# Concentrations of macro and trace minerals in giant tiger prawn, *Penaeus monodon* (Fabricius, 1798), from three different farming systems in southwestern Viet Nam

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**Abstract**. Giant tiger prawn (*Penaeus monodon*) is an economically valuable aquaculture species in Viet Nam. The objective of this study was to evaluate the mineral profile of 18 elements (B, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, Pb, Na, K, Ca, Mg, and P) in the muscle of *P. monodon* collected from three different farming models, consisting of rice-shrimp farming (RFS, n = 30), mangrove-shrimp farming (MFS, n = 26), and intensive shrimp farming (IFS, n = 20) in Ca Mau and Bac Lieu provinces, Southwest of Viet Nam. For most mineral element levels (except for Fe, Se, and K), statistically significant differences ($P<0.05$) among the three farming models were found. Concentrations of Al, As, Pb, and P in *P. monodon* muscle collected from the RFS had higher values than those from the other models, while shrimp taken from the MFS showed the highest concentrations of B, Cr, Mn, Co, Ni, and Zn. However, levels of Cu, Cd, Na, Ca, and Mg in the *P. monodon* muscle from the IFS were the highest. The levels of all minerals analyzed in the muscle tissue of *P. monodon* were far below the recommended limits for human consumption set by international and Vietnamese standards.
**Key Words**: composition, shrimp farming model, macro element, Mekong River delta, micro element.

**Introduction**. Since 2005, Viet Nam has been the fourth largest producer of aquaculture products in the world, after China, India, and Indonesia (FAO 2021). With its abundant coastal resources, Viet Nam has a great ability to develop brackish water shrimp (BWS) farming, particularly in provinces of the Mekong River delta (MRD) (FAO 2021; Tri et al 2021). In 2022, the BWS farming area was about 737 thousand hectares, with shrimp production volume reaching over 745 thousand tons and generating US$ 3.8 billion of export turnover, as stated by the Directorate of Fisheries (DoF 2021). Of this, *Penaeus monodon* accounted for 84% and 36% of the total farming area and production volume, respectively. Viet Nam is the world’s biggest exporter of *P. monodon*, followed by Bangladesh, Indonesia, India, and China (DoF 2021).

The MRD has the most diversified shrimp farming systems applied, including rotated in rice fields, integrated in mangroves, and various levels of intensified farming of BWS in ponds (Tri et al 2021). The rotated rice-shrimp farming system (RFS) was developed in 2001 in the MRD, where the *P. monodon* is produced in the dry season with brackish water, and rice is cultivated in the wet season with freshwater (Brennan et al 2002; Tri et al 2021). The mixed shrimp–mangrove farming system (MFS) is a traditional type of extensive aquaculture which relies on both tidal trapping of wild seed, and stocking of hatchery-raised post-larvae (PL) at low densities (Johnston et al 2000; Tri et al 2021). While the intensive farming systems (IFS) were established in the mid-1990s for the *P. monodon*, and they consist of earthen or HDPE-lined intensive shrimp ponds that are rather small in area (0.2-0.5 ha) and with high stocking densities (20-35 PL $m^{-2}$) (Tri et al 2021).

*P. monodon* is a valuable source of high-quality protein, and it provides other nutrients such as vitamins, antioxidants, and particularly macro and trace minerals (Bernard & Bolatito 2016; Dayal et al 2013). Nonetheless, the *P. monodon* has been reported to accumulate toxic metals in its tissues and these elements could potentially cause a high risk to local consumers (Biswas et al 2021; Tu et al 2008). Shrimp can ingest minerals from food or directly from water. In nature-based farming systems as in the RFS and MFS, the post-larvae (PL) of *P. monodon* feed on benthic detritus, while juvenile and adult shrimp mainly prey on macro and meiobenthos, comprising of gastropods, polychaetes, bivalves, insect and crab larvae, copepods, and nematodes (Abualreesh 2021). For the IFS, macro and trace elements from commercial feed are the main source of minerals to shrimp (Truong et al 2022; Truong et al 2020).

The presence of major and micro elements in the pond environment and feed may cause mineral uptake in shrimp. Unfortunately, very few studies have assessed the bioaccumulation of minerals in *P. monodon* from the varied farming practices in Viet Nam. Therefore, the monitoring of macro and trace minerals in *P. monodon* from the range of farming techniques is crucial. The purpose of this study was to characterize the concentrations of 18 minerals in muscle tissue of the most commercially farmed shrimp, *P. monodon*, collected from three different shrimp farming systems located in Southwestern Viet Nam. Another objective of this work was to examine the inter-mineral associations to explain co-exposure and/or related bioaccumulation patterns among minerals.

## Materials and Methods

***Sampling, storage, and sample preparation***. Samples of *P. monodon* were taken directly from the three different farming models, consisting of 30 RFS ponds, 26 MFS ponds, and 20 IFS ponds located in Ca Mau and Bac Lieu provinces, Southwest of Viet Nam (Table 1, Figure 1). Shrimp specimens were thoroughly rinsed by redistilled water, frozen in plastic bags, transported to Nong Lam University, Ho Chi Minh City, Viet Nam, and stored at −18 ± 2°C until being dissected. At the laboratory, for each sample, six individual shrimp of nearly the same weight were randomly selected. After discarding heads, legs, shells, tails and intestines, the remaining muscle tissue was separately dried at 80°C for 12 h, weighed again to determine water content, and then individually pulverized to a fine powder using a mortar and pestle. The same aliquot of each shrimp was carefully mixed to prepare a composite sample. The samples were kept in plastic bags in desiccators until chemical analysis. Details of biometry of the shrimp are listed in Table 1.

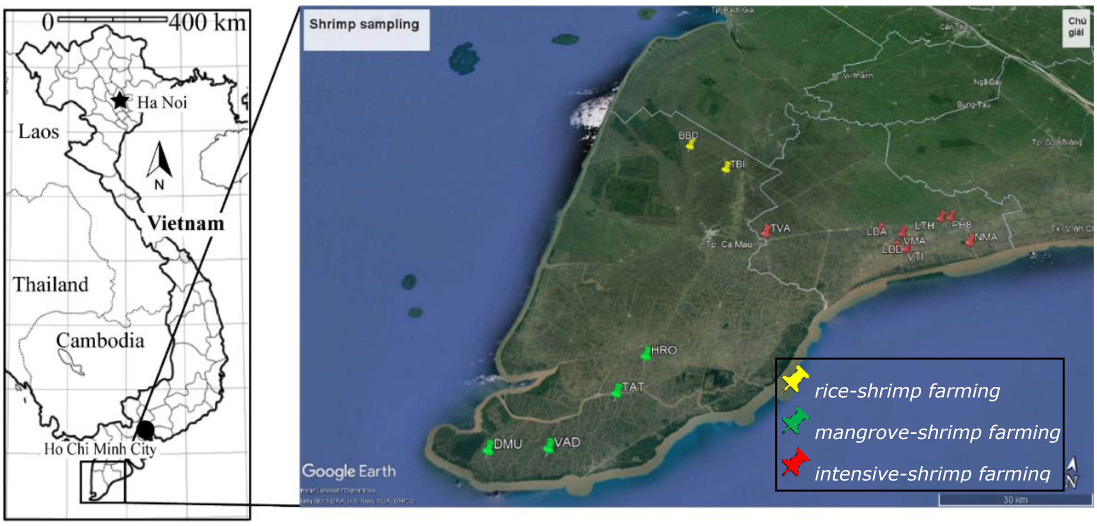


Figure 1. Map showing shrimp sampling locations.

Table 1

Biometry of *Penaeus monodon* collected from three farming systems in the Southwestern Viet Nam

| *Farming system/ Province* | *District* | *Commune* | *Code* | *Sampling date* | *Latitude* | *Longitude* | *n* | *Whole body wt. (g/shrimp)[a]* | *Conversion factor (dry:wet)[a]* |
|---|---|---|---|---|---|---|---|---|---|
| Rice-shrimp | | | | | | | | | |
| Ca Mau | Thoi Binh | Thoi Binh | TBI | 18/03/2022 | 09°21'04" | 105°09'27" | 4 | 40.7 ± 7.3 | 4.3 ± 0.1 |
| | | | | 17/04/2022 | | | 6 | 37.3 ± 11.4 | 4.3 ± 0.2 |
| | | | | 10/06/2022 | | | 6 | 43.3 ± 4.9 | 4.5 ± 0.1 |
| | Thoi Binh | Bien Bach Dong | BBD | 18/03/2022 | 09°24'50" | 105°03'33" | 3 | 47.2 ± 1.4 | 4.2 ± 0.1 |
| | | | | 17/04/2022 | | | 5 | 38.5 ± 18.1 | 4.4 ± 0.1 |
| | | | | 10/06/2022 | | | 6 | 31.2 ± 8.5 | 4.8 ± 0.2 |
| Mangrove-shrimp | | | | | | | | | |
| Ca Mau | Ngoc Hien | Dat Mui | DMU | 23/03/2022 | 08°36'13" | 104°49'20" | 3 | 41.4 ± 2.0 | 4.5 ± 0.1 |
| | | | | 19/04/2022 | | | 3 | 42.1 ± 4.9 | 4.7 ± 0.3 |
| | Ngoc Hien | Vien An Dong | VAD | 23/03/2022 | 08°37'26" | 104°55'48" | 2 | 41.3 ± 0.2 | 4.7 ± 0.0 |
| | | | | 19/04/2022 | | | 4 | 44.3 ± 3.1 | 4.4 ± 0.1 |
| | Ngoc Hien | Tan An Tay | TAT | 24/03/2022 | 08°44'52" | 105°01'40" | 2 | 41.5 ± 2.9 | 4.4 ± 0.3 |
| | | | | 10/05/2022 | | | 2 | 36.9 ± 2.3 | 4.2 ± 0.0 |
| | | | | 05/07/2022 | | | 4 | 39.1 ± 2.2 | 4.5 ± 0.1 |
| | Nam Can | Ham Rong | HRO | 24/03/2022 | 08°49'59" | 105°04'04" | 1 | 49.4 | 4.4 |
| | | | | 05/05/2022 | | | 2 | 40.5 ± 6.3 | 4.4 ± 0.1 |
| | | | | 11/07/2022 | | | 3 | 44.7 ± 4.7 | 4.4 ± 0.2 |
| Intensive-shrimp | | | | | | | | | |
| Bac Lieu | Bac Lieu City | Nha Mat | NMA | 01/10/2022 | 09°13'13" | 105°43'27" | 4 | 41.5 ± 1.2 | 4.1 ± 0.1 |
| | | Ward 8 | PH8 | 17/12/2022 | 09°17'51" | 105°41'38" | 2 | 54.6 ± 15.1 | 4.6 ± 0.2 |
| | Vinh Loi | Long Thanh | LTH | 01/10/2022 | 09°17'29" | 105°40'17" | 4 | 36.6 ± 4.8 | 4.1 ± 0.1 |
| | Dong Hai | Long Dien Dong A | LDA | 16/10/2022 | 09°13'59" | 105°31'55" | 2 | 32.4 ± 17.2 | 4.7 ± 0.3 |
| | | Long Dien Dong | LDD | 16/10/2022 | 09°11'19" | 105°34'00" | 4 | 29.7 ± 7.9 | 4.6 ± 0.2 |
| | Hoa Binh | Vinh Thinh | VTI | 16/10/2022 | 09°11'27" | 105°35'24" | 1 | 40.7 | 4.7 |
| | | Vinh My A | VMA | 17/12/2022 | 09°13'57" | 105°34'57" | 1 | 47.6 | 4.6 |
| Ca Mau | Ca Mau City | Tac Van | TVA | 17/12/2022 | 09°10'21" | 105°16'18" | 2 | 41.4 ± 4.1 | 4.7 ± 0.0 |

[a] Mean and standard deviation (SD)

***Sample digestion and analysis***. About 0.5 g of the dried muscle tissue was soaked in mixture of 4 mL nitric acid (Emsure®, Merck, 65%) and 2 mL hydrochloric acid (Emsure®, Merck, 37%) for two hours, heated at 110°C in a hotplate for 12 hours, and then digested at 160°C for one hour. The digested samples were cooled, transferred into clean volumetric flasks, and made up to 25 ml with redistilled water. Concentrations of 13 micro mineral elements (B, Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Cd, and Pb), four macro mineral elements (Na, K, Ca, and Mg), and P were determined by using an inductively coupled plasma-mass spectrometer (Agilent 7700x, USA), atomic absorption spectrometer (AA 6300, Shimadzu, Japan), and ICP-optical emission spectroscopy (Perkin Elmer Optima 7300 DV, USA), respectively. Method accuracy was verified by analyzing a certified reference material DORM-4 supplied by the National Research Council of Canada. The recoveries of minerals were in the range of 98–105% of certified values. Mineral concentrations in shrimp muscle tissue were determined based on dry weight (wt) and the corresponding transfer factors given in Table 1 were used to convert to wet wt to allow for comparison with values from other studies and standards. All levels of minerals in shrimp muscle are presented on a wet wt basis unless otherwise mentioned.

***Statistical analyses***. All statistical analyses were done according to guidelines described by the US EPA (2000) and Zar (2010), and using the SPSS Statistics for Windows software 22.0 (IBM Corporation, Armonk, NY, USA). One-half of the value of the limit of detection (0.03 ng $g^{-1}$) was replaced for the non-detect Cd value and applied in statistical analysis. A Kolmogorov–Smirnov goodness-of-fit and a Levene test were performed to evaluate the normal distribution and equality of the variances, respectively. Because most of the variables were not normally distributed, the data were logarithmically transformed using $\log(X+1)$ (where $X$ is mineral data) and subjected to parametric statistics. Due to the small sample size in some communes and little variation in elemental levels in shrimp muscle tissue among sampling times in each commune, the shrimp sampling times in the same commune were pooled for farming system comparisons. Because there was no association between body weight and mineral level in muscle, Tukey's honestly significant difference test, together with one-factor analysis of variance (ANOVA) was used to compare differences in mineral concentration among farming systems. The inter-mineral relationships were tested using Pearson correlation. A P-value of <0.05 was considered statistically significant.

**Results**. Summary results of mineral element levels observed from analysed *P. monodon* collected from the southwestern coast of Viet Nam are in Table 2. Levels of individual macro and trace elements in shrimp muscle differed by an order of magnitude. Elements with the highest levels in shrimp muscle from the farming models measured comprised Na, K, Ca, Mg, and P, which averaged nearly 300 μg $g^{-1}$ in specimens from at least one site, with K having the highest general means (Table 2). Concentrations of mineral elements in muscle tissue of *P. monodon* from three farming models are presented in Table 2. With respect to the RFS model, the mean concentrations of Al, Mn, Se, Na, Mg, and P in shrimp muscle from the Thoi Binh (TBI) commune were higher than those from the Bien Bach Dong (BBD) site, whereas average levels of Cr, Fe, As, Cd, K, and Ca in shrimp muscle from the BBD commune were greater than those from the TBI farms (Table 2). Among the MFS sampling sites, average concentrations of Na in the Dat Mui (DMU) shrimp, Ca in the Vien An Dong (VAD) shrimp, B, Cr, Fe, Cu, Zn, K, Mg, and P in the Tan An Tay (TAT) shrimp, and Al, Mn, Co, Ni, As, Se, Cd, and Pb in the Ham Rong (HRO) shrimp were the highest (Table 2). For shrimp in the IFS model, average contents of B, Zn, Se, and Cd from the Nha Mat (NMA), Mn from the Ward 8 (PH8), Al, Co, Cu, Pb, Na, Ca, and Mg from the Long Thanh (LTH), Cr from the Long Dian Dong (LDD), K from the Vinh Thinh (VTI), Fe and P from the Vinh My A (VMA), and As, and Ni from the Tac Van (TVA) showed the most elevated values (Table 2). Overall, statistically significant differences (P<0.05) among the three farming models were found for most of the mineral element levels in *P. monodon* (Table 2). Concentrations of Al, As, Pb, and P in *P. monodon* tissue collected from the RFS had higher values than those from the other models, while shrimps taken from the MFS showed the highest concentrations of B, Cr, Mn, Co, Ni and Zn.

Table 2

Mineral element concentrations (mean ± standard deviation; μg $g^{-1}$ wet wt) in *Penaeus monodon* collected from three farming systems in Southwestern Viet Nam

| *Farming system* | *Code* | *n* | *B* | *Al* | *Cr* | *Mn* | *Fe* | *Co* | *Ni* | *Cu* | *Zn* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rice-shrimp | | | 0.264 ± 0.072$^{a}$ | 3.17 ± 1.17$^{a}$ | 1.24 ± 1.00$^{a}$ | 0.581 ± 0.332$^{a}$ | 11.4 ± 10.3$^{a}$ | 0.009 ± 0.003$^{a}$ | 0.050 ± 0.038$^{a}$ | 6.31 ± 1.30$^{a}$ | 15.6 ± 1.2$^{a}$ |
| | TBI | 16 | 0.256 ± 0.061 | 3.43 ± 1.33 | 0.930 ± 0.631 | 0.666 ± 0.414 | 8.22 ± 5.04 | 0.009 ± 0.003 | 0.053 ± 0.049 | 6.37 ± 0.95 | 15.5 ± 1.2 |
| | BBD | 14 | 0.273 ± 0.084 | 2.86 ± 0.92 | 1.59 ± 1.23 | 0.485 ± 0.174 | 15.0 ± 13.5 | 0.009 ± 0.003 | 0.046 ± 0.020 | 6.25 ± 1.66 | 15.6 ± 1.2 |
| Mangrove-shrimp | | | 0.400 ± 0.064$^{b}$ | 2.84 ± 0.80$^{a}$ | 1.63 ± 0.63$^{b}$ | 1.05 ± 0.45$^{b}$ | 9.80 ± 2.67$^{a}$ | 0.020 ± 0.009$^{b}$ | 0.099 ± 0.071$^{b}$ | 6.24 ± 1.49$^{a}$ | 16.8 ± 1.3$^{b}$ |
| | DMU | 6 | 0.398 ± 0.035 | 2.84 ± 1.06 | 1.23 ± 0.21 | 0.830 ± 0.212 | 8.15 ± 0.91 | 0.016 ± 0.005 | 0.082 ± 0.032 | 5.47 ± 1.06 | 16.4 ± 0.8 |
| | VAD | 6 | 0.401 ± 0.038 | 2.77 ± 1.05 | 1.53 ± 0.29 | 0.920 ± 0.227 | 9.35 ± 1.83 | 0.015 ± 0.004 | 0.101 ± 0.062 | 5.64 ± 1.15 | 16.7 ± 1.5 |
| | TAT | 8 | 0.413 ± 0.074 | 2.72 ± 0.67 | 1.96 ± 0.91 | 1.12 ± 0.53 | 10.8 ± 3.6 | 0.020 ± 0.006 | 0.088 ± 0.024 | 7.03 ± 1.80 | 17.2 ± 1.8 |
| | HRO | 4 | 0.383 ± 0.099 | 3.06 ± 0.51 | 1.69 ± 0.54 | 1.28 ± 0.60 | 10.5 ± 2.8 | 0.028 ± 0.012 | 0.130 ± 0.133 | 6.59 ± 1.34 | 16.8 ± 0.9 |
| Intensive shrimp | | | 0.265 ± 0.141$^{a}$ | 2.14 ± 0.50$^{b}$ | 1.38 ± 0.39$^{ab}$ | 0.974 ± 0.306$^{b}$ | 11.4 ± 3.0$^{a}$ | 0.012 ± 0.004$^{a}$ | 0.078 ± 0.020$^{ab}$ | 10.7 ± 4.6$^{b}$ | 16.2 ± 2.1$^{ab}$ |
| | NMA | 4 | 0.436 ± 0.097 | 2.46 ± 0.14 | 1.27 ± 0.23 | 0.925 ± 0.228 | 9.81 ± 1.16 | 0.011 ± 0.003 | 0.076 ± 0.018 | 15.3 ± 1.0 | 18.0 ± 1.1 |
| | PH8 | 2 | 0.155 ± 0.016 | 1.61 ± 0.07 | 1.57 ± 0.34 | 1.28 ± 0.51 | 12.0 ± 2.0 | 0.013 ± 0.003 | 0.086 ± 0.028 | 6.07 ± 1.39 | 14.6 ± 2.1 |
| | LTH | 4 | 0.399 ± 0.098 | 2.53 ± 0.63 | 1.18 ± 0.21 | 0.940 ± 0.283 | 11.7 ± 3.1 | 0.015 ± 0.004 | 0.084 ± 0.024 | 16.2 ± 1.4 | 17.6 ± 2.0 |
| | LDA | 2 | 0.144 ± 0.048 | 1.96 ± 0.17 | 1.04 ± 0.39 | 0.556 ± 0.029 | 7.72 ± 1.46 | 0.007 ± 0.004 | 0.054 ± 0.003 | 8.69 ± 4.38 | 14.2 ± 3.6 |
| | LDD | 4 | 0.170 ± 0.020 | 1.89 ± 0.33 | 1.74 ± 0.59 | 0.971 ± 0.384 | 12.1 ± 2.7 | 0.011 ± 0.004 | 0.077 ± 0.019 | 8.29 ± 1.24 | 15.2 ± 1.7 |
| | VTI | 1 | 0.164 | 1.75 | 1.14 | 1.09 | 10.1 | 0.009 | 0.063 | 5.98 | 15.6 |
| | VMA | 1 | 0.145 | 2.92 | 1.24 | 0.954 | 19.6 | 0.010 | 0.066 | 6.87 | 17.2 |
| | TVA | 2 | 0.185 ± 0.004 | 1.72 ± 0.23 | 1.62 ± 0.17 | 1.21 ± 0.12 | 12.3 ± 1.4 | 0.013 ± 0.002 | 0.097 ± 0.014 | 5.91 ± 0.56 | 15.3 ± 1.0 |

| *Farming system* | *Code* | *n* | *As* | *Se* | *Cd*[#] | *Pb* | *Na* | *K* | *Ca* | *Mg* | *P* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Rice-shrimp | | | 2.92 ± 2.50$^{a}$ | 0.322 ± 0.093$^{a}$ | 5.42 ± 3.08$^{a}$ | 0.021 ± 0.021$^{a}$ | 1,068 ± 128$^{a}$ | 2,419 ± 581$^{a}$ | 442 ± 94$^{a}$ | 301 ± 32$^{a}$ | 1,159 ± 193$^{a}$ |
| | TBI | 16 | 2.35 ± 1.66 | 0.369 ± 0.070 | 5.26 ± 3.17 | 0.019 ± 0.020 | 1,101 ± 137 | 2,367 ± 680 | 438 ± 119 | 308 ± 25 | 1,205 ± 221 |
| | BBD | 14 | 3.57 ± 3.14 | 0.268 ± 0.089 | 5.61 ± 3.07 | 0.022 ± 0.022 | 1,030 ± 108 | 2,478 ± 461 | 446 ± 59 | 293 ± 37 | 1,106 ± 145 |
| Mangrove-shrimp | | | 0.981 ± 0.374$^{b}$ | 0.292 ± 0.046$^{a}$ | 0.268 ± 0.590$^{b}$ | 0.013 ± 0.004$^{ab}$ | 1,141 ± 136$^{a}$ | 2,530 ± 274$^{a}$ | 619 ± 105$^{b}$ | 329 ± 46$^{b}$ | 758 ± 173$^{b}$ |
| | DMU | 6 | 0.756 ± 0.118 | 0.273 ± 0.009 | 0.087 ± 0.206 | 0.013 ± 0.006 | 1,180 ± 104 | 2,456 ± 199 | 648 ± 53 | 321 ± 30 | 750 ± 41 |
| | VAD | 6 | 0.722 ± 0.125 | 0.266 ± 0.020 | 0.003 ± 0.000 | 0.012 ± 0.003 | 1,054 ± 143 | 2,326 ± 130 | 698 ± 118 | 299 ± 18 | 715 ± 163 |
| | TAT | 8 | 1.06 ± 0.24 | 0.289 ± 0.042 | 0.136 ± 0.268 | 0.012 ± 0.003 | 1,169 ± 162 | 2,738 ± 271 | 538 ± 87 | 350 ± 68 | 809 ± 193 |
| | HRO | 4 | 1.36 ± 0.51 | 0.338 ± 0.062 | 0.892 ± 0.991 | 0.015 ± 0.004 | 1,151 ± 109 | 2,529 ± 301 | 617 ± 94 | 341 ± 29 | 742 ± 251 |
| Intensive shrimp | | | 1.01 ± 0.51$^{b}$ | 0.315 ± 0.053$^{a}$ | 14.7 ± 12.2$^{c}$ | 0.011 ± 0.004$^{b}$ | 1,311 ± 290$^{b}$ | 2,357 ± 368$^{a}$ | 790 ± 460$^{b}$ | 356 ± 46$^{b}$ | 553 ± 180$^{c}$ |
| | NMA | 4 | 0.966 ± 0.096 | 0.355 ± 0.031 | 32.0 ± 5.9 | 0.010 ± 0.002 | 1,729 ± 196 | 2,369 ± 183 | 1,091 ± 172 | 377 ± 5 | 424 ± 26 |
| | PH8 | 2 | 0.252 ± 0.072 | 0.314 ± 0.005 | 7.93 ± 0.66 | 0.008 ± 0.001 | 1,004 ± 203 | 2,381 ± 1,066 | 450 ± 64 | 333 ± 48 | 814 ± 46 |
| | LTH | 4 | 1.21 ± 0.53 | 0.308 ± 0.018 | 23.2 ± 8.5 | 0.012 ± 0.005 | 1,446 ± 90 | 2,332 ± 82 | 1,478 ± 279 | 421 ± 29 | 408 ± 52 |
| | LDA | 2 | 0.858 ± 0.155 | 0.280 ± 0.020 | 2.28 ± 1.29 | 0.007 ± 0.000 | 1,250 ± 139 | 2,433 ± 112 | 485 ± 212 | 317 ± 5 | 438 ± 40 |
| | LDD | 4 | 0.889 ± 0.202 | 0.265 ± 0.050 | 4.33 ± 3.886 | 0.014 ± 0.006 | 1,209 ± 97 | 2,497 ± 248 | 394 ± 47 | 334 ± 30 | 550 ± 134 |
| | VTI | 1 | 1.48 | 0.440 | 9.22 | 0.010 | 1,204 | 2,699 | 487 | 345 | 723 |
| | VMA | 1 | 0.291 | 0.381 | 7.39 | 0.008 | 881 | 2,595 | 447 | 351 | 971 |
| | TVA | 2 | 1.93 ± 0.06 | 0.296 ± 0.035 | 8.96 ± 0.28 | 0.010 ± 0.001 | 1,048 ± 156 | 1,715 ± 164 | 575 ± 209 | 301 ± 29 | 670 ± 68 |

[#] ng/g; Comparing among three shrimp farming systems, mean values in the same column with different superscript letters differ significantly (One-way ANOVA, Tukey test, $P<0.05$).

Table 3

Correlation matrix among mineral element concentrations in the muscle tissue of *Penaeus monodon* from three farming systems

| | *Al* | *Cr* | *Mn* | *Fe* | *Co* | *Ni* | *Cu* | *Zn* | *As* | *Se* | *Cd* | *Pb* | *Na* | *Mg* | *P* | *K* | *Ca* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B | 0.278$^{*}$ | | | | 0.345$^{**}$ | | | 0.556$^{**}$ | | | -0.290$^{*}$ | | 0.362$^{**}$ | | | | 0.531$^{**}$ |
| Al | | | | | | | | | | | -0.254$^{*}$ | 0.336$^{**}$ | | | 0.406$^{**}$ | 0.380$^{**}$ | |
| Cr | | | 0.529$^{**}$ | 0.783$^{**}$ | 0.506$^{**}$ | 0.517$^{**}$ | | | | -0.271$^{*}$ | | | | | -0.335$^{**}$ | | |
| Mn | | | | 0.414$^{**}$ | 0.580$^{**}$ | 0.601$^{**}$ | | | -0.440$^{**}$ | | -0.239$^{*}$ | | 0.232$^{*}$ | 0.481$^{**}$ | -0.462$^{**}$ | 0.241$^{*}$ | 0.409$^{**}$ |
| Fe | | | | | 0.304$^{**}$ | 0.435$^{**}$ | | | | -0.250$^{*}$ | | 0.233$^{*}$ | | 0.259$^{*}$ | -0.254$^{*}$ | | |
| Co | | | | | | 0.519$^{**}$ | | 0.262$^{*}$ | -0.245$^{*}$ | | -0.326$^{**}$ | | | 0.348$^{**}$ | -0.358$^{**}$ | | 0.299$^{**}$ |
| Ni | | | | | | | | 0.269$^{*}$ | -0.237$^{*}$ | | -0.284$^{*}$ | | | 0.229$^{*}$ | -0.298$^{**}$ | 0.233$^{*}$ | 0.296$^{**}$ |
| Cu | | | | | | | | 0.554$^{**}$ | | 0.312$^{**}$ | 0.473$^{**}$ | | 0.628$^{**}$ | 0.573$^{**}$ | -0.490$^{**}$ | | 0.564$^{**}$ |
| Zn | | | | | | | | | | 0.243$^{*}$ | | | 0.363$^{**}$ | 0.343$^{**}$ | | 0.269$^{*}$ | 0.432$^{**}$ |
| As | | | | | | | | | | | 0.279$^{*}$ | | -0.281$^{*}$ | -0.318$^{**}$ | 0.420$^{**}$ | | -0.332$^{**}$ |
| Se | | | | | | | | | | | | | | 0.280$^{*}$ | | | |
| Cd | | | | | | | | | | | | | | | | -0.289$^{*}$ | |
| Pb | | | | | | | | | | | | | | | 0.239$^{*}$ | | |
| Na | | | | | | | | | | | | | | 0.637$^{**}$ | -0.513$^{**}$ | 0.295$^{**}$ | 0.593$^{**}$ |
| Mg | | | | | | | | | | | | | | | -0.564$^{**}$ | 0.263$^{*}$ | 0.613$^{**}$ |
| P | | | | | | | | | | | | | | | | | -0.661$^{**}$ |
| K | | | | | | | | | | | | | | | | | |

Only significant values ($P<0.05$) are presented. * and ** indicated significant correlation at 0.05 and 0.01, respectively.

Contrarily, the levels of Cu, Cd, Na, Ca, and Mg in the muscle of *P. monodon* from the IFS were the greatest (Table 2) while Fe, Se, and K showed no significant differences between shrimp farming models. To detect the source and co-exposure of the studied mineral elements, Pearson's correlation analyses were performed, and a correlation matrix among the mineral elements from shrimp samples is presented in Table 3. The association can be significant or highly significant and positive or negative (Table 3). Significantly positive correlations were found among major mineral elements, including Na, K, Ca, and Mg ($P<0.05$), but P levels were negatively associated with levels of most minerals ($P<0.05$). Moreover, notably positive relationships were discovered among Al with B, Pb, P, and K, As with Cd and P, and Pb with P ($P<0.05$) (Table 3). Furthermore, there were positive correlations observed among micro mineral elements, including Cr, Mn, Fe, Co, and Ni ($P<0.05$). Also, a significantly positive association was identified between B and Co, Na and Ca, Fe and Pb, Zn and B, Co, Ni, Cu, and between major minerals (Na, K, Ca, Mg), Cu and Se, Cd, Na, Mg, and Ca ($P<0.05$). Interestingly, there were slightly negative correlations found among major and trace mineral elements ($P<0.05$) (Table 3).

## Discussion

***Concentrations of macro and trace minerals in shrimp***. Elements (Na, K, Ca, Mg, and P) are typically the most abundant mineral within shrimp (Truong et al 2022). Potassium is frequently considered with Mg, Na and Cl for their vital functions in acid-base balance and osmoregulation. In addition, Ca, together with P, is a main component in the exoskeleton of shrimp (Jannathulla et al 2017; Truong et al 2022). Besides, Mg acts as a catalyst for a wide array of enzymes vital for the metabolism of carbohydrates, lipids, nucleic acids, and proteins. Additionally, P exists naturally in shrimp as phospholipids, ATP/ADP and creatine phosphate energy molecules, nucleic acids, and buffers (e.g., phosphates) (Jannathulla et al 2017; Truong et al 2022).

Among micro minerals, the highest concentration of Zn was found across all of the *P. monodon* of farming systems, followed by Fe and Cu. Metals with the lowest mean concentrations out of the metals analyzed were Co, Cd, and Pb, with Cd having the lowest concentrations found throughout samples from three farming systems (Table 2). Essential trace elements, including Cr, Mn, Fe, Co, Cu, Zn, and Se, are related with a specific protein in metalloenzymes and generate a unique catalytic function. High concentrations of Zn were consistently found in the muscle tissue of *P. monodon* (15.6–16.8 $\mu g\ g^{-1}$). Zinc is essentially involved with the metabolism of lipids, protein, and carbohydrates. In addition to absorbing Zn from their feed, shrimp take up Zn across the gills and intestinal track (Truong et al 2022). Levels of Fe and Cu were also relatively elevated in the muscle of *P. monodon* (Table 2). Copper, a main component of hemocyanin, plays a role in the activation of a myriad of enzymes relating to reproduction, growth, connective tissue development and pigmentation of skin appendages (Truong et al 2022). However, decapods can regulate their body Cu level to a constant level over a broad range of dissolved Cu existing in their surrounding water (Rainbow & White 1989; White & Rainbow 1982). Among the mineral elements studied across taxa, Fe has the most extensive interspecific variation. Some decapods accumulate high amounts of Fe granules, whereas in others these are totally absent (Vogt & Quinitio 1994).

In this study, the average concentrations of Al and As were comparatively high in the shrimp samples, with ranges of 2.14–3.17 $\mu g\ g^{-1}$ and 0.981–2.92 $\mu g\ g^{-1}$, respectively. Acid sulphate soils (ASS), which are common in south-western Viet Nam, are naturally enriched with Al and As (Gustafsson & Tin 1994; Kawahigashi et al 2008), which may explain their accumulation in pond bottom soils and subsequent transfer to shrimp tissue. The high As accumulation in *P. monodon* is also reflective of As levels in the marine environment, as indicated by Tu et al (2008; 2012). Boron has demonstrated its importance in certain biological functions in other species, but it has received limited focus in aquaculture nutrition (Truong et al 2020). For *P. monodon*, Truong et al (2020) reported that the addition of B significantly enhanced feed efficiency, growth, and nutrient (protein, lipid) and energy retention. The levels of Ni, Cd, and Pb (non-essential metals) within muscle tissue were relatively low compared to essential metals of Cu and Zn, indicating these were present in lower concentrations in situ.

***Inter-relationships of macro and trace minerals in shrimp***. A positive correlation between given mineral elements may show similar types of contamination and/or release from the same source of contamination, mutual influence, and equivalent behavior when being transported to the aquatic system (Hossain et al 2022). In this study, the inter-correlations among major mineral elements show they may come from main sources: shrimp feed, mineral supplements, release from soil, etc. within the farming system. To meet the mineral requirements for cultured shrimp, farmers usually provide macro mineral premixes containing predominately Ca (as Ca chloride, carbonate or phosphate), K (as K iodide, phosphate or chloride), Mg (as Mg sulphate), and Na (as Na phosphate or chloride) (Truong et al 2022). Moreover, the addition of certain minerals such as aqueous Mg and K can promote growth in shrimp, particularly in low salinity environments (Truong et al 2022). A decrease of pH in the ASS can enhance the release of metal ions from clay minerals into the pond water, particularly of Al, Fe, Na, K and Mg. Furthermore, the oxidation of this soil can release toxic elements (such as Cd, Pb, and As) into the pond water (Hoa et al 2004; Russell et al 2019). Whereas micro essential elements positively correlated with each other but negatively related with macro elements, suggesting that these micro elements may have been introduced from the same source, but differed from the source of macro minerals. According to Nho et al (2019b), the dissolution of Fe and Mn oxyhydroxides in reducing conditions during the breakdown of organic matter in mangrove ecosystems may be a main source of dissolved metals, including Fe, Mn, Ni, Cr, Cu, Co, and As, in pore waters. Subsequently, these dissolved elements can be transferred to mangrove species of invertebrates, fish and other taxa that comprise the coastal food web.

***Farming-dependent variations of macro and trace minerals in shrimp***. The high accumulation of Al, As, Pb, and P in shrimp muscle and positive inter-correlation among these elements from the RFS may be related to the farming method. Annually, the RFS practice in Viet Nam is comprised of two cultivation cycles: rice culture in the wet season, between July and December, and shrimp culture in the dry season, between January and June. During rice cultivation, the 60-40-40 NPK fertilizer were periodically applied at 10, 25, and 45 days after sowing (Ngoc et al 2023). Furthermore, shrimp in the RFS contained high levels of Al, As, and Pb, which could result from the release of these metal ions from the ASS. In the shrimp-crop farming, to prepare for stocking PL, the pond is left to dry for about 30 days (starting 7–10 days before rice is harvested and 15–20 days for pond preparation) (Ngoc et al 2023). Lowering of the water table and re-flooding water in this soil can result in the formation of sulfuric acid ($H_2SO_4$), which can be subsequently transported into the pond water. This low pH induces the dissociation of mineral elements from pond soil, particularly Al, As, and Pb, thus increasing their solubility, and subsequently these may accumulate in shrimp (Nho et al 2019a; Russell et al 2019).

The higher concentrations of B, Cr, Mn, Co, Ni, and Zn observed in the muscle of *P. monodon* from the MFS model may have resulted from the reductive dissolution of Fe and Mn oxyhydroxides as stated earlier by Nho et al (2019b). Similarly, Hoa et al (2004) reported that the concentration of Cr, Fe, Mn, Ni, and Zn in the canal nearby the ASS area was 67, 58, 38, 413, and 31 times, respectively, higher than those in non-ASS. Moreover, the higher concentrations of Mn, Co, Ni, and Zn in the muscle of *P. monodon*, a detritus eater, are likely related to the higher concentrations of these elements in mangrove detritus. In mangrove tree components, concentrations of Mn, Co, Ni, and Zn are mainly concentrated in live and dead roots (Alongi 2021), while there is no data on the role of B in mangrove nutrient cycling (Alongi 2021). But Fernández-Cadena et al (2014) stated that B content in surface sediment sampled from Estero Salado mangrove located in Guayaquil, Ecuador exceeded the threshold values established by international environmental quality standards. The authors presumed that extensive anthropogenic activities have led to high accumulation of B in that area. This element was widely used in the production of synthetic herbicides, fertilizers, porcelain, detergents, enamels, etc. In this regard, B releases into the aquatic ecosystem are mostly via irrigation water, wastewater, fertilizer, herbicide, etc.

(Brdar-Jokanović 2020; Li et al 2008). Therefore, the higher bioaccumulation of B in shrimp muscle tissue from the MFS could have come from human activities in these regions.

In the current study, the concentrations of Cu, Cd, Na, Ca, and Mg in shrimp muscle from the IFS were higher than those from the other two farming models (Table 2). Besides the discharge of Cu from industrial operations, shrimp farming itself leads to Cu contamination because copper sulfate is regularly utilized in ponds for the control of filamentous algae (Boyd & Tucker 1998). Artificial inputs of feed, fertilizers and other chemical additives also add Cu into the pond water (Lacerda et al 2006). Of these sources, shrimp feed are certainly the biggest contributor to the higher Cu levels into shrimp ponds due to the large quantity used (Lacerda et al 2006). Cd is a chronic-toxicity-causing element occuring in the natural environment at very low levels. Aquatic ecosystems may have Cd from industrial waste, and the use of phosphate fertilizers in agricultural fields (McGeer et al 2011). The same trend of high levels of Cd in the *P. monodon* and other aquatic animals from the MRD were also observed in previous studies (Tu et al 2008, 2011, 2022). These authors suggested that the source of this element may have come from the use of phosphate fertilizers. Furthermore, some studies showed that feed contributes in a major proportion to the Cd bioaccumulation in farmed fish and shrimp. Squid liver powder (SLP), a fisheries by-product (heads, feet, and viscera) of processing squid, is routinely applied as a dietary additive for farmed fish and shrimp to increase their feed intake. This powder contains a significantly high concentrations of Cd, of about 26 mg $kg^{-1}$ (Jang et al 2021). In a study of the effect of a feed with SLP on the growth of and Cd accumulation in Japanese seabass, Mai et al (2006) showed that the Cd levels in the kidney, liver and gill were positively related to the dietary Cd levels. Fish fed diets with 50 and 100 mg $kg^{-1}$ diet had significantly higher Cd levels in the kidney (3.25, 5.85 μg $g^{-1}$, respectively), liver (0.76, 1.26 μg $g^{-1}$, respectively), and gill (0.42, 0.58 μg $g^{-1}$, respectively) compared with the control group (0.82, 0.34 and 0.32 μg $g^{-1}$, respectively). In another study of Jang et al (2021), which evaluated the effects of SLP content on the growth performance, Cd accumulation, and non-specific immune response in juvenile olive flounder, reported that Cd contents in the viscera including liver significantly increased as dietary SLP content increased. Until now, no research has been done to assess the influence of SLP supplement into shrimp feeds on Cd accumulation in the tissues of shrimp. Compared to the RFS and MFS, the IFS has higher stocking densities and biomass, as well as faster growth and a higher frequency of molting. Therefore, higher levels of feeding and mineral supplements (e.g., feed additives, water minerals, etc.) are required in these systems (Truong et al 2022). Shrimps can obtain their essential elements of Na, Ca, and Mg from both pond water and their food. As stated earlier, to satisfy the essential mineral needs of cultured shrimp, farmer regularly supply macro mineral premixes containing largely Ca, Mg, and Na (Truong et al 2022). Moreover, sodium bicarbonate ($NaHCO_3$) is used for raising total alkalinity, which keeps the pH stable in a shrimp pond. Additionally, application of $CaCO_3$ or dolomite in shrimp ponds is used treat water and to increase both the total hardness and alkalinity of pond water (Truong et al 2022).

***Comparison of mineral levels in Vietnamese shrimp with those in other countries and the standards***. Chromium concentrations in the muscle tissue of *P. monodon* from Southwest of Viet Nam were observed to be higher than those reported from other regions (Table 4). The concentrations of other minerals in *P. monodon* in this study were consistent with Tu et al (2008). For Mn, mean concentrations of 6.55–37.9 μg $g^{-1}$ and 4.83 μg $g^{-1}$ were reported in cultured *P. monodon* muscle in Khulna and Cox's Bazar, respectively, Bangladesh (Biswas et al 2021; Sultana et al 2022), which were higher than our findings. However, other studies from different parts of the world recorded Mn values more similar to our results (Mokhtar et al 2009; Rumisha et al 2016). The observations on Fe are similar to several studies (Eludoyin et al 2018; Mokhtar et al 2009; Rumisha et al 2016), but lower than in Khulna, Bangladesh (Biswas et al 2021) and Sunderban, India (Guhathakurta & Kaviraj 2000) (Table 4). Concentrations of Co, Ni, Cu, Zn, and As found in the present study were comparable to the earlier works (Table 4).

Table 4

Comparison of mean concentrations of minerals (μg $g^{-1}$ wet wt) in the muscle tissue of *Penaeus monodon* with those from other countries and human consumption guidelines

| *Country* | *Region* | *Cr* | *Mn* | *Fe* | *Co* | *Ni* | *Cu* | *References* |
|---|---|---|---|---|---|---|---|---|
| Viet Nam | Rice-shrimp | 1.24 | 0.581 | 11.4 | 0.009 | 0.050 | 6.31 | This study |
| | Mangrove-shrimp | 1.63 | 1.05 | 9.80 | 0.020 | 0.099 | 6.24 | |
| | Intensive shrimp | 1.38 | 0.974 | 11.4 | 0.012 | 0.078 | 10.7 | |
| | Ho Chi Minh City[a] | 0.16 – 0.27 | 0.419 – 0.746 | | 0.020 – 0.021 | | 13.5 – 16.2 | Tu et al (2008) |
| | Mekong River Delta[a] | 0.18 – 0.40 | 0.683 – 2.32 | | 0.014 – 0.077 | | 9.21 – 28.2 | |
| Bangladesh | Khulna | <0.01 – 0.235 | 6.55 – 37.9 | 184 – 359 | | <0.01 – 0.080 | | Biswas et al (2021) |
| | Cox's Bazar | 0.69 | 4.83 | | | | 9.43 | Sultana et al (2022) |
| Malaysia | Bandar | ND | 0.177 | 5.17 | | 0.026 | 3.57 | Mokhtar et al (2009) |
| | Jugra | ND | 0.193 | 7.21 | | 0.122 | 2.21 | |
| India | Sunderban[a] | | | 5.0 – 495 | | | | Guhathakurta & Kaviraj (2000) |
| | East Coast[a] | 0.69 | | | 1.15 | 1.38 | 1.16 | Acharya et al (2023) |
| Nigeria | Bodo Creek[a†] | | | 48.9 | | 3.78 | | Eludoyin et al (2018) |
| Tanzania | East Coast | 0.02 – 0.09 | 0.5 – 2.8 | 7.9 – 22.7 | 0.01 – 0.03 | 0.01 – 0.08 | 9.6 – 16.3 | Rumisha et al (2016) |
| WHO guideline | | 50 | 1 | 100 | | 0.5 – 1.0 | 30 | WHO (1999) |

| Country | Region | Zn | As | Se | Cd | Pb | References |
|---|---|---|---|---|---|---|---|
| Viet Nam | Rice-shrimp | 15.6 | 2.92 | 0.322 | 0.005 | 0.021 | This study |
| | Mangrove-shrimp | 16.8 | 0.981 | 0.292 | 0.0003 | 0.013 | |
| | Intensive shrimp | 16.2 | 1.01 | 0.315 | 0.015 | 0.011 | |
| | Ho Chi Minh City[a] | 48.8 – 51.1 | 5.5 – 15 | 1.2 – 1.5 | 0.003 – 0.013 | 0.008 – 0.024 | Tu et al (2008) |
| | Mekong River Delta[a] | 45.9 – 52.3 | 0.83 – 18 | 0.63 – 1.5 | 0.005 – 0.043 | 0.009 – 0.028 | |
| Bangladesh | Khulna[a] | 73.4 – 84.1 | | | 0.040 – 0.049 | 0.354 – 0.691 | Biswas et al (2021) |
| | Cox's Bazar | 18.9 | 0.44 | | 0.09 | 17.75 | Sultana et al (2022) |
| Malaysia | Bandar | 13.0 | | | 0.254 | ND | Mokhtar et al (2009) |
| | Jugra | 11.3 | | | 0.254 | ND | |
| India | Sunderban[a] | 7.3 – 4,810 | | | 0.11 – 3.22 | 22.9 – 42.1 | Guhathakurta & Kaviraj (2000) |
| | East Coast[a] | 4.41 | | | 0.28 | 0.68 | Acharya et al (2023) |
| Nigeria | Bodo Creek [a†] | 2.65 | | | 2.47 | 1.48 | Eludoyin et al (2018) |
| Tanzania | East Coast | 19.9 – 25.3 | 0.3 – 2.0 | | 0.01 – 0.03 | 0.00 – 0.37 | Rumisha et al (2016) |
| Viet Nam guideline | | | | | 0.5 | 0.5 | MOH (2011) |
| EC guideline | | | | | 0.5 | 0.5 | EC (2006) |
| WHO guideline | | 100 | | | 1 | 2 | WHO (1999) |

ND = Not Detected; [a] based on dry wt (dry – wet conversion factor of 4 – 5); [†] whole body

Contrastingly, levels of Co, Ni, and Zn observed in this study were lower than those from the east coast of India (Acharya et al 2023), Bodo Creek, Nigeria (Eludoyin et al 2018), and Sunderban, India (Guhathakurta & Kaviraj 2000), respectively. This study shows that the average levels of Cd and Pb in *P. monodon* collected from Southwestern Viet Nam were comparable to those in specimens from the east coast of India and the east coast of Tanzania, but lower than in those in *P. monodon* from Bangladesh, Malaysia, India, and Nigeria (Table 4).

Some trace elements, including Cr, Ni, As, Cd, and Pb, are highly toxic and harmful to humans. Compared with Vietnamese and international organization guidelines, levels of all minerals in *P. monodon* found in our study were below limits for human consumption in crustaceans (Table 4).

**Conclusions**. Overall, the farming model-specific variations in macro and micro minerals in the muscle tissue of *P. monodon* could reflect farming practice differences. Concentrations of Al, As, Pb, and P in *P. monodon* muscle collected from the RFS had higher values than those from the other models, while shrimps taken from the MFS showed the highest concentrations of B, Cr, Mn, Co, Ni and Zn. However, the levels of Cu, Cd, Na, Ca, and Mg in the muscle of *P. monodon* from the IFS were highest. The contents of all minerals analyzed in the muscle tissue of *P. monodon* were lower than the permissible levels of the current national technical regulation on the limits of metal contamination in food established by the Vietnamese Ministry of and international organizations. Therefore, further studies of macro and micro minerals addressing pond water and sediment, and natural and commercial feeding is warranted.

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**Conflict of interest**. The authors declare no conflict of interest.

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