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The characteristics and potential transport trajectory of epimicroplastic red tide species in the Taiwan Strait

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Due to the carrier's role of microplastics, attached microalgae may be transported further, posing a threat to marine ecosystems, especially those red tide species. By combining the investigated results of Dongshan Bay and Quanzhou Bay with the simulation of transport trajectories using the Lagrangian particle tracking model, this study systematically investigated the characteristics and transport trajectories of epimicroplastic red tide species. Based on the investigations of Dongshan Bay and Quanzhou Bay respectively in summer of 2022, the characteristics of epimicroplastic red tide species were learned. Results showed that totally 13 red tide species were found in two bays, with 6 species in Dinophyta, 5 species in Diatom, 1 species in Ochrophyta and 1 species in Cyanophyta respectively. Also, the potential transport trajectories of epimicroplastic species were simulated to study their effect to the ecological environment of the surrounding waters. According to the simulated transport trajectories, those species could be transported further by microplastics while some particles would be obstructed during these three-month processes. During the transport processes, epimicroplastic red tide species from two bays would influence three provinces, which have high records of red tide outbreak in China. This study firstly combined models to investigate the potential transport trajectory of epimicroplastic red tide species, providing insights into the mechanisms of red tide outbreak.

KEYWORDS

microplastics, red tide species, particle tracking model, the Taiwan strait, transport trajectory

1 Introduction

Red tide (also known as harmful algal blooms, HABs) recorded with those proliferations of algae that can cause fish kills, or contaminate seafood with toxins, or form unsightly scums, or detrimentally alter ecosystem function have been increasing in frequency, magnitude, and duration worldwide (Glibert et al., 2014). There was a global increase in the frequency, magnitude, and geographic extent of HAB events over the preceding decades (Anderson et al., 2012). Generally, the expansion of red tide is used considered to be caused by ballast water transport, climate change and eutrophication (Anderson et al., 2012). In addition to eutrophication of seawater, there are many factors that affect the occurrence of red tide (Gao et al., 2024). Regions of convergence resulting from dynamic processes like tidal fronts, Langmuir circulation, and thermal convection can agglomerate organisms, significantly increasing plankton concentrations beyond those in surrounding waters (Gao et al., 2024). These physical mechanisms engender a transport impact on red tide organisms. In instances of vigorous wind and ocean current interplay, they also function as diffusion mechanisms (Steidinger and Haddad, 1981; Gao et al., 2024). To date, some researchers have suggested that floating plastics may play potential roles on the expansion of HABs (Wang et al., 2022; Do Prado Leite et al., 2022). Microplastics (MPs) are plastic particles smaller than 5 mm in size (Thompson et al., 2004; Rocha-Santos, 2018), which contaminate marine habitats across the globe (Eriksen et al., 2014) and are recognized as a significant environmental challenge requiring urgent management (UNEP, 2016; Green et al., 2016). Previous studies have proposed that MPs can affect the algal growth, photosynthesis, antioxidant system (Su et al., 2020; You et al., 2021; Zhang J. et al., 2022), and further influence the phytoplankton community and marine ecosystem. However, through exposure experiment, Zhang J. et al. (2022) found that the effects of MPs on microalgae will likely not be substantial in future warming scenarios if MPs concentrations are controlled at a certain level. Therefore, the carrier effect of MPs to red tide species should be pay more attention to in the future study. Naik et al. (2019) indicated that MPs in ballast water could be an emerging source and vectors for harmful chemicals, antibiotics, metals, bacterial pathogens and red tide species.

MPs, as novel substrata for microbial colonization within aquatic ecosystems, are a matter of growing concern due to their potential to propagate foreign or invasive species across different environments (Song et al., 2022). Xianbiao et al. (2023) defined microalgae colonizing on MPs as epimicroplastic microalgae (EMP-MA). Meanwhile, harmful species have been found on EMP-MA community in many bays worldwide (Masó et al., 2003; Wang et al., 2022). Because MPs persist longer than other natural substrates such as feathers, wood, and macroalgae, it can traverse significant distances, and it has been shown to transport invasive species (Senderovich et al., 2010; Zettler et al., 2013). These invasive species may proliferate rapidly and even develop into HABs in suitable environment (Wang et al., 2022). An illustrative example of such transportation is the Great East Japan Tsunami of March 2011, which carried vast amounts of plastic debris into the North Pacific Ocean (González-Ortegón et al., 2024). In the following years, numerous coastal species from Japan were found on polyethylene, polystyrene, polyvinyl chloride, and fiberglass materials in North America and Hawaii (Haram et al., 2023; González-Ortegón et al., 2024).

Previous studies focused on the modeling transport process of microplastics or red tide species, by combining hydrodynamic model and particle tracking model, to assess their respective negative effects to marine ecosystem. Many studies indicated that while algae continually grow and perish during their diffusion, they generally move as a cohesive unit, allowing particle tracking methods to be utilized for simulating HABs trajectories (Yamamoto and Okai, 2000; Chen et al., 2007; Kuang et al., 2016). While red tide species transporting with microplastics, a stable substrate, their impact on the marine ecosystem as a whole is more long-lasting and wide-ranging.

In this study, the potential transport effects of epimicroplastic red tide species in marine environment were learned. Based on the survey data and current reanalysis data of epimicroplastic red tide species in Dongshan Bay and Quanzhou Bay, located on the west side of the Taiwan Strait of China in 2022, this paper investigates the characteristics and transport trajectories of epimicroplastic red tide species under the ocean currents by using the Lagrangian particle tracking model. This study firstly combined models to investigate the potential transport trajectory of epimicroplastic red tide species, providing new insights into the mechanisms of red tide.

2 Materials and method

2.1 Study area

Dongshan Bay and Quanzhou Bay, both are typical bays around west of the Taiwan Strait, playing important roles in the socio-economic development of coastal areas in China (Figure 1). The Taiwan Strait connected the South China Sea and the East China Sea, is an important pathway for the water and materials, and the main navigation channel (Hong et al., 2011; Yang, 2021). Dongshan Bay, located along the southwestern coast of the Taiwan Strait, is an important area for mariculture and seawater fishing in China (Zheng, 2019; Wang, 2023). With unique location advance and rich fishery resource, Quanzhou Bay is an inner bay of Fujian Province, surrounding by Meizhou Bay, Weitou Bay and the Taiwan Strait (Xie, 2021).

2.2 Sample collection and analysis

Surveys were conducted on April 22, 2022 in Dongshan Bay and on May 17, 2022 in Quanzhou Bay, respectively. The procedure of sample collection was according to Wang et al. (2022). Floating microplastics were collected by a 330 μm manta trawl and rinsed gently with sterile artificial seawater (salinity = 30) for three times, then transferred into 10 mL glass vials containing 2–5 mL of sterile artificial seawater and 1 mL of formaldehyde solution (Wang et al., 2022). Epimicroplastic red tide species were separated by ultrasonic cleaner at 300 W for 25 s and identified under a research microscope (Leica DMi8A) (Wang et al., 2022).

2.3 Modelling approach

2.3.1 HYCOM

The three-month (90-day) potential transport trajectories of these particles were calculated with the 3 hourly 1/12° flow fields from the Hybrid Coordinate Ocean Model (HYCOM, https://www.hycom.org, accessed 3 January 2024) Global Ocean Forecast System (GOFS) 3.1 output. HYCOM simulations include the Navy

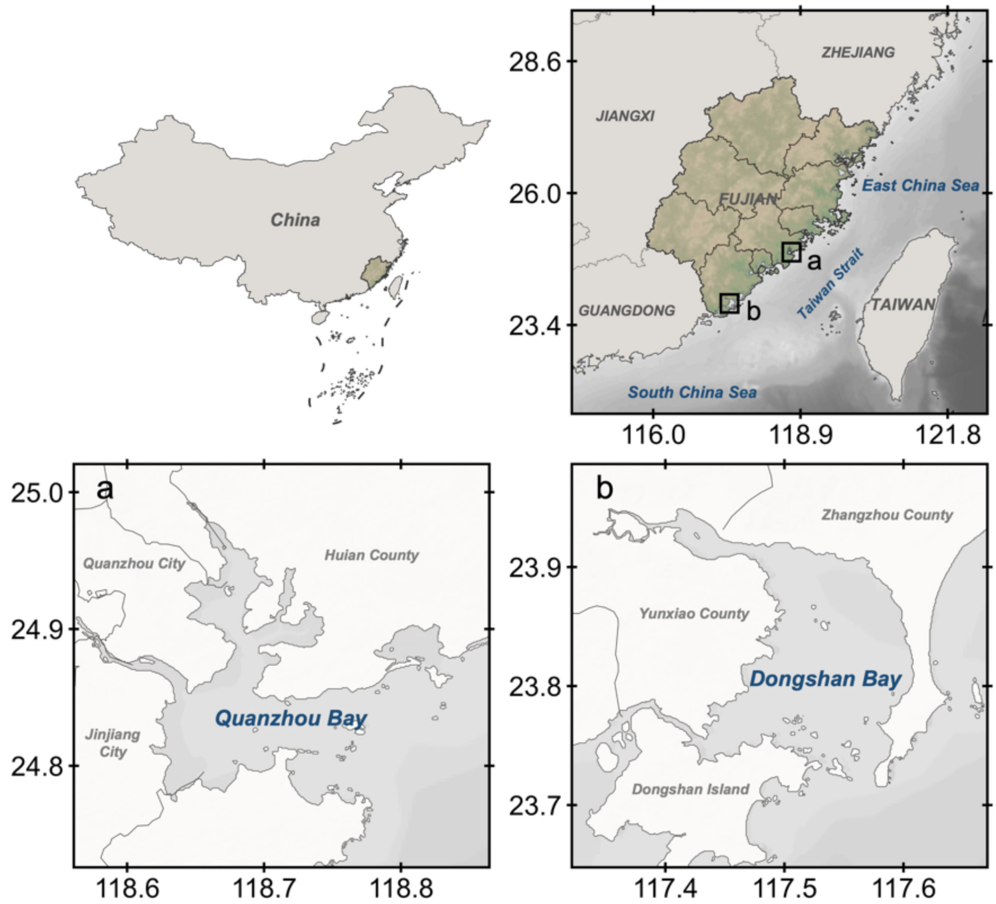

FIGURE 1
Geographic location of the investigated areas in this study. **(a)** Quanzhou Bay; **(b)** DongshanBay.

Coupled Ocean Data Assimilation data (NCODA) (Cummings, 2006; Cummings and Smedstad, 2013; Allende-Arandía et al., 2023). We used the eastward (u-component) and northward (v-component) surface current velocity from the HYCOM + NCODA GOFS 3.1 reanalysis from April to August, 2022.

2.3.2 Particle tracking

Using the Lagrangian particle tracking model to develop the potential transport process of epimicroplastic red tide species from Dongshan Bay and Quanzhou Bay. Following a Lagrangian framework, microplastics were assimilated to point-like particles whose passive movement is completely consistent with that of surface water masses (Guerrini et al., 2021). Studies on the plastisphere have shown strong shifts of distinct communities throughout the early stage of colonization (Dey et al., 2022). However, in mature biofilms, microbial communities are converged over time and remained stable (Dey et al., 2022). Cultivation experiments have demonstrated little difference in epimicroplastic microalgae community structure over a 7-month period, and no significant community succession characteristics have emerged (Wang et al., summited)[1]. Therefore, any internal or external factors affecting community succession or structure variation were not considered in the simulated processes. 1,000 particles were placed randomly and uniformly within a radius of 10 km in the mouth of two bays and those on land were removed. Therefore, the number of particles in the actual tracking simulation of Dongshan Bay and Quanzhou Bay were 897 and 876, respectively (Table 1).

In the model, microplastics in water bodies were treated as discrete particles to simulated their transport processes in the water. There were three assumptions in this model: (1) though the potential transport trajectory of red tide species was discussed, the microplastics, as a vector, do not have the ability to move autonomously, so the particles in the model only transport passively with the ocean currents; (2) the density of microplastics is relatively small, and these samples in this study were collected from the surface water, so the transport trajectory was only simulated in horizontal direction, which may cause the estimated trajectory longer than the actual; (3) the particles in the model are conservative particles and do not participate in biochemical reactions. The changes of their positions are described by the following equations:

$$X(t) - X_0 = \int_0^t U_{surfacewater}(t')dt'$$

1 Wang, K., Peng, C. H., Lin, H., Dong, X., Lin, H. N., Chen, B. H., et al. Epimicroplastic harmful algae in Fujian coastal waters of China. (Submitted).

TABLE 1 Summary of the particle tracking simulation performed.

Investigated area	Particle deployment position		Number of the placed particle	Number of the particles in the simulated processes	Processed duration
	Longitude	Latitude			
Dongshan Bay	117.54 E	23.7 N	1000	897	April 22 – July 20, 2022
Quanzhou Bay	118.9 E	24.85 N	1000	876	May 17 – August 14, 2022

In the above equation, $X_{(t)}$ is the position of the particles at time *t*, and X_0 is the initial position of the particle. The migration rate is represented by the surface current, with a time step of 3 hours.

2.4 Data analysis

Statistics and calculation were performed in Microsoft Excel 2021 (Microsoft Corporation, Washington, DC, USA). Lagrangian particle tracking model was run by MatLab and the figures of the transport trajectory was drawn with Qgis (3.32).

3 Result

3.1 Biodiversity of epimicroplastic red tide species in two bays

In this study, 1022 and 433 items of microplastics particles were collected and processed for the identification of epimicroplastic red tide species in Dongshan Bay and Quanzhou Bay, respectively. A total of 13 epimicroplastic red tide species from 4 phyla (Diatom, Dinophyta, Ochrophyta and Cyanophyta) were observed by optic microscope, with 5 species in Diatom and 6 species in Dinophyta, which contributed 38.5% and 46.2% of the species richness, respectively (Table 2). However, the composition and diversity of those epimicroplastic species between two bays were different. There were 4 species shared in these two bays, and 1 and 8 unique species were observed in Dongshan Bay and Quanzhou Bay, respectively. Some typical red tide species, such as *Prorocentrum donghaiense* from Dinophyta and *Trichodesmium erythraeum* from Cyanophyta, were only found in Quanzhou Bay. The unique species in Dongshan Bay was *Pseudo-nitzschia pungens*, a potentially toxic species from Diatom. Another toxic species was *Chattonella marina* from Ochrophyta, occurring in both two bays.

3.2 Potential transport trajectories of epimicroplastic red tide species

Three-month transport trajectories of epimicroplastic red tide species from Dongshan Bay were simulated (Figure 2). During the

TABLE 2 Epimicroplastic red tide species in Dongshan Bay and Quanzhou Bay (Wang, 2024).

Phylum	Species	Mode	Toxin	Abundance (cells/m^3)	
				Dongshan Bay	Quanzhou Bay
Diatom	*Amphora coffeaeformis*	Benthic		2.53	11.36
	Thalassionema nitzschioides	Planktic		0.71	12.16
	Melosira moniliformis	Planktic		0.73	0.29
	Pseudo-nitzschia pungens	Benthic/ Planktic	Neurotoxin domoic acid (Lundholm et al., 2009)	0.26	
	Chaetoceros debilis	Planktic			1.21
Dinophyta	*Ceratium fusus*	Planktic			0.21
	Katodinium glaucum	Planktic			0.08
	Prorocentrum donghaiense	Planktic			0.30
	Prorocentrum mexicanum	Planktic			0.27
	Prorocentrum micans	Planktic			0.38
	Prorocentrum triestinum	Planktic			0.08
Ochrophyta	*Chattonella marina*	Planktic	Ichthyotoxin (Lundholm et al., 2009)	0.28	0.54
Cyanophyta	*Trichodesmium erythraeum*	Planktic			0.10

first-month transportation, the particles transported along the coastal water of Guangdong Province in a southwestward direction. About 50% particles had reached Mirs Bay and the surrounding waters areas of Hong Kong in Day 30. The particle started to transport in the opposite direction until they reached around the Pearl River Estuary at the beginning of the second month. Meanwhile, some particles started to be obstructed. According to the second month transport trajectories, the particles turned back to Fujian coastal water and entered the middle part of the Taiwan Strait. A total of 46.4% particles were obstructed in other sea areas during the second month, including 22.2% particles in West Lamma Channel, 19% particles in Daya Bay, 5.1% particles in Port Shelter and 0.1% particle in Mirs Bay. In the last month, some particles were dispersed in northern Fujian waters, like Pingtan sea area, and kept transporting in a northeastward direction. Meanwhile, 36.1% particles were obstructed, of which 24.7% particles in Mirs Bay. In these epimicroplastics red tide species transport trajectories from Dongshan Bay, about 82.5% particles were obstructed in the surrounding sea area of Guangdong Province and Hong Kong, while mainly obstructed in Daya Bay, Mirs Bay and West Lamma Channel.

Three-month transport trajectories of epimicroplastic red tide species from Quanzhou Bay were simulated (Figure 3). During the first month, the particles transported in a southwestward direction, then turned back to the surrounding waters of Quanzhou Bay, and finally transported to other sea areas in a northeastward direction. According to the first-month transport trajectories, Xiamen Bay, Shenhu Bay and Weitou Bay were potentially affected by those red tide species. In the second month, the particles spread northeastward to Meizhou Bay and other waters, and reached as far as the coast of Zhejiang Province, but most of the particles always lingered around Quanzhou Bay. However, due to the influence of coastal topography and hydrological characteristics, some particles started to be obstructed in the second month, including 5.9% particles in Weitou Bay and 0.6% particles in Shenhu Bay. In the third month, 16.3% particles were obstructed, including 12.2% and 4.1% particles in Weitou Bay and Shenhu Bay, respectively. In these transport trajectories from Quanzhou Bay, only 2.2% particles moved into waters further, while other 97.8% particles still transported or be obstructed in the surrounding waters of Quanzhou Bay.

4 Discussion

4.1 The potential effect of epimicroplastic red tide species to the marine environment

With an increasing frequency, red tide outbreak has posed a threat to the marine ecosystem (Yan, 2022), by changing the community structure of marine organisms (Yu et al., 2017),

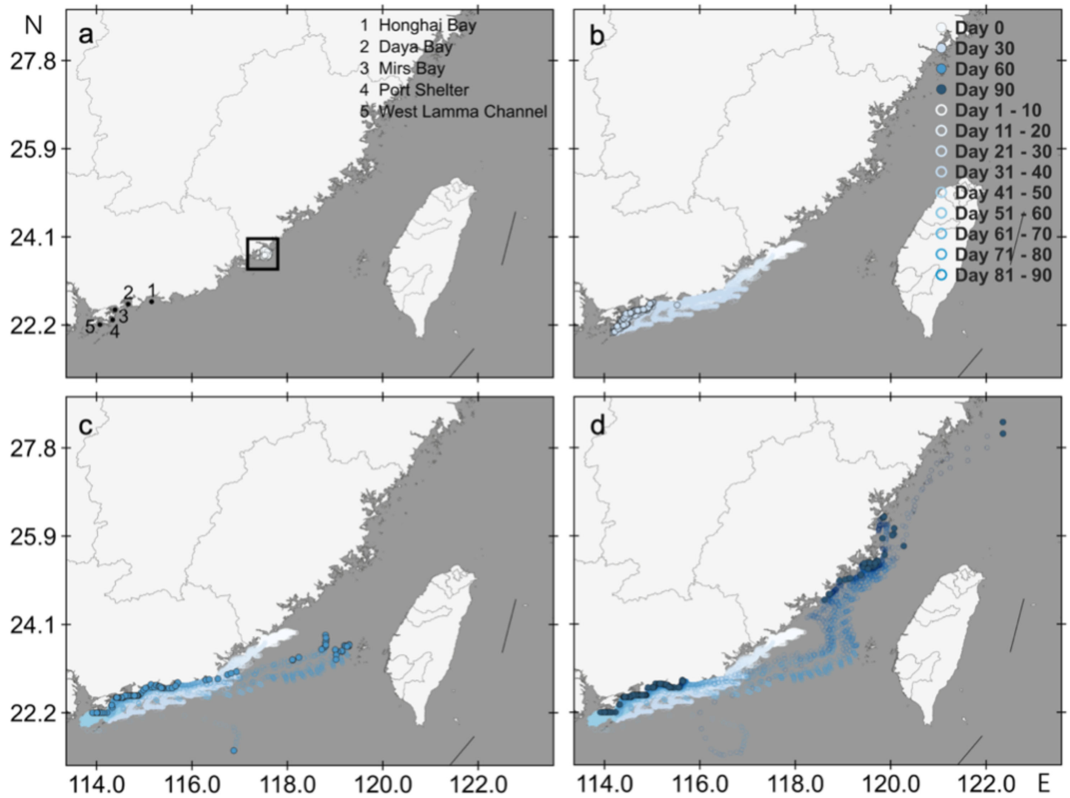

FIGURE 2
Three-month transport trajectory of epimicroplastic red tide species from Dongshan Bay. **(a)** Initial position of the released particle; **(b)** Potential transport trajectory within 30 days; **(c)** Potential transport trajectory within 60 days; **(d)** Potential transport trajectory within 90 days.

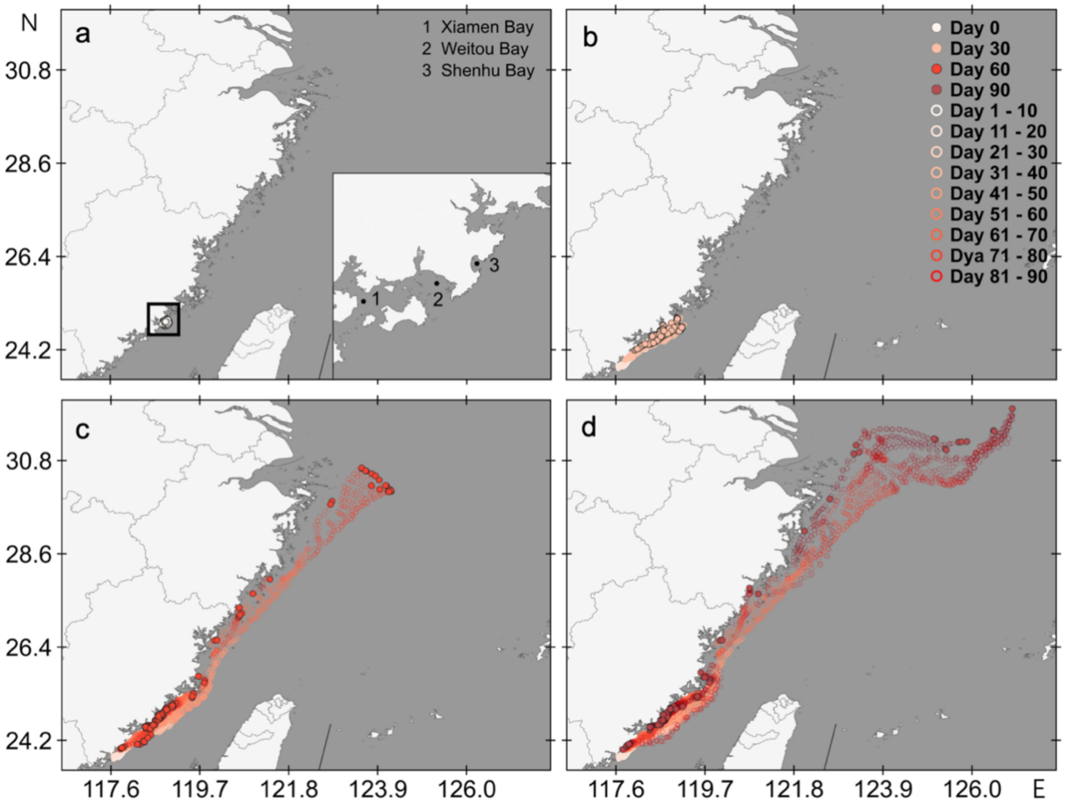

FIGURE 3
Three-month transport trajectories of epimicroplastic red tide species from Quanzhou Bay. **(a)** Initial position of the released particle; **(b)** Potential transport trajectory within 30 days; **(c)** Potential transport trajectory within 60 days; **(d)** Potential transport trajectory within 90 days.

destroying the fisheries resources and harming human health (Song et al., 2018; Baohong et al., 2021). In the recent years, researchers have started to suggest that red tide species can transported by attaching to microplastic in addition to ballast water and ocean currents, which has been confirmed by the discovery of the red tide species in the EMP-MA community (Wang et al., 2021, 2022; Pasqualini et al., 2023). In this study, totally 13 epimicroplastic red tide species from 4 phyla were found, with 5 species in Diatom and 6 species in Dinophyta. Among them, two species have been identified as may contain algal toxins in previous studies, namely *C. marina* may produce Ichthyotoxin (Lundholm et al., 2009); and *P. pungens* may produce neurotoxin domoic acid (Lundholm et al., 2009). Additionally, *A. coffeaeformis* has been reported to have the ability to produce neurotoxin domoic acid (Shimizu et al., 1989), while this finding has been disputed (Bates, 2000; Zabaglo et al., 2016). In our simulated potential transport processes, epimicroplastic red tide species from Dongshan Bay and Quanzhou Bay would influence three provinces, including Guangdong Province, Fujian Province and Zhejiang Province, all of which have high records of red tide outbreak in China. *T. nitzschioides* and *P. donghaiense*, found in the epimicroplastic community in our study, were two of the main red tide species in these three provinces (Li et al., 2019; Shiyong et al., 2021; Zhang, 2022). The remaining 10 red tide species, except for *A. coffeaeformis*, also have outbreaks records in Chinese coastal waters (Chen and Zhang, 2021; Chen and Chen, 2021), indicating that they have the potential to become main causative species to the other provinces' waters in the future. Previous studies about epimicroplastic microalgae, also identified as a part of "plastisphere" (Zettler et al., 2013) or biofilm, have proved their species specificity (Wang et al., 2022) and community stability (Dey et al., 2022) in natural waters. When we describe the transportation of red tide species by the vector of microplastics and further causing red tide outbreak in other waters, the ability of those species to detach from microplastics in the waters with suitable nutrient condition become a crucial node. A laboratory experiment has demonstrated that microalgae in the biofilm consortium could easily detach and develop in the pelagic phase by dispersal following shaking and movements (Binda et al., 2024). This does not mean, however, that the microplastics will be completely 'washed' by physical factors such as marine currents. Same experiment also showed that besides colonizing the pelagic environment, species composing in the biofilm further colonize the plastic surface (Binda et al., 2024). The epimicroplastic red tide species we found in this study were almost planktonic, and the species richness between Diatom and Dinophyta were almost the same. Most studies have proved that

Diatom dominated in the epimicroplastic microalgae community, since these diatom species are benthic and capable of adhesion and motility on natural or artificial substrata (Chiovitti et al., 2006; Wang et al., 2022). Over the last decades, red tide outbreak associated with epiphytic dinoflagellates (BHABs) have also been reported more frequently, as most of their representatives are potential toxin producers (Wang et al., 2022). Do Prado Leite et al. (2022) suggested that plastics provides significant surfaces for potential colonization by planktonic and benthic harmful microalgae and for the adsorption of their toxins. Binda et al. (2024) has found that microplastic can be xenobiotic substrates for benthic species, leading to competition with the natural pelagic community and posing risks for the depletion of available nutrients. Those benthic microalgae can even form another biofilm community at the bottom of all microcosms while engaging in competition in the surface (Binda et al., 2024). This means that as long as those epimicroplastic benthic species turn over with the currents for a certain period of time in the waters, they have the potential to cause an outbreak event.

Microplastics in aquatic environments have been shown to absorb pollutants from surrounding water (Wang et al., 2021). Many studies have examined the absorption ability of various pollutants on microplastics (Guo and Wang, 2019; Guo et al., 2020) and thoroughly reviewed by several researches (Koelmans et al., 2016; Mei et al., 2020; Wang et al., 2021). Recently, the absorption of pollutants on biofilm-developed microplastics has been studied by *in situ* experiments and laboratory studies (Richard et al., 2019; Wang et al., 2020; Wang, 2024). Extracellular polymeric substances, natural dissolved organic matter, and other organic macromolecules can be absorbed onto the micro(nano)plastic surface to form the so-called eco-corona (Wei and Xinghui, 2024). The formation of biofilm on the surface of MPs changes its surface morphology, roughness, surface functional groups, and other physical and chemical properties (He et al., 2022; Tu et al., 2020; Yan et al., 2024), which further affect its adsorption behavior with environmental pollutants (Bhagwat et al., 2021; Xu et al., 2021). Numerous studies have demonstrated that biofilm formation increases the adsorption capacity of MPs for various environmental pollutants, such as organic pollutants (José and Jordao, 2022), heavy metals (Zhou et al., 2022), and radionuclides (Johansen et al., 2018; Yan et al., 2024). Microplastics with biofilm have higher affinities to pollutants than virgin microplastics, which may pose more serious consequences (Wang et al., 2021). Microplastics, with attaching red tide species and adsorbed pollutants, transport in the coast water, the harm they cause to the marine ecological environment will be aggravated.

4.2 Hydrodynamic conditions during the transport process of the epimicroplastic red tide species

Red tide outbreak event involves algal growth and migration (Chen, 2019). In addition to the effects of temperature (Singh and Singh, 2015), light (Edwards et al., 2015) and nutrients (Wang et al., 2016), hydrodynamic conditions are also considered to be essential factors affecting the growth and aggregation of algae in the waters (Chen et al., 2015; Zhong et al., 2024). Algal migration can lead to the aggregation of algae in the surface water within a short period of time, causing red tide outbreaking (Chen, 2019). Under certain conditions, algal aggregation is mainly affected by hydrodynamic conditions (Chen, 2019). Hydrodynamic conditions, including water velocity, changes in water flow and water level, directly affect the survival and growth of algae in the waters, which in turn play a crucial role in the occurrence and development of a red tide outbreak event (Zhong et al., 2024). The mechanism of hydrodynamic conditions on algal growth is mainly reflected in three aspects: (1) It affects the distribution of nutrient, regulating the growth and enrichment of algae; (2) It alters the transport process of nutrient, impacting the function of the algal cell; (3) It destroys the structural integrity of the algal cell structure of algae, rendering their inactive (Zhong et al., 2024). However, most red tide species possess a certain degree of autonomous motility, allowing them alter their movements in response to changes in current characteristics (Chen, 2019). For example, *P. donghaiense*, which allow the algal cells to move independently through the movement of these flagella (Chen, 2019). Motile algae exhibit distribution patterns different from scalar particles in various environments, such as phototaxis, thermotaxis, chemotaxis, and rheotaxis (Rusconi and Stocker, 2015; Pedley and Kessler, 1992). Water flow plays a role in carrying and transporting algae, thereby influencing their spatial distribution. When the transportation of red tide species in the waters carried by microplastics, the impact of the algal swimming ability may be negligible. Therefore, this study only considers the physical process of epimicroplastic species transportation with ocean currents, without taking into account the algal autonomous swimming ability. Additionally, this study does not consider the deposition caused by the weight of microplastics; the entire migration process occurs at the surface, so the only physical factors needed to consider are current velocity. The surface current velocity is generally greater than that at other depth levels in the vertical direction; therefore, this study only considers surface currents, resulting in a relatively larger simulated transport range.

Simulating by Lagrangian particle tracking model, the transport trajectories of epimicroplastic red tide species from Dongshan Bay and Quanzhou Bay were learned in this study. Results showed that particles in those simulated processes of this study were crossing the South China Sea and the East China Sea, covering the coastal waters of three provinces – Guangdong, Fujian and Zhejiang through the Taiwan Strait. The duration of the simulation process is in summer, when the Taiwan Strait is mainly influenced by the wind field. Therefore, driven by the southwestern monsoon, a northeasterly flow in the same direction as the wind direction occurs along the western coast of the Taiwan Strait (Figure 4). Our study was conducted in the spring, which is the main red tide outbreak season in Fujian Province. Additionally, the ocean currents affecting the transport process are primarily influenced by the season and currents, so the simulated transport trajectory outside of spring would differ from the actual ones.

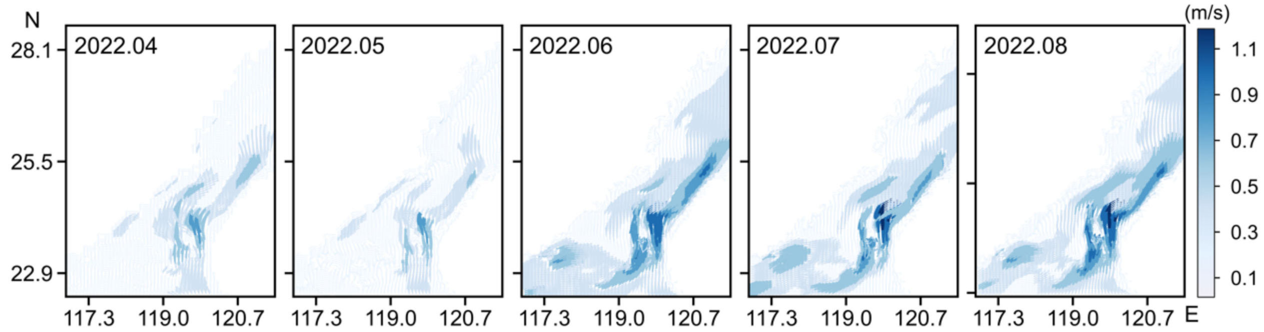

FIGURE 4
Time-averaged wind-driven current in the Taiwan Strait during April to August 2022.

According to two simulated trajectories in our study, epimicroplastic red tide species were transported under the current velocities below 0.5m/s in the Taiwan Strait. Generally, hydrodynamic conditions affect the growth of algae mainly in the form of low flow rate to promote growth (Cao et al., 2008), medium intensity of disturbance will increase the nutrient uptake by algal cells and promote algal metabolism (Xiao et al., 2016); on the contrary, high intensity of disturbance inhibits algal growth, nutrient uptake and cellular metabolism (Tan et al., 2019; Zhang H. et al., 2022). However, the response of different algal species to flow velocity varies significantly in different water bodies (Zhong et al., 2024). When algal species are present in the water column in an epiphytic state, the effect of flow velocity on them is not that much. Similar with other biofilms, epimicroplastic community ("plastisphere") generally involves microbial attachment, secretion of extracellular polymeric substances, and microbial proliferation (Zettler et al., 2013; Du et al., 2022). Biofilms often feature open-channel and pore structures, enhancing solute and microbial transport and promoting frequent cell-cell contacts (Flemming and Wingender, 2010; Wuertz et al., 2004; Dang and Lovell, 2016). Due to the close positioning of microorganisms, the protective nature of the EPS matrix, and the development of sensing, signaling, and regulatory mechanisms and social behaviors among different microorganisms in biofilms (Davey and O'Toole, 2000; Nadell et al., 2009; Dang and Lovell, 2016), the functional efficiency of biofilm microbial communities should be higher and more stable than those of planktonic microbial communities. biofilm-associated microbial communities may thrive in extreme or hostile environments where individual microorganisms would find the maintenance of activity and growth, even survival, challenging (Dang and Lovell, 2016). Meanwhile, hydrodynamic conditions still influence the epimicroplastic species. For example, in laminar flows, the biofilm is patchy and comprises round cells; in turbulent flows, it comprises wavy and elongated cells (Stoodley et al., 1998). The flow rate affects the density of the biofilm coverage on microplastics surfaces (Xiao et al., 2023; Qin et al., 2024).

5 Conclusion

By attached on the surface of microplastics, those red tide species may be transported further and posing a threat to marine ecosystems. Combined the investigated data of Dongshan Bay and Quanzhou Bay and the simulated transported trajectories, the characteristics and potential transport trajectory of epimicroplastic red tide species were learned in this study. 13 red tide species were totally found in two bays, with 6 species in Dinophyta and 5 species in Diatom. According to the simulated transport trajectories, epimicroplastic species could be transported further by microplastics while some particles would be obstructed during this three-month process. In these simulated trajectories from two bays, 82.50% particles from Dongshan Bay were obstructed in the surrounding waters of Guangdong Province and Hong Kong. However, 97.8% particles from Quanzhou Bay would be transported or be obstructed in the surrounding waters of Quanzhou Bay. During the transport processes, epimicroplastic red tide species from two bays would affect the surrounding waters of three provinces, which all have high records of red tide outbreak in China. This study firstly combined models to investigate the potential transport effect of epimicroplastic red tide species, providing insights into the mechanisms of red tide outbreak.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CP: Formal analysis, Methodology, Software, Writing – original draft. KW: Conceptualization, Formal analysis, Investigation, Resources, Writing – original draft. HL: Conceptualization, Funding acquisition, Project administration, Writing – review & editing. SC: Resources, Validation, Writing – review & editing. XD:

Resources, Supervision, Writing – review & editing. YG: Conceptualization, Project administration, Writing – review & editing. BC: Conceptualization, Funding acquisition, Methodology, Project administration, Writing – review & editing. FK: Methodology, Resources, Software, Validation, Writing – review & editing.

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