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The impact of wind farm construction on swimming animals in the South Yellow Sea: An evaluation based on the biodiversity and microplastics

Jincheng He [a,1], Kexin Song [d,e,1], Ying Chang [a], Xin Wang [a], Weijia Song [a], Shuo Wang [a], Ruilin Zhang [a], Zhihua Feng [a,b,c,*]

[a] Jiangsu Key Laboratory of Marine Bioresources and Environment, Jiangsu Ocean University, Lianyungang, 222005, PR China
[b] Co-Innovation Center of Jiangsu Marine Bio-industry Technology, Jiangsu Ocean University, Lianyungang, 222005, PR China
[c] Key Laboratory of Coastal Salt Marsh Ecology and Resources, Ministry of Natural Resources, Jiangsu Ocean University, Lianyungang, 222005, PR China
[d] Analytical Instrumentation Center, Institute of Deep-sea Science and Engineering, Chinese Academy of Sciences, Sanya, 572000, PR China
[e] University of Chinese Academy of Sciences, Beijing, 100190, PR China

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ABSTRACT

Wind farms (WFs) have grown significantly in recent years, especially in the offshore. However, their construction can adversely affect marine life and expose species to microplastics (MPs) pollution, posing a threat to human health through seafood consumption. In order to further understand the impact of WF construction activities on swimming animal resources and the accumulation of MPs ingested by dominant economic species occupying significant ecological niches, this study investigated changes in swimming animal resources over six periods during three years of WF construction in the South Yellow Sea and evaluated MPs ingestion in three economically valuable dominant species (*Portunus trituberculatus*, *Collichthys lucidus*, and *Coilia nasus*) before and after construction. The study found that the most significant negative impacts on swimming animal resources occurred during the early construction stages, with recovery observed as construction finished. By the operational phase in autumn 2021, all indicators had exceeded pre-construction levels from spring 2019, except for biomass, which had not fully recovered. MPs were identified in every biological sample, and the MPs contamination in the gills was higher than that in the gut and skin tissues. The average abundance of MPs and the overall MPs hazard index of the three organisms were higher than those in other areas and pre-construction levels. WF construction in the South Yellow Sea caused short-term negative impacts on swimming animal resources with long-term recovery, but the increased MPs pollution during the construction process requires continuous monitoring and management to achieve sustainable development.

1. Introduction

Offshore wind power, utilizing marine spaces and abundant wind resources, offers carbon-free electricity, reduces reliance on fossil fuels, lowers emissions, and supports global climate change mitigation (Zhang et al., 2020; Belachew et al., 2023). In the field of clean energy advancement, offshore wind power has emerged as a vital energy resource for many nations in their endeavor to promote worldwide carbon neutrality, owing to its significant capacity, exemplary efficiency, and other advantageous attributes (Hernandez et al., 2014; Li et al., 2020; Ren et al., 2024). In recent years, the growing demand for renewable energy has accelerated the rapid development of China's offshore wind power sector (Lu et al., 2015). By 2018, the country's cumulative installed capacity of wind power accounted for 35.7% of the global total, establishing its position as a leader in the industry (Zhang et al., 2020). According to estimates from the IEA, 2019, global offshore wind power capacity is projected to reach 560 GW by 2040. Wind farms (WFs) meet the substantial demand for energy, but also brings about a multitude of issues. The impact of WF operations on marine organisms, including fish, marine mammals, and seabirds, cannot be overlooked

Abbreviations: WF, wind farm; MPs, microplastics; OWF, outside of the wind farm; *P trituberculatus*, *Portunus trituberculatus*; *C lucidus*, *Collichthys lucidus*; *C nasus*, *Coilia nasus*; PS, polystyrene; PET, polyethylene terephthalate; RY, rayon; CE, cellulose; PP, polypropylene; PE, polyethylene.

* Corresponding author. Jiangsu Key Laboratory of Marine Bioresources and Environment, Jiangsu Ocean University, Lianyungang, PR China.
E-mail address: fengzhihua@jou.edu.cn (Z. Feng).

[1] These authors have contributed equally to this work and share first authorship.

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(Ren et al., 2021; Rezaei et al., 2023). WF construction processes, such as the removal and alteration of the seabed, may release particles that can cause habitat disturbance. This includes sediment dispersal and deposition, which can affect seabed geomorphology and benthic biota (Hernandez et al., 2021).

The rapid socioeconomic progress of coastal regions and the escalating implementation of WF and other marine initiatives will not only cause modifications to marine ecological elements, but also have consequences on the distribution of marine animal populations, thereby influencing the biodiversity within the maritime (Bulleri and Chapman, 2010; Bergström et al., 2014; Wang et al., 2024). Swimming animals are vital to the marine ecosystem and coastal economies, but they are at risk from human activities that could impact their survival and ecological balance (Nagelkerken et al., 2023). The modification in the composition of swimming animals communities holds significant potential to exert a substantial impact on the overarching equilibrium of marine ecosystems (Knap et al., 2002; Zhong et al., 2020).

Ever since the discovery of plastics in the preceding century, they have been extensively employed in diverse (Andrady and Neal, 2009). Given the rising need for plastic commodities, the worldwide plastic manufacturing surpassed 390 million metric tonnes in the year 2021 (Plastics Europe, 2022). As a result of insufficient management practices, the existence of plastic pollution in the marine environment has emerged as a substantial peril to the marine ecosystem, thus instigating profound anxieties surrounding of this environment. Microplastics (MPs), which are plastics less than 5 mm as defined by Thompson et al. (2004), have gained significant attention as an emerging pollutant. In the context of WF construction, potential MPs pollution may occur during construction and operation (Liu and Gao, 2014; Gao et al., 2023).

Thus far, the presence of MPs has been widely detected and monitored across worldwide, encompassing diverse environmental mediums such as water and sediment (Liang et al., 2023; Song et al., 2023a, 2023b; Al-Tarshi et al., 2024). MPs were also found in various marine plants and animals due to accidental ingestion, adsorption, and other factors (Feng et al., 2020; Zhang et al., 2022; Salomone et al., 2023; Song et al., 2024a). Feng et al. (2019) have provided evidence to substantiate the phenomenon of MPs accumulation in the gills, gut, and skin of fish. Crustaceans, specifically crabs, as plentiful marine benthic organisms, assume a fundamental responsibility in upholding the efficacy and constancy of benthic ecosystems (Jonah et al., 2015; Zhang et al., 2021; Wang et al., 2023a). As a crucial link in the marine food chain, fish play an irreplaceable role in maintaining ecosystem balance and stability through predator-prey interactions, while providing essential food sources and ecological interactions for other organisms (Siple et al., 2021; Dişa et al., 2024). The accumulation of MPs in the biological bloodstream and digestive tract has the potential to cause obstruction and physical harm if not gradually removed (Cheng et al., 2022; Li et al., 2023a; Das, 2023). Hence, the pollution caused by MPs poses a prospective threat to both human health and the stability of ecosystems.

However, there have been few studies conducted on the impact of WF construction on swimming animals and MPs pollution. Therefore, the primary objectives of this study were 1) to investigate the effects of WF construction on swimming animal resources and biodiversity; 2) to explore levels of MPs abundance in important economic swimming animal species in and outside the WF before and after construction were detected, and the MPs pollution risk index was evaluated.

2. Materials and methods

2.1. Sampling strategy

Swimming biological samples were collected in the South Yellow Sea within and outside the WF region during six periods from 2019 to 2021 (Fig. 1). The period of investigation was in the spring of 2019, followed by the construction period from autumn 2019 to autumn 2020, and finally the operation period in the spring of 2021. The catches were encapsulated, frozen and transported to a laboratory for species identification and analysis (Table S1). From the captured swimming animal

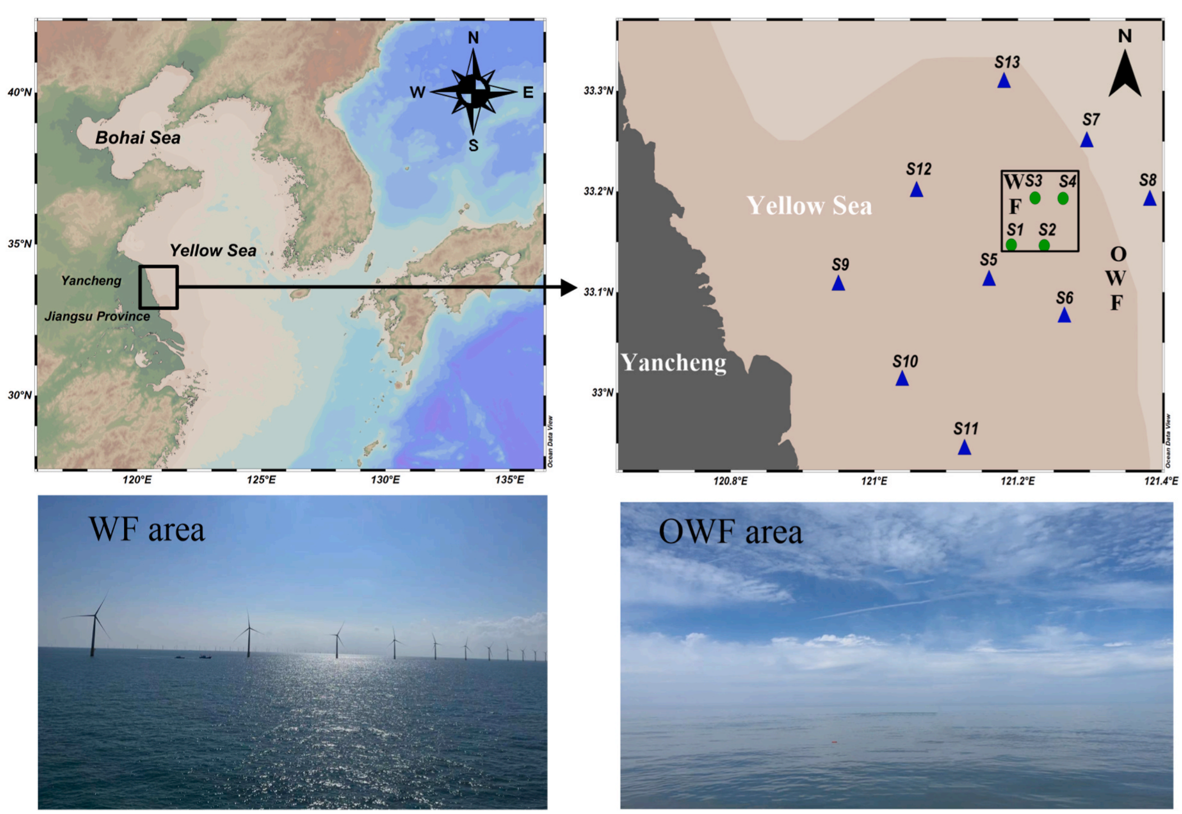

Fig. 1. The map displays sampling stations in the South Yellow Sea, China.

samples, we selected the three most dominant species, *P. trituberculatus*, *C. lucidus*, and *C. nasus*, to assessed their MPs pollution characteristics before and after the construction of WF (Table S2). We assessed MPs pollution in three swimming animals before and after WF construction at four stations (S1-S4) in spring 2019 and at eight stations in the WF (S1-S4) and outside of the wind farm (OWF) (S5-S8) regions in spring 2021 after the construction period of the WF. These species, selected for their ecological importance and research alignment, are highly representative and critical for evaluating environmental changes. They offer distinct functional roles and economic value, providing a comprehensive assessment of ecological impact.

The swimming animal resources were investigated according to the technical standards of marine fishery resources investigation. We used a new Agassiz trawl (2.2 m × 0.65 m × 4 m; mesh size 20 mm) for bottom trawl sampling at thirteen locations, with each site being trawled at a speed of about 3 knots for 60 min. When the trawling was completed, the catch was brought on board using a winch. The contents of the catch were transferred from the trawl to a large screen with a mesh size of 5 mm. Seawater, supplied by the onboard water pipes, was used to wash the screen. After cleaning, the biological samples were collected for further processing. Samples were collected in the field, frozen and stored, and brought back to the laboratory for species identification and classification. The collection, preservation and measurement of samples refer to GB/T 12763.6–2007 Standard for Marine Biological Survey.

2.2. Quality control

During the six sampling phases, a new trawl was used for each trawl operation to prevent pollution. All instruments and equipment underwent three rinses with deionized water. Throughout the experiment, participants wore white cotton clothing and blue nitrile gloves. The dissection time of each organism was limited to 5 min to reduce pollution caused by air deposition (Feng et al., 2019). Before usage, the solutions underwent meticulous filtration utilizing a 2.7 μm glass microfiber membrane. The process of solution preparation and sample dissection occurred within a laminar flow cabinet (SW-CJ-2F, SUJING, China). During sample processing, six procedural blanks were created to assess potential MPs contamination in the laboratory environment. The results indicated that the control group was free of MPs.

2.3. Sample dissection and digestion

Following thawing, the organisms underwent a gentle cleansing with distilled water for the purpose of eliminating any impurities and sediment adhering to their surfaces. Before the construction of WF in the spring of 2019, there was no anatomical analysis of the organs of the three organisms. In the spring of 2021, after the completion of the WF construction, the organs of three organisms were processed and analyzed. The organs were weighed and carefully arranged in a 250 mL beaker and subsequently sealed with tin foil. Following previous methods (Zhang et al., 2021; Song et al., 2022), tissue samples were soaked in 100 mL 10% KOH at 40 °C for 48 h. After cooling, the solution was filtered through a 2.7 μm glass microfiber membrane into a sterile Petri dish and dried at room temperature for further observation.

2.4. Observation and identification of MPs

A Nikon SMZ 1500 N stereomicroscope sourced from Japan, accompanied by a CCD camera, was employed to undertake visual observation, measuring, and photography of the dimensions, color, and morphology of MPs. Particles exhibiting distinctive biological characteristics were omitted from the examination. Around 30% of the membranes were subjected to random sampling in order to ascertain the material composition of MPs. Suspected MPs were examined utilizing micro-Fourier Transform Infrared Spectroscopy (μ-FT-IR) through the utilization of the Nicolet iN10 instrument manufactured by Thermo Fisher Scientific, America. Data analysis was carried out using the OMNIC software. The spectral range utilized for analysis ranged from 650 to 4000 cm^{-1}, with a total of 64 scans performed for each measurement. Polymers exhibiting a spectral similarity surpassing the threshold of 70% were identified as MPs in accordance with the research conducted by Cai et al. (2019).

2.5. Hazard index assessment

The MPs polymers hazard index (H) was utilized to evaluate the pollution risk posed to swimming animals as a result of MPs polymers. The specific formula is as follows (Lithner et al., 2011)

$$H = \Sigma M_i \times S_i \tag{1}$$

The hazard index (H) of the materials was assessed in relation to the percentage (M_i) and hazard ranking score (S_i) of MPs made from various materials. Lithner et al. (2011) reported S_i values for different materials, including polystyrene (PS), polyethylene terephthalate (PET), polyester, rayon (RY), cellulose (CE), polypropylene (PP), polyethylene (PE), and Nylon, which were determined to be 30, 4, 1414, 0, 0, 1, 11, and 0, respectively.

2.6. Statistical analysis

To examine the biodiversity in the South Yellow Sea region of China, an analysis was conducted using the Shannon-Wiener index (H') (Krebs, 1989), Margalef richness index (D) (Margalef, 1958), and Pielou evenness index (J) (Pielou, 1966).

The specific formula is as follows：

$$H' = -\sum_{i=1}^{s} p_i \ln \rho_i \tag{2}$$

$$D = \frac{s-1}{\ln N} \tag{3}$$

$$J = \frac{H'}{\ln s} \tag{4}$$

Where P_i is the proportion of the biomass of the i species to the total biomass (n_i/N), S is the total number of species, and N is the total mantissa.

To identify significant changes in community structure, abundance/biomass curves (ABC curves) were used to offer a sensitive response to any physical, biological, and pollution disturbance-induced changes in the biological community (Clarke and Warwick, 2001a). W represents the relative relationship between mantissa and biomass in ABC curve, and the calculation formula is as follows:

$$w = \sum_{i=1}^{s} \frac{Bi - Ai}{50(s-1)} \tag{5}$$

Where, B_i is the percentage of the biomass of the i species in the total biomass, A_i is the percentage of the mantissa of the i species in the total mantissa, and S is the number of total species. When the biomass dominance curve is above the mantissa dominance curve, W is positive; otherwise, W is negative, and the value range is [-1, 1]. When W tends to 1, the species composition is not disturbed. When W approaches 0, the species composition is moderately disturbed. When W tends to −1, it indicates that species composition is seriously disturbed.

Furthermore, bioclustering features were investigated through the utilization of Bray-Curtis similarity cluster analysis (Cluster) (Field et al., 1982) and non-metric multidimensional scaling (NMDS) ordination analysis (Clarke and Warwick, 2001b). When the stress coefficient <0.05, the anastomosis is very good. Stress coefficient <0.10 indicates good coincidence; Stress coefficient <0.20 indicates general coincidence; Stress coefficient >0.30 indicates poor anastomosis.

The statistical analysis was conducted employing the SPSS v.27 software. The data were expressed as mean ± SD (standard deviation). Each treatment group exhibited a normal distribution (Shapiro-Wilk, $P > 0.05$) and equal variances (Levene's test, $P > 0.05$). A one-way ANOVA was utilized to compare the abundance of MPs across various time periods. Independent sample t-tests were utilized to examine differences in MPs abundance between biological tissues in the two regions following the construction of WF. In order to determine the relationship between the weight of biological material and the abundance of MPs, Pearson correlation analysis was conducted. Moreover, all the conducted analyses were accompanied by the computation of 95% confidence intervals.

3. Results

3.1. Impact of WF construction on swimming animal resources

3.1.1. Biomass and abundance

In terms of temporal variation, there was a significant decline in biomass during the early stages of construction in autumn 2019. However, the biomass gradually recovered after the completion of construction in autumn 2020 (Fig. 2). The highest average biomass (730.48 kg/km^2) was observed in the spring of 2019, before the construction of the WF building. Biomass reached its lowest point in autumn 2019, measuring at 190.12 kg/km^2 at the beginning of the construction period. It then gradually increased from autumn 2019 and recovered to 617.04

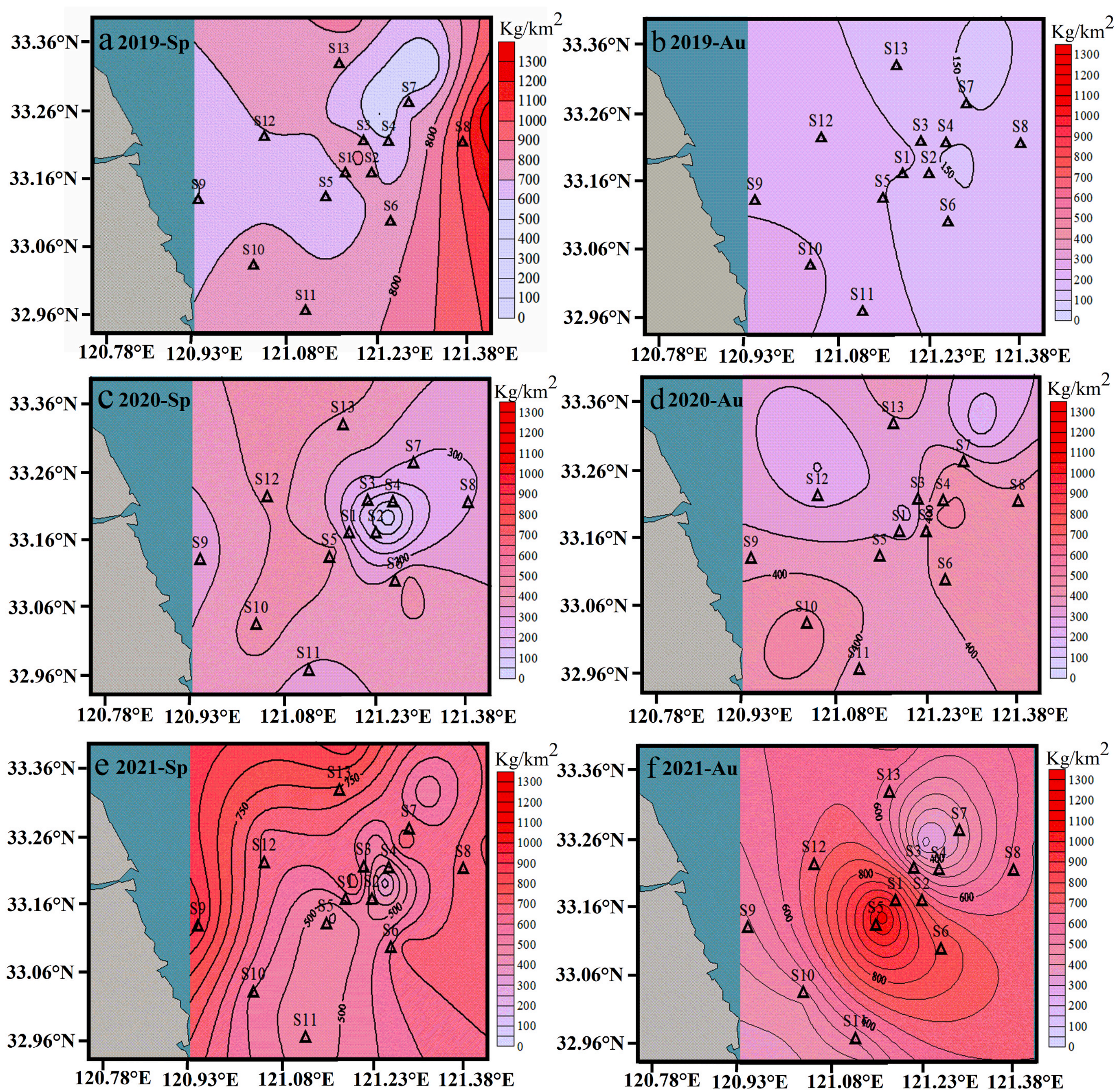

Fig. 2. Contour distribution of biomass in the South Yellow Sea area varies across different seasons: The pre-construction period was spring 2019 (2019-Sp), the construction period was Autumn 2019 to Autumn 2020, and the operation period was spring 2021 (2021-Sp) to spring 2021 (2021-Au).

kg/km^2 by spring 2021.

A similar tendency can be found in the analysis of temporal variation of abundance (Fig. S1), the lowest abundance among the six batches surveyed was observed in autumn 2019 at the beginning of the construction period of WF construction (2445.96 ind/km^2). The abundance gradually increased with temporal changes, reaching its peak in autumn 2021 at 12836.44 ind/km^2. The abundance levels of the three batches from autumn 2020 to autumn 2021 were all higher, with an average abundance of 11582.85 ind/km^2.

3.1.2. Biodiversity

The diversity index for WF areas ranged from 0.68 to 2.27, while for other areas it varied from 0.70 to 2.55. The evenness index of the WF area ranged between 0.33 and 0.84, while the richness index varied from 0.8 to 2.84 across other areas. The WF diversity index reached its peak in autumn 2021, while the lowest point was observed in autumn 2019, indicating an overall downward trend followed by an upward trend. The trends in the evenness and richness indices were generally consistent with the diversity index (Fig. 3). Diversity and evenness indices exhibited significant differences ($P < 0.05$) between the WF and OWF areas in spring 2019. Additionally, a notable variance ($P < 0.05$) was noted in the richness index between the WF and OWF areas in autumn 2019. Furthermore, only the diversity indices of the OWF was significantly different between the pre-construction period and the post-construction period ($P < 0.05$).

3.1.3. Analysis of biome structure before and after the construction of WF

The utilization of both the Bray-Curtis similarity cluster analysis and NMDS ordination analysis demonstrated that swimming organism taxa in the study area of the South Yellow Sea exhibited the formation of two primary clusters across the six study phases. Group 1 was assigned for the semesters of Spring (2019), Spring 2021; Autumn 2021, while Group 2 was designated for Autumn 2019, Spring 2020; Autumn 2020 (Fig. 4a). The stress coefficient of the spatial structure of the community of swimming animals was 0.0377, indicating that the results were well representative (Fig. 4b). The results of NMDS sequencing and cluster analysis were relatively consistent, and the results showed that the non-construction period: spring 2019, spring 2021 and autumn 2021 clustered into one branch, and the construction period: autumn 2019, spring 2020 and autumn 2020 also clustered into one branch.

The ABC curve (Fig. 5) results showed that the biomass curve was consistently above the abundance curve in spring 2019, spring 2021, and autumn 2021. The abundance curve for autumn 2019 is positioned above the biomass curve, while both the spring 2020 and autumn 2020 biomass curves partially intersect with the abundance curve. In addition, the W values in the autumn 2019 (W = 0.047), spring 2020 (W = 0.010), and autumn 2020 (W = - 0.019) during the construction period were all lower than those in the spring 2019 (W = 0.085), spring 2021

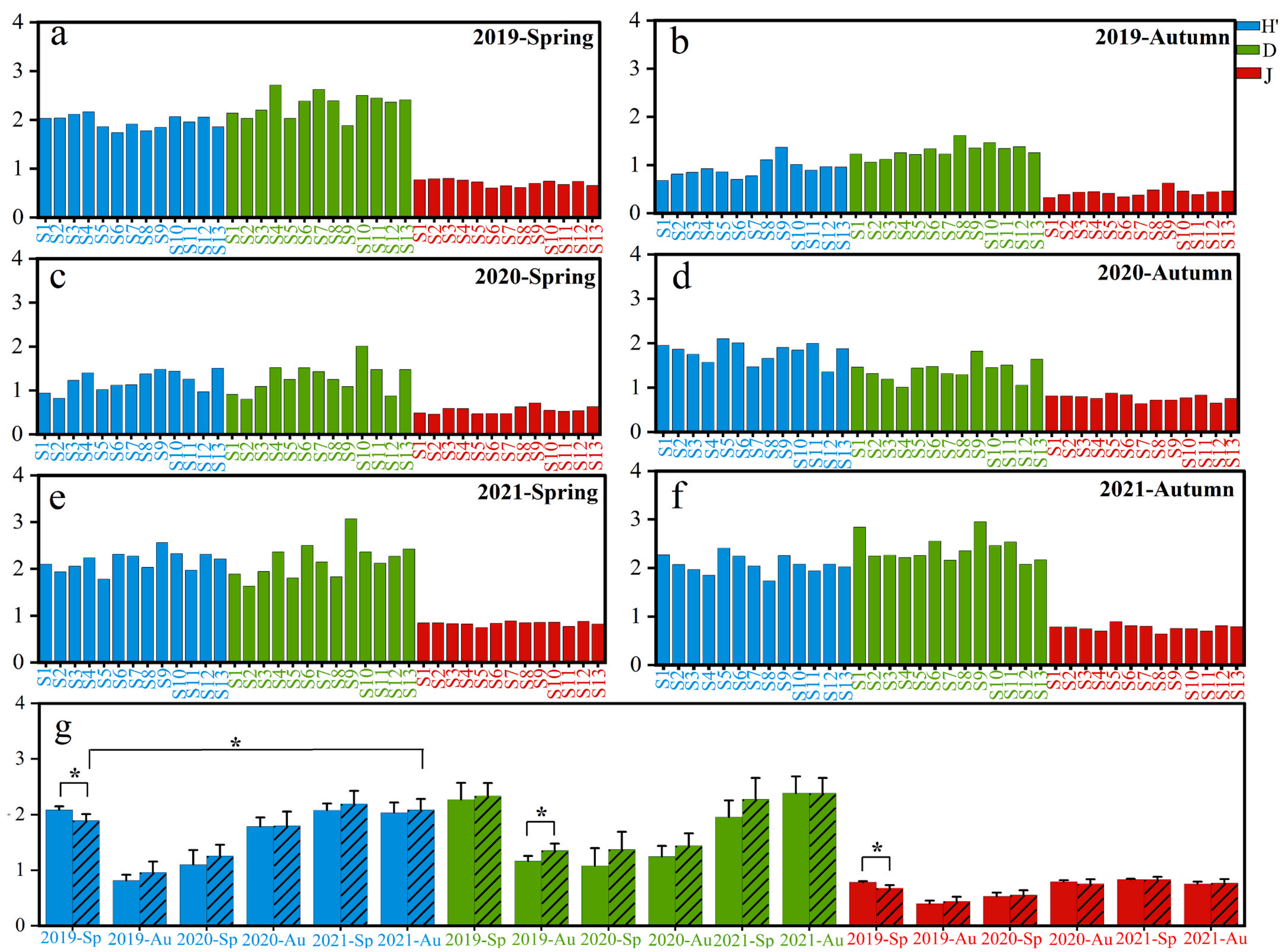

Fig. 3. The figure illustrates alterations in species diversity indices. H′ denotes the Shannon diversity index, D signifies the Margalef richness index, and J represents the Pielou evenness index. The areas denoted by S1-S4 encompass WF regions, whereas S5-S13 correspond to OWF regions. In the fig g, slanted lines indicate OWF areas, while those without slashes represent WF areas. * denote significant differences at a confidence level of below 0.05.

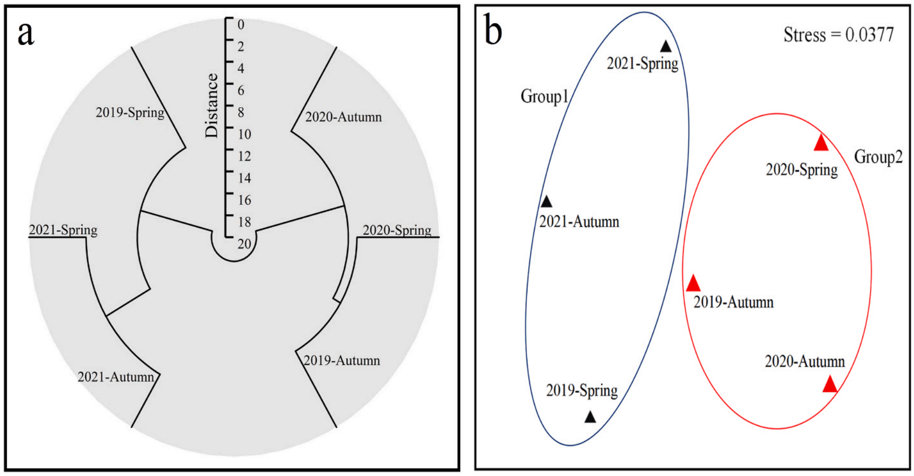

Fig. 4. Graph of cluster analysis and NMDS analysis.

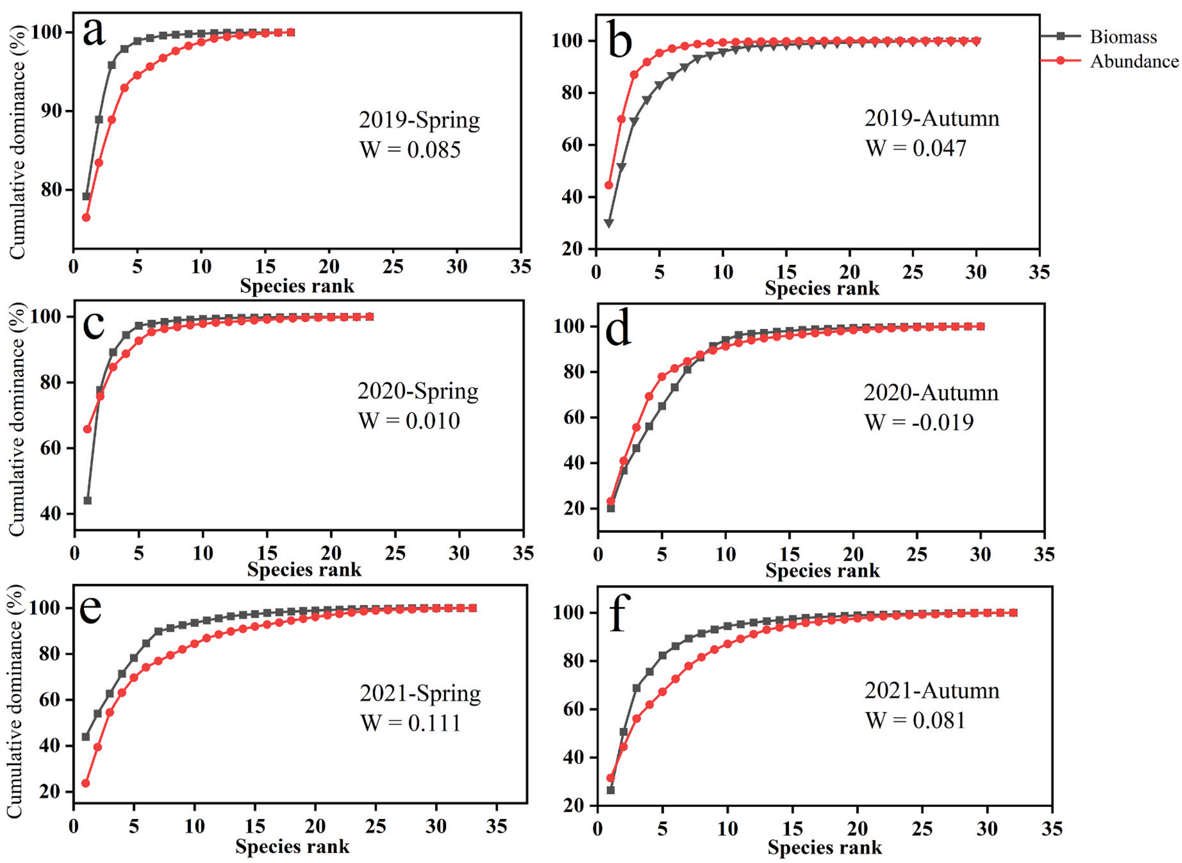

Fig. 5. ABC plots of swimming organisms in different seasons. The W value is a statistical value for curve evaluation, where two curves intersect or overlap, and the closer the W value is to 0, the more disturbed the community is.

(W = 0.111), and autumn 2021 (W = 0.081) during the non-construction period, and the W values in the construction period were more close to or less than 0, indicating that the degree of species disturbance in the non-construction period was lower than that in the construction period.

3.2. Impact of WF construction on MPs pollution characteristics

3.2.1. Distributional characteristics of MPs abundance

The average abundance of MPs in swimming animals within the WF area (8.98 ± 5.58 items/individual) was significantly higher compared to the OWF area (5.64 ± 3.36 items/individual) and pre-construction levels (5.27 ± 2.12 items/individual). The results demonstrated that the mean abundance of MPs for the three species in the WF region surpassed that of the OWF region and pre-construction levels, as measured by items/individual and items/g (Fig. 6a and b). The abundance of *P. trituberculatus* was greater in the WF compared to the OWF and pre-construction. However, there were no statistically significant differences ($P > 0.05$) observed in terms of items per individual and items per gram. *C.lucidus* had a higher average abundance of MPs in the WF compared to the OWF and pre-construction, both in terms of items/individual and items/g. The average abundance of MPs in *C.lucidus* was

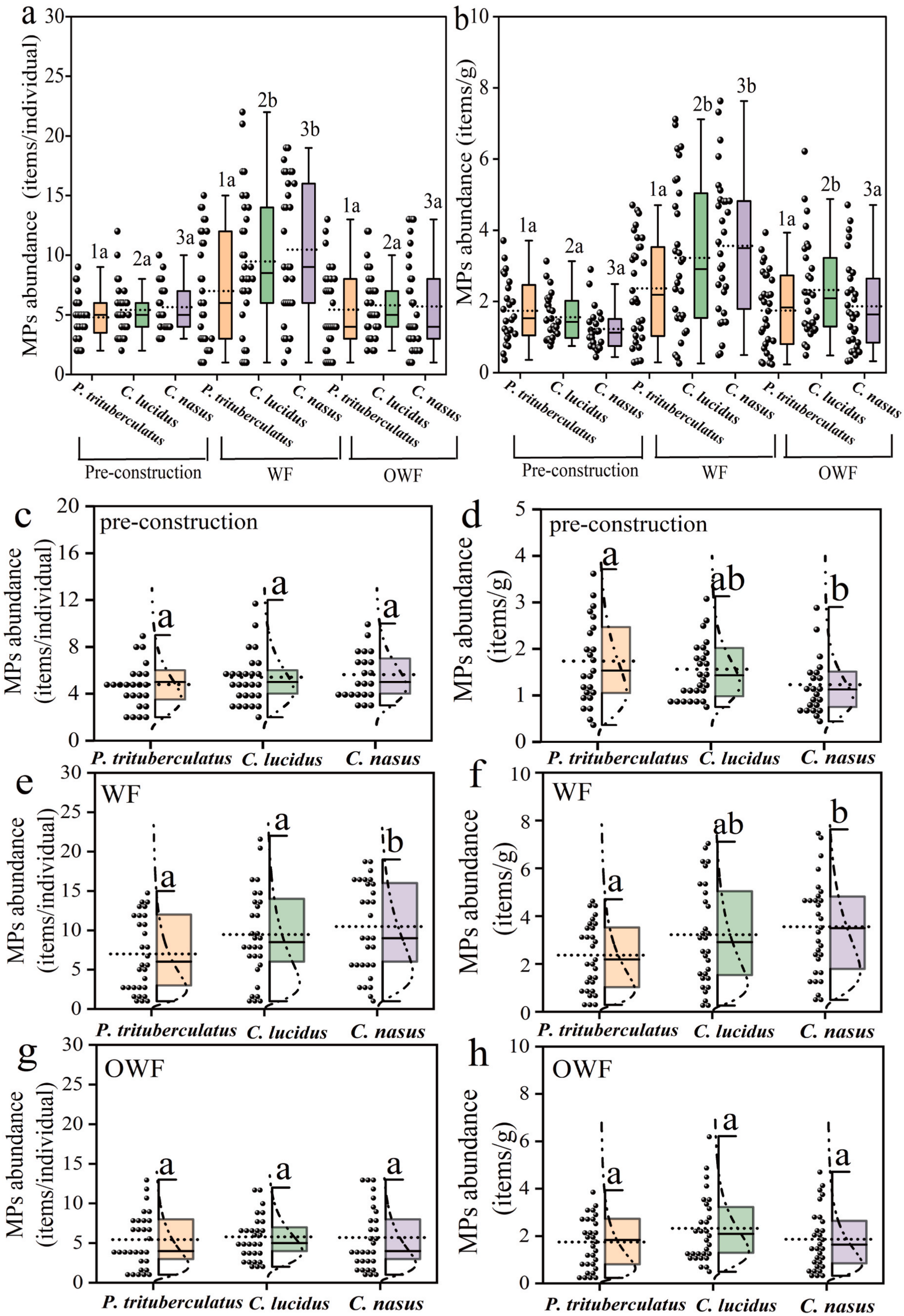

Fig. 6. The abundance of three species was assessed at different time intervals, quantified in terms of items/individual (a) and items/g wet weight (b) with mean ± standard deviation values. The abundance of MPs for each species at the same locations was determined in terms of items/individual (c, e, g) and items/g wet weight (d, f, h). Significant differences were indicated by distinct letters above the bar, while the absence of significant differences was represented by the same letter. The mean and median values were depicted by the black dashed and solid lines, respectively.

found to be significantly lower ($P < 0.05$) before the construction and the OWF region after construction, compared to the WF region in terms of items/individual. However, there was no significant difference ($P > 0.05$) in the average abundance of MPs per gram between the WF and OWF areas after construction, but both were significantly higher than before construction ($P < 0.05$). The average abundance of MPs in the WF area for *C. nasus* was significantly different from before WF construction and in the OWF area ($P < 0.05$) on an individual/individual and items/g basis.

Before the construction of WF, the abundance of MPs varied among the three species in the same area. *C. lucidus* and *C. nasus* had a higher MP abundance in terms of items/individual compared to *P. trituberculatus* (Fig. 6c). Nevertheless, the three organisms exhibited comparable results, with no statistically significant distinction present ($P > 0.05$). However, in terms of items/g (Fig. 6d), *P. trituberculatus* exhibited a greater presence of MP than *C. lucidus* and *C. nasus*, with a significant disparity observed between *P. trituberculatus* and *C. nasus* ($P < 0.05$). In the WF region, the mean abundance of MPs for *C. lucidus* and *C. nasus* surpassed that of *P. trituberculatus* in terms of both items/individual and items/individual (Fig. 6e and f). The average abundance of MPs in *P. trituberculatus* and *C. lucidus* was significantly lower than in *C. nasus* when calculated for items/individual ($P < 0.05$). Furthermore, the mean abundance of MPs from *P. trituberculatus* was significantly lesser than that of *C. nasus* when measured in terms of items per gram ($P < 0.05$, Fig. 6e). Within the OWF, there was no notable distinction in the mean abundance of MPs between *C. lucidus* and *C. nasus* when compared to that of *P. trituberculatus* ($P > 0.05$, Fig. 6g and h).

3.2.2. MPs abundance in different biological tissues

MPs were detected in the selected tissues of all three organisms, and the characteristics of MPs contamination varied among different tissues. The gills had the highest amount of MPs, followed by the gut, and then the skin with the lowest amount. There was no significant difference in the mean abundance of MPs in the gills and gut of *P. trituberculatus* between the WF and OWF areas ($P > 0.05$) in terms of items/individual (Fig. S2a) or items/g (Fig. S2d). However, for *C. lucidus* (Fig. S2 b, e), the mean abundance of MPs in the skin was significantly lower ($P < 0.05$) in the OWF area compared to the WF area in terms of items/individual. The mean abundance of MPs in the gills of *C. lucidus* was also noticeably diminished ($P < 0.05$) in the OWF in comparison to the WF, both in terms of items/individual and items/g. Moreover, the average abundance of MPs in the digestive tract of *C. lucidus* was substantially lower in the OWF area than in the WF area ($P < 0.05$) when calculated as items per individual. As for *C. nasus*, the mean abundance of MPs in the skin, gills, and digestive tract at the OWF was significantly lower ($P < 0.05$) than that at the WF, regardless of whether it was measured as items per individual (Fig. S2c) or items per gram (Fig. S2f).

A examination of the data through correlation analysis has uncovered a significant and positive association between the weight of gills and the overall abundance of MPs in *P. trituberculatus* within the WF region ($P < 0.05$, Fig. S3a). Similarly, in the WF area, there were significant positive correlations between skin weight and MPs abundance per item per individual ($P < 0.05$, Fig. S3b), as well as per item per gram ($P < 0.05$, Fig. S3c) of *C. lucidus*. In the WF region, a significant and robust inverse relationship ($P < 0.01$, Fig. S3e) was observed between the gut weight of *C. lucidus* and the quantity of MPs present per item. Within the OWF region, a noteworthy association ($P < 0.05$, Fig. S3d) was observed between the skin weight in *C. lucidus* and the abundance of MPs per individual. In addition, a profoundly significant negative relationship ($P < 0.01$) was witnessed between the gut weight and the abundance of MPs (items/g) within *C. lucidus* in the OWF area (Fig. S3f).

3.2.3. MPs characteristics in swimming organisms

In all three organisms, the presence of MPs of different colors was observed, and these identified and isolated MPs were classified into five distinct color groups: red-pink, yellow-orange, white-transparent, blue-green, and black-gray (Fig. 7a). Before construction and in WF and OWF after construction, MPs were mainly black-gray, accounting for 41.93%, 68.56% and 59.13% respectively, followed by blue-green, 32.55%, 14.73% and 18.06% respectively. After comparison, it was determined that the proportion of black-gray in WF sea area was higher than that of OWF and pre-construction, but the proportion of blue-green in WF area was lower than that of OWF and pre-construction. In addition, the percentage of yellow-orange (15.67%) and red-pink (3.97%) in OWF was higher than the proportion of yellow-orange (9.28%) and red-pink (2.85%) in WF and the proportion of yellow-orange (5.73%) and red-pink (2.60%) before construction.

The shapes of MPs were categorized into four categories: fibers, fragments, films, and foams (Fig. 7b). The shape distribution of the three organisms was similar, with fibers and fragments being the most abundant, and foams being the least abundant. Before construction and in WF and OWF after construction, MPs were mainly fibers, accounting for 52.60%, 63.93% and 67.33% respectively, followed by fragments, 31.25%, 23.01% and 20.59% respectively. The proportion of fibers in WF and the proportion of fibers in OWF were both higher than the proportion of fiber before construction. In addition, the percentage of foams (3.91%) before construction was higher than the proportion of foams (0.75%) in the WF and the proportion of foams (0.99%) in the OWF.

Before the construction, seven major polymers (Fig. 7c), PE (22.4%), PET (15.5%), PP (13.8%), Nylon (12.1%), CE (10.3%), Polyester (6.0%) and PS (5.1%) were detected, with PE accounting for the highest percentage. After the construction, CE (39.3%) and RY (19.8%) accounted for the highest proportion of polymers in the WF zone. However, the proportion of CE (34.9%) and PET (22.4%) in the OWF region was the highest. Before the construction, the hazard index of MPs for *P. trituberculatus*, *C. lucidus*, and *C. nasus* was evaluated as 120, 76, and 53, respectively, using a specific formula. In the WF area, the hazard index of MPs for *P. trituberculatus*, *C. lucidus*, and *C. nasus* was evaluated as 346, 251, and 201, respectively. In the OWF area, the hazard index of MPs for *P. trituberculatus*, *C. lucidus*, and *C. nasus* was evaluated as 238, 195, and 217, respectively (Fig. 7d). The analysis of *P. trituberculatus*, *C. lucidus*, and *C. nasus* revealed a similar trend in the size distribution of MPs in all three organisms (Fig. S4). MPs smaller than 1000 μm were the most common size category for each organism, whereas MPs sized between 4000 and 5000 μm were the least abundant. As the size increased, there was a gradual decline in the quantity of MPs across all three.

4. Discussion

4.1. Impact of WF construction on biological resources

In terms of temporal changes, there was a significant decrease in biomass, abundance, and biodiversity during the initial construction phase in autumn 2019. The indicators remained at a low level during the subsequent construction phase, indicating that the biological community was affected by the construction of the WF. This may include noise from wind turbine pile driving that drives away swimming animals or increased suspended solids brought up by construction-induced churning of the water column, which can affect fish behavior (Debusschere et al., 2014; Bray et al., 2016; Causon and Gill, 2018; Wang et al., 2024). Destruction of sensitive habitats, such as submarine structures, during construction activities such as piling and laying of submarine cables may also result in a decrease in biomass in these areas (Hernandez et al., 2021; Coolen et al., 2022).

The NMDS sorting results were in line with the cluster analysis results, further confirming the validity of the cluster analysis outcomes. Furthermore, the ABC curves and the W-value were employed in order to evaluate the influence of environmental factors and disturbance levels on the biomes. From autumn 2019 to autumn 2020, the biomass curve intersected the abundance curve, indicating potential disturbance and ongoing impacts at the station. However, from spring 2021 to autumn

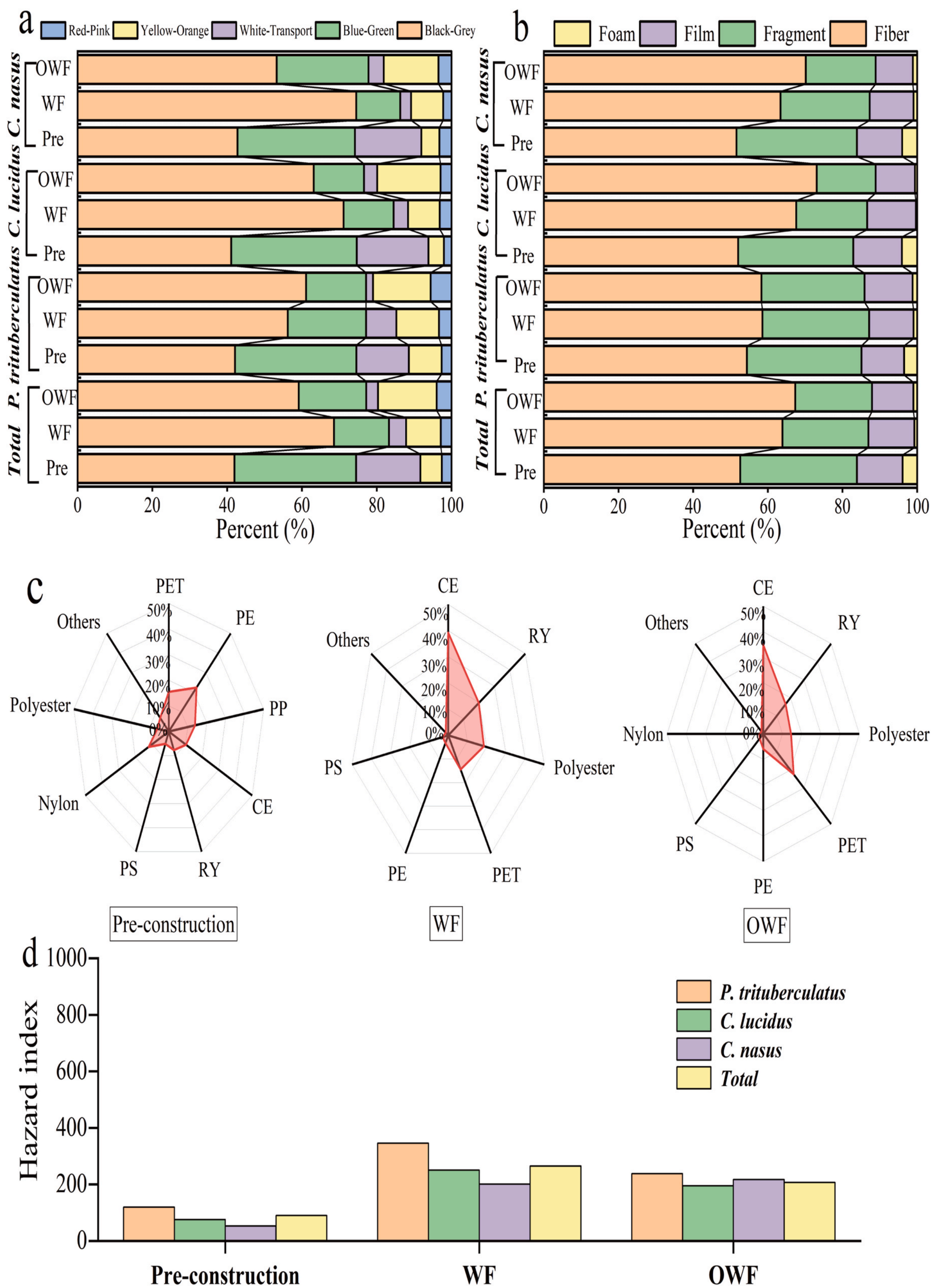

Fig. 7. Color (a), shape (b), material (c) distribution of the MPs of the three species and Hazard index (d).

2021, there was a gradual stabilization and reduced disturbance observed. The W value showed that the influence of disturbance in non-construction period was lower than that in construction period. The aforementioned findings offer further evidence demonstrating that the organisms in the sea area of the WF are impacted by human disturbance resulting from WF construction.

This study found that due to the reduction and completion of WF construction operations, the biomass, abundance and diversity index of swimming organisms in the South Yellow Sea showed significant recovery from the autumn of 2020. By the autumn 2021 operating period, all metrics have largely recovered or exceeded spring 2019. The impacts on biological resources may be summarized as short-term negative impacts, followed by long-term positive impacts. Previous studies have shown that the foundations of wind turbines in WF area can create an artificial reef-like effect, attracting algae and aquatic plants which then attract other organisms, leading to increased biodiversity in the region (Degraer et al., 2020; Werner et al., 2024). Langhamer et al. (2016) concluded that the establishment of new offshore wind energy installations would create new hard habitats for marine organisms, leading to the formation of artificial reefs and an increase in biodiversity. WF construction can serve as an artificial reef, positively affecting the biodiversity of the WF areas over the long term. This conclusion is in line with previous studies. Thus, the construction of WF initially reduced biomass, but by completion, biomass and diversity of swimming animals showed a noticeable increase due to the creation of new habitats on underwater structures, which act as artificial reefs, enhancing biodiversity over the long term (De et al., 2015).

4.2. Pollution characters of MPs in swimming animals

The study revealed that the abundance of *P. trituberculatus*, *C. lucidus*, and *C. nasus* was significantly higher in the WF region compared to the OWF region and prior to WF construction. This indicated that the construction activities in the WF area had contributed to an increase in MPs pollution. Compared to the OWF, the WF experienced more intensive human activities, leading to higher concentrations of MPs contamination in environmental media (Wang et al., 2018; Feng and Yu, 2023). During the construction of WF, a large amount of plastic waste, such as packaging materials and maintenance equipment, directly or indirectly entered the ocean, exacerbating MPs pollution (Hernandez et al., 2021). The construction of WF can cause changes in water flow and sediment distribution on the seabed, which in turn increases the shear stress on the seabed during low tide (Hammar et al., 2014; Wang et al., 2023b). This alteration can result in the migration and aggregation of MPs.

The abundance of MPs varied among the three typical swimming animals selected for this study in the same area. The ability of different species to accumulate MPs varies, and it is indirectly hypothesized that the structure of the biological community also influences the accumulation characteristics of MPs. The variation in MPs accumulation among different species was influenced by community structure, habitat stratification, and predatory behaviors (Srisiri et al., 2024). The transportation of MPs in the oceans is characterized by a process of sedimentation and suspension in disturbed water, which increases the risk of exposure to MPs for organisms near the ocean floor (Wang et al., 2019). In addition, animals with higher nutrient levels, due to their feeding habits and larger range of activities, lead to higher intake of MPs (Kangas et al., 2023). They accumulate MPs in their bodies due to biomagnification, resulting in a higher concentration of MPs (Wang et al., 2021a; Liao et al., 2023). Therefore, the abundance of MPs in the three species at the same site may vary depending on their ecological habits, feeding habits, habitat, behavioral patterns, and physiological characteristics. After construction, marine swimming organisms in the WF area exhibited a higher abundance of MPs and a greater MPs risk index compared to the pre-construction period and the OWF area. MPs primarily accumulate in the body, causing metabolic, hormonal, and immune disorders, and their capacity to absorb persistent organic pollutants amplifies ecological and human health risks (Guzzetti et al., 2018; Ma et al., 2020; Gao et al., 2021; Rafa et al., 2024).

A comparison of MPs abundance in the three organisms in the WF and OWF, on an items/g basis, found that MPs abundance was higher in both *C. lucidus* and *C. nasus* than in *P. trituberculatus*. It is hypothesized that the varying body weight sizes of organisms also influence the abundance of MPs. Correlation analysis in the WF indicated a positive relationship between MPs abundance and gill weight in *P. trituberculatus*, and between skin weight in *C. lucidus*, both per individual and per gram, while gut weight in *C. lucidus* showed a negative correlation with MPs per gram in both WF and OWF. Therefore, human consumption can avoid MPs contamination by removing gills and skin. Furthermore, gut weights of *C. lucidus* showed a negative correlation in both WF and OWF, in terms of items/g. Ji et al. (2023) also observed a significant negative correlation between the body weight, length, and the abundance of MPs in *Odontamblyopus rubicundus*. Furthermore, Song et al. (2024b) discovered a significant correlation between the abundance of MPs in shrimp and the length and weight of crustaceans. These studies suggest that larger organisms may have less MPs abundance, making them potentially safer for human consumption. Larger swimming animals, due to their strong selection and judgment abilities, rarely actively ingested MPs but may have accidently ingested them during hunting, typically excreting them without long-term accumulation (de Sá et al., 2015; Mazurais et al., 2015; Grigorakis et al., 2017). Additionally, MPs concentrations in high-trophic animals may be relatively low due to dilution effects in the food chain (Güven et al., 2017; Sun et al., 2019). Consequently, these larger animals are considered safer for human consumption.

Compared with MPs contamination in other marine organisms (Table S3), the abundance of MPs both inside and outside the WF area was higher than that in economic fish (2.14 $\pm$ 1.81 items/individual) in the Bohai Sea, China (Wang et al., 2021b). The abundance of MPs in the study area was higher than that of MPs in coral reef fishes (1.25 $\pm$ 2.36 items/individual) in the Xisha area of the South China Sea (Huang et al., 2023). It was also similar to the abundance of MPs in wild crabs (5.17 $\pm$ 4.43 items/individual) in the Yellow Sea and East China Sea fishing grounds (Zhang et al., 2021). However, it was lower than the abundance of MPs in hybrid grouper (35.36 $\pm$ 26.39 items/individual) in the Pearl River Estuary, southern China (Lam et al., 2022). Compared with other regions abroad, the abundance of MPs was higher than in the southwestern Atlantic *Patagonotothen guntheri* (2.50 $\pm$ 1.93 items/individual) (Ojeda et al., 2024) and higher than the abundance of MPs in economic marine fish (2.2 $\pm$ 0.89 items/individual) in the Bay of Bengal (Ghosh et al., 2021). It indicates that the WF construction area may experience a high level of MPs pressure.

This study discovered that fibers and debris were the most common types of MPs found in organisms. The study also revealed that the predominant colors of MPs were black-gray and blue-green. When comparing different locations, the percentage of black-gray MPs was higher in the WF compared to the OWF and pre-construction. Conversely, the percentage of blue-green MPs was lower. Furthermore, the proportion of fiber MPs was lower in the WF than in the OWF, while the proportion of debris MPs was higher in the WF compared to the OWF. Overall, it appeared that the MPs characterization in swimming organisms is similar in the WF and OWF. This could be due to the activities involved in wind farm construction, such as construction, ship traffic, and maintenance, which result in an increase in certain types of MPs. These disruptions may result in the buildup of MPs within organisms located within the construction area of the WF. The prevailing polymer types among the identified MPs in this study were CE and RY. These results are in agreement with previous studies by Wu et al. (2020) and Li et al. (2023b), which reported CE and RY as the predominant polymer types in economically significant species in Xiangshan Bay and the environment of Sishili Bay in the North Yellow Sea of China, respectively. In the sea area characterized by WF construction in the South Yellow Sea, swimming animals were found to have a wide range of MPs particle sizes. This study reveals that there is a significant negative correlation between the number of MPs and their size. Moreover, it was observed that smaller MPs were dominant, which aligns with the findings of Zhao et al. (2018). Larger pieces of plastic are constantly broken down into smaller particles in the environment and may be more easily absorbed by marine life.

4.3. Future perspectives

While offshore wind generates clean renewable energy and contributes to mitigating the effects of climate change, the human-disturbed processes associated with offshore wind construction can also pose problems. For instance, noise disturbances during WF construction, especially underwater noise generated during infrastructure installation (Bailey et al., 2014), may have adverse effects on marine organisms and nutrient levels in the marine food chain (Wang et al., 2024). For swimming animals, noise pollution can disrupt their coordinate systems, leading to alterations in migration patterns and disturbances in mating behavior. Moreover, the erection of piles is widely recognized as the most detrimental environmental activity linked to offshore wind energy advancement (Hammar et al., 2014). The construction of WF necessitates the placement of substantial infrastructure on the seabed, thereby posing direct implications for fisheries and benthic ecosystems (Bray et al., 2016; Maxwell et al., 2022). While developing wind power resources, minimize the negative impact on the Marine ecosystem, so as to achieve sustainable development. Therefore, in the process of WF construction, the best management measures can be adopted as far as possible to reduce the impact of construction on the environment, such as reducing noise during construction, reducing sediment disturbance, and controlling the emission of construction vessels. In addition, the impact of wind farms on marine ecosystems is constantly monitored during their construction and operation.

To enhance our understanding of the impacts of WF construction, future research must expand its scope to include more regions and ecosystems. It is crucial to further investigate the mechanisms of MPs accumulation and transfer across various species and ecosystems, particularly in light of the complex and dynamic environmental variables present in marine ecosystems, such as seasonal fluctuations and long-term climate changes. Establishing long-term monitoring mechanisms is essential for evaluating the ongoing effects of WF construction on marine organisms and MPs pollution, especially across different seasons and climates. Additionally, there should be a concerted effort to advocate for more stringent environmental policies and best management practices, ensuring that the development of WF is aligned with the sustainable health of marine ecosystems.

5. Conclusion

This study investigated the changes in biological resources of swimming animals in the South Yellow Sea before, during, and after the WF construction. Additionally, it examined the contamination of MPs in three economically important species due to WF construction before and after the completion, as well as the accumulation of MPs in various tissues. The construction of WF in the South Yellow Sea has demonstrated both immediate and long-term ecological impacts. Initial construction activities negatively affected swimming animal resources, but these populations showed significant recovery by the operational phase. However, the persistent and increasing MPs pollution in economically important species underscores the necessity for ongoing environmental monitoring and robust management strategies. The study underscores the necessity of a balanced approach to renewable energy development that protects marine biodiversity and human health. Future research should prioritize supporting renewable energy initiatives while minimizing their environmental impact.

CRediT authorship contribution statement

Jincheng He: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Kexin Song:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Ying Chang:** Methodology. **Xin Wang:** Investigation. **Weijia Song:** Methodology. **Shuo Wang:** Formal analysis. **Ruilin Zhang:** Data curation. **Zhihua Feng:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2024.120462.

Data availability

Data will be made available on request.

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