Baseline

Concentration distribution and potential health risk of heavy metals in *Mactra veneriformis* from Bohai Bay, China

Yuhu Li, Hui Liu, Hailong Zhou, Wandong Ma, Qian Han, Xiaoping Diao, Qinzhao Xue

ABSTRACT

To investigate the pollution level and evaluate the potential health risks of heavy metals, the concentrations of chromium (Cr), manganese (Mn), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), molybdenum (Mo), cadmium (Cd), antimony (Sb), and lead (Pb) were determined by inductively coupled plasma-mass spectrometry (ICP-MS) in 198 clams (*Mactra veneriformis*) collected from 11 sites of the Bohai Bay. The results showed that heavy metal concentrations in the clams were different at different sites (*p* < 0.05). Mn was dominant with a percentage of 22.08–77.03% in heavy metals, followed by Zn with 12.66–57.11%, and the concentration of Pb was the lowest with 0.45–1.04%. The potential health risk to consumers was evaluated by the target hazard quotient (THQ) and the maximum daily consumption rate (CR<sub>max</sub>). The results indicated that the THQs of Co were the highest with the values of 1.125, 1.665, and 1.144 at three sections; the values of other individual metals were <1, which indicated that consumption of clams from the study areas caused health risks due to Co. Moreover, the CR<sub>max</sub> values also indicated the potential health risk caused by Co in clams consumed in this area. Pearson correlation analysis and principal component analysis (PCA) indicated that there were significantly positive or negative correlations between the heavy metals (*p* < 0.05), and the studied metals were divided into four groups. The results indicated that the concentrations of heavy metals in clams were affected not only by pollution sources but also by the characteristics of clams that could absorb selectively and accumulate special metals. This study offers important information on the pollution levels of heavy metals in clams and warns consumers of the health risks associated with the consumption of clams in the area.

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body and they are related to many diseases, for example, nervous system, kidney, and bone diseases (Crump and Trudeau, 2009).

In order to protect aquatic organisms and humans, the levels of heavy metals have been regulated (CEC, 2006; FAD, 2011; NY 5073-2006, 2006). For example, the maximum allowable limits of Hg, Pb, Cd, and Cr in fishery products are 0.3, 0.5, 0.1, and 2.0 mg kg⁻¹, respectively, according to Chinese standards (GB18406.4-2001, 2001), and the limits of Pb, Cd, and Cr in shellfish are 1.7, 4.0, and 13.0 mg kg⁻¹, respectively, according to the standard of the United States Food and Drug Administration (FAD, 2011). The target hazard quotient (THQ) is a quantitative method of investigating the potential health risk caused by consumption of contaminated foodstuffs (US EPA, 2000), and it is used widely to evaluate the health risk of heavy metals to human beings (Yang et al., 2011; Copat et al., 2013; Fu et al., 2013).

Bivalves are filter feeders, and they can obtain heavy metals from water, foodstuffs, and intake of inorganic particulate materials. They can tolerate several environmental pollutants and accumulate large amounts (Bervoets et al., 2005). Moreover, they are distributed widely and are easy to collect. Therefore, they are used as bioindicators to monitor heavy metal pollution in many aquatic environments (Giusti et al., 1999; Liang et al., 2004). Surf clam, Mactra veneriformis, is distributed widely in the Bohai Bay, and it is a commercially important bivalve used widely as seafood, raw materials for manufacturing flavoring materials, and live feed at various aquaculture farms in China. The Bohai Bay is a semi-enclosed coastal water body of the Northwest Pacific Ocean, and it is surrounded by highly industrialized areas. The water change is very slow and the purification ability is also very limited. Therefore, it is being increasingly polluted, giving rise to many concerns (Gao and Chen, 2012; Hu et al., 2013). Land-sourced pollutants derived mainly from river input and industrial and urban sewage are the major pollutant sources of heavy metals in the Bohai Bay. Therefore, analyzing the concentrations of heavy metals in aquatic organisms can help monitor water quality and evaluate the potential health risk to consumers caused by consuming seafood.

In previous studies, most sampling sites were located along the coast of Bohai Bay (Liang et al., 2004) and few at other sections of the Bay. Moreover, although many studies focused on the temporal and spatial distribution of heavy metals in water and sediment, few studies have analyzed the concentrations in aquatic organisms and evaluated the potential risk in the Bohai Bay. In this study, we determined the concentrations of chromium (Cr), manganese (Mn), cobalt (Co), nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), selenium (Se), molybdenum (Mo), cadmium (Cd), antimony (Sb), and lead (Pb) in the soft tissues of clams, M. veneriformis, collected at 11 sites from three sections (A, B, and C) of the Bohai Bay, and to evaluate the potential health risk to consumers.

The sampling region was located in the Bohai Bay, China, and the specific locations are shown in Fig. 1. A total of 198 clams, M. veneriformis, were collected at 11 sites from three sections of the Bohai Bay in May 2008, and the distance between adjacent sites in each section was about 300 m. At each site, 18 clams (2.7–3.3 cm, body length) were collected and transported to the laboratory placed in ice. The clams were cut open using stainless steel knives, and the soft tissues were removed. Then, the soft tissues were washed with ultrapure water and freeze-dried for 72 h to constant weight, and then they were ground to a powder in a mortar. About 0.2 g of powder was weighted into a polytetrafluoroethylene vessel containing 3 mL of HNO₃ (65%) and 1 mL of H₂O₂ (35%) and it was digested using a Microwave Digestion System (Mars-5, CEM) (Mendil et al., 2010; Taweel et al., 2011). After digestion, the solution was diluted to 50 mL with ultrapure water and filtered through 0.45 μm Whatman filter paper (Germany). An internal standard was added to each sample and was analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) (Agilent 7500i, USA).

The heavy metal concentrations in the clams were measured by ICP-MS and quantified according to the calibration curves obtained using heavy metal standards (Agilent). Blank digestions were also carried out with the same method. The recoveries of the standard sample for all tested heavy metals were above 90%, and the relative standard deviations were all <15%. The measurement values were in good agreement with the certified values, and the correlation coefficients of the calibration curves were all >0.99. All glassware and polytetrafluoroethylene vessels were immersed in 50% HNO₃ for 12 h, washed with ultrapure water, and dried before use. All reagents were of analytical grade. HNO₃ (65%) and hydrogen peroxide (H₂O₂ (30%) were of ultrapure quality (Merck, Darmstadt, Germany). The replicate numbers of the sample for each site was six (six clams). In this study, heavy metal concentrations were obtained as wet weight (μg g⁻¹) with the water content assumed to be 80% (Usoro et al., 2005; Wei et al., 2014).

THQ and maximum daily consumption rate (CRmax) were used to evaluate the potential health risk of heavy metals caused by consumption of clams (US EPA, 2000; Taweel et al., 2013). The THQ and CRmax were calculated by the following equations: THQ = C × Wclam × ED × AF/(BW × RID × AN) × 10⁻³, CRmax = (RID × BW)/C, where C is the average concentration of heavy metals in clams (mg kg⁻¹, wet weight); Wclam represents the daily clam ingestion, which is 38.9 g day⁻¹ according to the data of the Chinese statistics yearbook (National Bureau of Statistics of China, 2009); ED represents exposure frequency (365 days/year); AF represents exposure duration (70 years, equivalent to the average lifetime); RID represents the oral reference dose based on the US EPA (US EPA, 2014); BW is the average body weight, about 63 kg for adults based on the communiqué of Chinese physical fitness monitoring (National Physique Monitoring Center of China, 2012); Atm represents the average exposure time for non-carcinogens (ED > 365 days/year); and 10⁻³ is the unit conversion factor. It is assumed that cooking has no effect on the toxicity of heavy metals in aquatic products (Chien et al., 2002). In general, if the value of THQ is <1, there will be no health risk. Conversely, if the value is >1, the health risk will occur with a higher probability (Chien et al., 2002).

All data were analyzed using Excel 2007 and SPSS 19.0, and the difference was considered significant at p < 0.05. All data in the present study were shown as mean ± standard deviation (SD) (n = 6), and all figures were created using Origin 8.0.

The measured values of heavy metal concentrations in the clams from the three sections are presented in Figs. 2–4, which indicate that the concentration of individual metal was different (p < 0.05) at different sites from the same sections. On the whole, the closer the sampling sites are to the shore, the higher are the heavy metal concentrations. The reasons may be that the sampling sites near the shore are relatively close to the pollution sources and the water mass exchange is slow. Moreover, the concentrations of heavy metals were also different in the clams from the different sections (p < 0.05), which indicated that the pollution levels of heavy metals were different at different sections. The average concentrations of heavy metals at each section are shown in Fig. 5, which indicated that the pollution levels of heavy metals at section B was the highest, followed by sections A and C. The concentration of Mn ranged from 15.74 to 94.90 μg g⁻¹ with the average value of 40.03 ± 29.66 μg g⁻¹ being the highest at sections B and C, Zn ranged from 9.24 to 16.63 μg g⁻¹ with the average value of 13.06 ± 2.32 μg g⁻¹, and the concentration of Pb ranged from 0.02 to 0.08 μg g⁻¹ with the average value of 0.04 ± 0.02 μg g⁻¹ being the lowest at all investigated sites. However, at section C, the concentration of Zn with the average value of 20.65 ± 2.07 μg g⁻¹ was higher than Mn with the average value of 7.99 ± 0.15 μg g⁻¹.
and Zn are cofactors of many enzymes that play an important role in normal metabolism, and are absorbed selectively by aquatic organisms, which may cause the high concentrations in the organisms. Sb and other nonessential metals are not crucial to normal metabolism, and they have adverse effects on the body health; therefore, their concentrations are relatively low in organisms. According to the standard (listed in Table 1), the concentrations of As, Cd, Pb, Zn, and Cr in the clams have exceeded the allowable limits. Moreover, compared with previous studies (Table 1), the concentration of Mn was the highest and the others were present at a moderate level in the Bohai Bay. Bioaccumulation of heavy metals in aquatic organisms is a complex process, which can be affected by many factors including endogenous and exogenous factors. The endogenous factors include species, size, age, and physiological stage, and the exogenous factors include all kinds of environmental parameters, such as metal bioavailability, salinity,
alkalinity, and temperature of living circumstances (Moiseenko and Kudryavtseva, 2001; Dhanakumar et al., 2015).

The composition patterns of heavy metal at different sites are shown in Fig. 6. This indicates that Mn and Zn were dominant in the analyzed heavy metals with the percentage of 22.08–77.03% and 13.49–57.11%, respectively; Cu, As, Se, and Ni were present at moderate levels with the percentage of 1.85–9.30%, 1.38–6.93%, 0.92–4.23%, and 1.69–3.01%, respectively; and the percentages of Mo, Cd, Sb, Pb, and Co at each site were relatively low. Moreover, the percentages of metals were significantly different (p < 0.05) in the soft tissues of clams from different sites. The results were in agreement with previous reports on the composition patterns of heavy metals in aquatic organisms (Sankar et al., 2006; Mitra et al., 2012; Tao et al., 2012), such as fish and shellfish. Because essential elements have an important role in the growth and development, immunity, reproduction, and other functions, aquatic organisms tend to accumulate relatively high levels of essential elements for normal life activities, but very high levels of the essential mineral elements will be harmful to the health of aquatic organisms and human beings (Gale et al., 2004).

The Pearson correlations between the heavy metal concentrations and body sizes (shell length and soft-tissue weight) of the clam *M. veneriformis* are listed in Table 2. The results showed that significant positive correlations (p < 0.05) were observed between the concentrations of some metals (Cr–Mn, Cr–Co, Cr–Ni, Cr–Pb, Mn–Co, Mn–Ni, Mn–Cu, Mn–Mo, Mn–Cd, Mn–Pb, Co–Ni, Co–Zn, Co–As, Co–Se, Co–Mo, Co–Cd, Co–Pb, Ni–Mo, Ni–Cd, Ni–Pb, Cu–Mo, Zn–As, Zn–Cd, Zn–Se, As–Se, As–Cd, Se–Mo, Se–Cd, Mo–Cd, and Mo–Pb). Moreover, weak but significantly negative correlations were observed between some metals (Cr–Zn, Cr–As, Cr–Se, and Se–Zn). The correlation coefficient between Cr and Pb was the highest (r = 0.88), followed by Co and Ni (r = 0.76), and the correlation between Mn and Zn was the lowest (r = 0.002). In previous reports, significantly positive or negative correlations between investigated heavy metals were also observed (Kljakovic et al., 2010; Jeksimovic et al., 2011; Velusamy et al., 2014), which may indicate that aquatic organisms selectively absorb specific heavy metals for normal metabolism, and heavy metals may interact with each other.

The body sizes of clams have an important effect on the accumulation of heavy metals in tissues, so it is vital to understand the relationship between body sizes (shell length and soft-tissue weight) and heavy metals. Table 2 shows that Zn and As had a significantly positive correlation with the shell length and the soft-tissue weight (p < 0.01), and Co, Se, Mo, and Cd had a significantly positive correlation with shell length (p < 0.01), which

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**Table 1**

Comparison of heavy metal concentrations in the soft tissues of shellfish from the Bohai Bay, other areas in China, and world marine waters.

| Site                     | Species              | Year | Cr  | Mn  | Co  | Ni  | Cu  | Zn  | As  | Se  | Mo  | Cd  | Sb  | Pb  | Reference                                      |
|--------------------------|----------------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------------------------------------------------|
| Catania Gulf             | *D. trunculus*       | w.w. | 0.5 | 0.3 | 0.4 | 0.7 | 5.3 | 0.9 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | Copat et al. (2013)                              |
| Saromikos Gulf           | Mussel               | w.w. | 0.2 | 0.2 | 0.3 | 0.6 | 2.6 | 0.9 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | Kalogeropoulos et al. (2012)                     |
| Cochin area              | *V. cyprinoides*     | w.w. | 0.4 | 1.0 | 0.9 | 0.6 | 4.4 | 9.9 | 0.9 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | Sivaperumal et al. (2007)                        |
| Cochin area              | *P. viridis*         | w.w. | 2.8 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | El Nemri et al. (2012)                           |
| Mediterranean            | Bivalve              | d.w. | 4.9 | 10.2 | 0.9 | 0.6 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | Pinto et al. (2015)                              |
| Adriatic coastal area    | *M. verrucosa*       | w.w. | 1.2 | 1.0 | 0.5 | 0.9 | 2.6 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | Jovic and Stankovic (2014)                       |
| Lagoon axis              | *C. rhizophore*      | d.w. | 1.2 | 7.8 | 0.4 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | Alfonso et al. (2013)                            |
| Venezuelan coastal area  | *M. chinesis*        | d.w. | 1.0 | 5.1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | Lei et al. (2013)                                |
| Shanghai                 | *M. opercularis*     | d.w. | 1.3 | 2.5 | 0.5 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | This study                                      |
| A site of the Bohai Bay  | *M. veneriformis*    | w.w. | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | This study                                      |
| B site of the Bohai Bay  | *M. veneriformis*    | w.w. | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | 1.9 | This study                                      |
| C site of the Bohai Bay  | *M. veneriformis*    | w.w. | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | This study                                      |
| Grade I*                 | Shellfish            | w.w. | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | SEPA (2001)                                     |
| Grade II*                | Shellfish            | w.w. | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | SEPA (2001)                                     |
| Grade III*               | Shellfish            | w.w. | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | SEPA (2001)                                     |

Note: w.w. respects wet weight, d.w. respects dry weight.

a Grade I: National Standard of China for Marine Biological Quality GB 18421-2001 Grade I applied for marine fishing, aquaculture and nature reserve.

b Grade II: National Standard of China for Marine Biological Quality GB 18421-2001 Grade I applied for water supply of general industry and scenic spot.

c Grade III: National Standard of China for Marine Biological Quality GB 18421-2001 Grade I applied for performance of harbor and industry development.

d 500 for ostracan.
indicated that the accumulation of these metals increased with the growth of body size in clams. Moreover, Cr and Pb showed a significantly negative correlation with the shell length and soft-tissue weight \((p < 0.01)\), and Ni showed a negative correlation with soft-tissue weight but not with shell length \((p > 0.05)\). Previous studies demonstrated that concentrations of Cr and Pb showed a significantly negative correlation with fish length \((\text{Nussey et al., 2000})\), and Zn had a significantly positive correlation with fish weight \((\text{Velusamy et al., 2014})\), which was similar to the results in this study.

Principal component analysis (PCA) was performed on the data of 11 metals with varimax rotation, and the results are shown in Table 3. The results of Kmo and Bartlett were 0.72 and 845.45 \((df = 66, p < 0.01)\), which indicated that the data could be analyzed by PCA. Four principal components were extracted with eigenvalues >1, and it explained 79.24% of total variance. With PC1 explaining 28.16% of the total variance, Cr, Ni and Pb had strong positive loadings \((0.89, 0.90, \text{and} 0.90, \text{respectively})\), and Mn and Co had moderate loadings \((0.67 \text{and} 0.59, \text{respectively})\). With PC2 explaining 22.07% of the total variance, Zn and As showed strong positive loadings \((0.84 \text{and} 0.87, \text{respectively})\), and Co and Cd had moderate positive loadings \((0.53 \text{and} 0.70, \text{respectively})\). PC3 explained 18.56% of the total variance, showing strong positive loadings for Cu \((0.83)\) and Mo \((0.88)\). PC4 explaining 10.44% of the total variance showed strong positive loading for Sb \((0.84)\) and moderate negative loading for Se \((-0.57)\). These metals were divided into four groups, which indicated that different pollution sources or controlling factors affected heavy metal concentrations in the soft tissue of clams. The pollution sources include natural sources (rock weathering and soil erosion) and anthropogenic sources (agricultural practices, industrial activities, and coal burning). Endogenous factors (species, size, age and physiological stage) and exogenous factors (all kinds of environmental parameters, such as metal bioavailability, salinity, alkalinity, and temperature of living circumstances) can also affect the heavy metal concentrations in clams \((\text{Moiseenko and Kudryavtseva, 2001; Dhanakumar et al., 2015})\). Compared with previous studies regarding the heavy metal contaminations in water or sediment from the Bohai Bay \((\text{Gao and Chen, 2012; Hu et al., 2013})\), the results of correlation analysis and PCA analysis for heavy metals in this study differed greatly. For example, the correlation coefficients of Cd–Cr, Cu–Cd, Cu–Cr, Cu–Ni, Pb–Cd, Pb–Cu, Zn–Cr, and Zn–Pb were 0.761, 0.609, 0.657, 0.758, 0.703, 0.634, and 0.745, respectively, in the sediment from the Bohai Bay, but the coefficients for clams in this study were \(-0.07, 0.10, 0.05, 0.18, 0.04, 0.11, -0.24, \text{and} -0.19, \text{respectively} \). \(\text{Ahn et al. (2006)}\) found that only Pb and Zn measured in clams had positive correlations with the surface sediment. \(\text{Ma et al. (2009)}\) found that the correlations for each metal between the clam tissue concentration and sediment concentration were weak, and the concentrations of Cd and Zn measured in clams were higher than the values measured in the surface sediment. These results indicated that the concentrations of heavy metals in clams are affected not only by pollution sources but also by the ability of clams to absorb selectively and accumulate special metals.

The potential health risk of heavy metals to consumers caused by consumption of clams was estimated by THQ and maximum

![Fig. 6. The composition of heavy metals in the clam Mactra veneriformis at the three sections from the Bohai Bay.](image-url)

### Table 3

| Variance | PC1 | PC2 | PC3 | PC4 |
|----------|-----|-----|-----|-----|
| Cr       | 0.89 | -0.24 | -0.09 | 0.15 |
| Mn       | 0.67 | 0.17 | 0.48 | -0.07 |
| Co       | 0.59 | 0.53 | 0.39 | -0.11 |
| Ni       | 0.90 | 0.17 | 0.25 | -0.04 |
| Cu       | -0.01 | -0.14 | 0.83 | 0.16 |
| Zn       | -0.09 | 0.84 | -0.09 | 0.06 |
| As       | -0.08 | 0.87 | -0.09 | 0.07 |
| Se       | -0.15 | 0.45 | 0.35 | -0.57 |
| Mo       | 0.30 | 0.11 | 0.88 | -0.14 |
| Cd       | 0.21 | 0.70 | 0.38 | -0.33 |
| Sb       | 0.07 | 0.12 | 0.13 | 0.84 |
| Pb       | 0.90 | -0.18 | 0.01 | 0.14 |

| Eigenvalues | 3.38 | 2.65 | 2.23 | 1.25 |
| Total variance % | 28.16 | 22.07 | 18.56 | 10.44 |
| Cumulative variance % | 28.16 | 50.23 | 68.80 | 79.24 |

Note: extraction method: principal component analysis. Rotation method: varimax.

### Table 2

| Pearson correlation between heavy metals and body sizes of Mactra veneriformis from the Bohai Bay. | Length | w.w. | Cr | Mn | Co | Ni | Cu | Zn | As | Se | Mo | Cd | Sb | Pb |
|-------------------------------------------------|--------|-----|----|----|----|----|----|----|----|----|----|----|----|----|
| | | | | | | | | | | | | | | | |
| **Length** | 1.00 | | | | | | | | | | | | | | |
| **w.w.** | 0.58 ** | 1.00 | | | | | | | | | | | | | |
| **Cr** | -0.34 ** | -0.42 ** | 1.00 | | | | | | | | | | | | |
| **Mn** | 0.11 | -0.12 | 0.43 ** | 1.00 | | | | | | | | | | | |
| **Co** | 0.50 ** | 0.06 | 0.27 ** | 0.63 ** | 1.00 | | | | | | | | | | |
| **Ni** | 0.07 | -0.33 ** | 0.71 ** | 0.70 ** | 0.76 ** | 1.00 | | | | | | | | | |
| **Cu** | 0.03 | 0.11 | 0.05 | 0.28 ** | 0.17 | 0.18 | 1.00 | | | | | | | | |
| **Zn** | 0.33 ** | 0.26 ** | -0.24 | 0.00 | 0.31 ** | 0.05 | -0.02 | 1.00 | | | | | | | |
| **As** | 0.44 ** | 0.34 ** | -0.21 | 0.07 | 0.33 ** | 0.02 | -0.08 | 0.71 ** | 1.00 | | | | | | |
| **Se** | 0.26 | 0.06 | -0.31 ** | 0.16 | 0.27 | 0.04 | 0.06 | 0.21 | 0.29 ** | 1.00 | | | | |
| **Mo** | 0.25 | -0.02 | 0.13 | 0.64 ** | 0.62 ** | 0.50 ** | 0.64 ** | -0.02 | 0.00 | 0.34 ** | 1.00 | | | | |
| **Cd** | 0.42 ** | -0.07 | -0.07 | 0.44 | 0.62 ** | 0.40 ** | 0.10 | 0.44 | 0.46 ** | 0.65 ** | 0.49 ** | 1.00 | | | |
| **Sb** | 0.04 | 0.14 | 0.12 | 0.08 | 0.06 | 0.07 | 0.02 | -0.04 | 0.03 | -0.17 | 0.01 | -0.01 | 1.00 | | |
| **Pb** | -0.22 ** | -0.38 ** | 0.88 ** | 0.52 ** | 0.33 ** | 0.73 ** | 0.11 | -0.19 | -0.19 | -0.23 | 0.24 | 0.04 | 0.15 | 1.00 | |

*Correlated at 0.05 significant level.  
**Correlated at 0.01 significant level (2-tailed).
daily consumption rate (CRmax). The calculation of As, toxic in its inorganic form, was made by assuming inorganic As to constitute 3% of the total concentration. In general, if THQ values are >1, the consumers will encounter the potential health risk. On the contrary, if the values are <1, there will be no obvious health risk to the consumers (Chien et al., 2002). Table 4 showed that the THQs of Co were the highest at sections A, B, and C with the values of 1.125, 1.665, and 1.144, respectively, which indicated that consumption of clams from the study areas entailed health risks due to Co. Moreover, the THQ values of the other individual metals were <1 at all sites, which showed that the concentration levels of other individual metals in the clams posed no health risk to consumers. Owing to the accumulation of heavy metals in clams, overconsumption of clams contaminated by heavy metals will cause adverse health effects. Hence, the maximum daily consumption rates of contaminated clams were estimated and the values are listed in Table 4. These values indicate that the Pb- and Mo-based maximum daily consumption rates were relatively high and the value of Co was the lowest compared with the other metals investigated. Therefore, based on the maximum daily consumption rates, the probability of health risk to the local consumers caused by Co was high. It should be noted that the source of heavy metals in this assessment just included clams, and other sources, such as seafood, vegetables, water, and rice, were not included. Hence, if all sources of heavy metals and the combined risk caused by metals are considered, the real health risk to consumers will be higher. Moreover, according to Chinese standards (Table 1), the concentrations of As, Cd, Pb, Zn, and Cr exceed Grade I level, which is applicable to marine fishing, aquaculture, and nature reserve except Cr at section C.

In conclusion, the heavy metal concentrations (Cr, Mn, Co, Ni, Cu, Zn, As, Se, Mo, Cd, Sb, and Pb) in clams, _M. veneriformis_, were significantly different between different sections and between different sites at the same section of the Bohai Bay, China. The heavy metal concentrations in clams at section B was the highest, followed by A and C, and they were relatively high at the sites close to the shore at the same sections. The concentrations of Mn were dominant, followed by Zn, and those of Pb were the lowest of all heavy metals. In contrast to other individual metals, Co caused a potential health risk to consumers of clams. It should be noted that the source of heavy metals in this assessment only included clams, and other sources, such as other seafood, vegetables, water, and rice, were not included. Hence, if the whole sources of heavy metals and the combined risk from all metals were considered, the real health risk to the consumers will be higher. Significantly negative and positive correlations were observed between the metals (p < 0.05), which may indicate that aquatic organisms selectively absorbed specific heavy metals for normal metabolism, and these heavy metals may interact with each other. Over-bioaccumulation in aquatic organisms will be harmful not only to themselves but also to consumers; therefore, the concentrations of heavy metals, especially of Co, should be controlled at a healthy level. Omics should be adopted to better understand the molecular toxicological mechanisms of heavy metals; at present, omics have been successfully used in many aquatic organisms, including the clam _Ruditapes philippinarum_ (Wu et al., 2013a,b).

### Conflict of interest statement

The authors declare that there are no conflicts of interest.

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