

1 **Variations in the distribution of trace elements in coral sand sediments at the green**
2 **turtle nesting ground in the Xisha Islands, South China Sea**

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13 **Abstract:** Coral sand sediments were collected from green turtle nests, vegetation areas, and
14 the high water line of the Xisha Islands in the South China Sea. The contents of 10 trace
15 elements (TEs) were analyzed, their ecological risks were assessed, and their sources were
16 explored. The contents of TEs in the coral sand sediments varied among the three locations.
17 Specifically, the levels of copper (Cu), zinc (Zn), selenium (Se), and lead (Pb) in the coral sand
18 sediments from green turtle nests were significantly higher than those in the vegetation and
19 high water line areas ($P < 0.0001$). In contrast, the concentrations of arsenic (As), iron (Fe), and
20 nickel (Ni) in the coral sands from the high water and vegetation line were significantly lower
21 than those in the turtle nests ($P < 0.0001$). The TEs in the coral sand sediments along the
22 vegetation line may be influenced by atmospheric deposition and plant litter. The TEs at the

23 high water line could be affected by seawater, whereas those within green turtle nests might be
24 impacted by the deposition of eggshells and unhatched eggs. The ecological risk values for each
25 TE in the coral sand sediments from various locations were below 40, and the potential
26 comprehensive ecological risk index was under 150, suggesting a minor ecological risk.

27 **Key words:** Trace elements; Coral sand sediments; Nesting ground; Risk assessment; Source
28 analysis; Xisha Islands

29 **1 Introduction**

30 Sea turtles possess a distinctive life history and traverse multiple ecosystems,
31 encompassing open oceans, coastal waters, and terrestrial nesting grounds (Lutz et al., 2003).
32 These unique life history strategies allow them to survive and reproduce in the intricate and
33 dynamic marine environment. Nevertheless, they also render sea turtles highly susceptible to
34 human activities (e.g. overharvesting, illegal trade, habitat loss, climate change, and marine
35 pollution) (Lin et al., 2021; Maurer et al., 2021; Dias et al., 2024). Owing to the continuous
36 decline in the global sea turtle population, all seven species of sea turtles worldwide have been
37 classified as globally endangered by the IUCN.

38 Currently, marine pollution has emerged as one of the significant threats to sea turtles. Sea
39 turtles, as long-lived vertebrates, can accumulate TEs in their tissues through their diet (Sakai
40 et al., 2000; Ng et al., 2018). Essential elements, such as Fe, Cu, Zn, and Se, are crucial for the
41 vital activities of organisms. Arsenic, cadmium (Cd), mercury (Hg), and lead (Pb) are not
42 known to have any beneficial functions in the human body and can exhibit toxicity at certain
43 levels (Tchounwou et al., 2012). Long-term exposure to toxic elements or high doses of
44 essential elements can adversely affect the health and reproduction of sea turtles (da Silva et

45 al., 2016; Villa et al., 2017; Morão et al., 2024). In particular, TEs can be transferred from
46 female sea turtles to their eggs (Lam et al., 2006; Jian et al., 2025). Nonessential elements, such
47 as Hg, in eggs can interfere with embryo development, resulting in reduced hatching rates
48 (Perrault et al., 2011). Moreover, high levels of TEs in the nesting environment can affect the
49 embryonic development and hatching success of reptiles (Marco et al., 2004; Simoniello et al.,
50 2011).

51 The concentration of TEs in marine sediments is influenced by multiple factors, including
52 the geochemical characteristics of source rocks, terrestrial input, atmospheric deposition, and
53 human activities (Liu et al., 2019; Fan et al., 2022; Hossain et al., 2023). Additionally, the bio-
54 transportation by organisms that move between different habitats also impacts the concentration
55 and distribution of TEs in beach sediments. For example, seabirds that hunt for food in the
56 ocean and regularly nest on land can transport marine-derived nutrients, metallic elements (such
57 as Hg), and organic pollutants to terrestrial ecosystems through fecal excretion and egg
58 deposition (Evenset et al., 2007; Duda et al., 2020). Sea turtles transport nutrients and energy
59 from the ocean to the land by nesting in beach habitats, provide crucial links between marine and
60 terrestrial ecosystems (Bouchard and Bjorndal, 2000; Raposo et al., 2025). Sea turtles exhibit a
61 high degree of fidelity to their habitats (Lutz et al., 2002). If the coastal waters where they forage
62 are contaminated by TEs, it may lead to the accumulation of high concentrations of TEs in their
63 bodies. These elements can also be transported to terrestrial nesting grounds by egg-laying,
64 potentially altering the concentration and composition of TEs in beach sediments. Therefore, it
65 is crucial to investigate and evaluate TEs in nesting grounds. In particular, conducting a source
66 analysis of TEs in sea turtle nesting areas is necessary, as it is essential for further understanding

67 the biogeochemical cycling of pollutants in these regions.

68 In China, approximately 90% of sea turtles are distributed in the South China Sea, mainly
69 green turtles (Mou et al., 2013). The Qilianyu Cluster in the Xisha Islands is the existing nesting
70 ground with the largest number of green turtle nests in China (Jia et al., 2019). The
71 concentrations of TEs in the sea waters of the South China Sea have shown an upward trend.
72 The levels of Pb and Ni surpass the national first-class seawater quality standards (Xu et al.,
73 2016; Wang et al., 2017). Research has shown that the levels of Se and Ni in the eggs of green
74 turtles from Hong Kong exceed toxic risk thresholds (Lam et al., 2006). Therefore, this study
75 investigated the concentrations and distribution of chromium (Cr), Ni, Cu, Zn, As, Cd, Pb, Hg,
76 Fe, and Se in coral sand sediments from three locations (high water line, vegetation line, green
77 turtle nests) within the green turtle nesting grounds of the Qilianyu Cluster. The sources of these
78 TEs in the coral sand sediments were explored, and the associated ecological risks were
79 evaluated. The objective of this study is to provide a theoretical foundation for understanding
80 the biogeochemical cycles of pollutants in sea turtle nesting habitats.

81 **2 Materials and methods**

82 **2.1 General situation of the study area**

83 The Qilianyu Cluster (16°55'-17°00' N, 112°12'-112°21' E) is located in the northeast of
84 the Xuande Archipelago in the South China Sea. It consists of 10 small islands, namely West
85 Sand, Zhaoshu Island, North Island, Middle Island, South Island, North Sand, Middle Sand,
86 South Sand, and others. Each small island is connected by reefs. Among them, North Island has
87 the largest area, approximately 0.4 square kilometers, and the number of green turtle nests
88 constitutes more than 60% (Jia et al., 2019).

89 **2.2 Sample collection**

90 Surface coral sand sediments (0-5 cm) were collected from the high water line and the
91 vegetation line at 32 stations across eight islands and sandbanks in the Qilianyu Cluster between
92 July and October 2020. The specific distribution is as follows: West Island (n = 4), Zhaoshu
93 Island (n = 6), North Island (n = 7), Middle Island (n = 4), South Island (n = 4), North Sand (n
94 = 2), Middle Sand (n = 3), and South Sand (n = 3) (Fig. 1). Approximately 500 g of wet samples
95 were stored in clean polyethylene bags, sealed, and refrigerated. In addition, 500 g of coral sand
96 sediments from the nests of green sea turtles were collected following the nesting period (the
97 majority of nests are distributed from the high water line to the vegetation line). A total of 54
98 coral sand sediments from the nests were gathered, with 36 samples from North Island, 10 from
99 South Island, 5 from North Sand, and 3 from South Sand.

100 **2.3 TE analysis**

101 In the laboratory, the coral sand sediments were freeze-dried, and impurities such as shells
102 and leaves were removed from them. Subsequently, they were ground using an agate mortar
103 and pestle and then sieved through a 100-mesh sieve. The freeze-dried coral sand sediment was
104 weighted at 0.25 ± 0.0005 g, and 8 mL of 65% HNO₃ was added to the digestion vessel (Jian
105 et al., 2021). The samples were then digested using a microwave digestion instrument (MARS6,
106 CEM Corp., USA). The digestion process was as follows: the temperature was raised to 120°C
107 within 0-15 min, then raised to 210°C in 15 min, and stayed at 210°C for 40 min. After the
108 digestion program was completed, when the temperature of the digestion vessel dropped below
109 80°C, the digestion solution was evaporated to approximately 1 mL at a temperature of 95°C,
110 and then diluted to 25 mL with ultrapure water for analysis.

111 The contents of Fe, Ni, Zn, Cr, Se, Cu, Pb, Cd in the digestion solution were determined
112 by an inductively coupled plasma–mass spectrometry (ICP-MS, X Series 2, Thermo Fisher
113 Scientific, USA). Arsenic and Hg contents were determined using atomic fluorescence
114 spectrometry (AFS-3000, Beijing Haiguang, China). The limits of detection of TEs in egg
115 contents were 0.005, 0.05, 0.002, 0.01, 0.01, 0.01, 0.001, 0.002, 0.02 and 0.001 $\mu\text{g}\cdot\text{g}^{-1}$ for Cr,
116 Fe, Ni, Cu, Zn, Se, Cd, Pb, As and Hg, respectively.

117 **2.4 Quality control and quality assurance**

118 Duplicate samples and procedural blank samples were added to every 12 samples to ensure
119 the accuracy and reliability of the analysis method. The experimental method for coral sand
120 sediments was verified using the standard reference material of offshore marine sediment
121 (GBW 07314). Trace elements were detected in the procedural blanks, but their contents were
122 much lower than those of most samples (<10%). The final concentration of the samples was
123 deducted by the blank value. In the parallel samples, the relative standard deviation (RSD) of
124 the target compounds was less than 15%. When comparing the measured average value of the
125 target elements in the reference material with that stated in the reference certificate, the RSD
126 was all <15%. The recovery of TEs in the blank spiked samples ranged from 90.4 to 108.9%.

127 **2.5 Data statistical analysis methods**

128 The normality of TE concentrations in coral sand sediments from three distinct locations
129 was examined using the Kolmogorov–Smirnov test. As the data did not follow a normal
130 distribution, the concentrations of TEs in the coral sand sediments are presented as the median,
131 upper and lower quartiles, and median absolute deviation. The non-parametric Mann-Whitney
132 test was utilized to assess the differences in TE concentrations among coral sand sediments

133 from various locations. Principal Component Analysis (PCA) was also applied to investigate
134 the distribution of TEs among sediments from the high water line, vegetation line, and green
135 turtle nests. Furthermore, the Spearman correlation coefficient and PCA were employed to
136 examine the relationships among TEs concentrations in coral sand sediments from the three
137 locations. The statistical significance of these correlations was evaluated using SPSS 25.0 and
138 OriginPro 2022 statistical software for Windows.

139 **2.6 Risk assessment methods for TEs**

140 The potential ecological risks index (RI) (Hakanson, 1980) were used to evaluate the
141 ecological risk of TEs in the coral sand sediments of the green turtle nesting ground in the Xisha
142 Islands. The specific calculation formulas are as follows:

$$143 \quad C_f^i = \frac{C_r^i}{C_n^i} \quad (1)$$

$$144 \quad E_r^i = T_r^i \times C_f^i \quad (2)$$

$$145 \quad RI = \sum_i^m E_r^i \quad (3)$$

146 Where C_f^i refers to the pollution index of pollutant i , C_r^i refers to the measured concentration
147 (mg/kg) of pollutant i , and C_n^i refers to the background value (mg/kg) of pollutant i (Zhang
148 and Du, 2011), as presented in Supplementary Table S1. E_r^i is the potential ecological risk
149 parameter of a single pollutant. T_r^i is the toxicity coefficient of pollutant i (Hakanson, 1980,
150 Xu et al., 2008), as shown in Supplementary Table S1. The assessment grades for the E_r^i and
151 RI value are listed in Supplementary Table S2.

152 **3 Results and Discussion**

153 **3.1 The content and distribution of TEs in coral sand sediments from the Xisha Islands**

154 The concentrations of TEs in coral sand sediments from the green turtles nesting ground

155 of the Xisha Islands were presented in Figure 2 and Supplementary Table S3. The median
156 concentration ($\mu\text{g/g}$) of TEs in the coral sand sediments were as follows: Fe (45.6) > Ni (6.03) >
157 Zn (2.63) > Cr (0.90) > Cu (0.41) > Se (0.28) > As (0.32) > Pb (0.09) > Cd (0.04) > Hg (0.01).
158 A comparison of TEs concentrations in sediments from sea turtle nesting grounds in worldwide
159 with our data obtained from Xisha Islands was shown in Supplementary Table S3. The
160 concentrations of most of TEs in the coral sand sediments from the beach of the Qilianyu cluster
161 are almost 10–100 times lower than those in the sediments from sea turtle nesting grounds in
162 Kazanlı (Çelik et al., 2006), Göksu Delta and Sugözü, northeast of the Mediterranean (except
163 for Zn, Candan et al., 2021), and Odisha, east coast of India (except for Cd, Veerasamy et al.,
164 2021). Furthermore, the concentrations of Ni and Cr in the sediments from the sea turtle nesting
165 ground in the Gulf of southern California, United States, are 140 times higher than those in the
166 coral sand sediments from the beach of the Qilianyu cluster (Villaescusa-Celaya et al., 2000).
167 Moreover, the concentrations of Cr, Ni, Cu, Zn, As, Cd, Pb, and Hg in the coral sand sediments
168 from the beach of the Qilianyu cluster were within the same range as those in the sediment of
169 Raine Island, Great Barrier Reef, Australia (Haynes and Johnson, 2000).

170 Overall, there were variations in the TEs content within the coral sand sediments at
171 different positions (Fig 2). The concentrations of Cu, Zn, Se, and Pb in the coral sand sediments
172 of green turtle nests were 2.77 to 5.33 times higher than those in the vegetation and at the high
173 water line ($P < 0.001$). Notably, the median proportions of Zn (17.5%), Cu (2.66%), Se (2.62%),
174 and Pb (1.3%) in the nest coral sand sediments were 11.7, 10.6 (compared with the vegetation
175 line) / 19.0 (compared with the high water line), 7.94, and 13.0 times greater than those in the
176 other two locations. Conversely, the concentrations of As, Fe and Ni in coral sand sediments

177 from the nests were significantly lower than those in the coral sand sediments from the high
178 water and vegetation line ($P < 0.001$). Especially, the concentration of Ni in the coral sand
179 sediments from the high water and vegetation line was 35.8 and 37.1 times higher than that in
180 the coral sand sediments from the nests. Furthermore, the levels of Cu, Zn, and Hg in the coral
181 sand sediments from the vegetation line were significantly higher than those in the high water
182 line ($P < 0.05$). Whereas, there was no significant difference in the concentrations of Ni, As,
183 Cd, Pb, and Se in the coral sand sediments between the vegetation and the high water line. The
184 results of the principal component analysis further indicated that the 10 TEs were divided into
185 two principal components (PC1 and PC2) (Fig 3). The highly representative elements, such as
186 Cu, Zn, Se, and Pb, align with the direction of PC1, accounting for 52.3% of the total variance.
187 The element cluster of Cr, As and Cd follows the direction of PC2, accounting for 18.9% of the
188 total variance. Overall, Cu, Zn, Se and Pb were closely related to the coral sand sediments from
189 the nests, while Ni, As and Fe were closely related to the coral sand sediments from the
190 vegetation and the high water line.

191 **3.2 The potential sources of TEs in coral sand sediments at three different locations**

192 To further explore the sources of TEs in coral sand sediments at different beach locations,
193 PCA was conducted on TEs in coral sand sediments from three distinct positions (Fig 4). For
194 the vegetation line coral sand sediments, TEs were categorized into two principal components.
195 PC1 accounted for 45.7% of the variance, exhibiting high loadings (>0.5) for Pb, Cd, Cu, Hg,
196 Fe, and As. PC2 explained 23.4% of the variance, with relatively high loading (>0.5) for Cu.
197 Correlation analysis also showed significant positive correlations among elements in the same
198 component (e.g. among Cu, As, and Pb, in the pairs Pb-Cd and Fe-As) (Table 1). For the high

199 water line coral sand sediments, PC1 accounted for 59.0% of the variance, dominated by Cd,
200 Cu, Hg and Pb (loading > 0.5), PC2 explained 19.2% of the variance, with representative Cu,
201 Zn and As showing higher loadings (>0.5) (Fig 4). Elements in the same component displayed
202 significant positive correlations (Tab. 1). For nest coral sand sediments, TEs were divided into
203 two main components. PC1 explained 37.1% of variance, with high loadings for As, Ni, Cu,
204 Cd, Cr and Fe. PC2 accounted for 19.4% of the variance, exhibited high loadings for Zn, Se
205 and Pb. Correlation analysis further revealed positive correlations between the pairs Se-Pb, Cu-
206 Se and Zn-Pb.

207 The significant relationships among TEs showed that they have similar geochemical
208 behaviors or common sources (Costa et al., 2023). Coral skeletons can record anthropogenic
209 inputs of marine TEs (Al-Rousan et al., 2007; Song et al., 2014; Xie et al., 2023). Metal cation
210 (e.g. Zn^{2+} , Cu^{2+} , Pb^{2+} and Zn^{2+}) in seawater may substitute for Ca^{2+} in the $CaCO_3$ lattice, thereby
211 incorporating into the coral skeleton (Saha et al., 2016). The metal cation to Ca ratios in the
212 coral skeletons correlated linearly with their ratios in seawater (Ram et al., 2025). Zinc, Pb, and
213 Hg concentrations in seawater at several sampling sites within the Qilianyuan cluster exceeded
214 the first-grade limit values of the GB 3097-1997 national standard in China, and Zn, Pb, and
215 Cu levels surpassed background values in the South China Sea (Jian et al., 2022). Antifouling
216 paints used for ships are enriched with heavy metals (e.g. Cu and Zn) (Wang et al., 2008; Egardt
217 et al., 2018). Therefore, the TEs (Pb, Cd, Cu, Hg) in PC1 of the coral sand sediments at the high
218 water and the vegetation line may be associated with the pollution emissions from ships during
219 activities such as maritime transportation and fishery fishing.

220 Compared with the high water line, the coral sand sediments at the vegetation line

221 exhibited significantly higher concentrations of Zn, Cu, and Hg. The decomposition of litterfall
222 plays a crucial role in element cycling within terrestrial ecosystems (Peng et al., 2023). The
223 forests soil concentrations of metals (e.g., Zn and Cu) are controlled by litter return (Zeng et
224 al., 2023). Additionally, metal cations in soil can be immobilized by organic matter (Lasota et
225 al., 2020; Wang et al., 2022). Furthermore, atmospheric Hg is largely assimilated by vegetation
226 and subsequently transferred to the soil by litter fall, thereby increasing soil Hg concentrations
227 (Wang et al., 2016; Yuan et al., 2022).

228 As previously described, the concentrations of Cu, Zn, Se and Pb in the coral sand
229 sediments from green turtle nests were higher than those at the vegetation and high water line.
230 Research has indicated that TEs can be transferred from female turtles to their eggs. Specifically,
231 essential elements such as Cu and Zn exhibiting a higher maternal transfer coefficient compared
232 to non-essential elements like Cd and Hg (Jian et al., 2025). It has been reported that Pb is
233 predominantly distributed in sea turtle eggshells rather than in the egg contents (du Preez et al.,
234 2018). The contents and proportions of Zn, Cu, Se in green turtle eggshells are higher than those
235 in coral sand sediments from Xisha Islands (Jian et al., 2021). Moreover, Jian et al. (2021) also
236 discovered significant correlations between the contents of Zn, Se and Pb in eggshells and coral
237 sand sediments. Consequently, sea turtles can act as biological vectors, transporting TEs (e.g.,
238 Zn, Se, and Pb) from oceanic habitats to terrestrial nesting sites. The deposition of hatched
239 eggshells and unhatched eggs may have an impact on the content and composition of TEs in
240 sandy sediments. This process might influence the biogeochemical cycles of TEs in remote
241 island sandy beach ecosystems, thus warranting further in-depth investigation.

242 Furthermore, the Ni content in the coral sand sediments from the nests was significantly

243 lower than that from the vegetation and the high water line. The Ni content in the coral sand
244 sediments from the vegetation and high water line exhibited insignificant correlations with most
245 elements, suggesting a distinct source or unique geochemical behavior of Ni. Research suggests
246 that particulate matter containing Ni, emitted from the combustion of fossil fuels, industrial
247 soot, infrastructure construction, and vehicle exhaust, may deposit onto topsoil (Flem et al.,
248 2022; Wang et al., 2023). Compared to the coral sand sediments within nests, the surface layer
249 of coral sand sediments at the high water and vegetation line may reflect a more recent
250 deposition of atmospheric particles.

251 **3.3 Potential ecological risk assessment**

252 The concentrations of Cr, Cu, Zn, As, Cd and Pb in all coral sand sediments were below
253 the first-grade limit values of the GB (8,668-2002 national standard in China (SEPA, 2002)
254 (Supplementary Table S3). The ecological risk parameters and potential ecological risk indices
255 for TEs in the coral sand sediments at nesting sites were calculated using the formulae from the
256 potential ecological risk index method, with the results presented in Table 2. It indicated that
257 the highest ecological risk parameters are those of Hg in the vegetation line (1.45) and green
258 turtle nest (1.41), as well as Ni in the high water line (1.34). Although there were differences
259 in the ecological risk values of TEs in coral sand sediments from various locations (vegetation
260 line, high water line, nest), all the RI (risk index) values were less than 150, indicating a slight
261 ecological risk. Overall, the ecological risk posed by TEs in the coral sand sediments from the
262 nesting grounds of green turtles in the Qilianyu cluster was relatively slight. Nonetheless, it
263 remains necessary to intensify monitoring efforts and continuously observe the cumulative
264 effects of heavy metals, as well as changes in the levels of ecological risk.

265 **4 Conclusion**

266 This research investigated the concentrations and ecological risks of 10 TEs in coral sand
267 sediments from green turtle nests, the vegetation line, and the high water line at the green turtle
268 nesting sites on Xisha Island in the South China Sea. The content and composition of TEs in
269 the coral sand sediments varied among the three locations. The findings revealed that the levels
270 of Fe, As, and Ni in the coral sand sediments at the vegetation and high water line were
271 significantly higher than those in the green turtle nests. In contrast, the concentrations of Cu,
272 Zn, Se, and Pb in the coral sand sediments at the nesting sites were considerably higher than
273 those at the vegetation and high water line. The content of TEs at the vegetation line may be
274 influenced by atmospheric deposition and plant litter. The TEs at the high water line may be
275 affected by dissolved metal ions in seawater, whereas those in the green turtle nests could be
276 influenced by the deposition of TEs from turtle eggshells and unfertilized eggs. This study
277 suggests that green turtles may transfer TEs, including both bio-essential and toxic substances,
278 from coastal sea areas to intertidal nesting grounds through egg-laying. Green turtles nesting in
279 the Xisha Islands might forage in economically developed coastal areas, potentially introducing
280 pollutants to these remote islands. Future research should focus on the nutrients and pollutants
281 that sea turtles transport to nesting beaches from distant foraging grounds, as well as the impact
282 these substances have on the beach ecosystem.

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284 Huang: Methodology, Writing- original draft; Jinfang Xiong: Investigation, Methodology;
285 Chudan Wang: Investigation, Methodology; Li Jian: Conceptualization, Investigation, Writing
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Table 1 Correlation analysis of the concentrations of various trace elements in three location coral sands. The symbol ‘**’ indicates a significant correlation at the 0.01 significance level (two-tailed), while the symbol ‘*’ indicates a significant correlation at the 0.05 significance level (two-tailed).

Vegetation line	Cr	Ni	Cu	Zn	As	Cd	Pb	Hg	Fe	Se
Cr	1.000									
Ni	-0.456**	1.000								
Cu	0.289	0.081	1.000							
Zn	0.311	-0.070	-0.045	1.000						
As	0.290	0.126	0.337*	-0.140	1.000					
Cd	0.288	-0.114	0.146	-0.013	0.237	1.000				
Pb	0.078	0.265	0.373*	0.023	0.633**	0.594**	1.000			
Hg	-0.053	0.280	0.312	0.053	0.133	0.404*	0.438**	1.000		
Fe	0.027	0.005	0.196	0.038	0.352*	0.274	0.564**	0.364*	1.000	
Se	0.093	0.337*	0.002	-0.134	0.396*	0.209	0.340*	0.385*	0.190	1.000
High water line	Cr	Ni	Cu	Zn	As	Cd	Pb	Hg	Fe	Se
Cr	1.000									
Ni	-0.116	1.000								
Cu	0.381*	-0.100	1.000							
Zn	0.102	0.271	0.565**	1.000						
As	0.227	0.256	0.434**	0.169	1.000					
Cd	0.422**	-0.074	0.385*	0.346*	0.041	1.000				
Pb	0.469**	0.292	0.522**	0.417**	0.433**	0.584**	1.000			
Hg	0.228	0.262	0.387*	0.446**	0.321*	0.502**	0.512**	1.000		
Fe	0.018	-0.173	0.354*	0.320*	0.364*	-0.047	0.186	0.066	1.000	
Se	-0.098	0.229	0.077	-0.034	0.288	-0.416**	0.017	0.079	0.240	1.000
Nest	Cr	Ni	Cu	Zn	As	Cd	Pb	Hg	Fe	Se
Cr	1.000									
Ni	0.583**	1.000								
Cu	0.191	0.404**	1.000							
Zn	-0.086	0.084	0.036	1.000						
As	0.253	0.399**	0.424**	-0.153	1.000					
Cd	0.161	0.398**	0.226	0.073	0.454**	1.000				
Pb	0.091	0.169	0.108	0.197	-0.174	-0.137	1.000			
Hg	-0.147	0.736*	0.177	0.088	0.118	-0.383*	0.702	1.000		
Fe	0.063	0.340*	0.260	0.033	0.268*	0.060	0.293*	0.088	1.000	
Se	0.287*	0.085	0.334**	-0.080	0.096	0.197	0.296*	0.059	-0.177	1.000

Table 2 Ecological risk assessment of trace elements in coral sands.

Trace elements		E_r^i								RI	Ecological risk level
		Cr	Ni	Cu	Zn	As	Cd	Pb	Hg		
Vegetation line	Minimum value	0.01	1.06	0.00	0.00	0.18	0.43	0.00	0.34	2.75	Slight ecological risk
	Maximum value	0.05	1.76	0.25	0.04	0.81	15.4	0.05	3.29	19.5	
	Median value	0.02	1.39	0.02	0.01	0.27	1.12	0.00	1.45	4.83	
High water line	Minimum value	0.01	0.98	0.00	0.00	0.18	0.18	0.00	0.38	2.34	Slight ecological risk
	Maximum value	0.04	1.63	0.07	0.03	0.46	9.79	0.01	1.91	13.2	
	Median value	0.02	1.34	0.01	0.01	0.25	1.06	0.00	1.09	4.25	
Nest	Minimum value	0.01	0.01	0.03	0.01	0.04	0.46	0.00	1.21	0.71	Slight ecological risk
	Maximum value	0.12	0.14	0.41	0.18	0.52	7.80	0.11	2.30	8.16	
	Median value	0.02	0.04	0.06	0.02	0.09	1.14	0.02	1.41	1.53	

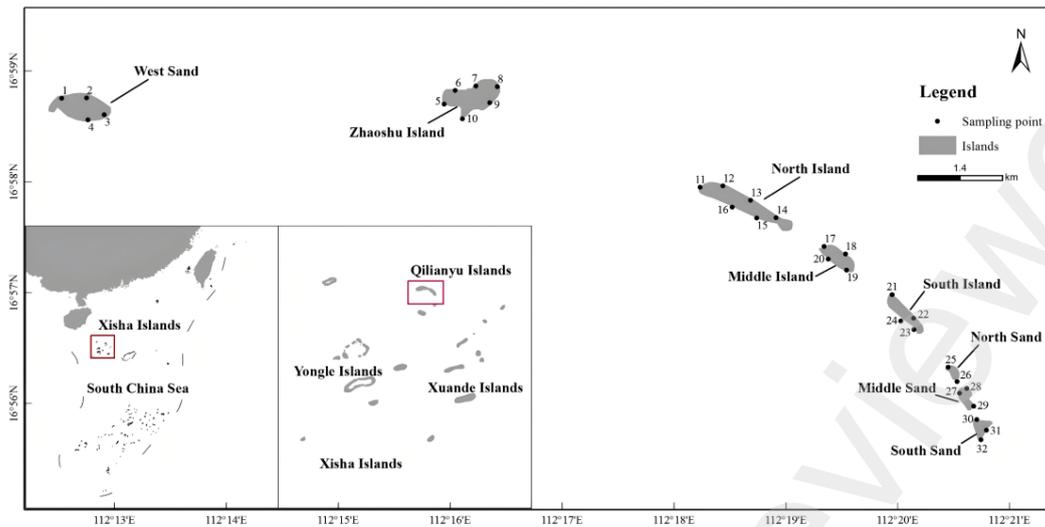


Figure. 1 Distribution map of sampling points. A total of 32 surface coral sand samples were collected from the high water line and vegetation line, while 52 nest coral sand samples were obtained from North Island, South Island, North Sand, and South Sand.

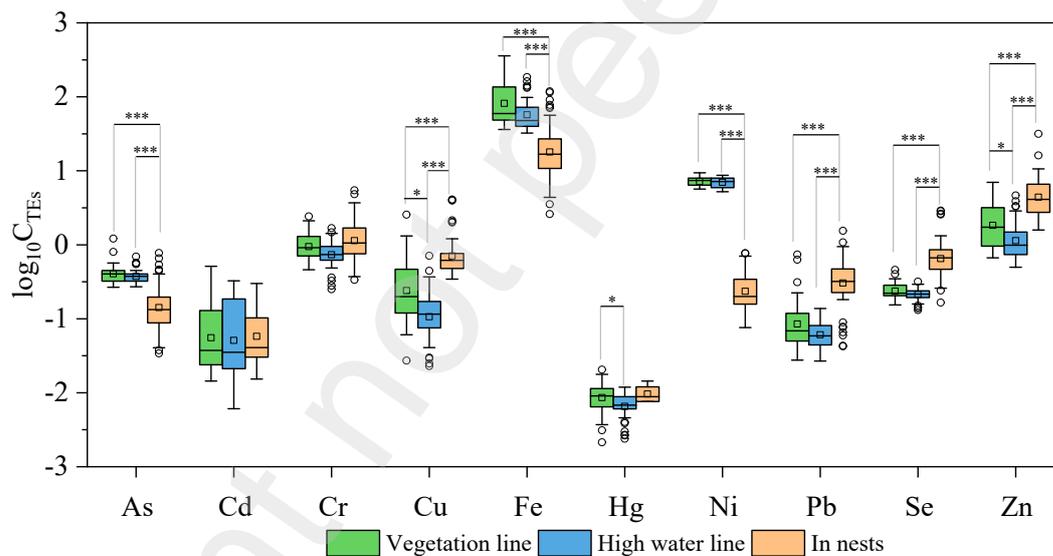


Figure. 2 The \log_{10} values of trace element concentrations ($\mu\text{g}\cdot\text{g}^{-1}$) in coral sands at various positions on the beach of the green turtle nesting ground in the Xisha Islands. The boundary of the box closest to zero indicates the 25th percentile, a black line within the box marks the median and the boundary of the box farthest from zero indicates the 75th percentile, small squares within the box marks the mean values. The small circle represents a value that is out of range. Samples from different locations are marked by color; Vegetation = green; High

water line = blue; Green turtle nests = Orange. The symbols ‘*’ indicate the significance of variations in trace element concentrations among coral sands at the vegetation line, high water line, and within green turtle nests (*, $p < 0.05$; ***, $p < 0.001$).

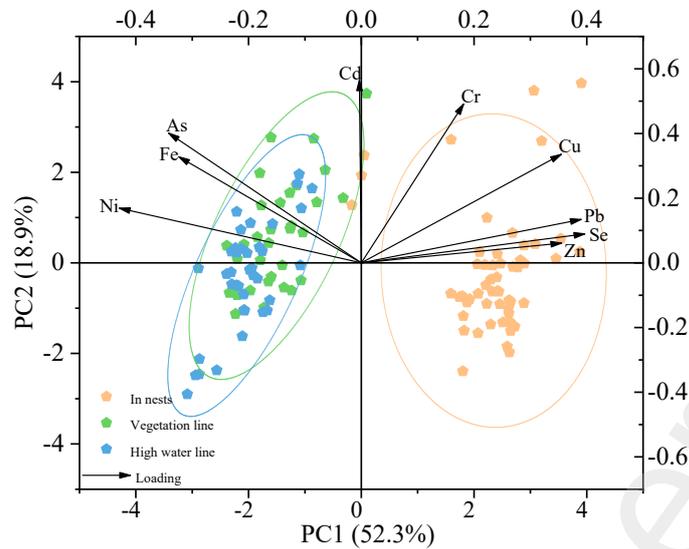


Fig. 3 Biplot of score and loading from Principal Component Analysis. Samples from different locations are marked by color; Vegetation = green; High water line = blue; Green turtle nests = Orange. PC1 explains most (52.3 %) of the total variation, PC2 explains 18.9% of the total variation.

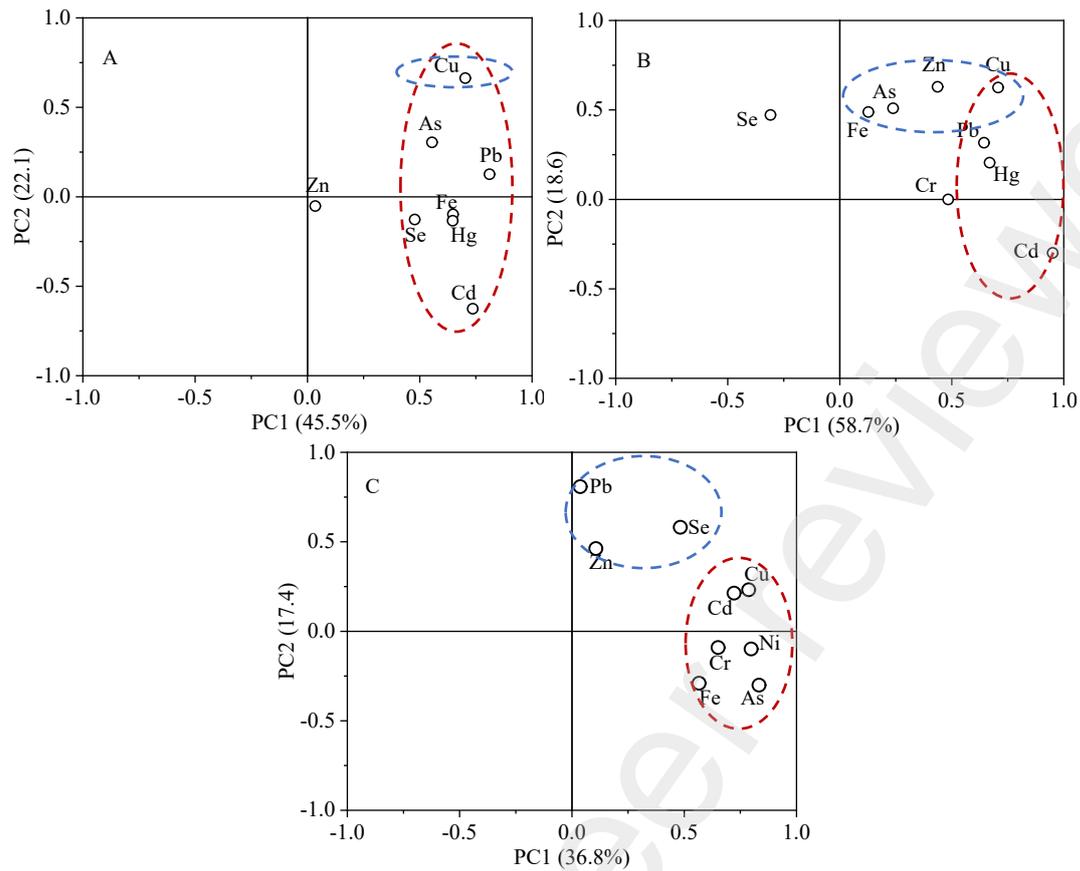


Fig. 4 Principal component distribution plot of trace elements in three location coral sands. The symbols of A, B, and C represent the vegetation line, high water line, and nesting sites, respectively. The trace elements within the red ellipse indicate the high loading elements of the first principal component (PC1), whereas those within the blue ellipse denote the high loading elements of the second principal component (PC2).