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Evidence that offshore wind farms might affect marine sediment quality and microbial communities

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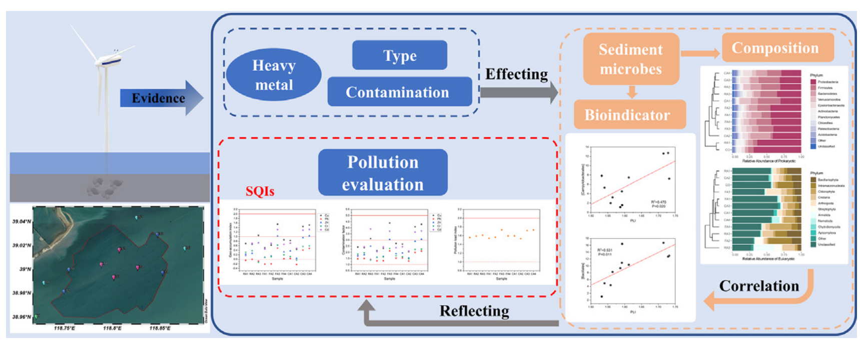
HIGHLIGHTS

- Environmental assessment of the sediments under the Putidao offshore wind farm.
- The heavy metals occurring in the sediments were significantly and positively associated with each other.
- The abundances of certain microbial species were affected by the presence of heavy metals.
- Bioindicators based on sensitive microbial taxa were developed.

GRAPHICAL ABSTRACT



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ABSTRACT

Offshore wind power is a typical example of clean energy production and plays a critical role in achieving carbon neutrality. Offshore wind farms can have an impact on the marine environment, especially sedimentary environments, but their influence on sediments remain largely unknown. This study, which uses the control-impact principle to define different areas, investigated the characteristics of marine sediments under the Putidao offshore wind farm in Bohai Bay, China. We used chemical and microbiological observations to evaluate sediment quality and microbial community structure. According to both the geo-accumulation index (I_{geo}) and contamination factor (CF) indexes, copper, chromium and zinc were the major contaminants in the offshore wind farm sediments. The pollution load index (PLI) index showed that the various sites on the wind farm were only lightly polluted compared with baseline values. Closer to the wind farm's center, the metal concentrations started to rise. The physicochemical features of the sediments could better explain changes in the microorganisms present, and screening the microbiomes showed a correlation with heavy metal levels, linking the relative abundance of microorganisms to the sediment quality index. This comprehensive study fills a knowledge gap in China and adds to our understanding of how to assess the sedimentary environments of offshore wind farms.

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1. Introduction

Achieving a low-carbon economy by accelerating the transformation of the energy production system has attracted worldwide attention (Strunz, 2018). Wind power generation provides clean energy and has grown rapidly all over the world in recent years (Vargas et al., 2019). Offshore wind farms use large structures, and have long operational periods, high power generation efficiency, clear development value, and high utilization potential (Dhanju et al., 2011). As a result, the industry's installed capacity has skyrocketed. Offshore wind power, as a source of renewable energy, is seen as a bridge to carbon neutrality goals, as well as providing benefits such as habitats for marine organisms (Krone et al., 2017; Li et al., 2020b; Ten Brink and Dalton, 2018). Plans to integrate marine aquaculture systems into offshore wind farms are being carried out in countries such as Germany (Buck et al., 2017). However, studies have indicated that the corrosion prevention systems used in offshore wind farms might potentially leak 26 different heavy metals into the surrounding water, including Al, Zn, Pb, and Cd (Reese et al., 2020), which could harm the local ecosystem. It is therefore necessary to understand this aspect of the impact of offshore wind farms on the benthic environment.

It is important to understand sediment characteristics because they constitute sinks or sources of many types of pollution (Burton and Johnston, 2010; Long et al., 2021) and can store information on ecosystem disturbances due to natural processes and/or anthropogenic activities (Christophoridis et al., 2019; Won et al., 2017). The assessment of sediments allows a thorough understanding of their degree of contamination through anthropogenic effects such as industry and agriculture (Ali et al., 2022; Hidayati et al., 2021; Strand et al., 2003). The geo-accumulation index (I_{geo}) has been used to identify heavy metal sources in Laizhou Bay, China (Zhang et al., 2017), and the pollution load index (PLI) has been used to evaluate the impact of mining on sediments (Ali et al., 2018). Previous studies of the benthic environments around offshore wind power developments have shown that microbial species abundance, density and richness, and sediment organic content decrease with increasing distance from turbine structures (Bartley et al., 2018; Lefaible et al., 2018; Lu et al., 2019). This may be closely related to the impacts of offshore wind farm operation on the benthic environment. Evaluating sediment quality under offshore wind farms and calculating the sediment quality index will show whether pollution enrichment occurs, filling an important knowledge gap.

Microbial communities are a crucial component of the sediment ecosystem and play an important role in the biogeochemical cycle on a global scale (Begmatov et al., 2021). Microbial communities can respond quickly to environmental disturbances (Di Cesare et al., 2020; Sutcliffe et al., 2019) and can be used as environmental indicators (Saingam et al., 2020). They can help to indicate the current sediment quality when combined with information on the physical and chemical sediment properties (Li et al., 2020a; Simonin et al., 2019). Combining information in this way has been proposed as a strategy to indicate general environmental health (Arfaeinia et al., 2016; Zhang et al., 2022b) since serious anthropogenic pollution is often indicated by changes in microbial community diversity (Zhang et al., 2022a). Along the west coast of South Korea, environmental contaminants have caused major shifts in the occurrence of Cyanobacteria and Firmicutes, suggesting that they could be used as bioindicators (Lee et al., 2020).

Will the operation of offshore wind farms have any impact on sediment quality and microbial communities? We used information from sediments and microbial communities to explore: (i) the physicochemical characteristics of sediments under an operational offshore wind farm; (ii) the structure of the microbial communities in the wind farm sediments; and (iii) the relationships between microbial communities and sediment quality at the farm. Offshore wind farms could have an impact on sediment quality, and the interactions between microbial communities and sediment quality at a farm could provide useful bioindicators for sediment evaluation. Our results provide evidence that offshore wind farms could affect marine sediment quality and microbial communities.

2. Materials and methods

2.1. Study area and site description

The Putidao offshore wind farm (POWF) is located in Bohai Bay, Laoting County, Tangshan City, Hebei Province, China (118°44′–118° 54′ E, 38° 57′–39° 03′N) (Fig. 1). The POWF was completed in three phases in 2017, with a total power output of 300 MW provided by 75 wind turbine units, in water depths ranging from 9 to 23 m, 15 km offshore. The corrosion prevention systems used at the POWF comprise modified epoxy resin paint, glass flake with a thickness of 900 μm, and sacrificial aluminum alloy anodes. Following Control-Impact (CI) design recommendations (Methratta, 2021; Underwood, 1994), we chose a coastal study site

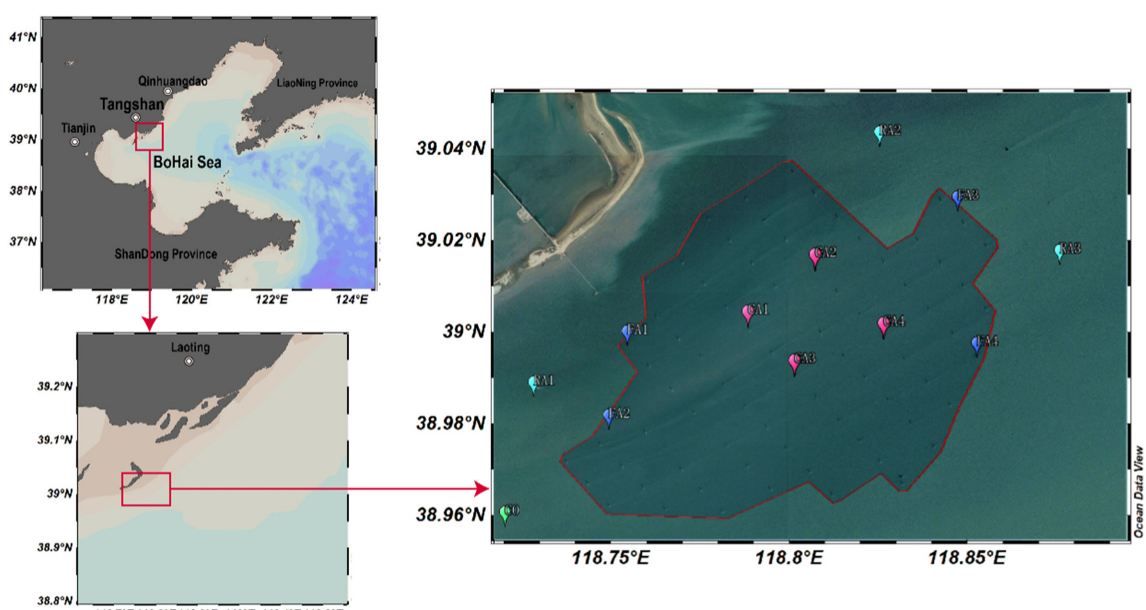


Fig. 1. Location of the Putidao offshore wind farm (POWF) in China, as well as the four types of sediment sampling sites ($n = 12$). POWF is surrounded by the red line; red locators represent core sites; blue locators represent fringe sites; and white locators represent reference sites.

19 km distant from the POWF, and a control site (CO) 8.77 km distant to provide baseline data. The POWF was divided into three parts, based on distance from the center: (i) core internal sites, 0–2 km distant (CA1, CA2, CA3, CA4); (ii) fringe sites, 4–5.5 km distant (FA1, FA2, FA3, FA4), and (iii) and reference sites, 5.5–7 km distant (RA1, RA2, RA3). These areas were chosen to clarify the effects of the POWF on sediments and sediment microbial communities.

2.2. Sampling and analysis

During June 2021, sediment samples (0–3 cm depth) were collected in triplicate at each of the 12 sampling sites. We used a multi-parameter water quality meter (EXO2 multiparameter sonde, YSI, Yellow Springs, USA) to measure dissolved oxygen, temperature, and the depth of the sediment bottom layer at each sampling site. For each well-mixed sample, physicochemical variables such as particle size, sedimentary organic matter (SOM), mineralogical properties, and trace metallic elements including Cu, Pb, Zn, Cr, Cd were measured. Particle-size composition was determined using a Cilas 1190 Laser Scattering Particle Size Distribution Analyzer (Cilas, ADD CITY, France) with measuring capabilities of: clay, 0.01–2.0 μm; silt, 2.0–62.5 μm; and sand, 62.5–2000 μm. SOM was estimated using the burning method. Mineralogical properties were estimated using an X-ray fluorescence spectrometer (XRF) scanner. Analysis of the metals in the sediment was conducted using inductively coupled plasma–mass spectrometry (ICP–MS). Composite sediment samples were put into 15 mL sterile Corning ® polypropylene centrifuge tubes and stored in an ice chamber at 4 °C, and the samples were subsequently stored in a freezer at −80 °C in the laboratory prior to DNA extraction.

2.3. Sediment quality assessment

2.3.1. Geo-accumulation index (I_{geo})

The geo-accumulation index was used to assess the sediment environmental conditions to quantify the degree of toxic metal contamination (I_{geo}) in the sediment samples (Muller, 1969). I_{geo} was calculated according to the following equation (Ruiz, 2001):

$$Igeo = \log_2\left[\frac{Cn}{1.5B_n}\right]$$

where Cn denotes the measured concentration of metal n in the sediment and Bn is the element n's geochemical baseline concentration. The factor 1.5 was introduced to reduce fluctuations in background values attributed to lithogenic processes (Varol, 2011). The value ranges of I_{geo} were set as <0, 0–1, 1–2, 2–3, 3–4, 4–5, and >5 to denote unpolluted, unpolluted to moderately polluted, moderately polluted, moderately to strongly polluted, strongly polluted, strongly to very strongly polluted, and extremely polluted conditions, respectively. The baseline values for I_{geo} were determined from the CO sediment analyses.

2.3.2. Contamination factor (CF) and pollution load index (PLI)

Contamination factors were used to characterize the levels of contamination, calculated according to the following equation (Hakanson, 1980):

$$CF = \frac{C_{metal}}{C_{background}}$$

Where C_{metal} = concentration of an individual metal, and $C_{background}$ = the baseline concentration of that metal.

The number of heavy metal concentrations observed in a sediment sample at a concentration higher than their background concentrations, gives the pollution load index (PLI). PLI therefore provides a collective indication of the degree of heavy metal concentration overall, and is calculated according to the following equation:

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \ldots\ldots \times CF_n)^{\frac{1}{n}}$$

The calculated CF of each element at each sample site was then classified following Pena-Icart et al. (2017): low (CF < 1); moderate (1 < CF < 3); considerable (3 < CF < 6); and extremely high (CF > 6).

2.4. Sediment DNA extraction, PCR amplification, sequencing, and bioinformatics analysis

2.4.1. Sediment DNA extraction, amplification, and sequencing

Bacterial DNA was extracted from 0.5 g subsamples of each sediment sample using HiPure Soil DNA Kits (Magen, Guangzhou, China), according to the manufacturer's protocols. The V3–V4 region of the 16S rRNA gene was amplified using the universal primers 341F (CCTACGGG NGGCWGCAG) and 806R (GGACTACHVGGGTATCTAAT), and the V4 region of the 18S rRNA gene was amplified using the forward 528F (GGCA AGTCTGGTGCCAG) and 706R (AATCCRAGAATTTCACCTCT) broad eukaryotic primers. Amplicons were extracted from 2 % agarose gels and purified using AxyPrep DNA Gel Extraction Kits (Axygen Biosciences, Union City, U.S.), according to the manufacturer's instructions, and quantified using an ABI StepOnePlus Real-Time PCR System (Life Technologies, Foster City, USA). Purified amplicons were pooled in equimolar solution and paired-end sequenced (PE250) using an Illumina platform according to the standard protocols. The raw reads were submitted to the NCBI Sequence Read Archive (SRA) database (https://www.ncbi.nlm.nih.gov/sra, Accession Number: PRJNA 836721 and PRJNA837338).

2.4.2. Bioinformatics analysis

The sequences were filtered and processed using QIIME-1.9.1 (http://qiime.org/). The clean tags were clustered into operational taxonomic units (OTUs) of ≥97 % similarity using the UPARSE-9.2.64 pipeline (https://drive5.com/uparse/). The species annotation of representative OTU sequences was performed using the SILVA database (https://www.arb-silva.de/) with a confidence threshold value of 0.8. The diversity and complexity of microbial species were analyzed and Chao1, ACE, Shannon, Simpson, Good's coverage indexes were calculated using QIIME-1.9.1.

2.5. Statistical analysis

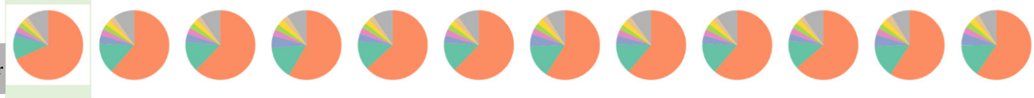
Redundancy analysis (RDA) was executed using the R project Vegan package (https://www.r-project.org/) to clarify the influence of environmental factors on microbial community composition. Pearson and Spearman correlation coefficients between environmental factors and species were calculated using the R Project Psych package (https://www.r-project.org/). Regression analyses was used to determine the quantitative relationships between bioindicators and pollution levels using Origin 2022 software (https://www.originlab.com/getstarted). Figures were drawn using Ocean Data View (https://odv.awi.de/), Origin 2022, and R-4.1.3 (https://www.r-project.org/) software. All differences were considered significant at $P < 0.05$.

3. Results

3.1. Sediment physicochemical properties

The results of the sediment analysis for each sample site are shown in Table 1. Each site's sediment samples were found to be distinct. At the reference sites, the smallest 50 % of the sediment particle sizes at most sites were composed of sand, except at site RA3 where it was composed of silt. At the fringe sites, the smallest 50 % of the particle sizes of most sites were composed of silt, except at site FA2 where it was composed of sand. At the core sites, the smallest 50 % of the sediment particle sizes were all composed of silt. There were no significant differences in the mineralogical

Table 1
Sediment quality parameters detected in a composite of the three samples collected at each sample site (mg/kg).

Study area		MDL	Control Site	Reference Area			Fringe Area				Core Area			
Sample location		-	CO	RA1	RA2	RA3	FA1	FA2	FA3	FA4	CA1	CA2	CA3	CA4
PS	Diameter at 10.00 %		4.747	5.508	3.942	2.346	3.400	3.468	2.166	2.731	3.163	2.782	2.166	2.687
	Diameter at 50.00 %		174.138	183.016	71.721	10.605	62.017	85.781	13.983	27.207	39.011	54.983	13.983	17.027
	Diameter at 90.00 %		366.563	355.988	238.009	43.799	263.911	291.877	119.540	276.390	243.151	143.286	119.540	47.693
Mineralogical characteristics SiO_2 Al_2O_3 Fe_2O_3 K_2O Na_2O MgO CaO Other														
SOM (mg/g)		-	19.63	43.70	40.93	67.64	35.69	38.66	79.02	45.66	48.90	40.26	83.51	78.95
Cu (10^{-6})		0.007	7.5	18.2	17.8	23.4	16.0	17.4	32.9	20.4	20.0	15.3	30.6	32.1
Pb (10^{-6})		0.001	12.4	18.1	18.6	17.6	16.1	16.2	26.2	18.9	19.1	15.9	24.7	26.0
Zn (10^{-6})		0.002	27.9	49.0	50.3	69.7	44.5	46.5	85	52.5	54.2	43.2	81.0	85.6
Cr (10^{-6})		0.003	33.1	61.8	64.7	45.5	52.6	53.9	76.7	57.0	54.1	48.6	73.7	74.8
Cd (10^{-6})		0.001	0.141	0.237	0.344	0.350	0.290	0.344	0.525	0.335	0.347	0.297	0.514	0.528

MDL = method detection limit; PS = particle size; SOM = sedimentary organic matter. Highlighted green columns represent the baseline site; pie charts represent the mineralogical characteristics of the sediment.

properties between sites, the sediments at all sites being mainly composed of silica. The SOM content at the sites increased as they got closer to the center of the offshore wind farm (Fig. 2). The average levels of the metals surveyed fell as the distance from the central region of the POWF increased (Fig. 2). Within the wind farm, the sites with the greatest heavy metal levels were CA3, CA4, and FA3.

Fig. 3 shows the results of the correlation analysis between the concentrations of metals and the physical attributes of the sediments. The occurrence of the metal elements were significantly positively correlated ($R^2 >$ 0.80, $P < 0.01$). However, the correlations between the various physicochemical features of the sediments differed between the various metal contents: the depth of the sediment sample, dissolved oxygen, and heavy metal content were all positively correlated, but the associations were weak. The sediment SOM concentration was significantly correlated with all of the heavy metal concentrations ($R^2 < 0.90$, $P < 0.05$). The heavy metal concentrations were negatively correlated with the 50 % particle size and temperature of the sediment, whereas the 50 % particle size of the sediment was negatively correlated with the heavy metals, except Cr ($R^2 < 0.50$, $P >$

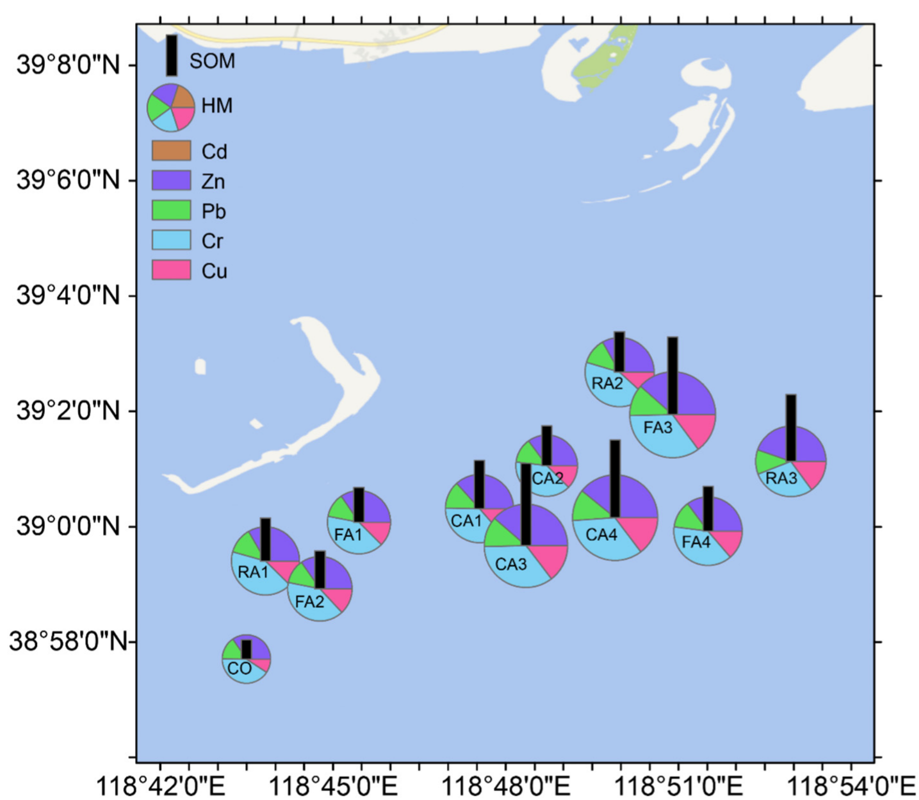


Fig. 2. The distribution diagrams of SOM and heavy metals at the POWF. The size of the sector diagram represents the total concentrations of heavy metals, and the height of the bar diagram represents the content of SOM.

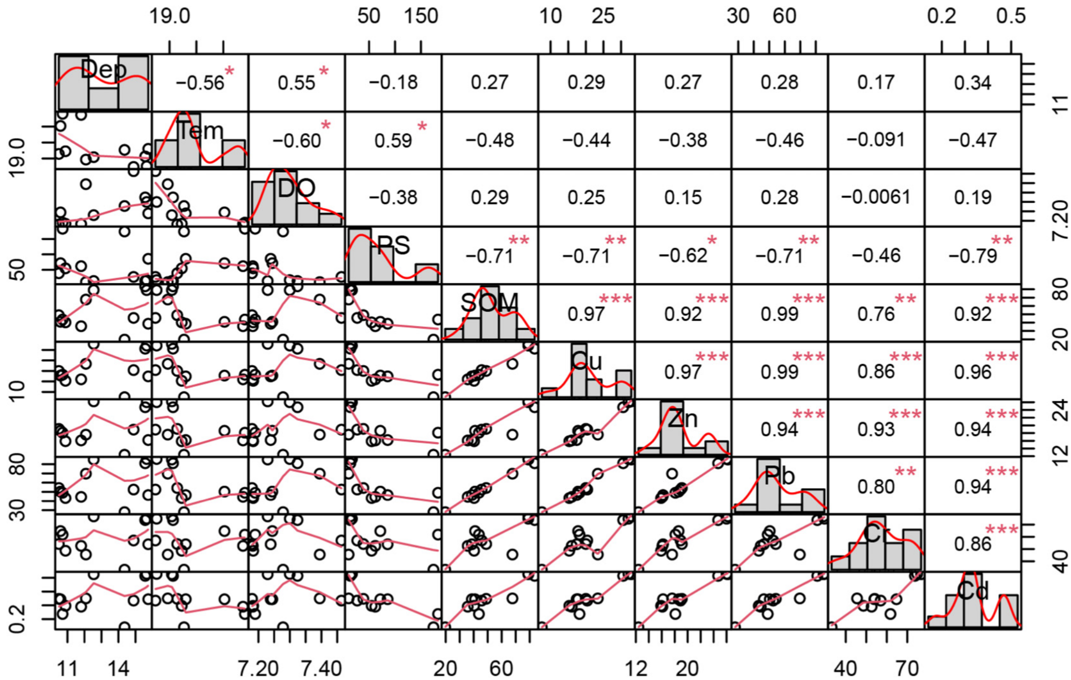


Fig. 3. Correlation analysis between heavy metal element concentrations and the physicochemical properties of sediments. The numbers marked in the figure represent the correlation coefficients (*$P < 0.05$; ** $P < 0.01$, *** $P < 0.001$).

0.01). The links between depth (Dep), temperature (Tem), and dissolved oxygen (DO) were also consistent with previous research.

The sediment quality indicators (SQIs) for all sites are summarized in Fig. 4. The baseline values were calculated using data from the CO site. The contamination by hazardous metals in the study area was ranked in the following order, based on average I_{geo} and CF values: Cu > Cd > Zn > Cr > Pb. The average I_{geo} values showed that the majority of the study area was "unpolluted to moderately polluted" ($0 < I_{geo} < 1$), with the Cu and Cd levels at FA3, CA3, and CA4 being "moderately polluted" (1 < Igeo < 2). Similar to the I_{geo} results, Cu was again highlighted as accumulating at higher levels according to the CF classification, i.e., above the "considerable" level (3 < CF < 6) at sites FA3, CA4, CA3, and RA3, and "moderate" at the rest of the sample sites. The second most enriched element, Cd, reached its maximum contamination level ("moderate") at sites RA3, FA3, CA3, and CA4. A site is entirely polluted by hazardous metals if its PLI score is greater than one. The overall PLI value in our study area (1.532–1.729) was somewhat higher than the baseline station, indicating that there is some heavy metal pollution in all areas of the offshore wind farm.

3.2. Analyzing the microbial community structure of sediments

3.2.1. Taxonomic composition and microbial diversity in sediments

After removing the low-quality sequences and mismatches in the 12 sediment samples collected from the various sites around the POWF, prokaryote samples contained a total of 112,347 effective tags, comprising 14,768 OTUs through clustering (97 % similarity), and with a per sample average of 2945 OTUs. Regarding prokaryotic samples, we generated a total of 12,2691 effective tags comprising 2579 OTUs, with a per sample average of 777 OTUs.

Among the prokaryotic samples (Fig. 5), classification of the OTUs yielded two domains, 55 phyla, 152 classes, 266 orders, 308 families, 442 genera, and 154 species. At the phylum level, Proteobacteria (41.84 ± 12.91 %), Firmicutes (19.00 ± 9.60 %), and Bacteroidetes (12.58 ± 6.23 %) dominated in almost all sediments, followed by Verrucomicrobia (5.97 ± 4.22 %), Epsilonbacteraeota (5.81 ± 3.92 %), Planctomycetes (2.58 ± 1.27 %), Actinobacteria (2.49 ± 1.10 %), Chloroflexi (2.00 ± 0.85 %), Patescibacteria (1.34 ± 0.57 %), and Acidobacteria (1.29 ± 0.34 %). The dominant phylum, Proteobacteria, mainly consisted of *Vibrio* spp. (16.68 ± 11.94 %), *Bacillus* spp. (7.91 ± 4.10 %), *Sulfurovum* spp. (5.53 ± 3.68 %), and *Persicirhabdus* spp. (4.93 ± 3.99 %). At the genus level, a total of 442 genera were identified, and *Bacillus selenatarsenatis* (5.42 % on average) (class Bacilli) showed pronounced dominance, followed by other frequently detected genera including *Shewanella*, *Tepidibacter*, *Woeseia*, *Photobacterium*, *Lutibacter*, and *Tenacibaculum* (with mean relative abundances ranging from 2.71 %–1.88 %). Among the eukaryotic samples (Fig. 5), classification of the OTUs yielded four domains, 24 phyla, 68 classes, 127 orders, 170 families, 153 genera and 155 species. Bacillariophyta (10.48 ± 5.82 %) and Intramacronucleata (9.81 ± 9.94 %)

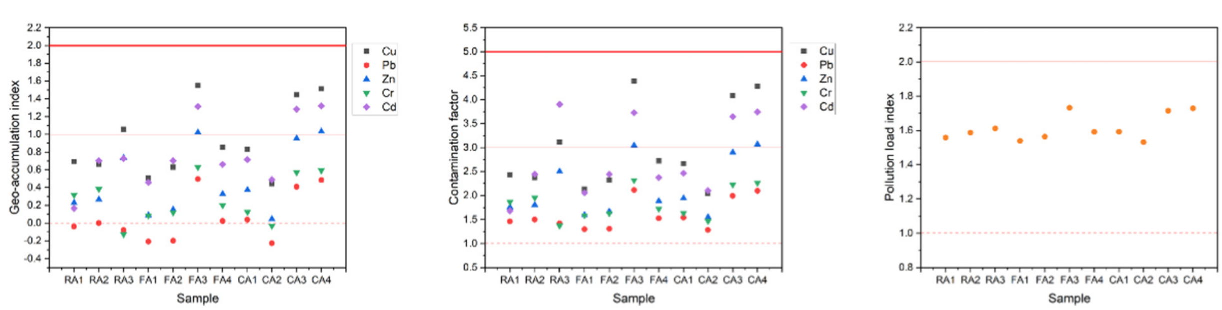


Fig. 4. Sediment quality indicators (SQIs) of metal element contamination; red lines indicate contamination levels.

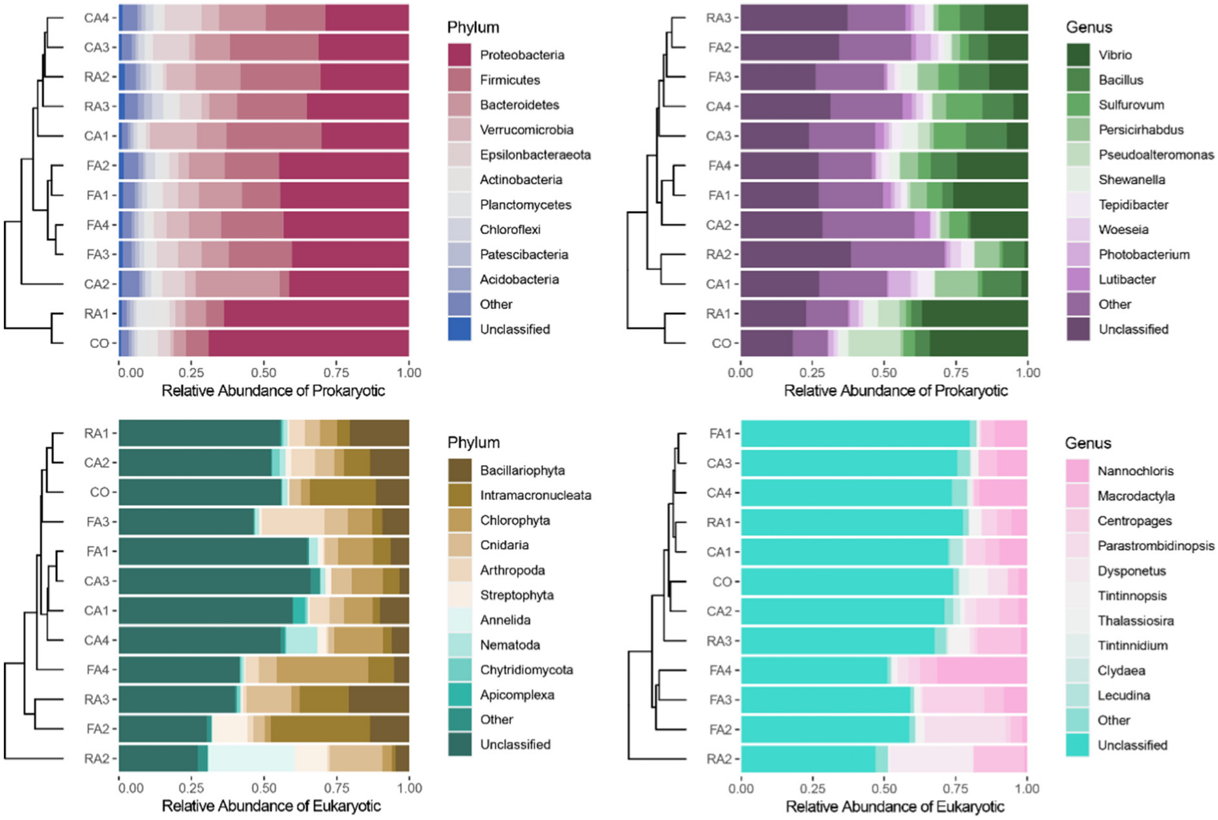


Fig. 5. Taxonomic stack distribution of prokaryotes and eukaryotes at the phylum and genus levels (top 10).

(domain Eukaryota), Chlorophyta (9.15 ± 8.42 %) (domain Viridiplantae), and Cnidaria (7.17 ± 4.78 %) (domain Metazoa) were the predominant phyla occurring at all sites (>5.00 %). they were followed by other top phyla including Arthropoda, Streptophyta, Annelida, Nematoda and Chytridiomycota (mean relative abundances ranging from 4.33 %–0.64 %). The remaining species were all classified as Other (1.04 ± 1.15 %), and tags that could not be annotated to species level were classified as Unclassified (49.57 ± 12.65 %). From the results of a cluster analysis based on Bray distance, it can be seen that the samples do not group together by area.

Microbial alpha diversity was estimated for each sample (Table S1). The Good's coverage results were between 0.99 and 1.00, showing that the sequencing clearly represented microbial biodiversity at each site. Most of the sediment samples had higher prokaryotic micro-diversity indices than eukaryotic micro-diversity.

3.2.2. Links between microbial communities and sediment physiochemical conditions

The results of a detrended correspondence analysis (DCA) showed that the value of the first axes of the lengths of gradient was <3.0, and the RDA was therefore recommended. Using RDA, the first and second axes together explained 81.03 % and 69.25 % of the cumulative variance of the prokaryotic and eukaryotic community-environmental factor correlations, respectively (Fig. S1). We also analyzed the correlations between sediment physicochemical characteristics: depth – Dep; temperature – Tem; dissolved oxygen – DO; particle size – PS; sedimentary organic matter – SOM, and heavy metal concentrations, and the relative abundance of the microbial communities at various levels (phylum, order, and genus) to gain insights into how sediments affect the composition of microbial communities (Fig. 6). Among the prokaryotic samples, there was a generally positive correlation between the physical properties of the sediment and the microorganisms found there. The relative abundance of Epsilonbacteraeota (including the order Bacillales and genus *Bacillus,* and the order Campylobacterales and genus *Campylobacterales*) showed uniformly positive associations with SOM, and Cu, Zn, Pb and Cd concentrations. We observed mainly negative correlations between particle size and microorganisms (genera *Bacillus*, *Anaeromicroblum* and *Fictibacillus*); temperature and the class Acidimicrobiia; and depth and the class Thermodesulfovobroina. However, the relative abundance of Proteobacteria (including the order Vibrionales) showed uniformly negative associations with Cd concentrations. Fewer prokaryotes showed correlations with sediment physicochemical properties. We found that only the phyla Intramacronulea and Rotifera, and the order Tintinnida showed a negative correlation with Cr concentration.

3.3. Establishing bioindicators

Based on the results of this study, we screened metal-sensitive prokaryotic microorganisms (Bacillales and Campylobacterales) and used their relative abundance to establish indicators reflecting sediment contamination. [X] represents the relative abundance of X, and [*Bacillales*] and [*Campylobacterales*] the relative abundances of Bacillales and Campylobacterales, respectively. Linear regression analysis was performed using the two selected biological indicators and the heavy metal PLI (Fig. 7, $P < 0.05$, $0.470 < R^2 < 0.531$), and the results of the model confirmed its suitability to reflect heavy metal contamination of sediments in field investigations. This study fills a gap in this field by using novel combinations of microbial communities to diagnose sediment quality.

4. Discussion

4.1. Effects of offshore wind farms on sediment quality

This study examined an operational offshore wind farm to determine sediment particle size, sediment composition, and heavy metal concentrations. In general, after the development and operational phases of a new wind farm are completed, the SOM and heavy metal levels inside it will

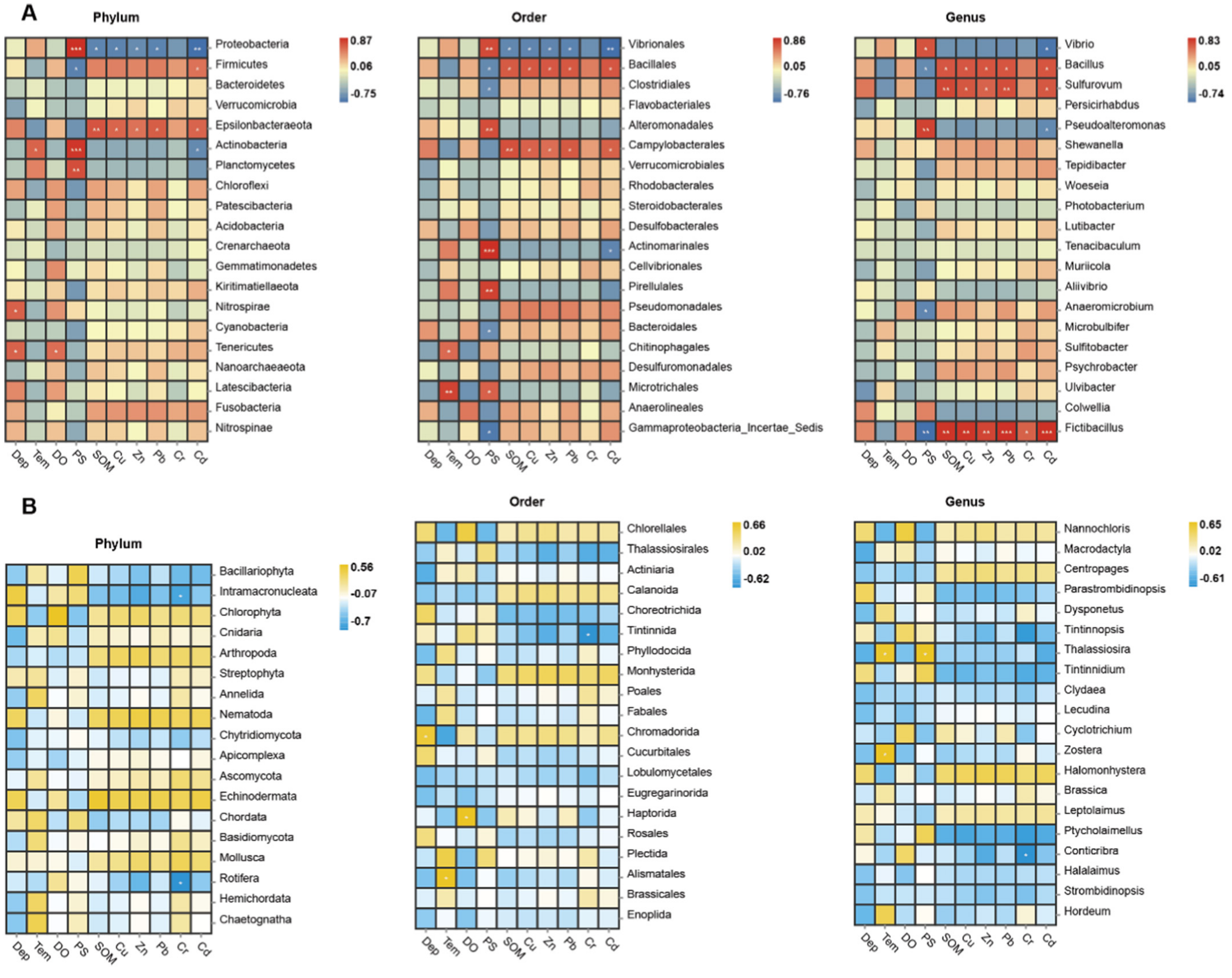


Fig. 6. Correlations between sediment physicochemical properties and the relative abundance of microbial taxa at different levels (phylum, class, and order) (*$P < 0.05$; ** $P < 0.01$, *** $P < 0.001$), A: prokaryotes and B: eukaryotes.

increase. Disturbances in marine sediments caused by offshore wind farm construction and operation may result in the return of contaminants that have accumulated in the seabed over the last century (Zaborska et al., 2017). During the construction phase, engineering activities may result in sediment heavy metal contamination (Bailey et al., 2014). During the operational phase, the anti-corrosion systems of offshore wind farms causes the precipitation of anti-corrosion heavy metals (Kirchgeorg et al., 2018). The copper used in underwater cables and the steel used in wind turbines have the greatest heavy metal ecotoxicity impact (Huang et al., 2017). Studies have shown that the anti-corrosion measures for offshore wind power

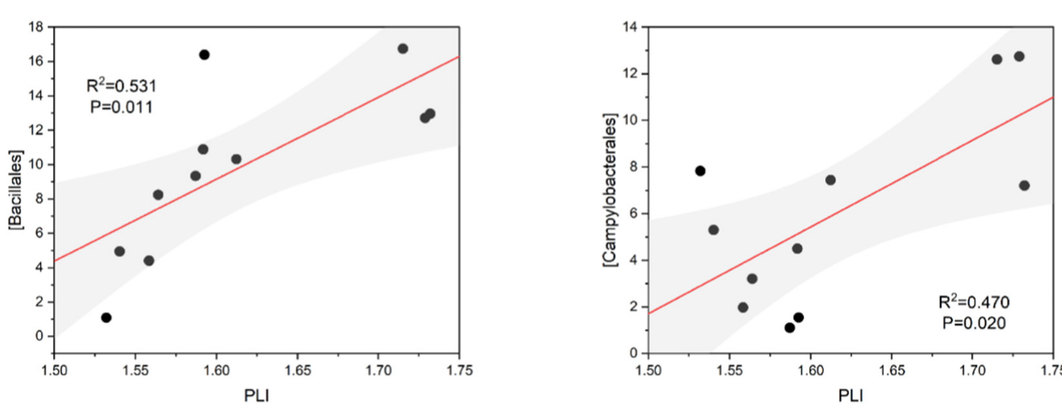


Fig. 7. Linear regression models using each selected bioindicator, [*Bacillales*] and [*Campylobacterales*], against pollution load indexes (PLI). Solid lines indicate mean estimates and the shaded areas denote 95 % confidence intervals.

steel structures result in Zn, Al, Cu, and Cd contamination, and according to studies of the anti-corrosion systems in the German North Sea >80 kg Al-anode material can be emitted per monopile foundation each year (Reese et al., 2020). An I_{geo} index >1 shows that heavy metals in the sediment have been released by non-lithogenic effects. Significant correlations between heavy metals also suggest that these elements have comparable origins, interdependencies and similarities (Mohsen et al., 2022). This means that offshore wind power may emit heavy metal pollution and affect the quality of the sedimentary environments.

The artificial reef effect of offshore wind turbine foundations (Klain et al., 2020; Krone et al., 2013; Maar et al., 2009; Ten Brink and Dalton, 2018) may attract large numbers of attached organisms, such as oysters and mussels, which can purify seawater (Hung, 2020; Kamermans et al., 2018; Krone et al., 2013; Slavik et al., 2018) and concentrate heavy metals into their feces (Fan et al., 2022; Galimany et al., 2017; Pavon et al., 2022; Smith et al., 1981). In a field survey of a wind farm in the North Sea, it was also found that the organic matter content began to increase from 0.4 ± 0.01 % at 100 m to 2.5 ± 0.9 % at 15 m near the foundation (Coates et al., 2014). That there was a significant correlation between heavy metals and SOM in our study gives strong support to this idea. SOM has a beneficial effect on heavy metal levels, combining with them to produce metal complexes (Qu et al., 2019). The larger the sediment particle size, the smaller its specific surface area and the weaker the absorption capacity per unit of the metal, resulting in significant negative correlations (Nguyen et al., 2016; Wang et al., 2020). In addition, differences between sampling locations result in varying sampling water depths, resulting in different responses to temperature and dissolved oxygen, which can also have a small impact on heavy metal levels, as has been reported in some previous studies (Chou et al., 2018; Liu et al., 2019; Liu et al., 2022).

The PLIs indicated that the sediments inside the wind farm were marginally affected compared with the baseline reference point. This concurs with our findings regarding sediment quality. The accuracy of our study's findings was mostly based on a comparison with the baseline point, which may be inappropriate due to the fact that the baseline location is only distinguishable by distance (Christie et al., 2019). To back up the findings of this study, long-term environmental monitoring should be performed in the future.

4.2. Links between microbial communities and sediments at offshore wind farms

Proteobacteria, Firmicutes, and Bacillariophyta dominated the microbial community composition in the bulk of the samples studied, similar to many studies in the Yellow Sea (Lee et al., 2021; Sun et al., 2010; Xie et al., 2017). Despite the fact that no variations in microbial community organization were discovered in this study, some microbial groups were closely linked to sediment physical features. Changes in microbial communities are often associated with environmental factors, and microorganisms that are highly sensitive to heavy metals can be used as biological indicators of heavy metal contamination (Li et al., 2020a; Zhuang et al., 2019). Some studies have established biological species indicators, metabolites and the relative abundance of metal resistance genes (MAGs) that can be used to predict sediment characteristics through the relationship between microorganisms and SQIs (Chen et al., 2019; Di Cesare et al., 2020; Li et al., 2020a). Similar to the results of this study, after a significant metal (metalloid) spill, the proportion of Proteobacteria in a reservoir sediment bacterial community fell drastically, indicating that metal (metalloid) spill could have a serious negative influence on Proteobacteria (Guo et al., 2019). Proteobacteria and Epsilonbacteraeota dominated the system's capacity to remove polycyclic aromatic hydrocarbons (PAHs) (Hung et al., 2022). Another study developed a quantitative model to predict the level of aryl hydrocarbon receptor (AhR) activity based on the relative abundances of Acetobacteraceae and Oxyuricides (Xie et al., 2018). Similarly, our use of linear regression models to predict the level of PLIs based on the relative abundances of Bacillales and Campylobacterales appears to hold promise.

While studies have shown that using microbial taxa as indicators can be sufficiently sensitive, in extreme cases it can lead to misleading conclusions (Tang et al., 2019). Someone therefore recommend that biological indicators established based on microbial function are more reliable (Li et al., 2020a). A study of the area surrounding the Greenside coal mine in South Africa showed that soil microorganisms are at greatest risk from heavy metal contamination (Zerizghi et al., 2022), and other studies have revealed a link between microorganisms and contaminants and have established correlations with sediment quality indexes. When the value of 1/[*Nitrification*], or 1/[*Aerobic nitrite oxidation*] is very large, sediments are likely to be polluted by heavy metals due to the linear relationship between bioindicators and PLI (Li et al., 2020a). A deficiency of this study is that it used 18S amplicon technology to study the eukaryote community structure, and information at the species level was relatively lacking. Data on eukaryotes was limited and more advanced technologies should be used to include eukaryote taxa in the future. Studies combining other benthic taxa that are also sensitive to sediment characteristics provide more supporting data for our study (Khim et al., 2018; Palmer et al., 2022).

5. Conclusion

This study shows that the construction and operation of offshore wind farms may produce heavy metal pollutants and have an impact on sediment quality, but that the impact is limited and weak. More research and long-term environmental monitoring are required to properly assess the impact of offshore wind farms on the sedimentary environment. Although the operation of offshore wind farms does not lead to changes in the structure of benthic microbial communities, the Bacillales and Campylobacterales communities in sediment under a farm were significantly positively correlated with heavy metal levels and can potentially be used as bioindicators for heavy metal contaminants. The above results provide evidence that offshore wind farms might affect marine sediment quality and microbial communities.

CRediT authorship contribution statement

Ting Wang: Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Xiaoshang Ru:** Conceptualization, Supervision, Funding acquisition. **Beini Deng:** Investigation. **Chenxi Zhang:** Investigation. **Xu Wang:** Investigation. **Bo Yang:** Supervision. **Libin Zhang:** Conceptualization, Methodology, Supervision, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare no competing or financial interests.

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Appendix A. Supplementary data

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