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Baseline

Bioaccumulation and health risk assessment of heavy metals to bivalve species in Daya Bay (South China Sea): Consumption advisory

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ABSTRACT

Bivalves are one of the key components of the biogeochemical cycle in the marine system, and respond to heavy metal (HM) sensitively as filter feeders. To determine relationship of HMs in edible bivalve and seawater and HM effects on human health when digesting bivalves, HMs were analyzed in bivalves and seawater. The results showed that the mean HM concentrations in bivalves decreased in the order of Zn > Cu > Cr > Pb > As > Cd > Hg. Generally, all the bioconcentration factor values of bivalves were higher than 100, suggesting that bivalves have a high bioaccumulation ability. Nonmetric multidimensional scaling analysis indicated that all bivalves have a high bioaccumulation capacity for Cu and Zn. It was found that there are health risks associated with consuming bivalves, and children are more vulnerable than adults. Finally, the maximum allowable consumption rates of non-carcinogenic and carcinogenic risk were determined. These results provide the underlying insights needed to guide the consumption of seafood.

The rapid development of industry and agriculture has led to an increase in the use of heavy metals (HMs). Consequently, a large number of toxic HMs are released into the marine environment, which has an adverse effect on fish, invertebrates, and humans (Rajeshkumar et al., 2018, Yigit et al., 2018). In recent years, HM pollution has become a worldwide environmental issue due to its toxicity, persistence, and bioaccumulation in the environment (Widdows et al., 1995; Chen et al., 2018; Liu et al., 2018b; Nasyitah Sobihah et al., 2018). HMs are mostly transported into marine ecosystems via rivers, sewage outlets or atmospheric deposition, and could be accumulated in seawater, posing a potential threat to marine organisms due to their bioavailability and bioaccumulation (Khodami et al., 2017). HMs can be absorbed by marine organisms from seawater, and then be re-released into seawater after the death and disintegration of marine organisms through complex physical and chemical processes (Zhang et al., 2017). Therefore, such system in which organisms and seawater interact is an important source and sink of HMs. HMs could be accumulated in marine organisms (e.g. fishes and bivalves) and pose toxicity to human health via the food chain (Chakraborty et al., 2016; Azizi et al., 2018a, 2018b). Therefore, it is necessary to study the correlation of HMs between organisms and seawater, and the bioaccumulation ability of edible marine organisms.

Bivalves are one of the major types of seafood in the human diet and are a key component of the biogeochemical cycle in the marine system as filter feeders. Thus, they can accumulate HMs in seawater through feeding, and then serve as prey for the other marine organisms at higher trophic levels (Kodama et al., 2012). Due to their tolerance to diverse environmental conditions because of long-term sedentary adulthood and their ability to accumulate various pollutants including HMs (Han et al., 2000), bivalves are commonly used as an indicator for marine pollution (Feldstein et al., 2003; Copat et al., 2013; Bogdanovic et al., 2014). Furthermore, bivalves are also commonly used in ecotoxicological studies because they comprise a wide range of species with different tolerances and responses to natural or anthropogenic pollution stressors (Pilo et al., 2017).

Liu et al. (2018), Bean et al. (2018) and Jia et al. (2018) have studied the distribution, contamination and accumulation of HMs in freshwater fish and shellfish from rivers. Qiu (2015), Fang and Dai (2017) and Jonathan et al. (2017) have also pointed out that there was a strong relationship between HMs in farmed organisms and seawater. However, most of the studied marine organisms were fish, and less attention was paid to bivalve species (Wu et al., 2017). Comparatively, little information is available regarding bivalve species and seawater. Hence, the demand for biological studies of marine organisms,

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especially commercialized edible bivalves, is growing and becoming a research hotspot in marine biology (Prato et al., 2019). Moreover, several studies have pointed out that the HMs in bivalves are related to seawater, but the related phenomena are not well understood, especially whether the quality of seawater influences HMs in bivalves.

Moreover, it is necessary to evaluate the HM pollution of bivalves in regions where the cultivation of bivalves is widespread, because the bivalves produced in these areas are closely related to the seafood intake source of humans. The lack of information is particularly worrying because an ongoing discussion exists about how much their risk to human health is and whether such seafood would also be a source of contaminants for consumers (Qiu, 2015; Fang and Dai, 2017; Jonathan et al., 2017).

Therefore, the objectives of this study are 1) to investigate the concentration level and distribution of HMs in bivalves and seawater; 2) to determine and compare the bioaccumulation of HMs in seawater and explore the relationship between HM levels of bivalves and parameters of the seawater quality; 3) to assess human health risk from HMs and identify the maximum allowable consumption rate (MACR) for adults and children, respectively, in the areas with widespread cultivation of bivalves. This study can provide guidelines to consume specific seafood, and to some extent, inform decision-makers in selecting suitable areas for developing maricultural activities.

The study area is located in the northwest region of Daya Bay, which is a typical subtropical bay on the south coast of China (Ni et al., 2017; Tang et al., 2018). In recent years, the pollution brought by the rapid development of the economy in the study area has resulted in a deteriorating ecological environment and high ecological protection pressure (Liu et al., 2018a). The semi-enclosed bay area was selected because semi-enclosed marine ecosystems are more easily affected by natural and anthropogenic climate changes (Li et al., 2019) and can accumulate the elements more easily (Rydin and Kumblad, 2019) than ecosystems in open oceans. Therefore, it can offer a suitable environment for analyzing the relationship of HMs in edible bivalves and seawater. Moreover, the cultivation of bivalves is widespread in the study area. Therefore, investigating the HM concentration in bivalves and identifying the health risk of consuming bivalves farmed in this area can provide a clear indication of the potential threat from seafood to human beings. The sampling site settings are shown in Fig. 1. In April and May 2016, 20 seawater samples and 13 bivalve samples were collected in the study area, respectively.

Seawater samples were collected using 5 L acid-washed polyethylene sample bottles from 20 sites at the bottom of the study area and filtered with 0.45 μm membranes. Filtrates were acidified (pH < 2) and then stored in the dark at 4 °C. The seawater quality parameters (pH, salinity (SAL), temperature (T), dissolved oxygen (DO), chemical oxygen demand (COD_{Mn}), suspended solids (SS), inorganic nitrogen (IN), petroleum contaminants (PC), potassium orthophosphate (PO_4-P) and sulfide (S)) were detected by the method of Cao et al. (2018) and detailed in Supplementary material.

The bivalve samples were collected from the surface of intertidal sediment with a sampling frame (0.25 m × 0.25 m square). To exclude the effect of individual bivalve specimens on the research results, only the adult individuals with approximately similar size and weight were selected. Specifically, the following types of bivalves were selected: mussel (*P. viridis* and *M. edulis*): length, width and weight: 83.1 ± 3.4 mm, 32.8 ± 2.7 mm and 118.1 ± 21.6 g, respectively; oyster (*O. glomerata*): length, width and weight: 40.3 ± 1.9 mm, 15.2 ± 3.1 mm and 23.9 ± 3.4 g, respectively; and clam (*B. virescens*, *G. divaricatum* and *C. scripta*): 42.7 ± 5.9 mm, 12.6 ± 4.3 mm and 30.8 ± 7.1 g. There were more than six individual samples of each analyzed bivalves at each sampling site. The method of determining HMs concentration in bivalves and seawater was detailed in Supplementary material.

Health risk assessment was employed herein to assess the chemical quality of organisms and to evaluate the possible risks associated with their consumption. The potential non-carcinogenic and carcinogenic risks of each individual heavy metal were expressed as the Hazard Quotient (HQ) and Carcinogenic Risk (CR), respectively (USEPA, 2000). If the HQ value is > 1, it indicates that the consumption of contaminated organisms has a potential non-carcinogenic health risk to consumer health. Higher HQ value means higher non-carcinogenic risk to the human body, and vice versa. The HQ value for each heavy metal was calculated using the ratio of the estimated amount of a contaminant ingested with contaminated organisms to the reference oral dose (RfDo) for individuals. CR was obtained via multiplying the Chronic Daily Intake (CDI) by the Cancer Slope Factor (CSF). HQ and CR associated with the consumption of bivalve species were assessed based on the standard assumption for an integrated USEPA risk analysis as follows (USEPA, 2000):

$$\mathrm{CDI}(\mathrm{mg}\cdot\mathrm{kg}^{-1}\cdot\mathrm{day}^{-1}) = \sum_{i=1}^{n} \frac{C_i \times IR_i \times EF_i \times ED_i}{BW \times AT_i} \tag{1}$$

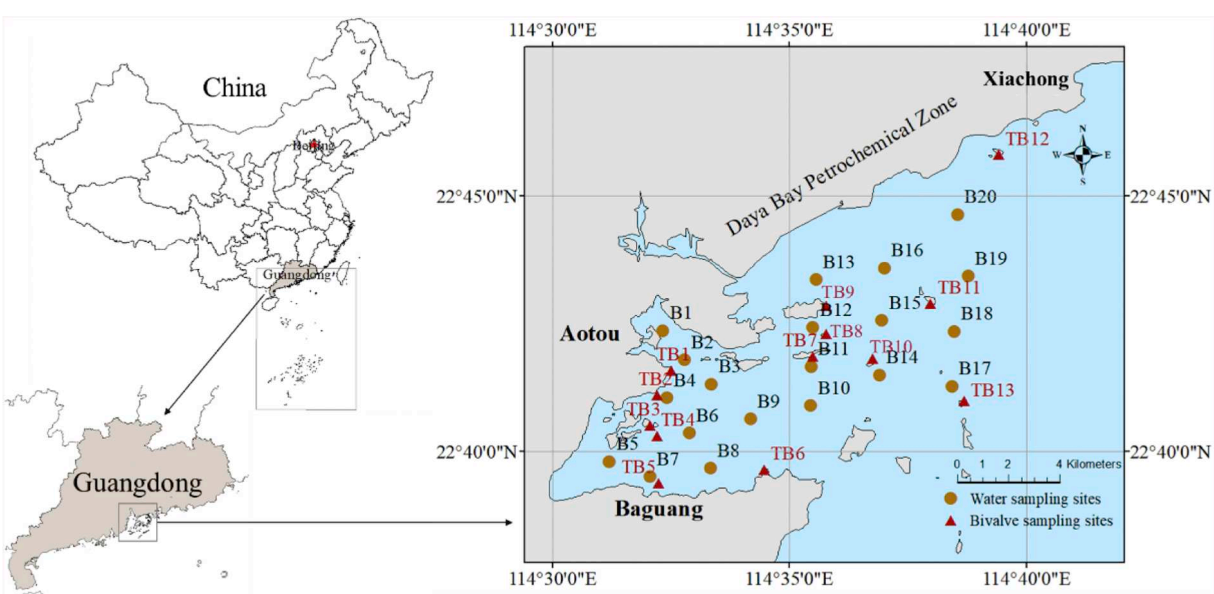

Fig. 1. The location of sampling sites in the study area.

$$HQ = \frac{CDI}{RfDo} \tag{2}$$

$$CR = CDI \times CSF \tag{3}$$

where CDI is chronic daily intake, the mass of the substance ingested per unit body weight per unit time; RfDo is the oral reference dose specific for each contaminant when provided, based on values of 1×10^{-3}, 4×10^{-3}, 3×10^{-3}, 4×10^{-2}, 0.3, 1×10^{-4} and $3 \times 10^{-4}\,mg \cdot kg^{-1} \cdot day^{-1}$ for Cd, Pb, Cr, Cu, Zn, Hg and As, respectively (USEPA, 2000; Chen et al., 2018). CSF is the cancer slope factor, based on values of 1.5, 0.5, 0.0085, and 0.38 $mg \cdot kg^{-1} \cdot day^{-1}$ for As, Cr, Pb and Cd, respectively (USEPA, 2011).

Here, C_i (mg/kg) is the metal concentration in bivalves expressed as wet weight (w.w.) and IR_i ($kg \cdot person^{-1} \cdot day^{-1}$) is the daily ingestion rate; EF_i is the exposure frequency (365 $days \cdot year^{-1}$); ED_i is the exposure duration (70 years for a person is assumed in this study, equivalent to the average lifetimes); BW ($kg \cdot person^{-1}$) refers to the average body weight, and an average body weight of 58.1 kg is assumed for a Chinese adult (Gu et al., 2006); AT_i is the average exposure time for non-carcinogenic effects (ED × 365 $days \cdot year^{-1}$). Since there is no data available on the daily bivalve consumption, the data for average daily shellfish consumption was used instead (29 $g \cdot person^{-1} \cdot day^{-1}$) (Zhang et al., 2018) is used instead of it.

According to the standard of USEPA (2000), HQ is categorized into six classes: HQ < 1 (no health risk); 1 < HQ < 1.5 (low health risk); 1.5 < HQ < 2 (medium-low health risk); 2 < HQ < 2.5 (medium risk); 2.5 < HQ < 3 (next higher risk); 3 < HQ (high risk). If CR is above the threshold value of the acceptable lifetime risk (ALR) of 10^{-5}, it indicates a probability > 1:100,000 of an individual developing cancer (USEPA, 2000).

The overall potential non-carcinogenic effects posed by exposure to more than one heavy metal in each species and the accumulation risk (AR) for multiple HMs were determined based on the USEPA Guidelines (USEPA, 2000) for Health Risk Assessment of Chemical Mixtures.

$$AR = \sum HQ \tag{4}$$

Statistical data treatment was carried out with R 3.5.0. Descriptive statistics were used to describe the HM levels and distributions in the bivalves and seawater. Pearson correlation analysis and Principal Components Analysis (PCA) were used to investigate the relationship between HMs in bivalves and environmental factors. Moreover, Nonmetric Multidimensional Scaling (NMDS) analysis was used to investigate HM distributions in different bivalve species. The similarity matrix for NMDS was calculated using Bray-Curtis Similarity (BCS).

The seawater quality parameters are provided in Table S1 (in Supplementary materials) and all the HM concentrations in bivalves and seawater in the study area are summarized in Table 1. HMs in seawater could be ingested by filter feeders like bivalves, and then enriched by high trophic levels in the food chain and finally cause an amplified impact on the human body (Romeo et al., 1999; Bour et al., 2018). As shown in Table 1, the highest mean concentrations of Zn and Cu were observed in bivalves. This can be attributed to the fact that most bivalves possess high affinity for the bioaccumulation of Zn and Cu due to numerous aspects of cellular metabolism by hundreds of critical enzymes (Bovine Cu—Zn superoxide dismutase (orgotein), etc.) (Paez-Osuna and Osuna-Martinez, 2011; Jonathan et al., 2017). The mean values of the HM concentrations in bivalves decreased in the order of Zn (10.78 mg/kg) > Cu (3.07 mg/kg) > Cr (0.90 mg/kg) > Pb (0.47 mg/kg) > As (0.40 mg/kg) > Cd (0.44 mg/kg) > Hg (0.02 mg/kg). Comparing the levels of HMs in bivalves analyzed in this work to those found in literature from different coastal areas, it was found that similar results were reported for domestic and foreign regions, and these two metal concentrations varied widely among different areas (Table S2). All the average values of HM concentrations in bivalves were lower than the limits set by FAO (1989), USEPA (2002) and the Chinese Food Health Criterion (GB 2762-2017). I In addition, all the HM concentrations in seawater were lower than the limits set by the Chinese water quality standards (GB 3097-1997), which may be related to dilution by rainfall due to the sampling time being in the wet season (Francesconi and Edmonds, 1998), dilution of surface seawater currents, or seawater exchange with the open ocean (Laura Miserendino et al., 2018).

As shown in Fig. 2, the HM concentrations varied significantly between the different sites and different bivalves. The difference in HM concentrations at different sampling sites may be due to the diverse growth environments, while the difference in HMs among species might be the result of differences in ecological and biological factors such as metabolic activities, habitats and feeding habits (Romeo et al., 1999; Monikh et al., 2013).

Among the seven HMs studied, only the concentrations of Cd (TB5, TB6, TB9 and TB11) and As (TB1, TB8, TB9, and TB10) exceeded the standard of Chinese Food Health Criterion (GB2762-2012), suggesting that Cd and As may be involved in biological activities or have high assimilation efficiency but a low elimination rate, leading to high concentrations in bivalves (Fang and Dai, 2017; Lim et al., 1998; Loaiza et al., 2015). Previous studies have reported a similar phenomenon (Luoma and Bryan, 1978; Widdows et al., 1995; Wang et al., 2018). Unique metabolism could account for the fact that Cd is highly concentrated in bivalves. Cd tends to form metal-ligand complexes (especially with sulfur) in +II valence state and is mainly chelated by soluble, low molecular weight proteins (e.g. metallothionein, glutathione) in the cytosol (Francesconi et al., 1994; Feldstein et al., 2003). Generally, As exists in marine organisms in the form of methylated arsenic compounds, which may be related to the methylation ability of algae and phytoplankton in the photic zone. The anoxic bacterial decomposition of algae or phytoplankton produces As derivatives which are then converted into arsenobetaine, which is present in many marine organisms including bivalves (Francesconi and Edmonds, 1998).

Although the concentrations of Pb, Cr, Cu, Zn and Hg in bivalves were lower than the standard of Chinese Food Health Criterion (GB2762-2012), excess consumption may cause some health problems (Beninger and Lucas, 1984). In addition, these HMs in bivalves may be harmful to humans through the food chain due to their higher concentration (Zimmermann and Sures, 2018).

Table S3 shows the levels of HMs in bivalve species analyzed in this work compared to those found in literature from different global coastal areas. In general, very few published studies are available for the species studied herein and no data were found for *C. scripta*, *G. divaricatum* and *B. virescens*. It can be seen from Table S3 that HM concentrations of *O. glomerata* in Lake Macquarie (New South Wales) (Schneider et al., 2018) are generally higher than those in Daya Bay (China), while HM concentrations in Daya Bay (China) are about the same as those in Taranto (Italy) (Prato et al., 2019). The spatial distribution of each Mytilus species is thought to be controlled by their tolerances of environmental factors (especially temperature and salinity) (Beyer et al., 2017). The main native distribution ranges of the different Mytilus taxa are: *M. edulis* (North Atlantic region) and *M. galloprovincialis* (Mediterranean). Thus, these two allied species exhibited a large difference in their affinity for accumulating metals. The measured levels of HMs in *P. viridis* were lower or at least comparable with those reported in literature data (Liu and Wang, 2015; Yap et al., 2016).

The bioaccumulation of HMs in bivalves results primarily from their contact with seawater, from breathing or from feeding. In order to describe the translocation capacity of HMs from seawater to the bivalves, the Bioconcentration Factor (BCF) of HMs was calculated as follows (Widdows et al., 1995):

$$BCF = \frac{C_{Bivalve}}{C_{Seawater}} \tag{5}$$

where $C_{Bivalve}$ and $C_{Seawater}$ are the HM concentrations in bivalves and seawater, respectively. If BCF > 1, it indicates that the organism can accumulate the HMs (Baker, 1981). BCF > 100 means that the HM

Table 1
The mean ± SD of HM concentrations in different bivalve species (mg/kg-dry weight (d.w.)) and seawater (μg/L).

		n	Cu	Pb	Zn	Cd	Cr	Hg	As	References
Bivalve	*O. glomerata*	16	12.04 ± 6.28	0.47 ± 0.24	10.59 ± 1.48	0.41 ± 0.41	0.76 ± 0.48	0.02 ± 0.01	0.48 ± 0.20	This study
	P. viridis	10	1.58 ± 0.18	0.48 ± 0.12	11.95 ± 1.06	0.31 ± 0.11	0.78 ± 0.21	0.02 ± 0.00	0.50 ± 0.28	
	C. scripta	6	0.90 ± 0.03	0.34 ± 0.10	9.79 ± 0.82	0.07 ± 0.03	1.79 ± 0.90	0.02 ± 0.01	0.29 ± 0.05	
	M. edulis	7	1.49 ± 0.15	0.44 ± 0.18	10.36 ± 1.41	0.06 ± 0.02	1.08 ± 0.06	0.01 ± 0.004	0.22 ± 0.12	
	G. divaricatum	8	1.10 ± 0.59	0.24 ± 0.13	10.64 ± 0.52	1.14 ± 0.25	0.78 ± 0.17	0.02 ± 0.01	0.50 ± 0.06	
	B. virescens	7	1.32 ± 0.49	0.83 ± 0.24	11.32 ± 1.54	0.66 ± 0.14	0.23 ± 0.31	0.03 ± 0.01	0.39 ± 0.01	
	Average		3.07 ± 4.40	0.47 ± 0.20	10.78 ± 0.76	0.44 ± 0.41	0.90 ± 0.51	0.02 ± 0.00	0.40 ± 0.12	
Seawater		20	1.48 ± 0.87	0.77 ± 0.35	12.25 ± 5.60	0.08 ± 0.08	0.72 ± 0.66	0.007 ± 0.001	0.77 ± 0.21	

	Cu	Pb	Zn	Cd	Cr	Hg	As	References
Chinese Food Health Criterion (mg/kg)	50	1.5	50	0.5	2	0.5	0.5	(GB 2762-2017)
USEPA (mg/kg)	50–150	1.7	200–500	1.4		1	2–4	(USEPA, 2002)
FAO (mg/kg)	20	3	30	1	1	0.5	4	(FAO, 1989)
MSQ I (μg/L)	5	1	20	1	5	0.05	20	(GB 3097-1997)

USEPA: United States Environmental Protection Agency.
FAO: Food and Agriculture Organization.
MSQ I: I grade of the Marine Seawater Quality Standard issued by the China State Bureau of Quality and Technical Supervision.

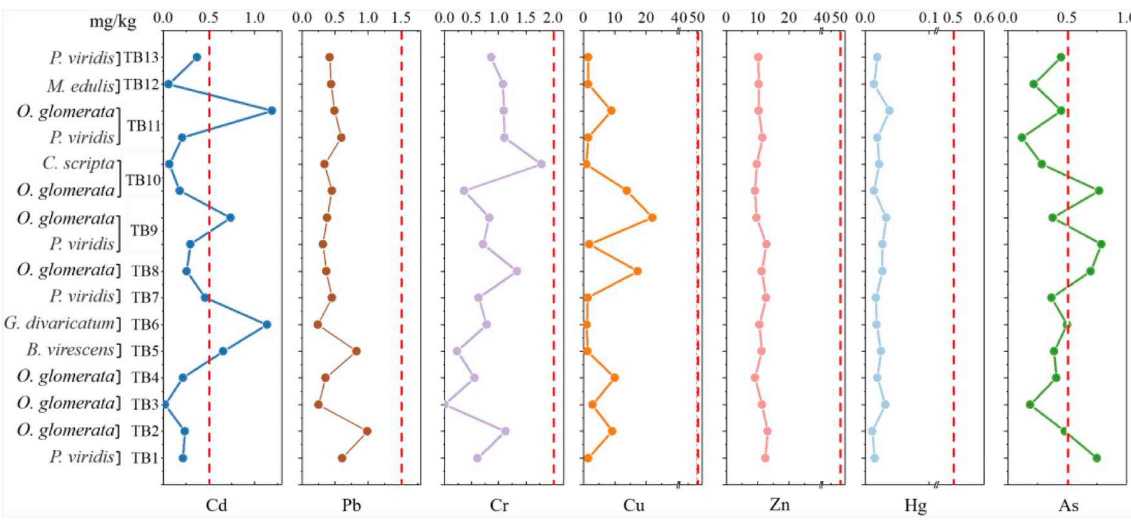

Fig. 2. Distribution of HM concentrations in different bivalve species and different sites. The red line is the values of the Chinese Food Health Criterion (GB 2762-2017) for each metal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

bioaccumulation capacity of the organism is significant (Feldstein et al., 2003).

The BCF values for the HMs in bivalves are listed in Table S4. Generally, the BCF values for the HMs in bivalves followed the order of Cd > Hg > Cu > Cr > Zn > Pb > As. Cd had the highest BCF value (5727), considerably higher than that of other HMs, indicating that bivalves could accumulate Cd more easily than other metals. All the BCF values for the HMs in bivalves in this study were higher than 100, suggesting that bivalves have a high bioaccumulation ability for HMs. The mean values of BCF in bivalves ranged from 515 to 5727, indicating that bivalves are very sensitive to the changes in contaminant levels in seawater. For most bivalves, filtration feeding allows them to contact with large amounts of seawater for nutrition, respiration and excretion (Han et al., 1998; Monteduro et al., 2007).

The BCF values varied significantly among different bivalve species (Fig. S1). In terms of HMs, Cd, Hg and Cu showed significant bioconcentration, indicating that the bivalves have higher bioaccumulation ability for these three HMs than the others. Bivalves have a strong ability to accumulate Cd. Especially in *G. divaricatum*, the value of BCF_{Cd} reached 14,783, which is consistent with the finding of Fang and Dai (2017). Their study revealed that bivalves have high Cd assimilation efficiencies from phytoplankton and a low elimination rate, leading to high Cd concentrations in bivalves. A similar result was found in Merbok Estuary, Malaysia (Lim et al., 1998). However, in the Kaozhou Bay oyster culture zones of the South China Sea, the BCF of Zn was the highest among the studied HMs (Luo et al., 2018). Cu is an essential trace element for bivalves due to its biological function in hemoglobin synthesis or hemocyanin (Sivaperumal et al., 2007), and bivalves can store Cu in granules leading to elevated concentrations (Schneider et al., 2018). In this study, the results also showed that all bivalves have a higher bioaccumulation ability for Hg and Zn. Several previous studies have shown that oysters generally display higher bioaccumulation capacity for some HMs such as Hg and Zn than other organisms, probably because of the occurrence of specific metal storage processes (Hedouin et al., 2010).

The results in Fig. S1a also revealed that different bivalves exhibited significant differences in their bioaccumulation ability. *O. glomerata* showed strong bioaccumulation ability for Cu (8162), Cd (5316) and Hg (3651), *P. viridis* for Cd (4019) and Hg (2775), *C. scripta* for Hg (3213) and Cr (2502), *M. edulis* for Hg (2044), Cr (1509), and Cu (1010), *G. divaricatum* for Cd (14783) and Hg (1090), and *B. virescens* for Cd (8558) and Hg (3651), respectively. The differences in the bioaccumulation ability of HMs may be related to the bioavailability and uptake mechanisms of different HMs (Ruiz et al., 2018). After the

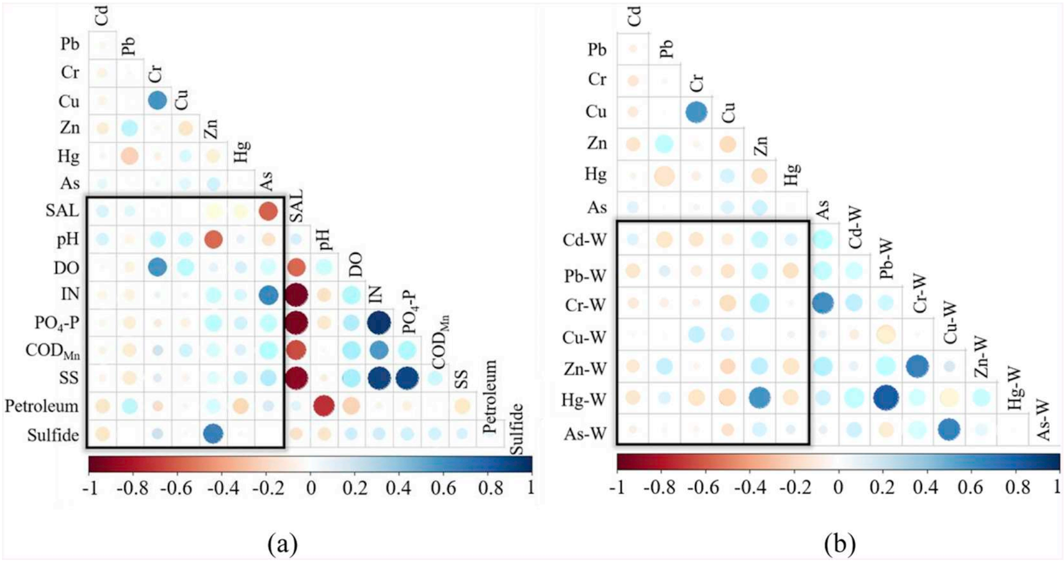

Fig. 3. Matrices of Spearman correlation between variables in bivalves and seawater obtained by averaging the correlation coefficients. (a) is the correlation of HMs in bivalves and physicochemical parameters in seawater; (b) is the correlation of HMs in bivalves and HMs in seawater. Red and blue dots correspond to negative and positive correlations, respectively. Small dots with light color represent low correlations while big dots with darker colors correspond to higher correlations. The rows in the correlation matrices referring to parameters in water and bivalves are included in a rectangular box. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

uptake of HMs by bivalves, some of the HMs are excreted and the residual HMs are distributed in different subcellular and intercellular parts of the organism. Thus, each metal has a different bioaccumulation capacity in different bivalves.

Previous studies have shown that some key physiological functions of marine organisms such as acid-base regulation, protein turnover and mitochondrial bioenergetics may be affected by both physicochemical parameters of seawater and trace metal exposure (Ivanina and Sokolova, 2015; Cao et al., 2018). Therefore, it is necessary to investigate the relationship between HMs in bivalves and the physicochemical parameters of seawater. Water bodies strongly influence the bioavailability of HMs and the main biological processes of bivalves such as growth, development and reproduction. The ecology and life history of bivalves are the important factors to consider when interpreting the interaction between physicochemical parameters of water and HM concentration in organisms (Hall and Anderson, 1995). As shown in Fig. 3 and Table S5, As was significantly correlated with IN ($r = 0.630$, $p < 0.05$) and SAL ($r = -0.588$, $p < 0.05$), Zn with S ($r = 0.674$, $p < 0.05$) and pH ($r = -0.557$, $p < 0.05$), and Cr with DO ($r = 0.581$, $p < 0.05$). However, all the HMs in bivalves had no correlation with the same heavy metal in seawater, suggesting that the bioaccumulation of HMs in bivalves was related more to the physiological and biochemical processes of bivalves themselves.

To further investigate the relationship between HM distributions among different bivalve species, NMDS analysis was implemented in this study. The analysis results of the relationships between all bivalve species and HMs at an overall level showed that the cumulative explained variation of axes was categorized in 89.70% of BCS indices (Fig. 4a). Both Cu and Zn are essential elements for bivalves, and their concentrations were relatively high in six bivalves. All bivalves showed high bioaccumulation capacity for Cu and Zn from the environment, which may be closely related to their involvement in various biochemical and metabolic processes. At the same time, the results of NMDS analysis between each bivalve species and HMs at the individual level showed that the cumulative explained variation of axes was categorized in 95.87% of BCS indices (Fig. 4b). It can be seen from Fig. 4b that *O. glomerata* exhibited a significant accumulative preference for Cu and *C. scripta* showed preference for Cr. Moreover, *P. viridis* and *B. virescens* exhibited strong accumulative preference for Cd, Pb and Zn. In contrast, *M. edulis* and *G. divaricatum* showed no obvious accumulative preference for any of the HMs.

The studied bivalve species are primarily filter feeders, meaning that they strain large volumes of seawater through their bodies to concentrate food material such as microscopic algae. It is known that the algae's cell wall has different functional groups including amines, esters, hydroxyls, alkynes, etc. These functional groups also have an affinity for soft ions (e.g. Cd) or hard ions (e.g. Cr) to form strong bonds (Khan et al., 2017). Thus, the HMs can be bioaccumulated by bivalves through the food chain. The phenomenon of different bivalve species having different HM bioaccumulations is also related to the physiological characteristics or metabolic mechanisms of each bivalve species as mentioned above, but further studies should be carried out.

The analysis results of Hazard quotients of individual HMs and accumulative risk (AR) are shown in Fig. S2. For adults, there was no non-carcinogenic risk of any single heavy metal from consuming bivalves, because the HQ values of HMs for the six bivalves did not exceed one and were within the USEPA risk-free range (HQ ≤ 1) (Fig. S2a). For children, the HQ values of Cd, Cr and As exceeded one and were in the range of 1–4, indicating that these HMs may cause non-carcinogenic risk to children, especially As (Fig. S2b). Whether in adults or children, the main reason for the high AR value was the high concentration of As in bivalves, followed by Cd and Cr. Species-specific HQ values for Cd in children followed the order of: *G. divaricatum* (2.204) > *B. virescens* (1.276) > *O. glomerata* (0.793) > *P. viridis* (0.599) > *C. scripta* (1.135) > *M. edulis* (0.116). The HQ values for Cr in children followed the order of: *C. scripta* (1.154) > *M. edulis* (0.696) > *G. divaricatum* (0.503) = *P. viridis* (0.503) > *O. glomerata* (0.490) > *B. virescens* (0.148). The HQ values for As in children followed the order of: *P. viridis* (3.222) = *G. divaricatum* (3.222) > *O. glomerata* (3.093) > *B. virescens* (2.513) > *C. scripta* (1.869) > *M. edulis* (1.418).

When the non-carcinogenic risks of these single HMs are superimposed in a particular species, it can be seen that the consumption of *O. glomerate*, *P. viridis*, *G. divaricatum* and *B. virescens* would have an adverse impact on the health of adults because their AR values reached low-risk levels. For children, the AR values of all bivalve species were > 1, and reached a high-risk level, except for *M. edulis* (Medium risk), indicating that children who consume bivalve seafood have a greater non-carcinogenic risk.

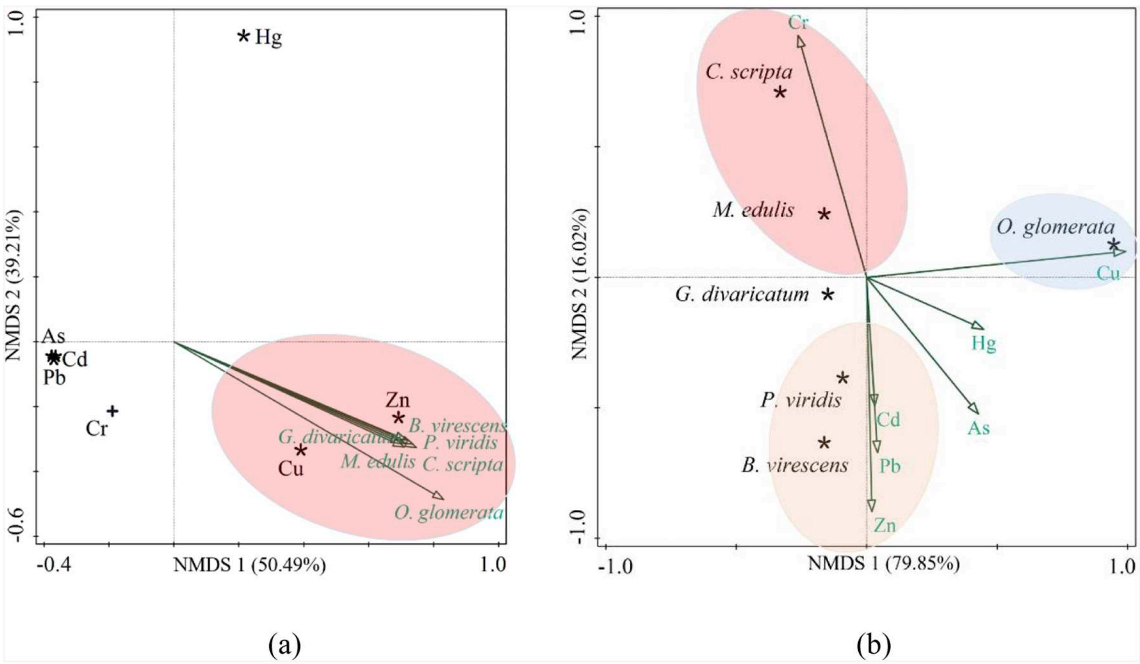

Fig. 4. The plot of nonmetric multidimensional scaling (NMDS) with parameters of bivalves in the study area.

Table 2
Carcinogenic risks (CRs) of individual HMs of Pb, Cr, As and Cd for adults and children.

Bivalve species	Pb	Cr	As	Cd
	CR_{adult}/CR_{child}	CR_{adult}/CR_{child}	CR_{adult}/CR_{child}	CR_{adult}/CR_{child}
O. glomerata	1.99E−06/7.72E−06	1.90E−04/7.35E−04	3.59E−04/1.39E−03	7.78E−05/3.01E−04
P. viridis	2.04E−06/7.89E−06	1.95E−04/7.54E−04	3.74E−04/1.45E−03	5.88E−05/2.28E−04
C. scripta	1.44E−06/5.59E−06	4.47E−04/1.73E−03	2.17E−04/8.41E−04	1.33E−05/5.14E−05
M. edulis	1.87E−06/7.23E−06	2.70E−04/1.04E−03	1.65E−04/6.38E−04	1.14E−05/4.41E−05
G. divaricatum	1.02E−06/3.94E−06	1.95E−04/7.54E−04	3.74E−04/1.45E−03	2.16E−04/8.38E−04
B. virescens	3.52E−06/1.36E−05	5.74E−05/2.22E−04	2.92E−04/1.13E−03	1.25E−04/4.85E−04

According to the USEPA's screening level of chemical pollutants, oral exposure to Pb, Cr, As and Cd through consumption of certain seafood may raise the carcinogenic risk. Therefore, the carcinogenic risks of individual heavy metals including Pb, Cr, As and Cd in adults and children were assessed in this study.

It can be seen from Table 2 that the CR values of Cd, Cr and As ranged from 1.33×10^{-5} to 8.38×10^{-4}, 5.74×10^{-5} to 1.73×10^{-3} and 1.65×10^{-4} to 1.45×10^{-3}, respectively, which were all above the acceptable lifetime risk (10^{-5}). Thus, these HMs pose potential carcinogenic risk to bivalve consumers. However, the CR values for Pb (1.02×10^{-6} to 1.36×10^{-5}) were within the acceptable range ($< 10^{-5}$), indicating that the Pb concentration in bivalves from the study area was insufficient to cause carcinogenic risk.

As discussed above, both potential carcinogenic and non-carcinogenic risks should be considered for consumption of bivalves from the study area especially for children. The health risk results were comparable to the results reported by Gu et al. (2016a). Another study also showed that As in shrimps and crabs from Daya Bay posed significant health risk (Zhang et al., 2018). In addition, several previous studies have reported that HMs can pose potential risks to humans, because HMs can be absorbed through the gastrointestinal tract and distributed into the body through blood circulation, thus affecting the normal body functions. For example, As can cause spotted melanosis, lung cancer, cardiovascular disease and infertility (Occupational Safety and Health Administration, 2004). Cd can lead to high blood pressure, high risk of fracture (Alamdar et al., 2017), tumor (Zhu et al., 2011), liver dysfunction (Rahman et al., 2012) and male infertility (Zafar et al., 2015). Cr is involved in lipid metabolism and insulin function, and can cause damage to DNA and internal organs such as the liver and kidneys, and accumulate in the human body (Ahmed et al., 2015). Therefore, it is necessary to set the daily maximum consumption levels for the different bivalves in the study area, to minimize both carcinogenic and non-carcinogenic risks to human consumers.

According to the health standards issued by USEPA (2000), the HQ and CR standard values (1 for HQ and 10^{-5} for CR) were substituted into formula (1), formula (2) and formula (3) to obtain the daily ingestion rate (IR), which is also the Maximum Allowable Intake Rate (MACR). As shown in Table S6, in the absence of carcinogenic and non-carcinogenic health risks, the MACR values ranged from 0.65 to $1.08\,g \cdot person^{-1} \cdot day^{-1}$ for adults and from 0.17 to $0.28\,g \cdot person^{-1} \cdot day^{-1}$ for children in the study, respectively, which are almost 2 orders of magnitude lower than the actual daily intake.

In summary, the results of this work showed that bivalves could be an important dietary source of As for humans, and also provide Cr and Cd to some extent. The other studied metals (i.e., Cu, Pb, Zn and Hg) had high concentrations in all bivalve species, but within the permissible limits. Thus, they do not pose any considerable health threat to consumers. Health risk results also showed that for each bivalve species, children were more likely to suffer from the risk of HMs than adults.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2019.110717.

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