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Spatial and seasonal distributions of ten species of benthic macrofauna and twelve water environmental factors in a subtidal zone near the Daya Bay nuclear power plant

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In this study, we analyzed the spatial and seasonal distributions of ten species of benthic macrofauna and 12 water environmental parameters at thirty-six sampling stations in the subtidal zone near the Daya Bay Nuclear Power Plant. The results showed that there were four types of distribution characteristics for 10 species of macrobenthic animals and 12 water environmental factors near the Daya Bay nuclear power plant: (1) three species of benthic macrofauna, namely *Apionsoma (Apionsoma) trichocephalus*, *Amphioplus (Lymanella) laevis*, and *P. bidentata*, and six water environmental parameters, including water depth, salinity, dissolved oxygen, suspended solids, chromium, and lead increased from inside the bay to outside the bay. (2) Three species of benthic macrofauna, *P. cristata*, *T. lata*, and *T. scabra*, and four water environmental parameters, including oils, arsenic, total phosphorus, and silicate, decreased from inside to outside the bay. (3) Two species of benthic macrofauna, *A. dibranchis,* and *P. undulatus* and one water environmental parameter, pH, were higher in the central bay than inside and outside the bay. (4) One species of benthic macrofauna, *Sigambra hanaokai*, and one water environmental parameter, total nitrogen, were lower in the central bay than inside and outside the bay. Correlation and BIO-ENV analyses confirmed that water depth was the main environmental factor affecting the ten species of benthic macrofauna. Understanding the distributions of the dominant benthic macrofauna could help protect nuclear cold source systems from benthic macrofaunal blockage and explore marine ecosystem connectivity.

KEYWORDS

benthic macrofauna, environmental factor, nuclear power plant, subtidal zone, Daya Bay

1 Introduction

Daya Bay is located in the eastern Guangdong Province between Red (Honghai) Bay and Mirs Bay, with a total area of 650 km^2. The Daya Bay coast contour twists and turns, with smaller bays set into the larger bay. The main bays inside Daya Bay include Chimney (Yancong) Bay, Xunliao Port, Fanhe Port, Aotou Port, and Xiaogui Bay. Daya Bay Nuclear Power Base encompasses two nuclear power stations: Daya Bay and Ling'ao.

Construction of the Daya Bay Nuclear Power Plant began in 1987 and was put into commercial operation in 1994. Subsequently, the Lingao Nuclear Power Plant was built near the Daya Bay Nuclear Power Plant, and the two nuclear power plants jointly formed a nuclear power base.

Benthic macrofauna and water environmental factors in the subtidal zone of Daya Bay were surveyed before the construction of the Daya Bay Nuclear Power Plant and have been continuously monitored since 1986. Over the past 35 years, the most dominant species have remained the same. These include *T. scabra*, *P. undulatus*, *L. brevirostris*, and *Amphioplus (Lymanella) laevis* (Jiang et al., 1990a; Jiang et al., 1990b; Du et al., 2008a; Du et al., 2008b; Du et al., 2009; Du et al., 2011; Yuan et al., 2017; Rao et al., 2020a). *Terebellides stroemii*, *Paucibranchia belli*, and *Glycera alba* were the dominant species in macrozoobenthic communities in the cage culture area (Huang et al., 2005), and *Paraprionospio cristata* was the dominant macrozoobenthic community species in the mariculture area (Rao et al., 2021). *Timoclea scabra*, *P. undulatus*, *L. brevirostris*, and *A. (Lymanella) laevis* were the dominant species of macrozoobenthic communities in the sea area around the Daya Bay Nuclear Power Station (Zhang et al., 2007) and from benthic trawling in Daya Bay (Zhang et al., 2017).

Most previous studies have divided benthic macrofauna into several communities according to the dominant species in different regions. The benthic macrofauna from 50 sampling stations in Daya Bay in 1988 and 1989 were divided into six communities (Jiang et al., 1990b). According to the survey data from four voyages in 2004, three communities of benthic macrofauna were identified (Du et al., 2009).

Some studies have focused on the effects of warm drainage in nuclear power plants on benthic macrofauna (Zhang et al., 2007), and the effects of sewage discharge and mariculture on benthic macrofauna (Huang et al., 2005; Rao et al., 2021), while others have focused on the ecological environmental changes in Daya Bay (Wang et al., 2004; Wang et al., 2008).

Although many benthic macrofaunal communities have been monitored before and after the construction of the Daya Bay nuclear power plant, little research has been conducted on the spatial and seasonal distribution of common benthic macrofauna and their relationships with the water environment. The main goals of this study were to (1) analyze the spatial and temporal distribution characteristics of common benthic macrofauna in the subtidal zone near the Daya Bay Nuclear Power Plant, (2) analyze the spatial and temporal distribution characteristics of some water environmental factors in the subtidal zone near the Daya Bay Nuclear Power Plant, (3) analyze the relationships between common benthic macrofauna and water environmental factors in the subtidal zone near the Daya Bay Nuclear Power Plant. To achieve these goals, we simultaneously sampled benthic macrofauna and measured environmental parameters in the subtidal zone near the Daya Bay Nuclear Power Plant.

2 Materials and methods

2.1 Sampling and treatment of benthic macrofauna

Sixty-five grid-based sampling stations were established and divided into three sectors (inner, middle, and outer) according to their relative geographic locations and environmental conditions (Rao et al., 2020a; Rao et al., 2021). Sampling surveys were conducted in the autumn (November 2017), winter (January 2018), spring (April 2018), and summer (July 2018). However, in this study, we only selected data from 36 sampling stations, namely, 12 sampling stations in the inner bay, 12 sampling stations in the middle of the bay, and 12 sampling stations outside the bay (Figure 1).

Benthic macrofauna were collected using a 0.05 m^2 van Veen grab at each station. The sediments were washed through a 0.5 mm mesh sieve, and the residues were transferred to sample containers with 5% formalin buffer *in situ* for further identification. In the laboratory, benthic macrofauna were identified to the lowest possible taxon and enumerated under a dissecting microscope. They were then weighed using an electronic balance (0.1 mg, FA1204) after blotting surface water off with clean absorbing paper (Rao et al., 2020a; Rao et al., 2021).

2.2 Selection of 10 macrozoobenthic species

There are many benthic animals in the Daya Bay subtidal zone (Jiang et al., 1990a; Jiang et al. 1990b; Du et al., 2008a; Du et al., 2008b; Du et al., 2009; Du et al., 2011; Rao et al., 2020a; Rao et al., 2021). In this study, ten species of benthic animals were considered based on the following three points: (1) according to the relative importance index (IRI) value (Zhang et al., 2017), based on four surveys in 2017 and 2018 that found *Aglaophamus dibranchis, P. undulatus*, *L. brevirostris*, *A. laevis* and *P. cristata* to be the top five species for average IRI values, and *Sigambra*

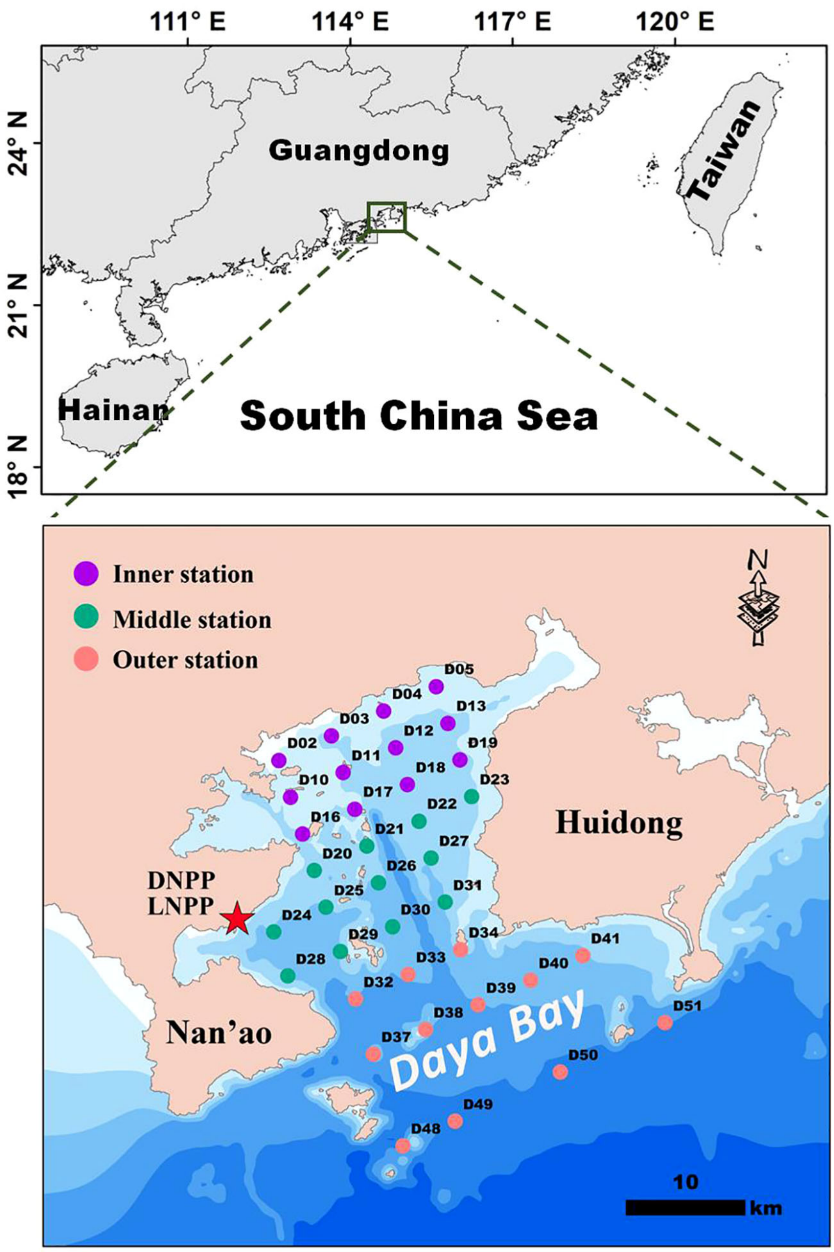

FIGURE 1
Schematic diagram of benthic macrofaunal sampling stations in the Daya Bay Subtidal zone. Stations are divided into three sectors: inner (purple circle, n = 12), middle (green circle, n = 12) and outer (orange circle, n = 12). DNPP, Daya Bay Nuclear Power Plant; LNPP, Ling'ao Nuclear Power Plant.

hanaokai and *T. lata* to be the first seven and the first 20, respectively; (2) potential disaster-causing animals in the nuclear power coldsource system, including *A. dibranchis*, *P. cristata*, *P. undulatus*, *L. brevirostris*, *Apionsoma (Apionsoma) trichocephalus*, and *P. bidentata* (Cai et al., 2022b); (3) historically recorded dominant species, including *T. scabra*, *P. undulatus*, *L. brevirostris*, and *A. laevis* (Jiang et al., 1990a; Jiang et al., 1990b; Du et al., 2008a; Du et al., 2008b; Du et al., 2009; Du et al., 2011; Yuan et al., 2017; Rao et al., 2020a; Rao et al., 2021).

2.3 Determination of water environmental factors

Water depth was determined using portable bathymetry (SPEEDTECH SM-5A, USA). Salinity and dissolved oxygen (DO) were measured using a portable water quality analyzer (WTW Multi 3430, Germany). Oils were extracted with n-hexane and measured using UV spectrophotometry procedures (Ehrhardt and Burns, 1993). The metal concentrations of Cr (chromium), As (arsenic), and Pb (lead) were determined using inductively coupled plasma mass spectrometry (Agilent 7700x, Agilent Technologies, USA). Quality assurance was performed using the procedure described by Wang et al. (2019). The samples for analyzing total nitrogen (TN) and total phosphorus (TP) were measured using the method of Varol and Şen (2012). Total nitrogen was measured by converting all nitrogen forms to nitrate *via* alkaline persulfate oxidation and subsequent analysis of nitrate was performed using spectrophotometric procedures. The total phosphorus was determined spectrophotometrically using the ascorbic acid method after persulfate digestion. The silicate content was measured using standard silicon molybdenum blue spectrophotometric procedures. Samples were filtered with 0.45 µm polycarbonate filters and analyzed later using the method of Dai et al. (2008). The samples for analyzing suspended solids (SS) were collected using 0.45 µm polycarbonate filters and were subsequently measured gravimetrically (Wang et al., 2015).

2.4 Statistical analysis

Variance analysis (ANOVA) and correlation analyses were performed using SPSS v25 software. ANOVA was used to determine whether there were significant differences in the ten species of benthic macrofauna and the 12 water environmental parameters in different seasons and regions. Correlation analysis was used to determine whether the densities and biomasses of the common benthic macrofauna were significantly correlated with the 12 water environment parameters. BIO-ENV analyses were performed using PRIMER v7 (Anderson et al., 2008). Similarities in benthic macrofauna between each pair of sites were determined using the Bray-Curtis similarity measure based on the fourth root transformed abundance data. Nonmetric multidimensional scaling (NMDS) ordination based on Bray-Curtis similarity was performed to explore the seasonal and site variation of the macrofaunal community. BIO-ENV analyses were used to examine the major environmental factors affecting the ten species of benthic macrofauna.

3 Results

3.1 The spatial and seasonal distributions of ten species of benthic macrofauna

From the spatial distributions of ten species of benthic macrofauna in the subtidal zone near the Daya Bay Nuclear Power Plant, the densities of *A. trichocephalus*, *A. laevis*, and *P. bidentata* increased from inside the bay to outside the bay. The densities of *P. cristata*, *T. lata*, and *T. scabra* decreased from inside to outside the bay. The densities of *A. dibranchis,* and *P. undulatus* were higher in the middle bay than in the inner bay and outside the bay. The densities of *S. hanaokai* and *L. brevirostris* were lower in the middle bay than in the inner bay and outside the bay (Figure 2). In addition, the density distribution of *L. brevirostris* was inconsistent with the biomass distribution, while the density and biomass distributions of the other nine macrobenthic species were consistent (Figure 3).

Two-way ANOVA results indicated that the densities of *A. trichocephalus*, *A. laevis*, *P. bidentata*, *P. cristata*, *A. dibranchis*, and *P. undulatus* showed significant regional variation (Table 1). The biomasses of *A. trichocephalus*, *A. laevis*, *P. cristata*, *P. undulatus*, and *L. brevirostris* showed significant regional variation (Table 2). The densities of *A. laevis*, *P. cristata*, *A. dibranchis*, *P. undulatus*, and *T. lata* showed significant seasonal variation (Table 1). The biomass of *A. laevis*, *A. dibranchis*, *P. undulatus*, and *T. lata* showed significant seasonal variation (Table 2).

3.2 The spatial and seasonal distributions of twelve environmental parameters

From the spatial distributions of 12 water environmental parameters in the subtidal zone near the Daya Bay Nuclear Power Plant, water depth, salinity, DO, suspended matter, Cr, and Pb increased from inside the bay to outside the bay. Oils, TP, and silicate decreased from the inside to the outside of the bay. The pH was higher in the central bay than in the inner bay and outside the bay. The TN was lower in the central bay than in the inner bay and outside the bay (Figure 4).

A two-way ANOVA indicated that water depth, salinity, Cr, silicate, and pH showed significant regional variation. Salinity, DO, suspended matter, Cr, Pb, silicate, oils, TP, pH, and TN showed significant seasonal variation (Table 3).

3.3 The relationship between ten species of benthic macrofauna and twelve environmental parameters

In terms of water environmental parameters, water depth was significantly correlated with the densities of six species of benthic macrofauna. There was a significant positive correlation between the densities of *A. trichocephalus*, *A. laevis*, *P. bidentata*, and *A. dibranchis* and water depth. There was a significant negative correlation between the densities of *P. cristata* and *T. lata* and water depth. Regarding benthic macrofaunal density, *A. laevis* and *T. lata* were significantly correlated with the five water environmental parameters. There was a significant positive correlation between the density of *A. laevis* and water depth, salinity, and Pb. There was a significant negative correlation between the densities of *A. laevis*, silicate, and TP. There was a

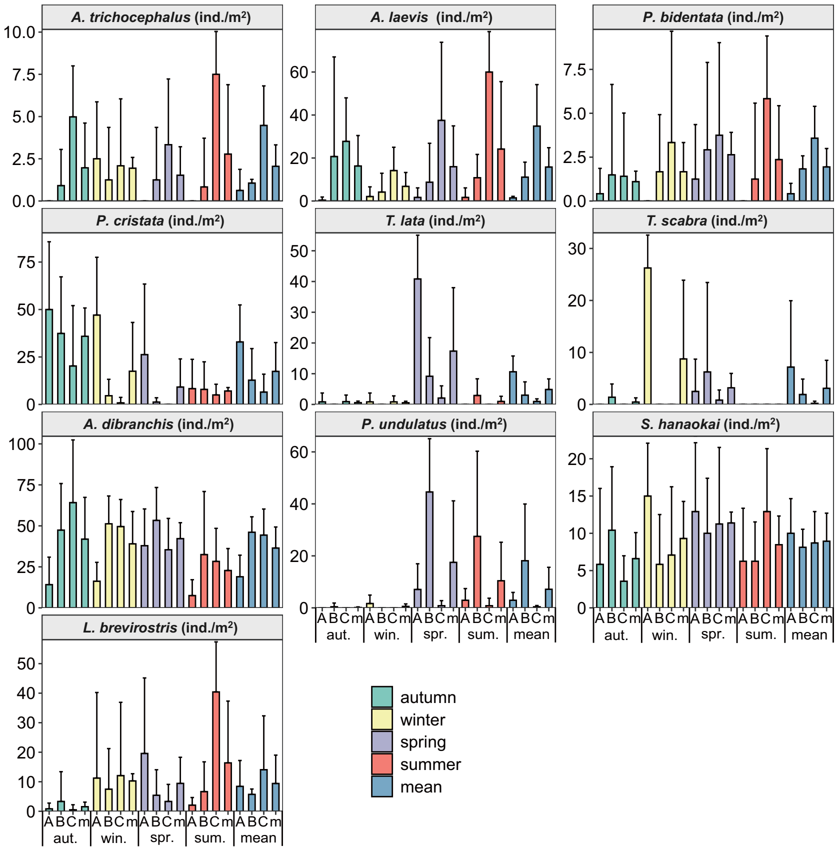

FIGURE 2
The density spatial and temporal distributions of ten species benthic macrofauna in subtidal zone near the Daya Bay Nuclear Power Plant. (A: represent the inner bay; B: represent the middle bay; C: represent the outside bay; m: represent the mean value).

significant positive correlation between the densities of *T. lata*, silicate, and TP. There was a significant negative correlation between the density of *T. lata* and water depth, salinity, and pH (Table 4).

In terms of environmental parameters, water depth was significantly correlated with the biomass of six species of benthic macrofauna. There was a significant positive correlation between the biomass of *A. trichocephalus*, *A. laevis*, and *P. bidentata* and water depth. There was a significant negative correlation between the biomass of *P. cristata*, *T. lata*, *S. hanaokai* and water depth. Among the benthic macrofaunal biomass, *A. laevis* and *T. lata* were significantly correlated with the five water environment parameters. There was a significant positive correlation between the biomass of *A. laevis* and water depth, salinity, As, and Pb. A significant negative correlation was observed between the biomass of *A. laevis* and silicate. There was a significant positive correlation between the biomass of *T. lata* and silicate and TP. There was a significant negative correlation between the biomass of *T. lata* and water depth, salinity, and pH (Table 5).

The BIO-ENV analysis showed that water depth was the first factor affecting 10 macrobenthic species, with a correlation coefficient of 0.191. The second factor affecting 10 macrobenthic species was salinity, with a correlation coefficient of water depth + salinity of 0.215.

4 Discussion

4.1 Effect of environmental factors on three species of polychaetes

This study involved three polychaetes: *P. cristata*, *A. dibranchis*, and *S. hanaokai*. Three species of polychaetes were the dominant species of macrozoobenthic communities in Daya Bay (Jiang et al., 1990a; Jiang et al., 1990b; Du et al., 2008a; Du et al., 2008b; Du et al., 2009; Du et al., 2011; Yuan et al., 2017; Cai et al., 2022b), and they were also the dominant species along the coast of China (Cai and Zheng, 1994; Huang et al., 2012; Chen et al., 2020; Rao et al., 2020b). *Sigambra hanaokai* is the

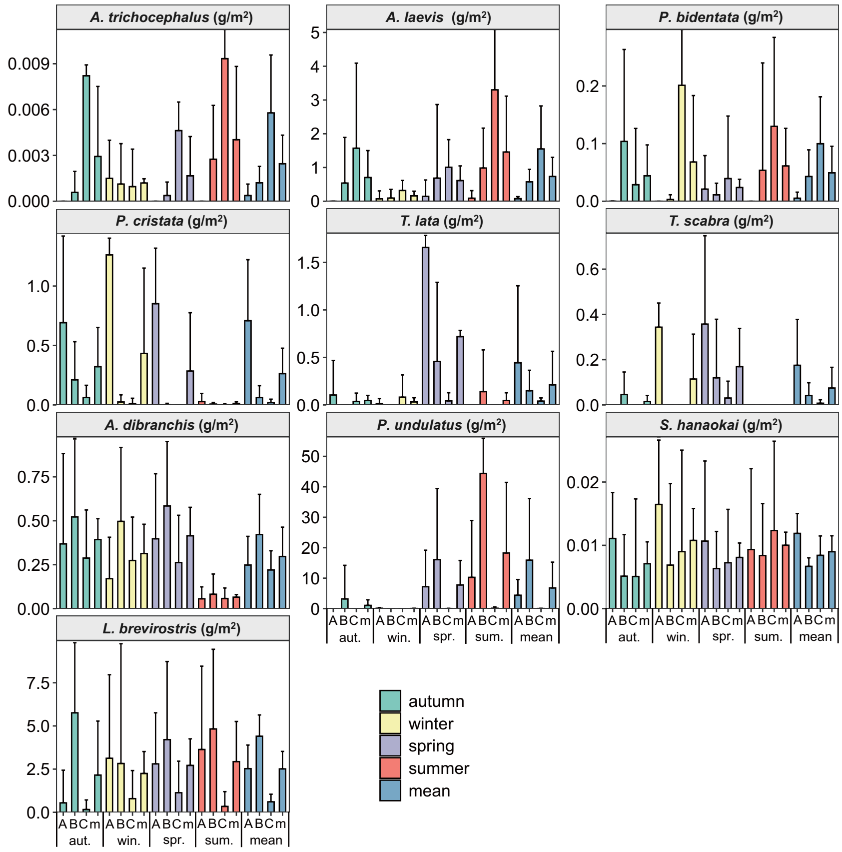

FIGURE 3
The biomass spatial and temporal distributions of ten species benthic macrofauna in subtidal zone near the Daya Bay Nuclear Power Plant. (A: represent the inner bay; B: represent the middle bay; C: represent the outside bay; m: represent the mean value).

TABLE 1 The F and P values between seasons and regions for density of ten benthic macrofauna species in subtidal zone near the Daya Bay Nuclear Power Plant.

Density	Region		Season		Region × Season	
	F	*P*	*F*	*P*	*F*	*P*
Apionsoma (Apionsoma) trichocephalus	12.874	<0.001[c]	1.324	0.269	1.795	0.105
Amphioplus (Lymanella) laevis	26.615	0.045[a]	3.406	0.020[a]	3.048	0.008[b]
P. bidentata	4.863	0.009[b]	0.696	0.556	0.667	0.677
P. cristata	11.699	<0.001[c]	7.935	<0.001[c]	1.767	0.111
T. lata	2.550	0.082	5.121	0.002[b]	2.668	0.018[a]
T. scabra	1.834	0.164	1.679	0.175	2.136	0.053
A. dibranchis,	16.334	<0.001[c]	4.536	0.005[b]	2.276	0.045[a]
P. undulatus	7.895	0.001[b]	4.522	0.005[b]	2.961	0.010[a]
Sigambra hanaokai	0.393	0.676	1.256	0.292	1.780	0.108
L. brevirostris	0.865	0.423	1.324	0.269	1.795	0.105

a: significant at the 0.05 level; [b]: significant at the 0.01 level; [c]: significant at the 0.001 level.

TABLE 2 The F and P values between seasons and regions for biomass of ten benthic macrofauna species in subtidal zone near the Daya Bay Nuclear Power Plant.

Density	Season		Region		Season × Region	
	F	*P*	*F*	*P*	*F*	*P*
A. trichocephalus	9.085	<0.001[c]	1.316	0.272	1.498	0.184
A. laevis	13.126	<0.001[c]	5.111	0.002[b]	2.644	0.019[a]
P. bidentata	1.867	0.159	0.241	0.868	0.795	0.576
P. cristata	15.105	<0.001[c]	2.418	0.069	2.264	0.041[a]
T. lata	2.565	0.081	5.049	0.002[b]	2.644	0.019[a]
T. scabra	2.549	0.082	1.593	0.194	1.005	0.425
A. dibranchis	4.409	0.014[a]	7.171	<0.001[c]	0.650	0.690
P. undulatus	6.102	0.003[b]	4.783	0.003[b]	2.545	0.023[a]
S. hanaokai	1.674	0.192	0.515	0.672	0.369	0.897
L. brevirostris	3.323	0.039[a]	0.096	0.962	0.364	0.901

a: significant at the 0.05 level; [b]: significant at the 0.01 level; [c]: significant at the 0.001 level.

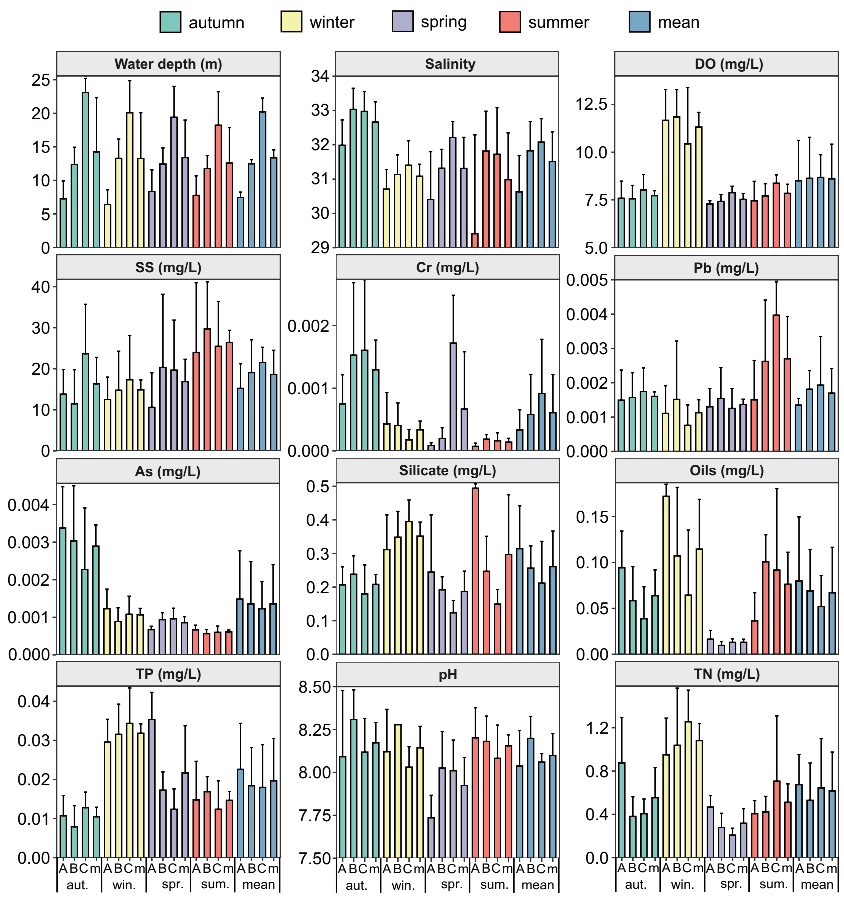

FIGURE 4
The spatial and temporal distributions of twelve environment factors in subtidal zone near the Daya Bay Nuclear Power Plant. (A: represent the inner bay; B: represent the middle bay; C: represent the outside bay; m: represent the mean value).

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TABLE 3 The F and P values between seasons and regions for twelve environment factors in subtidal zone near the Daya Bay Nuclear Power Plant.

Environmental factor	Region		Season		Region × Season	
Density	*F*	*P*	*F*	*P*	*F*	*P*
Water depth	132.242	<0.001[c]	1.104	0.350	1.591	0.155
Salinity	21.144	<0.001[c]	16.079	<0.001[c]	2.181	0.049[a]
DO	0.196	0.822	56.125	<0.001[c]	1.797	0.104
Suspended solids	2.327	0.102	4.780	0.003[b]	0.879	0.512
Cr	3.685	0.028[a]	8.282	<0.001[c]	2.666	0.018[a]
As	1.872	0.158	2.011	0.115	1.868	0.091
Pb	1.827	0.165	7.022	<0.001[c]	2.155	0.051
Silicate	18.011	<0.001[c]	30.436	<0.001[c]	15.576	<0.001[c]
Oils	2.168	0.118	14.508	<0.001[c]	3.826	0.002[b]
TP	2.053	0.132	20.537	<0.001[c]	3.587	0.003[b]
pH	5.561	0.005[b]	7.569	<0.001[c]	1.838	0.096
TN	1.674	0.191	23.000	<0.001[c]	3.003	0.009[b]

a: significant at the 0.05 level; [b]: significant at the 0.01 level; [c]: significant at the 0.001 level.

TABLE 4 Correlation analysis between densities of ten species benthic macrofauna and water environmental factors in subtidal zone near the Daya Bay Nuclear Power Plant.

Species	Depth	Salinity	DO	SS	Cr	As	Pb	Silicate	Oils	TP	pH	TN
A. trichocephalus	0.233**	0.160	0.035	0.041	0.006	-0.052	0.140	-0.198*	-0.070	-0.064	-0.100	0.043
A. laevis	0.418**	0.200*	-0.083	0.033	0.130	0.159	0.205*	-0.292**	-0.069	-0.191*	<0.001	-0.137
P. bidentata	0.249**	-0.173	0.277**	0.141	-0.014	-0.044	0.107	-0.112	-0.105	-0.025	-0.019	0.079
P. cristata	-0.372**	-0.032	0.008	-0.178*	0.060	-0.019	-0.037	0.085	0.186*	0.155	-0.141	0.076
T. lata	-0.181*	-0.291**	-0.114	-0.035	-0.060	-0.015	0.019	0.235**	-0.085	0.669**	-0.300**	-0.080
T. scabra	0.115	-0.294	0.187*	-0.109	-0.055	-0.018	-0.073	0.014	0.041	0.067	0.050	0.002
A. dibranchis	0.473**	0.214*	-0.066	-0.056	0.114	0.173*	0.053	-0.196*	0.012	0.039	0.039	0.012
P. undulatus	-0.064	-0.033	-0.118	-0.003	-0.099	-0.031	0.043	-0.115	-0.066	-0.043	-0.045	0.079
S. hanaokai	-0.089	0.037	-0.027	0.011	0.012	-0.074	-0.002	-0.106	0.050	-0.023	-0.004	-0.063
L. brevirostris	0.080	-0.083	0.052	0.017	-0.098	-0.033	0.011	0.138	0.020	0.306**	-0.090	0.315**

*: significant at the 0.05 level; **: significant at the 0.01 level.

dominant species in the macrobenthic community in the southern Yellow Sea (Xu et al., 2021).

P. cristata (It was previously identified as *Paraprionospio pinnata* in China and Korean, therefore, the *P. pinnata* reported in Chinese waters should be *P. cristata*) collected in Jiaozhou Bay and the Yellow Sea may be *P. inaequibranchia* and *P. coora* (Zhou et al., 2008). *P. cristata* has been widely reported in Korean waters (Yokoyama and Choi, 2010). *P. cristata* is considered an opportunistic species (Ji et al., 2022). In coastal waters along the Arabian Sea, *Cossura coasta*, the dominant species during the pre-monsoon period, was replaced by the surface deposit feeder *P. pinnata* during the monsoon and post-monsoon periods (Rehitha et al., 2019). *Paraprionospio pinnata* is only located in low-oxygen habitats in the Humboldt upwelling ecosystem (Fajardo et al., 2018) and it is the dominant species of the macrobenthic community in winter in the cage culture area of Daya Bay (Huang et al., 2005). The results of this study showed that the density of *P. cristata* was

TABLE 5 Correlation analysis between biomass of ten species benthic macrofauna and water environmental factors in subtidal zone near the Daya Bay Nuclear Power Plant.

Species	Depth	Salinity	DO	SS	Cr	As	Pb	Silicate	Oils	TP	pH	TN
A. trichocephalus	0.249**	0.108	0.010	0.030	-0.003	-0.039	0.110	-0.197*	-0.018	-0.120	-0.063	0.022
A. laevis	0.298**	0.177*	-0.081	0.105	-0.034	0.435**	0.271**	-0.224*	-0.088	-0.133	-0.022	-0.155
P. bidentata	0.232**	-0.013	0.350**	0.050	0.008	-0.023	0.050	0.051	-0.054	-0.006	0.037	0.198*
P. cristata	-0.385**	-0.199*	0.049	-0.123	-0.051	-0.032	-0.044	0.133	0.221**	0.394**	-0.243**	0.093
T. lata	-0.177*	-0.289**	-0.120	-0.047	-0.066	-0.016	0.062	0.173*	-0.072	0.586**	-0.284**	-0.086
T. scabra	0.107	-0.065	0.079	-0.144	-0.062	-0.022	-0.070	-0.045	-0.028	0.052	-0.042	-0.036
A. dibranchis	0.061	0.105	-0.108	-0.173*	0.079	-0.044	-0.071	-0.118	-0.097	-0.005	0.004	-0.031
P. undulatus	-0.093	-0.113	-0.125	0.118	-0.099	-0.031	0.046	-0.039	-0.019	-0.054	-0.025	-0.074
S. hanaokai	-0.167*	0.001	-0.003	-0.032	-0.076	0.038	-0.017	<0.001	0.053	0.011	-0.036	0.098
L. brevirostris	-0.119	0.024	0.032	0.005	-0.043	-0.039	0.152	0.055	-0.014	0.044	0.127	-0.100

*: significant at the 0.05 level; **: significant at the 0.01 level.

significantly negatively correlated with water depth and suspended solids, and significantly positively correlated with oil, whereas the biomass of *P. cristata* was significantly negatively correlated with water depth, salinity, and pH, and significantly positively correlated with oils and TP.

The relationship between *S. hanaokai* and the environmental factors in Chinese sea waters has been rarely reported, only a correlation analysis showed that there were significant negative correlations between the density of *S. hanaokai* and the content of organic carbon and nitrogen in the intertidal zone of Xiamen Crocodile Island (Cai et al., 2022c).

In winter and spring, the grappler method risk index (GMRI) of *A. dibranchis* is more than 50%, the risk of blocking the nuclear cold source system is at a medium-risk level. In summer and autumn, the GMRI of *A. dibranchis* is less than 50%, the risk of blocking the nuclear cold source system is at a medium-risk level. The risks of blocking the nuclear cold source system *P. cristata* and *S. hanaokai* are both at a low-risk level in Daya Bay in four seasons (Cai et al., 2022b).

4.2 Effect of environmental factors on *Apionsoma (Apionsoma) trichocephalus* and Listriolobus brevirostris

Apionsoma trichocephalus was not the dominant species in previous surveys in Daya Bay (Jiang et al., 1990a; Jiang et al., 1990b; Du et al., 2008a; Du et al., 2008b; Du et al., 2009; Yuan et al., 2017), but it poses a potential risk of blocking nuclear cooling source systems (Cai et al., 2022b). Although the average density of *A. trichocephala* was low in all four seasons in Daya Bay (below 4 ind./m^2), it was the dominant species in the subtidal zone of the East China Sea during all four seasons (Shou et al., 2018) and in the subtidal zone of the Chinese islands (Huang et al., 2012). However, there are few reports on the relationship between *A. trichocephala* and environmental factors. Our study found that *A. trichocephala* showed a significant positive correlation with water depth and a significant negative correlation with silicate.

L. brevirostris is one of the dominant species in macrozoobenthic communities in Daya Bay (Jiang et al., 1990a; Jiang et al., 1990b; Du et al., 2011; Yuan et al., 2017; Cai et al., 2022b). The results of this study showed that the density of *L. brevirostris* was significantly positively correlated with TN and TP. The density of *L. brevirostris* was high in sea areas with high organic matter content in Daya Bay (Jiang et al., 1990b).

Although the individual weight of *L. brevirostris* is large, its density is low and the distribution range is small; therefore, the risk of blocking the nuclear power cold source system is also low. Except for the GMRI in summer, which is over 50%, the risk of blocking is less than 50% in the other three seasons in Daya Bay (Cai et al., 2022b).

4.3 Effect of environmental factors on three species of bivalves

P. undulatus and *T. scabra* are the dominant species in macrozoobenthic communities in Daya Bay (Jiang et al., 1990a; Jiang et al., 1990b; Du et al., 2009; Du et al., 2011; Yuan et al., 2017; Cai et al., 2022a). The undulated surf clam, *Paphia undulata* (the new revised name in WoRMS is *P. undulatus*), is commercially cultured on the southern coast of China (Zhang et al., 2022a). Therefore, there have been many studies on the relationship between *P. undulatus* and environmental factors. *P.*

undulatus showed a significant positive correlation with the DO, clay, and chlorophyll-a content in the Beibu Gulf (Ye et al., 2010). Mud substrates with ≥ 40% water content in the temperature range of 20–30°C and salinity range of 20–40 psu were appropriate for *P. undulatus* burrowing and may be appropriate for its culture (Zhang et al., 2022a). *P. undulatus* is not only a cultured species but also a common dominant species in the macrozoobenthic community along the southeast coast of China (Ye et al., 2010; Du et al., 2011; Shu et al., 2015; Yuan et al., 2017; Rao et al., 2021; Cai et al., 2022a).

T. scabra is not an economically important species, but it is also a common dominant species in the macrozoobenthic community along the coast of Guangdong (Du et al., 2011; Li et al., 2016). *T. lata* is neither an economically important nor a dominant species on the southeast coast of China (Jiang et al., 1990a; Jiang et al., 1990b; Zhang et al., 2007; Du et al., 2008a; Cai et al., 2022a). Why do heavy metals have less impact on the Daya Bay bivalves? That is, there is no significant correlation between bivalves and heavy metals. This is because the sediment quality radically improved after the late-2000s, and heavy metals in nearshore sediments of Daya Bay were all closely related to the import of anthropogenic and/or terrestrial material, whereas those offshore were likely to be related to the joint influence of anthropogenic activities and natural processes (Du et al., 2008; Qu et al., 2018).

The GMRI of *P. undulatus* in all four seasons was less than 50%; therefore, the risk of blocking the nuclear power cold source system was low in Daya Bay (Cai et al., 2022b).

4.4 Effect of environmental factors on two species of echinoderms

Amphioplus (Lymanella) laevis has been a dominant species in Daya Bay for over 30 years (Jiang et al., 1990a; Jiang et al., 1990b; Zhang et al., 2007; Du et al., 2008a; Du et al., 2008b; Du et al., 2009; Huang et al., 2012; Zhang et al., 2017; Cai et al., 2022b). It is also a common dominant species on the coast and in the Gulf of China (Cai and Zheng, 1994; Chen et al., 2020). The genus *Amphioplus* is also dominant in some open-sea areas. *Amphioplus sinicus* was not only the dominant species of macrozoobenthic communities in Hailing Bay, western Guangdong, but also outside the bay, in addition to being the annual dominant species (Li et al., 2018). *A. laevis* is the dominant species in subtidal amphioxus habitats in Xiamen Bay (Chen et al., 2020; Rao et al., 2020b). BIO-ENV analysis revealed significant seasonal variations in environmental factors affecting community structure (including *A. laevis*) in semi-enclosed waters in Bohai Bay, China (Shi et al., 2022). This study found that the density of *A. laevis* showed a significantly positive correlation with water depth, salinity, and Pb and a significantly negative correlation with silicate and TP.

P. bidentata has not been the dominant species in previous surveys in Daya Bay (Jiang et al., 1990a; Jiang et al., 1990b; Du et al., 2008a; Du et al., 2008b; Du et al., 2009; Zhang et al., 2017; Yuan et al., 2017; Rao et al., 2020a), but it was a common species in the sea area near the nuclear power plant (Cheng et al., 2018; Li et al., 2020; Zhang et al., 2022b), It was a dominant species on the northern coast of Zhejiang Province (Yan et al., 2020) and in the surrounding waters of Qinshan Island (Mao et al., 2022). This study found that the density and biomass of *P. bidentata* were significantly positively correlated with water depth and DO.

The GMRI of *P. bidentata* in all four seasons was less than 50%, so the risk of blocking the nuclear power cold source system was low in Daya Bay (Cai et al., 2022b).

4.5 Effect of environmental factors on the zoobenthic community in Daya Bay

The main sources of pollution near the Daya Bay nuclear power plant were the warm drainage from the power plant and the shallow aquaculture area of Dapeng Ao, but the warm drainage from the power plant had less effect on benthic macrofauna in nearby waters (Zhang et al., 2007). From 1982 to 2004, the ecological environment of Daya Bay changed from 237 species in 1987 to 194 species in 1997 (Wang et al., 2004), and the mean biomass and species of benthic animals near power plants ranged from 317.9 g/m^2 in 1991 to 45.24 g/m^2 in 2004, and from 250 species in 1991 to 177 species in 2004 (Wang et al., 2008). The correlation analysis between the macrobenthos community and environmental factors indicated that secondary productivity was significantly affected by the content of inorganic nitrogen, phosphorus, dissolved oxygen of seawater, and organic carbon content of sediment (Liu et al., 2018). Changes in the ecological environment in Daya Bay are related to sewage discharge and mariculture. Small body size, short longevity, and high tolerance species are more abundant in industrial sewage discharge areas and mariculture areas (Rao et al., 2021). We believe that to accurately identify the main environmental factors affected, long-term monitoring and sufficient comparable data are needed.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials. Further inquiries can be directed to the corresponding author.

Author contributions

LC conceived of the study and obtained funding. LC, YR, XYZ, DY, DW, XPZ, and XY were responsible for field and laboratory work. LC, YR, and DY conducted the identification of benthic macrofauna. The manuscript was reviewed by LC. YR and XYZ helped analyzing the data and plotting the figures. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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