aquaculture products from other regions. Exposure and noncarcinogenic risk assessments were employed for dietary and health evaluations. Results showed that As (arsenic), Pb (lead), and Cd (cadmium) levels in *Cyprinus carpio* and *Carassius auratus* muscles exceeded safety standards, with concentrations of As 0.127–0.281, Pb 0.669–1.147, and Cd 0.101–0.693 mg·kg⁻¹. *Ctenopharyngodon idella* which also had a higher standard of Cd levels (0.107–0.190 mg·kg⁻¹) posed no significant health risks (target hazard quotient [THQ] < 1). Significant differences at the 95% level were observed in some trace elements compared to marine fish. Excessive crab and shrimp consumption may pose a potential carcinogenic risk due to Cu (copper). Overall, northeastern fish consumption presents no significant health risks, with *Ctenopharyngodon idella* deemed the safest.

Keywords: Northeast China; element content; health risk assessment; metal

Introduction

Fish meat is highly nutritious, providing essential vitamins, amino acids, and polyunsaturated fatty acids needed by the human body. Aquaculture, influenced by geographical environments, predominantly occurs in freshwater in the northeast region of China, including Heilongjiang Province (HLJ), Inner Mongolia Autonomous Region (IMAR), Liaoning Province (LN), and Jilin Province (JL). According to statistics, in 2021, *Cyprinus carpio* production in these four provinces ranked first, accounting for 23.57–39.86% of freshwater aquaculture production (Ministry of Agriculture

and Rural Fisheries Administration *et al.*, 2022). Due to their unique flavors, *Carassius auratus* and *Ctenopharyngodon idella* are highly favored by consumers. These three freshwater fish species are typically raised in earthen ponds, often located around farmlands. However, farmland soil in these areas is contaminated with arsenic (As), cadmium (Cd), and mercury (Hg) to varying degrees (Zhao *et al.*, 2023). Heavy metals, characterized by their persistence, bioaccumulation, and strong toxicity, pollute the aquaculture environment, thereby exerting significant impacts on fish, benthic organisms, and more (Zan *et al.*, 2011; Zhao *et al.*, 2020).

One of the important indexes to evaluate food safety is the content of trace elements (Lu *et al.*, 2017; Wu *et al.*, 2016; Li *et al.*, 2017). Lead (Pb) and Cd are harmful to the human body as they possess strong toxicity; also, they are not essential trace elements. Others like copper (Cu) and chromium (Cr) are essential trace elements closely related to human health. However, excessive intake of essential trace elements in food can also adversely affect consumer health (Qin *et al.*, 2015; Çelik *et al.*, 2007). Saira *et al.* (2024) found that before the rainy season begins, Pb (10.17–2.06 mg·kg⁻¹) consistently exceeded the standard limit in six fish from the River Indus in the Mianwali district of Pakistan. Although this did not pose a significant health risk, it was suggested that continuous monitoring in fish should be conducted. Alam *et al.* (2021) reported that in Bangladesh, farmed pangasius and tilapia showed heavy metal contamination in pond water, sediment, and feed, with high levels of Pb and Cr in the fish, posing potential risks to human health. Wang in 2020 conducted a survey of five metals in the samples of fish, shrimp, crabs, and shellfish from 32 provinces in China and found that at high exposure levels, the hazard index for fish in North China was greater than 1, indicating that there is a potential for noncarcinogenic risk. Gao *et al.* (2022) studied the levels of trace elements and health risks in *Chinese mitten crabs* farmed in the rice fields in China, noting that certain heavy metals posed potential risks. Meanwhile, Huang *et al.* (2022) compared and analyzed trace elements; health risk assessment was conducted on *Procambarus clarkii* farmed in the rice fields in southern China, finding that the intake of Fe (iron) exceeded the reference dose and recommending that dietary nutrient elements should also be included in risk assessments. Although researchers have conducted extensive studies on the health risks of metal elements in aquatic products, research in the health hazard of with minor elements in freshwater aquaculture products from Northeast China is relatively scarce. To understand the levels of trace elements in the main freshwater aquaculture products and their safety for consumption in Northeast China, this study employed inductively coupled plasma mass spectrometry (ICP-MS) to detect 22 elements, including 6 heavy metals or harmful elements (Cr, Cu, Cd, aluminum [Al], Pb, As) and 16 other elements (argentum [Ag], barium [Ba], beryllium [Be], cesium [Cs], cobalt [Co], Fe, gallium [Ga], lithium [Li], manganese [Mn], nickel [Ni], selenium [Se], strontium [Sr], titanium [Ti], uranium [U], vanadium [V], and zinc [Zn]) in the muscles of *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* produced in the northeastern provinces (HLJ, JL, LN, and IMAR). NY 5073-2006 and GB 2762-2022 standards were used to assess the heavy metal content in *Carassius auratus*, *Ctenopharyngodon idella*, and *Cyprinus carpio* as well as to evaluate the associated health risks. Finally, exposure assessment and noncarcinogenic risk assessment methods were employed to evaluate the safety.

The aim of this study is to provide data support for pollution monitoring of freshwater fish, guidance on production practices, and assurance of water product quality and safety.

Materials and Methods

Sample collection and processing

We collected 66 samples from the northeast region of China (HLJ, JL, LN, and IMAR), comprising 18 samples (HLJ), 18 samples (JL), 20 samples (LN), and 10 samples (IMAR). Additionally, 54 samples were collected from other regions (Anhui Province (AH) and Tianjin Municipality (TJ)), with 26 from AH and 28 from TJ. The samples included various species: *Cyprinus carpio* (24), *Carassius auratus* (21), *Ctenopharyngodon idella* (21), *Flounder* (4), *Litopenaeus vannamei* (20), *Oncorhynchus mykiss* (4), *Chinese mitten crab* (18), and *Procambarus clarkii* (8).

After collection, fish and shrimp samples were washed to remove surface mucus; heads and scales or skin were removed; and muscle was extracted. For crab samples, the body surface was cleaned, moisture wiped dry, and edible parts extracted by removing the shell. After this process, the muscles were homogenized, placed in polytetrafluoroethylene ziplock bags, and stored at -20°C waiting for inspection.

Analysis of trace elements in samples

Approximately 0.5 g of sample was weighed using an analytical balance and placed into a digestion vessel. Then, 2.5 mL of 65% nitric acid and 0.5 mL of 37% hydrochloric acid were added, followed by 7.0 mL of ultrapure water. The microwave digestion program was set at: microwave power 1.6 kW (50%) and ramp temperature 185°C. After digestion, the solution was transferred and appropriate volume was filled and a sample blank was prepared simultaneously (Qin *et al.*, 2014).

Data were collected by ICP-MS (Agilent 7500) with the following operating parameters: radiofrequency power of 1.5 kW, flow rate of nebulizer gas and auxiliary gas were 0.98 and 0.24 L min⁻¹, peristaltic pump rotation speed was 0.10 rps, sample lift rotation speed was 0.40 rps, and stabilization time was 30 s (Qin *et al.*, 2014).

Quality control and quality assurance

Using Sc (scandium), Rh (rhodium), and Bi (bismuth) as internal standards, the ICP-MS standard curve method

was employed to determine the contents of 22 metal elements, including 6 heavy metals or harmful elements and 16 other elements, with calibration curves (0–500 $\mu\text{g}\cdot\text{L}^{-1}$). The linear correlation coefficients were all above 0.9977. A blank sample was selected for low-, medium-, and high-level spiking, where the $1 \times \text{LOQ}$ (limit of quantification) listed in Table S1 represented low concentration spiking, $10 \times \text{LOQ}$ represented medium-level spiking, and $50 \times \text{LOQ}$ represented high concentration spiking. For samples exceeding the linear range, they were appropriately diluted to fall within the curve range for measurement. To minimize the impact on test results, 1 quality control sample was analyzed for every 10 samples. The reliability and accuracy of the results were improved by the above quality control methods. The recovery rate of the quality control sample was 86.8–100.96%, with the RSD (relative standard deviation) ranging from 0.18% to 7.10% (Table S1).

Data analysis

The data were represented by median (25%, 75%) and analyzed for significant differences in trace elements using the one-way analysis of variance (ANOVA) ($P < 0.05$). Use SIDI represented significant differences ($P < 0.05$), whereas N-SIDI represented no significant differences ($P > 0.05$). Preliminary analysis of the raw data was conducted using Excel 2010, followed by statistical analysis using data processing and analysis software.

Result and Analysis

Trace element content in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* muscles

Trace element content in Cyprinus carpio muscle

Table 1 presents the analysis of the contents of 22 trace elements, including 6 heavy metals or harmful elements and 16 other elements, in the *Cyprinus carpio* muscle from the northeast region (HLJ, JL, LN, and IMAR) and other regions (AH and TJ). The results indicated N-SIDI in the contents of Cr, Cu, Al, Pb, Cd, and As among the six provinces and municipalities.

There were SIDI in the Sr content in *Cyprinus carpio* muscle in IMAR, HLJ, JL, LN, AH, and TJ, and N-SIDI in HLJ, JL, LN, AH, and TJ. The U content in *Cyprinus carpio* muscle from LN differed significantly ($P < 0.05$) from that in IMAR, while there were N-SIDI in HLJ, JL, AH, and TJ compared to LN and IMAR.

Among the collected *Cyprinus carpio* samples, the contents of trace elements Cr and Cu was below the limits

set by NY 5073-2006 and GB 2762-2022. However, 8.33% of the samples exceeded the limits for As, with two samples from HLJ having concentrations of 0.144 and 0.161 $\text{mg}\cdot\text{kg}^{-1}$; 8.33% exceeded the limits for Pb, with two samples from HLJ having concentrations of 1.037 and 1.083 $\text{mg}\cdot\text{kg}^{-1}$; 41.67% exceeded the limits for Cd, with three samples from HLJ ranging from 0.177 to 0.693 $\text{mg}\cdot\text{kg}^{-1}$; two samples from JL at 0.101 and 0.103 $\text{mg}\cdot\text{kg}^{-1}$; two samples from IMAR at 0.135 and 0.146 $\text{mg}\cdot\text{kg}^{-1}$; one sample from AH at 0.107 $\text{mg}\cdot\text{kg}^{-1}$; and two samples from TJ at 0.104 and 0.132 $\text{mg}\cdot\text{kg}^{-1}$.

Cyprinus carpio is an omnivorous bottom-feeder that inhabits the lower layers of aquatic vegetation in rivers, lakes, reservoirs, and ponds, primarily feeding on benthic organisms and often ingesting mud during feeding. *Cyprinus carpio* lack a stomach and has a short intestine with rapid metabolism. Habib *et al.* (2023) detected Pb ($0.028 \pm 0.0005 \text{ mg}\cdot\text{kg}^{-1}$) and Cd ($0.022 \pm 0.001 \text{ mg}\cdot\text{kg}^{-1}$) in the fish feed and found that the heavy metal content in fish from earthen ponds was higher than those raised using Biofloc Technology Systems, with the fish raised using this technology containing metals similar to those found in fish feed. Ekpo *et al.* (2008) found that heavy metal content in water was lower than that in fish muscles and suggested that fish accumulated heavy metals (Pb, Cd, and Hg) from water over time (Table S2). Habib *et al.* (2023) and Ekpo *et al.* (2008) suggested that muscles have a lower capacity for accumulating heavy metals compared to the liver. *Cyprinus carpio* samples were all collected from earthen ponds, and the sources of As, Pb, and Cd in *Cyprinus carpio* muscles were more likely to be from feed and aquaculture water. Consumption of fish with high Pb content affects the normal functioning of the brain, kidneys, and so on, leading to liver damage and kidney failure (Bhattacharjee *et al.*, 2018). Organs tended to accumulate more heavy metals and other substances, and consuming a higher proportion of *Cyprinus carpio* viscera leads to the accumulation of heavy metals.

Trace element content in Carassius auratus muscle

Table 2 analyzes the contents of 22 trace elements, including 6 heavy metals or harmful elements and 16 other elements, in *Carassius auratus* muscles from the northeast (HLJ, JL, and IMAR) and other regions (AH). The results showed N-SIDI in the contents of trace elements of heavy metals or harmful elements Cr, Cu, Al, Pb, Cd, and As in the four provinces. However, there were SIDI in the Cs content in *Carassius auratus* muscles between MAR, and HLJ, AH; N-SIDI between IMAR and JL.

Among the 21 collected *Carassius auratus* samples, the content of trace elements Cr and Cu was below the limits set by NY 5073-2006 and GB 2762-2022. However, 9.52% of the samples exceeded the limits for As, with two

Table 1. The content of 22 trace elements in *Cyprinus carpio* from six regions of China.

	HLJ Median mg kg ⁻¹	JL Median mg kg ⁻¹	LN Median mg kg ⁻¹	IMAR Median mg kg ⁻¹	AH Median mg kg ⁻¹	TJ Median mg kg ⁻¹
Li	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]
Be	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]
Al	2.479 [1.619, 19.377] ^a	2.032 [0.763, 2.669] ^a	11.646 [9.094, 17.630] ^a	2.342 [1.579, 3.106] ^a	0.108 [0.098, 0.118] ^a	2.778 [1.721, 3.682] ^a
V	0.045 [0.010, 0.054] ^a	N.D [N.D, 0.037] ^a	0.017 [N.D, 0.038] ^a	N.D [-] ^a	N.D [-] ^a	0.024 [N.D, 0.049] ^a
Cr	0.035 [0.006, 0.131] ^a	N.D [N.D, 0.028] ^a	0.032 [0.026, 0.040] ^a	N.D [-] ^a	N.D [-] ^a	0.013 [N.D, 0.028] ^a
Mn	0.291 [0.109, 1.060] ^a	0.105 [0.068, 0.144] ^a	0.261 [0.192, 0.335] ^a	0.078 [0.068, 0.089] ^a	0.093 [0.070, 0.115] ^a	0.123 [0.085, 0.141] ^a
Fe	14.791 [11.635, 18.475] ^a	8.690 [6.071, 9.621] ^a	7.658 [6.574, 11.282] ^a	9.371 [8.843, 9.899] ^a	5.381 [4.648, 6.115] ^a	11.269 [9.707, 13.843] ^a
Co	N.D [N.D, 0.020] ^a	N.D [-] ^a	N.D [-] ^a	N.D [-] ^a	N.D [-] ^a	N.D [-] ^a
Ni	0.002 [N.D, 1.704] ^a	N.D [N.D, 0.003] ^a	0.002 [N.D, 0.006] ^a	N.D [-] ^a	N.D [-] ^a	N.D [N.D, 0.001] ^a
Cu	1.176 [0.260, 4.796] ^a	0.245 [0.058, 0.285] ^a	0.240 [0.128, 0.351] ^a	0.142 [0.113, 0.170] ^a	0.114 [0.107, 0.120] ^a	0.305 [0.064, 0.530] ^a
Zn	8.494 [6.279, 11.045] ^a	3.718 [3.215, 4.364] ^a	5.944 [5.220, 7.420] ^a	4.814 [4.318, 5.311] ^a	5.924 [4.594, 7.253] ^a	6.406 [5.683, 7.146] ^a
Ga	N.D [N.D, 0.063] ^a	N.D [-] ^a	0.022 [N.D, 0.050] ^a	N.D [-] ^a	N.D [-] ^a	N.D [-] ^a
As	0.031 [0.007, 0.117] ^a	0.014 [0.003, 0.021] ^a	0.051 [0.038, 0.066] ^a	N.D [-] ^a	0.019 [0.015, 0.023] ^a	0.020 [N.D, 0.051] ^a
Se	0.477 [0.330, 0.529] ^a	0.202 [0.154, 0.276] ^a	0.251 [0.235, 0.263] ^a	0.263 [0.202, 0.323] ^a	0.267 [0.254, 0.279] ^a	0.223 [0.186, 0.277] ^a
Sr	1.374 [1.023, 2.456] ^b	4.088 [1.841, 5.575] ^b	1.445 [1.004, 1.814] ^b	7.785 [7.777, 7.792] ^a	1.519 [1.449, 1.589] ^b	1.259 [1.135, 2.672] ^b
Ag	N.D [N.D, 0.098] ^a	N.D [-] ^a	0.001 [N.D, 0.002] ^a	N.D [-] ^a	N.D [-] ^a	N.D [-] ^a
Cd	0.135 [0.023, 0.358] ^a	0.067 [0.016, 0.093] ^a	0.006 [N.D, 0.012] ^a	0.141 [0.138, 0.144] ^a	0.082 [0.070, 0.094] ^a	0.052 [N.D, 0.111] ^a
Cs	N.D [-] ^a	N.D [N.D, 0.023] ^a	N.D [-] ^a	0.075 [0.073, 0.077] ^a	0.001 [0.001, 0.002] ^a	0.051 [N.D, 0.103] ^a
Ba	0.464 [0.160, 1.440] ^a	0.262 [0.220, 0.355] ^a	0.052 [N.D, 0.115] ^a	0.642 [0.615, 0.668] ^a	0.421 [0.378, 0.463] ^a	0.180 [0.047, 0.421] ^a
Ti	0.158 [0.074, 0.213] ^a	0.084 [0.055, 0.118] ^a	0.053 [0.033, 0.080] ^a	0.181 [0.178, 0.185] ^a	0.102 [0.086, 0.117] ^a	0.100 [0.051, 0.153] ^a
Pb	0.283 [0.072, 0.854] ^a	0.122 [0.037, 0.169] ^a	0.006 [0.003, 0.010] ^a	0.243 [0.239, 0.247] ^a	0.144 [0.123, 0.166] ^a	0.113 [0.016, 0.217] ^a
U	0.195 [0.056, 0.217] ^{ab}	0.138 [0.040, 0.193] ^{ab}	0.024 [0.008, 0.044] ^b	0.292 [0.286, 0.298] ^a	0.170 [0.144, 0.196] ^{ab}	0.112 [0.011, 0.228] ^{ab}

Different letters represent significant differences at 95% level in each line, the same as follows.

samples from JL having concentrations of 0.127 and 0.281 mg·kg⁻¹; 14.29% exceeded the limits for Pb, with two samples from HLJ having concentrations of 0.669 and 1.147 mg·kg⁻¹ and one sample from AH at 1.024 mg·kg⁻¹; 52.38% exceeded the limits for Cd, with four samples from HLJ ranging from 0.104 to 0.359 mg·kg⁻¹, two samples from

JL at 0.114 and 0.143 mg·kg⁻¹, three samples from IMAR ranging from 0.107 to 0.183 mg·kg⁻¹, and two samples from AH ranging from 0.139 to 0.314 mg·kg⁻¹.

Carassius auratus is an omnivorous fish that primarily feeds on plant-based foods in shallow waters with

Table 2. The content of 22 trace elements in *Carassius auratus* from four regions of China.

Province	HLJ Median mg kg ⁻¹	JL Median mg kg ⁻¹	IMAR Median mg kg ⁻¹	AH Median mg kg ⁻¹
Li	N.D [-]	N.D [-]	N.D [-]	N.D [-]
Be	N.D [-]	N.D [-]	N.D [-]	N.D [-]
Al	7.998 [3.774, 12.629] ^a	3.004 [0.343, 5.509] ^a	1.301 [N.D, 3.767] ^a	0.813 [0.649, 9.440] ^a
V	0.016 [0.002, 0.060] ^a	N.D [N.D, 0.171] ^a	N.D [-] ^a	N.D [-] ^a
Cr	0.043 [0.010, 0.083] ^a	N.D [N.D, 0.025] ^a	N.D [N.D, 0.008] ^a	N.D [N.D, 0.030] ^a
Mn	0.270 [0.187, 0.519] ^a	0.180 [0.091, 0.844] ^a	0.377 [0.208, 0.545] ^a	0.200 [0.161, 0.203] ^a
Fe	11.745 [10.225, 14.172] ^a	12.072 [7.180, 16.975] ^a	13.765 [7.361, 18.697] ^a	7.637 [5.295, 8.730] ^a
Co	N.D [N.D, 0.011] ^a	N.D [-] ^a	N.D [-] ^a	N.D [-] ^a
Ni	0.026 [0.005, 0.833] ^a	N.D [N.D, 0.026] ^a	N.D [N.D, 0.004] ^a	N.D [-] ^a
Cu	0.338 [0.099, 2.049] ^a	0.049 [N.D, 0.314] ^a	0.132 [0.050, 0.266] ^a	0.100 [0.085, 0.151] ^a
Zn	6.560 [4.379, 8.754] ^a	9.820 [7.717, 19.548] ^a	9.839 [5.352, 14.850] ^a	3.881 [2.382, 7.176] ^a
Ga	N.D [N.D, 0.055] ^a	N.D [-] ^a	N.D [-] ^a	N.D [N.D, 0.056] ^a
As	0.063 [0.014, 0.077] ^a	N.D [N.D, 0.095] ^a	N.D [-] ^a	N.D [N.D, 0.048] ^a
Se	0.249 [0.198, 0.295] ^a	0.211 [0.163, 0.483] ^a	0.175 [0.089, 0.267] ^a	0.251 [0.206, 0.269] ^a
Sr	2.375 [0.842, 5.518] ^a	2.569 [1.564, 60.117] ^a	5.318 [2.038, 26.768] ^a	0.876 [0.652, 0.956] ^a
Ag	N.D [N.D, 0.062] ^a	N.D [-] ^a	N.D [-] ^a	N.D [N.D, 0.002] ^a
Cd	0.116 [0.026, 0.188] ^a	0.084 [0.018, 0.109] ^a	0.125 [0.103, 0.153] ^a	0.084 [0.081, 0.139] ^a
Cs	N.D [-] ^b	N.D [N.D, 0.012] ^{ab}	0.020 [0.011, 0.029] ^a	N.D [N.D, 0.003] ^b
Ba	0.992 [0.730, 1.221] ^a	0.811 [0.685, 5.819] ^a	1.107 [0.830, 3.155] ^a	0.890 [0.889, 0.906] ^a
Ti	0.145 [0.076, 0.227] ^a	0.103 [0.071, 0.135] ^a	0.155 [0.129, 0.190] ^a	0.106 [0.101, 0.174] ^a
Pb	0.210 [0.063, 0.559] ^a	0.164 [0.094, 0.198] ^a	0.221 [0.181, 0.273] ^a	0.212 [0.157, 0.253] ^a
U	0.189 [0.054, 0.216] ^a	0.174 [0.059, 0.226] ^a	0.260 [0.215, 0.317] ^a	0.175 [0.169, 0.219] ^a

abundant aquatic vegetation, such as river shoals, bays, streams, and reed beds. The average values of Cd and Pb in the water environment of the Raohe Longkou section of the Poyang Lake Basin are 4.07 and 12.96 $\mu\text{g}\cdot\text{L}^{-1}$, respectively, while the concentrations of Cd and Pb in *Carassius auratus* muscles are 0.04 and 0.26 $\text{mg}\cdot\text{kg}^{-1}$, respectively (Li et al., 2020) (Table S2). The concentrations of Cd in

Carassius auratus were less than that for Pb, discovering a similar phenomenon in our study. The accumulation capacity of *Carassius auratus* for Cd was greater than that for Pb; additionally, the study found that microplastics may enhance the accumulation effects of Cu, Cd, and Pb to some extent and may lead to composite pollution effects.

Trace element content in *Ctenopharyngodon idella* muscle

Table 3 analyzes the contents of 22 trace elements, including 6 heavy metals or harmful elements and 16 other elements, in *Ctenopharyngodon idella* muscle from the northeast (HLJ, JL, and IMAR) and other regions (AH and TJ). The results pointed to N-SIDI in the trace

elements Cr, Cu, Pb, Cd, and As in the five provinces and municipalities, but there was SIDI in the content of Al and in *Ctenopharyngodon idella* muscle between AH and IMAR or TJ. There was SIDI in the content of Ga between AH and JL, IMAR and TJ, but N-SIDI in HLJ. There was SIDI in the Cs content in *Ctenopharyngodon*

Table 3. The content of 22 trace elements in *Ctenopharyngodon idella* from five regions of China.

Province	HLJ Median mg kg ⁻¹	JL Median mg kg ⁻¹	IMAR Median mg kg ⁻¹	AH Median mg kg ⁻¹	TJ Median mg kg ⁻¹
Li	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]
Be	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]
Al	6.845 [2.275, 10.426] ^{ab}	1.062 [0.315, 2.589] ^{ab}	0.348 [0.174, 1.022] ^b	9.148 [4.574, 17.071] ^a	1.059 [0.820, 1.298] ^b
V	0.010 [0.002, 0.043] ^a	N.D [N.D, 0.045] ^a	N.D [-] ^a	N.D [-] ^a	N.D [-] ^a
Cr	0.041 [0.022, 0.050] ^a	N.D [N.D, 0.028] ^a	N.D [N.D, 0.008] ^a	0.024 [0.012, 0.031] ^a	N.D [-] ^a
Mn	0.178 [0.134, 0.227] ^a	0.067 [0.058, 0.098] ^a	0.081 [0.057, 0.152] ^a	0.163 [0.111, 0.169] ^a	0.007 [0.00, 50.010] ^a
Fe	7.148 [5.994, 9.409] ^a	4.686 [3.472, 5.206] ^a	3.287 [2.364, 6.820] ^a	3.227 [2.871, 4.225] ^a	5.611 [5.433, 5.788] ^a
Co	N.D [N.D, 0.005] ^a	N.D [-] ^a	N.D [-] ^a	N.D [N.D, 0.003] ^a	N.D [-] ^a
Ni	0.024 [0.004, 0.404] ^a	N.D [N.D, 0.004] ^a	N.D [-] ^a	N.D [N.D, 0.001] ^a	N.D [-] ^a
Cu	0.210 [0.057, 1.164] ^a	N.D [N.D, 0.026] ^a	0.035 [0.022, 0.084] ^a	0.218 [0.109, 0.300] ^a	0.032 [0.020, 0.044] ^a
Zn	3.245 [1.986, 5.113] ^a	2.975 [2.496, 3.424] ^a	3.083 [2.798, 3.836] ^a	2.495 [2.128, 2.689] ^a	2.119 [2.051, 2.186] ^a
Ga	N.D [N.D, 0.035] ^{ab}	N.D [-] ^b	N.D [-] ^b	0.046 [0.023, 0.053] ^a	N.D [-] ^b
As	0.040 [0.009, 0.049] ^a	N.D [N.D, 0.025] ^a	N.D [-] ^a	0.028 [0.014, 0.035] ^a	N.D [-] ^a
Se	0.150 [0.124, 0.181] ^a	0.156 [0.124, 0.168] ^a	0.074 [0.06, 0.135] ^a	0.161 [0.160, 0.225] ^a	0.160 [0.148, 0.172] ^a
Sr	0.321 [0.232, 1.686] ^a	1.952 [1.545, 2.305] ^a	6.398 [3.073, 14.704] ^a	0.725 [0.586, 0.846] ^a	1.103 [0.977, 1.230] ^a
Ag	N.D [N.D, 0.028] ^a	N.D [-] ^a	N.D [-] ^a	0.002 [0.001, 0.002] ^a	N.D [-] ^a
Cd	0.064 [0.016, 0.073] ^a	0.081 [0.019, 0.091] ^a	0.089 [0.063, 0.115] ^a	0.015 [0.013, 0.061] ^a	0.098 [0.097, 0.098] ^a
Cs	N.D [N.D, 0.003] ^b	0.014 [0.001, 0.040] ^{ab}	0.021 [0.009, 0.033] ^{ab}	N.D [N.D, 0.018] ^{ab}	0.041 [0.038, 0.043] ^a
Ba	0.328 [0.149, 0.538] ^a	0.302 [0.188, 0.460] ^a	0.591 [0.274, 1.202] ^a	N.D [N.D, 0.180] ^a	0.237 [0.226, 0.248] ^a
Ti	0.081 [0.058, 0.114] ^a	0.103 [0.074, 0.114] ^a	0.111 [0.080, 0.142] ^a	0.096 [0.085, 0.115] ^a	0.123 [0.123, 0.124] ^a
Pb	0.125 [0.038, 0.291] ^a	0.144 [0.045, 0.167] ^a	0.159 [0.110, 0.204] ^a	N.D [N.D, 0.093] ^a	0.173 [0.172, 0.174] ^a
U	0.087 [0.030, 0.121] ^a	0.168 [0.050, 0.190] ^a	0.186 [0.131, 0.239] ^a	0.054 [0.047, 0.137] ^a	0.203 [0.202, 0.204] ^a

idella muscle between HLJ and TJ, while there were N-SIDI in the Cs content between HLJ or TJ and JL, IMAR, and AH, respectively.

Among the 21 *Ctenopharyngodon idella* samples collected, the content of Cr, Cu, As, and Pb was below the limits set by NY 5073-2006 and GB 2762-2022. However, 19.05% of the samples exceeded the limits for Cd, with one sample from HLJ at 0.190 mg·kg⁻¹, two samples from IMAR at 0.109 and 0.131 mg·kg⁻¹, and one sample from AH at 0.107 mg·kg⁻¹.

Ctenopharyngodon idella is a herbivorous fish that inhabits rivers, lakes, and ponds in flat plains, usually preferring the middle and lower layers of water and areas with abundant aquatic vegetation near the shore. Chen *et al.* (2022) found that the Cd in the water, sediment, and muscle of *Ctenopharyngodon idella* in the Dongting Lake Basin were 0.126 µg·L⁻¹, 0.78 mg·kg⁻¹, and 0.01 mg·kg⁻¹, respectively (Table S2), suggesting a significant and positive correlation between heavy metals in *Ctenopharyngodon idella* muscle and the breeding water, while the correlation with sediment was not significant. Comparatively, herbivorous fish (*Ctenopharyngodon idella*) showed lower enrichment capacity for heavy metals compared to omnivorous fish (*Carassius auratus*), consistent with the characteristic of hierarchical accumulation in the food web. Li *et al.* (2020) investigated the concentrations of Cd and Pb in the muscle of *Ctenopharyngodon idella* in the Raohe Longkou section of the Poyang Lake Basin, which were 0.07 and 0.34 mg·kg⁻¹, respectively (Table S2). There were N-SIDI in Cd and Pb contents in the *Ctenopharyngodon idella* muscle. *Ctenopharyngodon idella* had a greater accumulation capacity for Cd than Pb. Additionally, the study found that microplastics enhance the accumulation effects of Cu, Cd, and Pb to some extent, potentially leading to composite pollution effects. Existing research (Sheng *et al.*, 2014; Xie *et al.*, 2010) showed that one of the key factors affecting the change of heavy metal residues in fish was the feeding habits, with the bottom-dwelling fish higher than the upper layer fish. In this study, we found that the content of trace elements in the muscles of *Carassius auratus* and *Cyprinus carpio* was higher than that of *Ctenopharyngodon idella*, which could be related to the different habitat and feeding habits of the three fish species. The accumulation of heavy metal elements in fish occurs due to the biological amplification effect caused by the enrichment of heavy metals in fish bodies or due to the release, migration, and transformation of heavy metal elements at the microinterface of the “mud-water” layer in the water body. Pond water, sediment, feed, and drugs all affect the accumulation of heavy metal elements in fish, especially with high demand and intensity of feed and drugs. Over a relatively short breeding period, fish ingest large amounts of feed and medicine, leading to the

continuous accumulation of heavy metal elements, which are an important anthropogenic source of heavy metal residue in fish.

Comparison of trace element content in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* muscles with other aquatic products

Comparison with trace element content in the muscles of marine products

Table 4 compares the content of 22 trace elements, including 6 heavy metals or harmful elements and 16 other elements, in the muscles of freshwater-cultured fish (*Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella*) with marine fish (*Flounder* and *Litopenaeus vannamei*). The results showed that the content of Al, Cu, and Cd in the muscles of the freshwater cultured fish showed N-SIDI with *Flounder* and *Litopenaeus vannamei*. However, the content of As in the muscles of *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower than that in *Litopenaeus vannamei* ($P < 0.05$), whereas there was N-SIDI with *Flounder*. The content of Cr and Pb in the muscles of *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in *Flounder*, whereas there was N-SIDI with *Litopenaeus vannamei*.

There were N-SIDI in the content of V in *Cyprinus carpio* and *Carassius auratus* compared to *Flounder* and *Litopenaeus vannamei*, whereas there was SIDI in *Ctenopharyngodon idella* compared to *Litopenaeus vannamei*, but not with *Flounder*. The content of Ni, Ga, and Ag in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in *Flounder*, whereas there was N-SIDI with *Litopenaeus vannamei*. The contents of Mn, Fe, Sr, Zn, Se, Ba, Cs, and U in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* showed N-SIDI with *Flounder* and *Litopenaeus vannamei*.

The types and contents of metal elements in fish were related to the breeding environment. Ullah *et al.* (2023) interpreted the research results from the aspects of fish species, habitat, surrounding environment, feed, and life cycle, finding that biological habitats affect the accumulation of trace metals. Zhang *et al.* (2014) found that the total amount of trace elements in cultured freshwater pearls was lower than that in cultured seawater pearls. Yang *et al.* (2021) investigated the differences in the content of five metals between freshwater and marine fish in the Shandong Province, finding that the contents of As, Se, Cd, and Pb in marine fish was higher than that in freshwater fish (Table S3). In contrast, the content of As and Se in freshwater fish muscle

Table 4. The contents of 22 kinds of trace elements in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* were compared with other aquatic products.

Trace elements	Six provinc or city Median mg kg ⁻¹		Four province Median mg kg ⁻¹		Five province or city Median mg kg ⁻¹		Marine fishes Median mg kg ⁻¹		Flounder		Oncorhynchus mykiss		Chinese mitten crab ^A		Chinese mitten crab ^B		Procamburus clarkii	
	<i>Cyprinus carpio</i>	<i>Carassius auratus</i>	<i>Ctenopharyngodon idella</i>	<i>Carassius auratus</i>	<i>Ctenopharyngodon idella</i>	<i>Litopenaeus vannamei</i>	Flounder	Oncorhynchus mykiss	Chinese mitten crab ^A	Chinese mitten crab ^B	Procamburus clarkii	Procamburus clarkii						
Li	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	
Be	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	
Al	2.343	3.396	1.537	3.396	1.537	11.696	18.834	8.145	27.975	18.663	6.759	18.663	27.975	18.663	6.759	18.663	6.759	
V	N.D	N.D	N.D	N.D	N.D	0.066	0.008	N.D	0.114	0.114	N.D	N.D	0.114	0.114	N.D	N.D	N.D	
Cr	0.010	N.D	N.D	N.D	N.D	0.051	0.077	0.020	0.064	0.072	N.D	N.D	0.064	0.072	N.D	N.D	N.D	
Mn	0.139	0.245	0.107	0.245	0.107	0.848	0.315	0.143	7.799	6.760	1.570	6.760	7.799	6.760	1.570	6.760	1.570	
Fe	9.821	9.900	5.222	9.900	5.222	19.621	5.800	5.817	71.254	106.568	8.491	71.254	106.568	106.568	8.491	106.568	8.491	
Co	N.D	N.D	N.D	N.D	N.D	N.D	0.010	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	
Ni	N.D	N.D	N.D	N.D	N.D	0.029	0.702	N.D	0.178	0.115	N.D	0.178	0.115	0.115	N.D	N.D	N.D	
Cu	0.209	0.100	0.035	0.100	0.035	4.978	1.765	0.486	10.235	9.823	2.823	10.235	9.823	9.823	2.823	9.823	2.823	
Zn	5.928	7.382	2.882	7.382	2.882	9.910	3.031	2.361	20.160	19.369	4.935	20.160	19.369	19.369	4.935	19.369	4.935	
Ga	N.D	N.D	N.D	N.D	N.D	N.D	0.091	0.026	N.D	N.D	N.D	0.026	N.D	N.D	N.D	N.D	N.D	
As	0.024	N.D	N.D	N.D	N.D	0.352	0.365	0.501	0.508	0.036	0.036	0.501	0.508	0.508	0.036	0.036	0.036	
Se	0.255	0.251	0.156	0.251	0.156	0.320	0.414	0.268	0.439	0.136	0.136	0.268	0.439	0.439	0.136	0.136	0.136	
Sr	1.605	1.796	1.356	1.796	1.356	3.103	0.430	0.268	17.626	20.690	0.542	17.626	20.690	20.690	0.542	20.690	0.542	
Ag	N.D	N.D	N.D	N.D	N.D	N.D	0.063	0.001	0.017	0.013	N.D	0.001	0.017	0.013	N.D	N.D	N.D	
Cd	0.067	0.104	0.076	0.104	0.076	N.D	0.164	0.117	0.069	0.184	0.110	0.117	0.069	0.184	0.110	0.110	0.110	
Cs	N.D	N.D	0.005	N.D	0.005	N.D	N.D	0.025	N.D	0.013	0.013	0.025	N.D	N.D	0.013	0.013	0.013	
Ba	0.291	0.906	0.309	0.906	0.309	0.339	0.494	0.264	3.194	0.618	0.618	0.264	3.194	3.194	0.618	0.618	0.618	
Ti	0.096	0.131	0.103	0.131	0.103	0.044	0.188	0.136	0.043	0.058	0.058	0.136	0.043	0.058	0.058	0.058	0.058	
Pb	0.122	0.193	0.137	0.193	0.137	0.026	0.510	0.206	0.030	0.200	0.200	0.206	0.030	0.030	0.200	0.200	0.200	
U	0.138	0.195	0.140	0.195	0.140	0.010	0.127	0.153	0.021	0.068	0.068	0.153	0.021	0.068	0.068	0.068	0.068	

A: LN, B: AH, the same as follows.

was lower than that in *Flounder* and *Litopenaeus vannamei*, whereas the content of Cd and Pb in freshwater fish muscles was higher than that in *Litopenaeus vannamei* but lower in *Flounder*; this was similar to and different from Zhang (Zhang et al., 2014) or Yang (Yang et al., 2021). Additionally, the feeding habits of aquatic products could also affect their accumulation of metal elements. Zhang et al. (2021) found that heavy metals accumulate in water and sediment and transferred to higher trophic level organisms through the biological amplification effect of the food chain, and interactions such as antagonism, additive, synergy, and independent effects between heavy metals may inhibit or promote the enrichment of heavy metals. Therefore, it was speculated that due to factors such as food chain enrichment, different feeding habits, and different breeding environments, the content of trace elements in freshwater fish (*Cyprinus carpio*, *Carassius auratus*, *Ctenopharyngodon idella*) was lower than that of marine fish (*Flounder* and *Litopenaeus vannamei*).

Comparison with trace element content in the muscles of other freshwater products

Table 4 compares the content of 22 trace elements, including 6 heavy metals or harmful elements and 16 other elements, in the muscles of cultured freshwater *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* with other freshwater fish (*Oncorhynchus mykiss*, *Chinese mitten crab* (in LN and AH), and *Procambarus clarkii*). The results showed that the content of Al in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in LN and AH), whereas there was N-SIDI with *Oncorhynchus mykiss* and *Procambarus clarkii*. The content of Cr in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in AH), whereas there was N-SIDI with *Oncorhynchus mykiss* and *Procambarus clarkii*. The content of Cr in *Cyprinus carpio* and *Carassius auratus* showed N-SIDI with the *Chinese mitten crab* (in LN), whereas the content of Cr in *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in LN). The content of Cu in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in LN and AH) and *Procambarus clarkii*, whereas there was N-SIDI with *Oncorhynchus mykiss*. The content of As in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in *Oncorhynchus mykiss* and *Chinese mitten crab* (in LN and AH), whereas there was N-SIDI with *Procambarus clarkii*. The content of Cd in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in AH), whereas there was N-SIDI with *Oncorhynchus mykiss*, *Chinese mitten crab* (in LN), and *Procambarus*

clarkii. The content of Pb in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* showed N-SIDI with *Oncorhynchus mykiss*, *Chinese mitten crab* (in LN and AH), and *Procambarus clarkii*.

The content of Sr in *Cyprinus carpio* and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in LN and AH), whereas there was N-SIDI with *Oncorhynchus mykiss* and *Procambarus clarkii*. The content of Sr in *Carassius auratus* revealed N-SIDI with the *Chinese mitten crab* (in LN and AH), *Oncorhynchus mykiss*, and *Procambarus clarkii*. The content of Zn in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in AH), whereas there was N-SIDI with *Oncorhynchus mykiss*. The content of Zn in the *Chinese mitten crab* (in LN) and *Procambarus clarkii* was higher ($P < 0.05$) than that in *Ctenopharyngodon idella*, whereas there was N-SIDI with *Cyprinus carpio* and *Carassius auratus*. The content of Se in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in AH), whereas there was N-SIDI with *Oncorhynchus mykiss* and the *Chinese mitten crab* (in LN). The content of Ba in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower ($P < 0.05$) than that in the *Chinese mitten crab* (in AH), whereas there was N-SIDI with *Oncorhynchus mykiss*, *Chinese mitten crab* (in LN), and *Procambarus clarkii*. The content of Ni, Ga, Ag, Cs, and U in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* showed N-SIDI with *Oncorhynchus mykiss*, *Chinese mitten crab* (in LN and AH), and *Procambarus clarkii*.

In this study, the contents of Zn and Fe in aquatic products were in the order of *Chinese mitten crab* and *Litopenaeus vannamei* > *Cyprinus carpio* and *Carassius auratus* > *Procambarus clarkii*. The Cr content in the *Chinese mitten crab* (LN and AH) was higher than the results shown in Gao et al.'s (2022) study (Table S4). Crustacean aquatic organisms had a strong enrichment capacity for heavy metals, related to factors such as living habits, dietary habits, and tissue parts. The primary reason for the differences in heavy metal residues in fish was the different living and feeding habits, showing carnivorous > omnivorous > herbivorous, and bottom-dwelling fish higher than the upper layer fish (Sheng et al., 2014; Xie et al., 2010). Lee et al. (2017) found that most heavy metals accumulate in the heads of *Litopenaeus vannamei*, followed by shrimp shells and shrimp meat. *Procambarus clarkii* ingests *Litopenaeus vannamei* when cohabiting (James et al., 2024), increasing the accumulation of heavy metals in *Procambarus clarkii*. Wu et al. (2023) found that the highest content of Cd in different parts of *Eriocheir sinensis* was in the hepatopancreas and lowest in the chest muscles and leg

muscles; the Cd content in the crab yolk and leg muscles of the same crab body differs by 233 times. Chen (2020) investigated the composition of heavy metal content in the Huainan section of the Huai River and found that the Cd content ranged from 0.06 to 1.57 $\mu\text{g}\cdot\text{L}^{-1}$ and the Pb content ranged from 0.16 to 9.39 $\mu\text{g}\cdot\text{L}^{-1}$, with heavy metal content in the first half of the year higher than that in the second half of the year, except for the Lu Taizi sampling point. Gao *et al.* (2022) found that the Cd content in the muscle of *Chinese mitten crab* were 0.209 (AH) and 0.092 (LN) $\text{mg}\cdot\text{kg}^{-1}$, respectively, and the Pb was 0.001 (AH) and 0.009 $\text{mg}\cdot\text{kg}^{-1}$ (LN) (Table S4). Jiang *et al.* (2015) found that the Cd content in the muscle of the *Chinese mitten crab* was 0.69 (AH) and 0.56 (LN) $\text{mg}\cdot\text{kg}^{-1}$ and the Pb was 0.60 (AH) and 0.55 $\text{mg}\cdot\text{kg}^{-1}$ (LN) (Table S4), suggesting that the residual amounts of Pb and Cd in the crustacean aquatic products are geographically correlated. In this study, the Cd and Pb content in the *Chinese mitten crab* muscle in LN was lower than that in AH, the reason for which could be related to geographical locations. Cd and Pb were detected in *Procambarus clarkii* and *Chinese mitten crab* in AH and LN. The Cd content in the muscle of the *Chinese mitten crab* in AH and LN was lower than that in the results in Gao *et al.* (2022) and Jiang *et al.* (2015) studies, whereas the Pb content was higher than that in Gao *et al.* (2022) but lower than that in Jiang *et al.* (2015) study results (Table S4). In this study, the content of Al, Cu, and As in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* was lower than that in the crustacean aquatic products (*Chinese mitten crab*, *Procambarus clarkii*, and *Litopenaeus vannamei*). The Pb content was higher than that in the *Chinese mitten crab* but lower than that in *Oncorhynchus mykiss* and *Procambarus clarkii* and the Cd content was lower than that in the *Chinese mitten crab* (AH), *Oncorhynchus mykiss*, and *Procambarus clarkii*. *Procambarus clarkii* is omnivorous and *Oncorhynchus mykiss* is carnivorous, and in trace elements such as Al, Cr, Se, Cd, As, Ag, Ti, and Pb, *Oncorhynchus mykiss* was higher than in *Procambarus clarkii*, whereas the *Chinese mitten crab* was higher than *Litopenaeus vannamei* in trace elements such as Al, Cr, Se, Cd, As, and Ag. These results were due to food chain enrichment, breeding environment, geographical location, dietary habits, and sampling season, among other factors.

Exposure assessment

Cd, Cr, Cu, Pb, and Zn were selected from 22 trace elements for human tolerance assessment in this research. The actual weekly intake (AWI) of these elements for adults was evaluated based on the trace element content and the amount of aquatic products consumed by Chinese residents per week. The provisionally tolerable

weekly intake (PTWI) for these elements was compared with AWI to assess their levels of dietary safety:

$$\text{AWI} = C_i \times \text{WC}$$

$$\text{PTWI} = \text{WTI} \times \text{BW}$$

Here, C_i is expressed as the content of a certain trace element ($\text{mg}\cdot\text{kg}^{-1}$) in *Cyprinus carpio*, *Carassius auratus*, or *Ctenopharyngodon idella*; WC represents the average weekly consumption of aquatic products per capita ($\text{kg}\cdot\text{week}^{-1}$); BW represents the body weight of residents (kg); and WTI represents the provisionally tolerable intake of each trace element per unit BW per week ($\text{mg}\cdot[\text{kg}\cdot\text{week}]^{-1}$). The percentage of PTWI was evaluated for food safety with AWI, with a higher AWI/PTWI ratio indicating lower food safety levels.

The WHO (World Health Organization) and FAO (Food and Agriculture Organization) had established the provisionally tolerable intake of pollutants per unit weight as the basis for food safety assessment (WHO, 2004); therefore, Cd, Cr, Cu, Pb, and Zn was 0.007, 0.0233, 3.50, 0.25, and 7 $\text{mg}\cdot(\text{kg}\cdot\text{week})^{-1}$, respectively. According to the 2015 “Chinese Resident Nutrition Report,” WC was 0.168 $\text{kg}\cdot\text{week}^{-1}$ and the average BW of residents was 60 kg. Calculations were performed for these five trace elements (Table 5).

The results showed that the ratios of the average AWI to the PTWI for five trace elements in nine aquatic products ranged from 0.023% to 11.455%. Among them, the health risks associated with Cr were ranked as *Chinese mitten crab*^B > *Flounder* > *Chinese mitten crab*^A > *Litopenaeus vannamei* > *Cyprinus carpio* > *Carassius auratus* > *Procambarus clarkii* > *Oncorhynchus mykiss* > *Ctenopharyngodon idella*; Cu health risks were ranked as *Chinese mitten crab*^B > *Procambarus clarkii* > *Chinese mitten crab*^A > *Litopenaeus vannamei* > *Flounder* > *Cyprinus carpio* > *Oncorhynchus mykiss* > *Carassius auratus* > *Ctenopharyngodon idella*; Zn health risks were ranked as *Chinese mitten crab*^B > *Procambarus clarkii* = *Chinese mitten crab*^A > *Litopenaeus vannamei* > *Carassius auratus* > *Cyprinus carpio* > *Flounder* > *Ctenopharyngodon idella* > *Oncorhynchus mykiss*; Cd health risks were ranked as *Chinese mitten crab*^B > *Flounder* > *Oncorhynchus mykiss* > *Carassius auratus* > *Procambarus clarkii* > *Cyprinus carpio* > *Chinese mitten crab*^A > *Ctenopharyngodon idella* > *Litopenaeus vannamei*; and Pb health risks were ranked as *Flounder* > *Carassius auratus* > *Oncorhynchus mykiss* > *Cyprinus carpio* > *Procambarus clarkii* > *Ctenopharyngodon idella* > *Chinese mitten crab*^B > *Litopenaeus vannamei* > *Chinese mitten crab*^A. The consumption risk of Cr, Cu, Zn, and Cd trace elements was higher in the *Chinese mitten crab*^B in AH than in other aquatic products, while

Table 5. The actual weekly intake and the provisionally tolerable weekly intake by adults through consuming aquatic products.

		Cr	Cu	Zn	Cd	Pb
PTWI mg·week ⁻¹		1.398	210	420	0.420	1.500
<i>Cyprinus carpio</i>	Average mg·kg ⁻¹	0.033	1.134	6.548	0.101	0.195
	Max mg·kg ⁻¹	0.283	14.766	14.164	0.693	1.083
	Average of AWI mg·week ⁻¹	0.005	0.191	1.100	0.017	0.033
	Average of AWI/PTWI %	0.393	0.091	0.262	4.043	2.181
	Max of AWI mg·week ⁻¹	0.047	2.481	2.379	0.117	0.182
	Max of AWI/PTWI %	3.395	1.181	0.567	27.739	12.125
<i>Carassius auratus</i>	Average mg·kg ⁻¹	0.028	0.546	9.824	0.113	0.275
	Max mg·kg ⁻¹	0.124	3.404	32.458	0.359	1.147
	Average of AWI mg·week ⁻¹	0.005	0.092	1.650	0.019	0.046
	Average of AWI/PTWI %	0.330	0.044	0.393	4.535	3.080
	Max of AWI mg·week ⁻¹	0.021	0.572	5.453	0.060	0.193
	Max of AWI/PTWI %	1.491	0.272	1.298	14.354	12.848
<i>Ctenopharyngodon idella</i>	Average mg·kg ⁻¹	0.018	0.285	3.251	0.070	0.138
	Max mg·kg ⁻¹	0.060	2.980	10.327	0.190	0.397
	Average of AWI mg·week ⁻¹	0.003	0.048	0.546	0.012	0.023
	Average of AWI/PTWI %	0.222	0.023	0.130	2.817	1.544
	Max of AWI mg·week ⁻¹	0.010	0.501	1.735	0.032	0.067
	Max of AWI/PTWI %	0.723	0.238	0.413	7.598	4.448
<i>Litopenaeus vannamei</i>	Average mg·kg ⁻¹	0.059	5.741	11.757	0.004	0.034
	Max mg·kg ⁻¹	0.148	20.519	44.064	0.029	0.121
	Average of AWI mg·week ⁻¹	0.010	0.965	1.975	0.001	0.006
	Average of AWI/PTWI %	0.712	0.459	0.470	0.142	0.384
	Max of AWI mg·week ⁻¹	0.025	3.447	7.403	0.005	0.020
	Max of AWI/PTWI %	1.773	1.642	1.763	1.164	1.352
Flounder	Average mg·kg ⁻¹	0.083	1.980	3.408	0.169	0.566
	Max mg·kg ⁻¹	0.128	4.160	5.670	0.331	1.245
	Average of AWI mg·week ⁻¹	0.014	0.333	0.573	0.028	0.095
	Average of AWI/PTWI %	1.001	0.158	0.136	6.762	6.341
	Max of AWI mg·week ⁻¹	0.022	0.699	0.953	0.056	0.209
	Max of AWI/PTWI %	1.541	0.333	0.227	13.254	13.949
<i>Oncorhynchus mykiss</i>	Average mg·kg ⁻¹	0.025	0.798	2.455	0.116	0.222
	Max mg·kg ⁻¹	0.062	2.210	3.485	0.215	0.475
	Average of AWI mg·week ⁻¹	0.004	0.134	0.412	0.019	0.037
	Average of AWI/PTWI %	0.305	0.064	0.098	4.632	2.488
	Max of AWI mg·week ⁻¹	0.010	0.371	0.586	0.036	0.080
	Max of AWI/PTWI %	0.746	0.177	0.139	8.613	5.320
Chinese mitten crab ^A	Average mg·kg ⁻¹	0.070	10.040	20.115	0.083	0.034
	Max mg·kg ⁻¹	0.116	11.543	29.125	0.148	0.078
	Average of AWI mg·week ⁻¹	0.012	1.687	3.379	0.014	0.006
	Average of AWI/PTWI %	0.843	0.803	0.805	3.325	0.379
	Max of AWI mg·week ⁻¹	0.020	1.939	4.893	0.025	0.013
	Max of AWI/PTWI %	1.399	0.923	1.165	5.936	0.877

(continues)

Table 5. Continued.

		Cr	Cu	Zn	Cd	Pb
<i>Chinese mitten crab</i> ^B	Average mg·kg ⁻¹	0.107	13.859	29.424	0.286	0.047
	Max mg·kg ⁻¹	0.324	35.397	105.705	0.793	0.164
	Average of AWI mg·week ⁻¹	0.018	2.328	4.943	0.048	0.008
	Average of AWI/PTWI %	1.286	1.109	1.177	11.455	0.532
	Max of AWI mg·week ⁻¹	0.054	5.947	17.758	0.133	0.028
	Max of AWI/PTWI %	3.896	2.832	4.228	31.718	1.837
<i>Procambarus clarkii</i>	Average mg·kg ⁻¹	0.027	11.033	20.115	0.108	0.181
	Max mg·kg ⁻¹	0.115	68.409	128.125	0.230	0.307
	Average of AWI mg·week ⁻¹	0.005	1.854	3.379	0.018	0.030
	Average of AWI/PTWI %	0.323	0.883	0.805	4.324	2.022
	Max of AWI mg·week ⁻¹	0.019	11.493	21.525	0.039	0.052
	Max of AWI/PTWI %	1.383	5.473	5.125	9.214	3.440

the consumption risk of Pb trace elements was higher in *Flounder*. Overall, the health risks associated with trace elements in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* are relatively low.

Noncarcinogenic risk assessment

Ag, As, Ba, Cr, Cu, Cd, Pb, U, and Zn were selected from 22 trace elements to estimate the estimated daily intake (EDI) and conduct health risk analysis. USEPA (USEPA, 2011) recommended that THQ is used to assess the health risk of trace elements in fish to humans. The calculation formula was as follows:

$$EDI = \frac{IR \times C}{BW}$$

$$THQ = \frac{EDI}{RfD}$$

Here, EDI is expressed as the estimated daily intake ($\mu\text{g}\cdot(\text{kg}\cdot\text{d})^{-1}$), IR represented the daily intake ($\text{g}\cdot\text{d}^{-1}$), C is expressed as the highest content ($\text{mg}\cdot\text{kg}^{-1}$), BW represented the body weight of residents (kg), and RfD represented the reference dose. According to the “Chinese Resident Dietary Guidelines 2022,” the daily intake of fish meat for Chinese adults is 71.4 g d^{-1} . The RfD values for As, Cr, Cu, Zn, Cd, Ba, Pb, U, and Ag were 3.0, 1500, 40, 300, 1.0, 200, 1.5, 3.0, and 5.0, respectively (Gao *et al.*, 2022; Han *et al.*, 2021).

It was considered that the level of the trace element poses no significant carcinogenic risk to the exposed population when $THQ < 1$, but might pose a potential

carcinogenic risk to the exposed population when $THQ \geq 1$. The higher the THQ value, the greater the risk. The total THQ (TTHQ) was used to evaluate the health risk of complex pollutants (Qin *et al.*, 2015; Zhang *et al.*, 2018). TTHQ was the sum of THQ for multiple elements. $TTHQ \leq 1.0$ indicated no significant adverse effects, $TTHQ > 1.0$ indicated potential adverse effects on human health, and $TTHQ > 10.0$ indicated the presence of chronic toxic effects.

$$TTHQ = \sum_{i=1}^n THQ_i$$

Three essential trace elements (Cu, Zn, and Cr) and six toxic trace elements (As, Pb, Cd, Ba, U, and Ag) were detected for health risk assessment from the 22 trace elements. The RfD for U, Ag, Ba, Cd, Cr, and Zn were retrieved from the USEPA, and RfD values for As and Cu were not retrieved and were used as reported. The Pb data were obtained from the European Food Safety Authority (EFSA) database. The results are shown in Table 6.

From the perspective of sampling areas, the THQ values of all samples collected from HLJ, JL, LN, and IMAR were less than 1, indicating that consuming the analyzed samples would not pose significant health risks. However, the THQ values for the trace element Cu in the *Chinese mitten crab* and *Procambarus clarkii* samples from AH as well as the trace element As in the *Chinese mitten crab* (AH) and *Litopenaeus vannamei* (TJ) were greater than 1, indicating potential carcinogenic risks associated with Cu and As. This should be taken seriously, and overconsumption should be avoided for the shrimp and crab. The recommendation is to consume no more than 432.2 g of

Table 6. EDI and THQ of trace elements during eight kinds of aquatic products in China.

	<i>Cyprinus carpio</i>	<i>Carassius auratus</i>	<i>Ctenopharyngodon idella</i>	<i>Litopenaeus vannamei</i>	Flounder	<i>Oncorhynchus mykiss</i>	Chinese mitten crab ^a	Chinese mitten crab ^b	<i>Procambarus clarkii</i>
Cr	EDI	0.336	0.148	0.072	0.176	0.153	0.139	0.386	0.137
	THQ	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cu	EDI	17.572	4.050	3.546	24.418	4.950	13.737	42.123	81.407
	THQ	0.439	0.101	0.089	0.610	0.124	0.343	1.053	2.035
Zn	EDI	16.855	38.625	12.289	52.436	6.747	34.659	125.789	152.469
	THQ	0.056	0.129	0.041	0.175	0.022	0.116	0.419	0.508
As	EDI	0.192	0.334	0.068	3.637	0.993	1.014	3.469	2.019
	THQ	0.064	0.111	0.023	1.212	0.331	0.338	1.156	0.673
Ag	EDI	0.161	0.138	0.050	0.000	0.157	0.029	0.260	0.337
	THQ	0.032	0.028	0.010	0.000	0.031	0.006	0.052	0.067
Cd	EDI	0.825	0.427	0.226	0.035	0.394	0.177	0.944	0.274
	THQ	0.825	0.427	0.226	0.035	0.394	0.177	0.944	0.274
Ba	EDI	4.949	12.905	2.604	1.497	1.680	11.424	118.390	4.838
	THQ	0.025	0.065	0.013	0.007	0.008	0.057	0.592	0.024
Pb	EDI	1.288	1.365	0.473	0.144	1.482	0.093	0.195	0.365
	THQ	0.859	0.910	0.315	0.096	0.988	0.062	0.130	0.244
U	EDI	0.436	0.453	0.362	0.019	0.300	0.040	0.360	0.309
	THQ	0.145	0.151	0.121	0.006	0.100	0.013	0.120	0.103

Chinese mitten crab meat, 245.6 g of *Procambarus clarkii* meat, and 412.3 g of *Litopenaeus vannamei* meat per week.

In terms of species, *Cyprinus carpio*, *Carassius auratus*, *Ctenopharyngodon idella*, *Oncorhynchus mykiss*, and *Flounder* are safer compared to shrimp and crab. The Hazard Quotient values for essential trace elements were: Cu: $\text{THQ}_{\text{Procambarus clarkii}} > \text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Litopenaeus vannamei}} > \text{THQ}_{\text{Cyprinus carpio}} > \text{THQ}_{\text{Chinese mitten crabA}} > \text{THQ}_{\text{Flounder}} > \text{THQ}_{\text{Carassius auratus}} > \text{THQ}_{\text{Ctenopharyngodon idella}} > \text{THQ}_{\text{Oncorhynchus mykiss}}$; Zn: $\text{THQ}_{\text{Procambarus clarkii}} > \text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Litopenaeus vannamei}} > \text{THQ}_{\text{Carassius auratus}} > \text{THQ}_{\text{Chinese mitten crabA}} > \text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Cyprinus carpio}} > \text{THQ}_{\text{Ctenopharyngodon idella}} > \text{THQ}_{\text{Flounder}} > \text{THQ}_{\text{Oncorhynchus mykiss}}$; Cr: $\text{THQ}_{\text{Cyprinus carpio}} = \text{THQ}_{\text{Carassius auratus}} = \text{THQ}_{\text{Ctenopharyngodon idella}} = \text{THQ}_{\text{Litopenaeus vannamei}} = \text{THQ}_{\text{Flounder}} = \text{THQ}_{\text{Oncorhynchus mykiss}} = \text{THQ}_{\text{Chinese mitten crabA}} = \text{THQ}_{\text{Chinese mitten crabB}} = \text{THQ}_{\text{Procambarus clarkii}}$. The Hazard Quotient values for toxic trace elements are: As: $\text{THQ}_{\text{Litopenaeus vannamei}} > \text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Procambarus clarkii}} > \text{THQ}_{\text{Oncorhynchus mykiss}} > \text{THQ}_{\text{Chinese mitten crabA}} > \text{THQ}_{\text{Flounder}} > \text{THQ}_{\text{Carassius auratus}} > \text{THQ}_{\text{Cyprinus carpio}} > \text{THQ}_{\text{Ctenopharyngodon idella}}$; Pb: $\text{THQ}_{\text{Flounder}} > \text{THQ}_{\text{Carassius auratus}} > \text{THQ}_{\text{Cyprinus carpio}} > \text{THQ}_{\text{Oncorhynchus mykiss}} > \text{THQ}_{\text{Ctenopharyngodon idella}} > \text{THQ}_{\text{Procambarus clarkii}} > \text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Litopenaeus vannamei}} > \text{THQ}_{\text{Chinese mitten crabA}}$; Cd: $\text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Cyprinus carpio}} > \text{THQ}_{\text{Carassius auratus}} > \text{THQ}_{\text{Flounder}} > \text{THQ}_{\text{Procambarus clarkii}} > \text{THQ}_{\text{Oncorhynchus mykiss}} > \text{THQ}_{\text{Ctenopharyngodon idella}} > \text{THQ}_{\text{Chinese mitten crabA}} > \text{THQ}_{\text{Litopenaeus vannamei}}$; Ba: $\text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Carassius auratus}} > \text{THQ}_{\text{Chinese mitten crabA}} > \text{THQ}_{\text{Cyprinus carpio}} > \text{THQ}_{\text{Procambarus clarkii}} > \text{THQ}_{\text{Ctenopharyngodon idella}} > \text{THQ}_{\text{Flounder}} > \text{THQ}_{\text{Litopenaeus vannamei}} > \text{THQ}_{\text{Oncorhynchus mykiss}}$; U: $\text{THQ}_{\text{Carassius auratus}} > \text{THQ}_{\text{Cyprinus carpio}} > \text{THQ}_{\text{Ctenopharyngodon idella}} = \text{THQ}_{\text{Oncorhynchus mykiss}} > \text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Procambarus clarkii}} > \text{THQ}_{\text{Flounder}} > \text{THQ}_{\text{Chinese mitten crabA}} > \text{THQ}_{\text{Litopenaeus vannamei}}$; Ag: $\text{THQ}_{\text{Procambarus clarkii}} > \text{THQ}_{\text{Chinese mitten crabB}} > \text{THQ}_{\text{Cyprinus carpio}} > \text{THQ}_{\text{Flounder}} > \text{THQ}_{\text{Carassius auratus}} > \text{THQ}_{\text{Oncorhynchus mykiss}} > \text{THQ}_{\text{Ctenopharyngodon idella}} > \text{THQ}_{\text{Chinese mitten crabA}} > \text{THQ}_{\text{Litopenaeus vannamei}}$. Except for *Ctenopharyngodon idella*, the TTHQ values for seven aquatic products ranged from 1 to 10, indicating potential adverse effects on human health, whereas the consumption of *Ctenopharyngodon idella* in this study showed no significant adverse effects (TTHQ = 0.838).

Conclusion

This study investigated the contents of 22 trace elements in the muscle of the main cultured freshwater fish (*Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella*) in Northeast China, and compared them with seawater fish and other freshwater products while also conducting dietary assessments and noncarcinogenic risk evaluations.

In Northeast China (HLJ, JL, LN, and IMAR), only Sr, Cs, and U showed SIDI among the 22 trace elements in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* samples, while other trace elements (Pb, Cd, Cr, As, Cu, etc.) showed N-SIDI. The levels of Cr and Cu were below the limits specified in NY 5073-2006 and GB 2762-2022 while As, Pb, and Cd, exceeded the limits in *Cyprinus carpio* and *Carassius auratus*, and the standard rates were 8.33–9.52% (As), 8.33–14.29% (Pb), 41.67–51.38% (Cd), with Cd exceeding the limit in *Ctenopharyngodon idella* muscle, and the standard rates were 19.05%.

Regarding the sampled species, some trace elements in *Cyprinus carpio*, *Carassius auratus*, and *Ctenopharyngodon idella* showed SIDI compared to marine fish (*Flounder* and *Litopenaeus vannamei*) and other aquatic products (*Chinese mitten crab*, *Procambarus clarkii*, and *Oncorhynchus mykiss*) at the 95% level. The sequence of Cu trace element content was: *Ctenopharyngodon idella* < *Carassius auratus* < *Cyprinus carpio* < *Oncorhynchus mykiss* < *Flounder* < *Procambarus clarkii* < *Litopenaeus vannamei* < *Chinese mitten crab*; for Cr trace element, it was *Procambarus clarkii* = *Carassius auratus* = *Ctenopharyngodon idella* < *Cyprinus carpio* < *Oncorhynchus mykiss* < *Litopenaeus vannamei* < *Chinese mitten crab* < *Flounder*; for Cd trace element, it was *Litopenaeus vannamei* < *Cyprinus carpio* < *Chinese mitten crab* (LN) < *Ctenopharyngodon idella* < *Carassius auratus* < *Procambarus clarkii* < *Oncorhynchus mykiss* < *Flounder* < *Chinese mitten crab* (AH); for As trace element, it was *Ctenopharyngodon idella* < *Carassius auratus* < *Cyprinus carpio* < *Procambarus clarkii* < *Litopenaeus vannamei* < *Flounder* < *Oncorhynchus mykiss* < *Chinese mitten crab*; and for Pb trace element, it was *Litopenaeus vannamei* < *Chinese mitten crab* < *Cyprinus carpio* < *Ctenopharyngodon idella* < *Carassius auratus* < *Procambarus clarkii* < *Oncorhynchus mykiss* < *Flounder*.

Overall, consuming aquatic products from Northeast China (*Cyprinus carpio*, *Carassius auratus* and *Ctenopharyngodon idella*) posed a low health risk due to trace elements, all within acceptable ranges (THQ < 1). However, the aquatic products with higher consumption and health risks due to trace elements Cd and Pb were the *Chinese mitten crab* from AH and *Flounder*. In terms of species, *Cyprinus carpio*, *Carassius auratus*, *Ctenopharyngodon idella*, *Oncorhynchus mykiss*, and *Flounder* were safer compared to shrimp and the *Chinese mitten crab*. Overconsumption of *Chinese mitten crab* (AH), *Procambarus clarkii* and *Litopenaeus vannamei* could pose potential carcinogenic risks due to Cu or As. According to the Chinese Dietary Guidelines, the recommended weekly intake of *Chinese mitten crab* meat should not exceed 432.2 g and the recommended

weekly intake of *Procambarus clarkii* and *Litopenaeus vannamei* meat should not exceed 245.6 g and 412.3 g, respectively. From the perspectives of consumption risk and health risk, *Ctenopharyngodon idella* was the safest fish compared to *Cyprinus carpio* and *Carassius auratus*.

In the future, we will further collect aquatic product samples from the southern region to analyze the levels of trace elements in farmed aquatic products, assess the health risks and dietary recommendations for harmful metals across different latitudes in farmed aquatic products, elucidate the differences in the accumulation of trace elements between freshwater and marine fish and the reasons for these results, and consider how to mitigate or solve the threat of toxic elements to human health from the perspective of the food chain.

Authors Contribution

Li Huang: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, and Writing – original draft. Dongli Qin: Investigation, Resources, and Visualization. Shizhan Tang: Data curation, Investigation, and Methodology. Peng Wang: Funding acquisition, Supervision, Reviewing. Lei Gao: Conceptualization, Supervision, Writing Reviewing and Editing.

Conflicts of Interest

Not applicable.

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Data Availability Statement

Data will be made available on request.

Declarations and Ethical Approval

Not applicable.

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent for Publication

The authors affirm that human research participants provided informed consent for publication of the image in consent form. Competing interests: The authors declare no competing interests.

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Supplementary

Table S1. Quality control plus standard recovery rate and relative standard deviation.

Element	Linear range $\mu\text{g L}^{-1}$	Correlation coefficient	LOD $\text{mg}\cdot\text{kg}^{-1}$	LOQ $\text{mg}\cdot\text{kg}^{-1}$	Low level		Medium level		High-level	
					Recovery %	RSD %	Recovery %	RSD %	Recovery %	RSD %
Li	0 - 500	0.9982	0.002	0.005	99.97	0.96	99.20	1.26	100.96	1.17
Be	0 - 500	0.9977	0.002	0.005	99.13	0.25	95.40	1.79	99.62	0.18
Al	0 - 500	0.9982	0.5	2	100.77	1.93	93.73	3.55	97.51	1.89
V	0 - 500	0.9992	0.002	0.005	97.70	0.87	91.93	4.83	93.08	3.25
Cr	0 - 500	0.9995	0.05	0.2	98.13	0.56	93.40	3.66	98.93	2.94
Mn	0 - 500	0.9995	0.1	0.3	96.87	0.33	91.40	4.71	97.43	3.63
Fe	0 - 500	0.9994	1	3	98.00	0.27	96.47	2.13	99.72	2.37
Co	0 - 500	0.9996	0.001	0.003	88.93	0.43	95.20	2.00	97.98	1.94
Ni	0 - 500	0.9997	0.2	0.5	89.53	0.79	92.40	2.09	98.42	1.00
Cu	0 - 500	0.9987	0.05	0.2	91.13	1.10	92.27	7.10	96.83	1.91
Zn	0 - 500	0.9997	0.5	2	90.97	0.67	91.40	5.59	96.85	3.38
Ga	0 - 500	0.9996	0.002	0.005	93.20	2.04	95.27	3.15	95.37	2.00
As	0 - 500	0.9998	0.002	0.005	93.10	0.57	94.20	2.57	98.27	4.61
Se	0 - 500	0.9999	0.01	0.03	87.90	2.30	90.53	5.90	96.29	4.12
Sr	0 - 500	0.9998	0.2	0.5	88.63	1.82	92.67	1.00	98.01	2.14
Ag	0 - 500	0.9995	0.002	0.005	89.37	0.65	96.07	5.35	95.18	3.06
Cd	0 - 500	0.9999	0.002	0.005	86.80	2.95	95.80	5.33	97.05	1.39
Cs	0 - 500	0.9999	0.002	0.005	89.03	1.35	91.93	5.44	96.63	4.19
Ba	0 - 500	0.9993	0.02	0.05	94.70	5.02	94.73	3.11	96.83	1.91
Ti	0 - 500	0.9996	0.02	0.05	89.77	0.39	91.27	6.59	98.27	1.41
Pb	0 - 500	0.9985	0.02	0.05	94.27	2.39	94.20	1.53	94.52	3.49
U	0 - 500	0.9990	0.002	0.005	94.47	4.75	93.87	3.21	97.35	1.52

Table S2. Metal element (Pb and Cd) content compared with other studies.

Trace elements	The trace element content			References
	Water $\mu\text{g}\cdot\text{L}^{-1}$	Muscle $\text{mg}\cdot\text{kg}^{-1}$	Sediment $\text{mg}\cdot\text{kg}^{-1}$	
Pb	–	0.030–0.510	–	This research
Cd	–	ND–0.184	–	
Pb	1.0–5.0	0.00–0.004	–	Ekpo <i>et al.</i> (2008)
Cd	1.0	0.001–0.002	–	
Pb	4.07	0.26–0.34	–	Li <i>et al.</i> (2020)
Cd	12.96	0.04–0.07	–	
Cd	0.126	0.78	0.01	Chen <i>et al.</i> (2022)

Table S3. The content of trace elements (As, Se, Cd, Pb) in muscle of freshwater fish compared with seawater fish.

	As mg·kg ⁻¹	Se mg·kg ⁻¹	Cd mg·kg ⁻¹	Pb mg·kg ⁻¹	References
Freshwater fish	0.075	0.169	0.005	0.112	Yang <i>et al.</i> (2021)
Marine fish	1.370	0.292	0.024	0.289	
Freshwater fish	0.008	0.221	0.082	0.151	This research
Marine fish	0.358	0.367	0.082	0.268	

Table S4. The contents of Cd, Pb and Cr in Chinese Eriocheir crab in Anhui province and Liaoning province were compared.

Breeding province	Cd mg·kg ⁻¹	Pb mg·kg ⁻¹	Cr mg·kg ⁻¹	References
AH	0.184	0.033	0.072	This research
LN	0.069	0.030	0.064	
AH	0.209	0.001	0.002	Gao <i>et al.</i> (2022)
LN	0.092	0.009	0.057	
AH	0.69	0.60	–	Jiang <i>et al.</i> (2015)
LN	0.56	0.55	–	

Table S5. The contents of 22 kinds of trace elements in muscle of *Cyprinus carpio*, *Carassius auratus* and *Ctenopharyngodon idella* were compared with other aquatic products.

Trace elements	Six province or city Median mg·kg ⁻¹			Five province or city Median mg·kg ⁻¹			Marine fishes Median mg·kg ⁻¹			Freshwater fishes Median mg·kg ⁻¹		
	<i>Cyprinus carpio</i>	<i>Carassius auratus</i>	<i>Ctenopharyngodon idella</i>	<i>Litopenaeus vannamei</i>	Flounder	<i>Oncorhynchus mykiss</i>	Chinese mitten crab ^a	Chinese mitten crab ^b	<i>Procamburus clarkii</i>			
Li	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	
Be	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	N.D [-]	
Al	2.343 [0.922, 3.906] ^c	3.396 [0.649, 9.440] ^e	1.537 [0.320, 6.647] ^c	11.696 [5.042, 18.928] ^{bc}	18.834 [16.080, 22.535] ^{abc}	8.145 [1.329, 18.744] ^{bc}	27.975 [14.840, 34.590] ^{ab}	18.663 [15.218, 22.797] ^a	6.759 [0.794, 16.767] ^c			
V	N.D [N.D, 0.049] ^{bc}	N.D [N.D, 0.013] ^{bc}	N.D [N.D, 0.008] ^c	0.066 [0.055, 0.081] ^b	0.008 [N.D, 0.019] ^c	N.D [N.D, 0.002] ^c	0.114 [0.101, 0.142] ^a	0.114 [0.103, 0.144] ^a	N.D [N.D, 0.003] ^c			
Cr	0.010 [N.D, 0.037] ^{cd}	N.D [N.D, 0.040] ^{cd}	N.D [N.D, 0.038] ^d	0.051 [0.043, 0.064] ^{bd}	0.077 [0.053, 0.108] ^{ab}	0.020 [N.D, 0.045] ^{cd}	0.064 [0.057, 0.084] ^{abc}	0.072 [0.064, 0.101] ^a	N.D [N.D, 0.040] ^{cd}			
Mn	0.139 [0.076, 0.193] ^b	0.245 [0.135, 0.494] ^b	0.107 [0.059, 0.163] ^b	0.848 [0.616, 1.188] ^b	0.315 [0.248, 0.414] ^b	0.143 [0.085, 0.199] ^b	7.799 [6.048, 10.959] ^a	6.760 [4.456, 11.294] ^a	1.570 [1.246, 3.548] ^b			
Fe	9.821 [7.717, 13.811] ^c	9.900 [7.075, 16.649] ^c	5.222 [3.227, 6.197] ^c	19.621 [9.873, 30.796] ^c	5.800 [2.869, 9.232] ^c	5.817 [5.454, 6.251] ^c	71.254 [54.882, 76.542] ^b	106.568 [76.818, 115.922] ^a	8.491 [3.434, 28.145] ^c			
Co	N.D [-] ^a	N.D [-] ^b	N.D [-] ^b	N.D [-] ^b	0.010 [N.D, 0.020] ^a	N.D [N.D, 0.003] ^a	N.D [N.D, 0.005] ^a	N.D [-] ^b	N.D [N.D, 0.005] ^a			
Ni	N.D [N.D, 0.004] ^b	N.D [N.D, 0.032] ^b	N.D [N.D, 0.004] ^b	0.029 [0.018, 0.038] ^b	0.702 [0.015, 1.411] ^a	N.D [N.D, 0.247] ^b	0.178 [0.167, 0.201] ^b	0.115 [0.090, 0.127] ^b	N.D [N.D, 0.070] ^b			
Cu	0.209 [0.085, 0.530] ^c	0.100 [0.028, 0.387] ^e	0.035 [N.D, 0.218] ^c	4.978 [3.823, 6.226] ^{bc}	1.765 [0.264, 3.481] ^c	0.486 [0.222, 1.062] ^c	10.235 [9.132, 11.180] ^{ab}	9.825 [7.909, 14.559] ^a	2.823 [2.132, 4.154] ^{ab}			
Zn	5.928 [3.853, 8.587] ^{bc}	7.382 [4.827, 10.917] ^{bc}	2.882 [2.254, 3.488] ^c	9.910 [9.293, 10.688] ^{bc}	3.031 [2.601, 3.837] ^c	2.361 [2.067, 2.749] ^c	20.160 [17.097, 21.044] ^{ab}	19.369 [17.817, 21.171] ^a	4.935 [4.543, 5.452] ^{ab}			
Ga	N.D [-] ^b	N.D [-] ^b	N.D [-] ^b	N.D [-] ^b	0.091 [0.076, 0.551] ^a	0.026 [N.D, 0.054] ^b	N.D [-] ^b	N.D [-] ^b	N.D [N.D, 0.013] ^b			
As	0.024 [N.D, 0.046] ^e	N.D [N.D, 0.058] ^c	N.D [N.D, 0.037] ^c	0.352 [0.308, 0.542] ^b	0.365 [0.106, 0.669] ^{bc}	0.501 [0.288, 0.873] ^b	0.508 [0.414, 0.551] ^b	1.377 [1.018, 1.749] ^a	0.036 [0.005, 0.062] ^{bc}			
Se	0.255 [0.195, 0.352] ^{bc}	0.251 [0.171, 0.293] ^{bc}	0.156 [0.113, 0.184] ^c	0.320 [0.221, 0.409] ^{abc}	0.414 [0.361, 0.487] ^{abc}	0.268 [0.205, 0.314] ^{bc}	0.439 [0.412, 0.551] ^{abc}	0.548 [0.510, 0.609] ^a	0.136 [0.096, 0.220] ^{ab}			
Sr	1.605 [1.168, 4.163] ^b	1.796 [0.925, 6.372] ^{ab}	1.356 [0.725, 2.406] ^b	3.103 [2.130, 4.230] ^b	0.430 [0.384, 0.484] ^b	0.268 [0.256, 0.279] ^b	17.626 [14.626, 25.402] ^a	20.690 [9.328, 31.591] ^a	0.542 [0.405, 0.837] ^b			
Ag	N.D [-] ^{bc}	N.D [-] ^{bc}	N.D [-] ^{bc}	N.D [-] ^c	0.063 [0.003, 0.125] ^a	0.001 [N.D, 0.022] ^{bc}	0.017 [0.016, 0.023] ^{bc}	0.013 [0.008, 0.036] ^{abc}	N.D [N.D, 0.024] ^{ab}			

(continues)

Table S5. Continued.

Trace elements	Six province or city Median mg·kg ⁻¹		Four province Median mg·kg ⁻¹		Five province or city Median mg·kg ⁻¹		Marine fishes Median mg·kg ⁻¹		Freshwater fishes Median mg·kg ⁻¹		
	<i>Cyprinus carpio</i>		<i>Carassius auratus</i>		<i>Ctenopharyngodon idella</i>	<i>Litopenaeus vannamei</i>	Flounder	<i>Oncorhynchus mykiss</i>	Chinese mitten crabA	Chinese mitten crabB	<i>Procambarus clarkii</i>
Cd	0.067 [N.D, 0.113] ^{bc}		0.104 [0.074, 0.143] ^{bc}		0.076 [0.015, 0.098] ^{bc}	N.D [N.D, 0.003] ^c	0.164 [0.021, 0.313] ^b	0.117 [0.069, 0.163] ^{bc}	0.069 [0.054, 0.104] ^{bc}	0.184 [0.161, 0.268] ^a	0.110 [0.090, 0.121] ^{bc}
Cs	N.D [N.D, 0.035] ^{ab}		N.D [N.D, 0.015] ^{ab}		0.005 [N.D, 0.036] ^{ab}	N.D [-] ^b	N.D [-] ^b	0.025 [N.D, 0.061] ^a	N.D [-] ^b	N.D [-] ^b	0.013 [0.005, 0.022] ^a
Ba	0.291 [0.094, 0.493] ^b		0.906 [0.706, 1.221] ^b		0.309 [0.171, 0.485] ^b	0.339 [0.172, 0.533] ^b	0.494 [N.D, 1.094] ^b	0.264 [0.157, 0.418] ^b	3.194 [2.110, 3.521] ^b	8.914 [6.094, 14.563] ^a	0.618 [0.386, 1.065] ^b
Ti	0.096 [0.052, 0.153] ^b		0.131 [0.091, 0.177] ^b		0.103 [0.074, 0.125] ^{bc}	0.044 [0.040, 0.049] ^c	0.188 [0.125, 0.267] ^a	0.136 [0.108, 0.166] ^b	0.043 [0.039, 0.050] ^c	0.058 [0.051, 0.062] ^c	0.125 [0.084, 0.150] ^b
Pb	0.122 [0.009, 0.247] ^b		0.193 [0.141, 0.253] ^b		0.137 [0.014, 0.187] ^b	0.026 [0.014, 0.049] ^b	0.510 [N.D, 1.076] ^a	0.206 [0.114, 0.314] ^b	0.030 [0.027, 0.036] ^b	0.033 [0.026, 0.039] ^b	0.200 [0.153, 0.223] ^b
U	0.138 [0.011, 0.215] ^a		0.195 [0.153, 0.237] ^a		0.140 [0.054, 0.201] ^a	0.010 [0.009, 0.013] ^a	0.127 [0.069, 0.198] ^a	0.153 [0.107, 0.211] ^a	0.021 [0.019, 0.024] ^a	0.068 [0.041, 0.090] ^a	0.193 [0.143, 0.228] ^a