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Marine microplastics in the surface waters of "pristine" Kuroshio

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ABSTRACT

Microplastics (MPs) are ubiquitous in oceans. Their transboundary transport and fate have aroused global attention. Taiwan is located close to the western boundary current-Kuroshio, is an excellent location to study of MP mobility in the global current and Pacific Garbage Patch. This study is the first investigation to understand the microplastic contamination from Taiwan to the Kuroshio. MP concentrations in the area varied from N.D. to 0.15 items m^{-3}, with an average concentration of 0.05 ± 0.03 items m^{-3}. The majority of MPs were polypropylene, polyethylene, polyethylene and terephthalate. We found two MP hotspots near the coastal zone. One additional hotspot was also identified in the "pristine" Kuroshio suggesting rivers and local currents may play critical roles in transporting or injecting MPs from Taiwan into the North Pacific Gyre. These findings suggest that marine environments are altered by anthropogenic disposal and provide needed data for modelling and prediction of MPs.

1. Introduction

Marine plastic pollution is one of the most serious environmental challenges of the Anthropocene. Current estimates indicate that the annual production of plastic base materials in 2018 exceeded 350 million tons worldwide (Plastics Europe, 2019). At the current pace, the future trend of global plastic production is also expected to show continual growth and will double within the next two decades (Geyer et al., 2017). The low recycling rate for used plastics and other mismanagements have caused substantial accumulations of plastic litter in natural systems, especially in the ultimate environmental receptor-the oceans. Plastics, including fibers, beads, and fragments, are now observed in lakes, rivers, wastewater effluents, beaches, and coastal oceans, and they are even present in remote locations, such as deep-sea sediments, polar seas, and frozen ice cores (Alimi et al., 2018; Auta et al., 2017; Enfrin et al., 2019; Lebreton et al., 2017; Nizzetto et al., 2016; Picó and Barceló, 2019; Schmidt et al., 2018). These marine plastics are mostly released from terrestrial sources through a variety of pathways, including air-water exchange, treatment plant effluent, and river discharge (Auta et al., 2017; Picó and Barceló, 2019). More worryingly, the current models also estimate that approximately 50,000 billion pieces of plastic are floating in the oceans and that 5 million tons of plastics are transported into ocean areas from rivers every year (Eriksen et al., 2014; Lebreton et al., 2017).

During their transport in aquatic systems, fresh plastics are gradually broken down into microplastics (MPs; plastics sized <5 mm in diameter) and even nanoplastics (<1 μm) by mechanical fragmentation, chemical (oxidative and thermal) degradation, and biodegradation (Enfrin et al., 2019; Picó and Barceló, 2019). The MPs have adverse effects on aquatic organisms and have the potential for negative impacts on human health (Auta et al., 2017; Wang et al., 2020; Wright and Kelly, 2017). These plastic polymers have also been implicated as carriers responsible for the transboundary transport of harmful algal species, microbes, and pollutants (e.g., metals, persistent and emerging contaminants) that are detrimental to the natural microbe communities and ecosystem functions (Amaral-Zettler et al., 2020; Andrady, 2011; Reisser et al., 2014). We previously reported that micro- and nano-sized plastics cause high levels of cellular stress in marine phytoplankton cells and trigger extracellular polymeric substances secretion, further disturbing ecosystem functions, such as marine snow formation, and the dynamics of marine organic matter (Shiu et al., 2020a, 2020b). The effects of MPs on marine ecological systems are quite well known; however, the transboundary transport, accumulation, and mobility of MPs in the ocean remain unclear.

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The Kuroshio is one of the fast ocean currents in the world, flowing at 1 m/s in order as the Gulf stream. The Kuroshio originates from the North Equatorial Current near the tropic; it then flows northward along the east coast of Taiwan after the Philippines and passes through the Ruykyu Archipelago, extending to the north boundary of the North Pacific Subtropical Gyre. The waters of Kuroshio are believed “ultra-oligotrophic” and “pristine”, and can support a complex ecosystem and fishery activity, and their ecological importance and hydrological characteristics are similar to the Gulf stream in the North Atlantic. In addition, the formation of Pacific Garbage Patch is also highly affected by the massive North Pacific Subtropical Gyre, and the gyre's rotation is able to accumulate plastic materials from across the North Pacific via global plastic “conveyor belt” such as the California current, the Kuroshio, and the North Pacific current (Pan et al., 2019; Mann and Lazier, 2013; Van et al., 2012; Wong et al., 2000).

The Kuroshio is located close to the east coast of Taiwan, is an excellent location for the study of MP mobility in Pacific Garbage Patch. However, only a few studies on MPs in aquatic environments near Taiwan have been conducted, and these have tended to focus on rivers, beaches, and harbor areas (Chen et al., 2020; Chen and Chen, 2020; Chiu et al., 2020; Kunz et al., 2016; Wong et al., 2020), with little effort made to examine coastal areas and the open ocean. Therefore, the systematic investigation of MPs is therefore required to generate a holistic overview of the level of MP pollution in global oceans. The aim of the present study was to conduct a comprehensive survey of the occurrence and distribution of MPs in the surface sea waters off the eastern coast of Taiwan. The results can provide a first estimate of the spatial variation and type identification of MPs in these waters. The data also offer useful information about the MP contribution of eastern Taiwan to the western boundary current of the North Pacific.

2. Methods

2.1. Sampling methods

Marine floating MP samples were collected from September 11 to 18, 2019, from 18 stations at east ocean of Taiwan (encompassing a sampling area over 3000 km^2.) using a surface manta trawl with a mesh size of 330 μm and width of 1 m (Fig. 1). During the survey period (September 11 to 18, 2019), no extreme differences occurred in sea conditions. No stormy weather was encountered at the sampling sites, and the weather was mostly cloudy to sunny. At most of the sampling sites, winds were blowing northeast at speeds ranging from 11 to 16 knot in the most sampling sites (small waves), only the four sampling sites exhibited moderate waves (17-21 knots). Detailed information about each sampling site is listed in Table S1. A Hydro-Bios flowmeter (model 438,115) was fitted into the manta net frame to record the volume of water flowing through the net. The MP sampler was deployed on the sea surface via a reel-operated lift on the Taiwanese R/V “Ocean Researcher 2” (cruise OR2 1743). The sampling time was between 30 and 90 min at a speed of 1.5 to 3.0 knots at each field station. The ship speed to the ground was measured using the speedometer on the research ship. Additionally, the sampling directions opposite direction of the ocean current. When sampling was complete, the net was lifted at a speed of

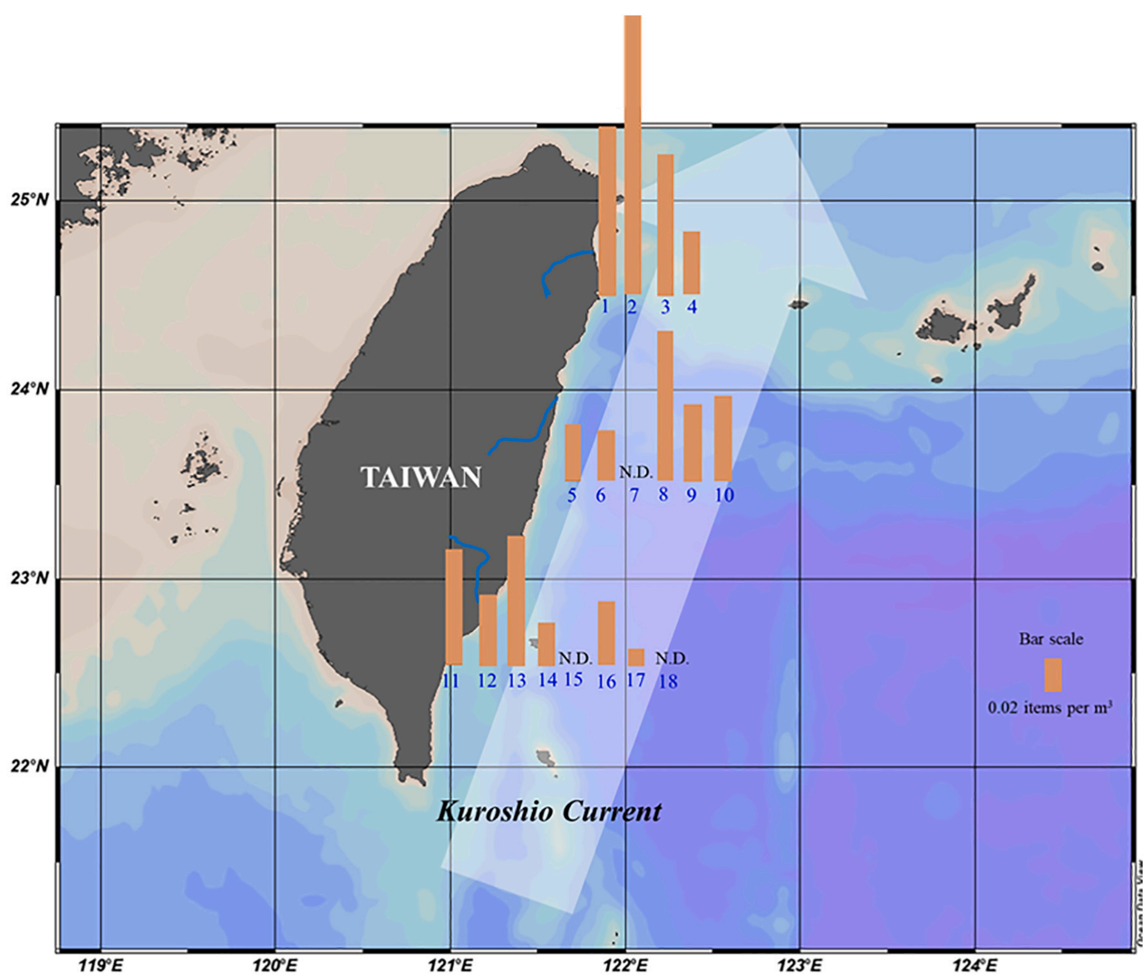

Fig. 1. Spatial distributions of microplastics (MPs) in the surface water off the east coast of Taiwan (Bar scale: 0.02 items m^{-3}). The white arrow indicates schematically the Kuroshio main stream. This map was produced by Ocean Data View.

less than 0.5 m/ s and rinsed with natural seawater onsite to drive all the samples to the sampling bottle and wash away the impurities outside the net. The net contents were washed into stacked stainless steel mesh sieves with mesh sizes of 5.0 mm and 0.3 mm. Residues on the 5.0 mm sieves were discarded, and all the materials on the 0.3 mm sieve were washed with Milli-Q water into a pre-cleaned glass vial for further processing in the laboratory. All samples were stored at 4 °C until further analysis.

2.2. Extraction of MPs

The MPs were extracted using the method of Masura et al. (2015). The collected materials in the glass vials were placed in a 90 °C oven for at least 48 h until completely dry. The chemical oxidation process was then used to digest away the organic material from the surfaces of the collected solids. Briefly, 20 mL aliquots of 0.05 M iron (II) solution were added to the beaker containing the dried 0.3 mm size fraction of the collected solids, followed by addition of 20 mL 30% hydrogen peroxide (H_2O_2). This mixture was covered with aluminum foil and heated at 75 °C on a hotplate, with further addition of another 20 mL aliquot of 30% H_2O_2 until the oxidation was complete (no organic material was left on the samples). A saturated NaCl solution (~5 M) was then used to increase the density of the solution to separate the MPs. About 6 g of NaCl was added to 20 mL of digested samples, the NaCl was allowed to dissolve, and the entire mixture was transferred to a density separator funnel, loosely covered with aluminum foil, and allowed to settle for 12 h. The solution was poured through a 0.3 mm sieve and the funnel was rinsed several times with Milli-Q water. Residues on the 0.3 mm sieves were collected for further analysis of the type, abundance, shape, and size of the MPs.

2.3. Visual and chemical identification

The MPs were dried prior to separation, counting, and classification by microscopy. MPs were preliminarily identified on a glass slide by visual examination with an SZX 16 stereomicroscope (Olympus, Tokyo, Japan). Most of the MPs were in the form of fibers, sheets, films, and fragments. The MPs were divided into three size ranges of 5–3 mm, 3–1 mm, and 1–0.3 mm. All MPs observed in all samples were recorded. All the potential MPs were picked and sorted based on their shapes and sizes. Suspected MPs were also picked out and sorted separately. Further plastic identification and composition were carried out using a DXR2 Micro-Raman spectroscopy instrument (Thermo Fisher Scientific, USA) for all the suspected and some selected potential MPs.

All the MP samples were excited with visible light at 532 nm and near-infrared radiation at 785 nm with diode lasers focused onto the sample for 1–10s. All spectra with a frequency resolution of ~3–5 cm^{-1} and range of 50–3500 cm^{-1} were analyzed using the OPUS 7.5 software (Opus Software Inc., San Rafael, CA). The chemical composition of MPs was determined by comparing the obtained spectrum with the light spectral database on the instrument (Hummel Polymer Sample Library, Organics by Raman Sample Library, Raman Sample Library, Sigma Biological Sample Library). Overall, fourteen traditional plastic polymers, namely polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyethylene terephthalate (PET), polyethylene (PE), poly(vinyl alcohol) (PVA), ethylene vinyl acetate (EVE), poly(trimellitamide imide) (MBI), polybutene, polyacetal, nylon, polybutadiene, cellophane, and, acrylonitrile were detected in our collected samples.

2.4. Quality control and error reduction

Several quality control measures were implemented because external contamination may affect the data. The measures taken during field work to ensure that no impurities remained included wearing cotton lab coats and cleaning the sieves and sampling bottles in advance. Glass sample containers were also used instead of plastic containers. All solutions and purified water were pre-filtered through glass fiber filters (GF/F Whatman, 47 mm diameter and 0.7 μm pore size). A 1–0.3 mm size fraction of high-density polyethylene (HDPE) particles in artificial seawater was also utilized to determine the recovery efficiency of the sample extraction. The range of mean recoveries was approximately 94.6 ± 10.8%.

2.5. Principal component analysis

For data exploration and description, data set will be treated with principal component analysis (PCA). This statistical tool is used as an explorative tool to extract the numbers of components needed for explaining variance in observed data. For simplicity, components explaining little data variance (less than 5%) will not be used and assumed to be mostly due to background and noise contributions (Savinov et al., 2000; Shiu et al., 2019). Varimax will be used for rotation in PCA and only highest coefficients will be retained in the varimax normalized matrix.

3. Results and discussion

3.1. Abundance and distribution

A total of 101 counts of floating MPs were detected in the surface water of the eastern side of Taiwan (western side of North Pacific), including the main stream of the Kuroshio (Table S1). The detection rate was approximately 83% of the collected samples in the 18 stations, only three sampling sites did not contain MPs. This phenomenon suggests a pervasiveness of MPs in ultraoligotrophic oceans, such as the Kuroshio. The MP abundance at the ocean surface ranged from not detected (N.D.) to 0.15 items m^{-3}, with an average value of 0.053 ± 0.034 items m^{-3}. The differences in the standard deviation values indicated an uneven distribution of the MPs throughout the study area. The highest concentration of MPs appeared on the northeast coast of Taiwan (stations 1–3, where concentrations ranged from 0.09 to 0.15 items m^{-3}) (Fig. 1). Throughout the study area, a decrease was observed in MP concentrations from areas near the coast to offshore. Relatively low MP levels were observed at the offshore sites, in water close to areas with low population density, and in water far from rivers, with the exception of the Kuroshio (stations 8–10). River and port water discharges were clearly the main sources of MP and other emerging pollutants to oceanic environments in Taiwan (Chen et al., 2020; Chiu et al., 2020; Kunz et al., 2016; Shiu et al., 2019). These studies may provide an explanation for the observed higher abundance of MPs in nearshore areas and that rivers play roles in anthropogenic input, environmental release, and dispersion of MPs into the Kuroshio and the North Pacific. Further study is needed to link river inputs to the sea in this area to better understand MP transport. In contrast, stations 17 and 18 can be used as background stations of the Kuroshio, as their MP concentrations ranged from N.D. to 0.01 items m^{-3}. Because of abundance magnitude were similar with the western Pacific (0.01-0.10 items m^{-3}) (Liu et al., 2021), the number may indicate again the background concentration of MPs in the open ocean. In general, the abundance and transport of MPs in various environmental matrices are distinct because they are driven by a blend of complex parameters, including the population density, distance from the source or hotspot of plastic pollution, hydrodynamics, human activities, wind field features, and local currents of the sampled area (Eerkes-Medrano et al., 2015). In the present study, the high density of MP accumulation in stations 1–3 might be attributed to their geographic proximity to the densely populated coastlines and to local current complexity. The most densely populated cities (such as Taipei and New Taipei) and fishing grounds surrounding this region (Fig. S1), as well as the location of the stations close to Su'ao Port and the Lanyang river, likely contributed to the high levels of MP pollutants in this coastal area. Some previous monitoring data in Taiwan also indicated that ports and rivers can transport MPs and other organic pollutants from land to the coastal zone (Chen et al., 2020; Shiu et al., 2019). Specific local currents also affect the distribution and accumulation of MPs (Chiu et al., 2020; Liu et al., 2021; Kunz et al., 2016).

The northern Taiwan coast also has complex local currents, as currents from both sides of Taiwan meet in this area (Fig. 2). Therefore, this area may receive complex water sources from major cities in Taiwan, thereby increasing the accumulation of MP pollution at these sites. This pattern was consistent with a previous survey of beach and marine litters in northern Taiwan, suggesting that currents near the northern coast, vortex currents, and many capes and bays along the northern coast can cause the accumulation of floating litter (Chiu et al., 2020; Kunz et al., 2016). Notably, stations 8–10 formed another MP hotspot located in the Kuroshio mainstream, but these sites were located at a distance more than 100 km away from the land and rivers. This finding indicates the injection, transport and contribution of plastics from coastal zones to open ocean the Kuroshio interior. We infer that MPs were conveyed to and accumulated at stations 8–10 due to local currents that transported terrestrial materials from coastal areas to offshore sites and even to the open ocean (Lebreton et al., 2017). The notion that the MP accumulation here might be affected by local currents was supported by further evidence from the geostrophic currents estimated based on the absolute dynamic topography, as shown in Fig. 2. The directions of the currents confirmed the northeastward currents (west of the Kuroshio mainstream) from land entering into the Kuroshio interior at about 23.5 °N, thereby possibly causing a higher MP abundance in the area (0.05–0.085 items m^{-3}) near stations 8–10 far from the coast.

Currently, although standardized methods for microplastic collection in ocean surface have been recommended (Michida et al., 2019), but MP sampling and monitoring in lectures is still not consistent yet (Cai et al., 2018; Galgani et al., 2021; Pan et al., 2019). Various MP samplers, such as manta trawls, plankton trawls, neuston nets, Niskin bottles, and combinations of metal steel filters with different mesh sizes,

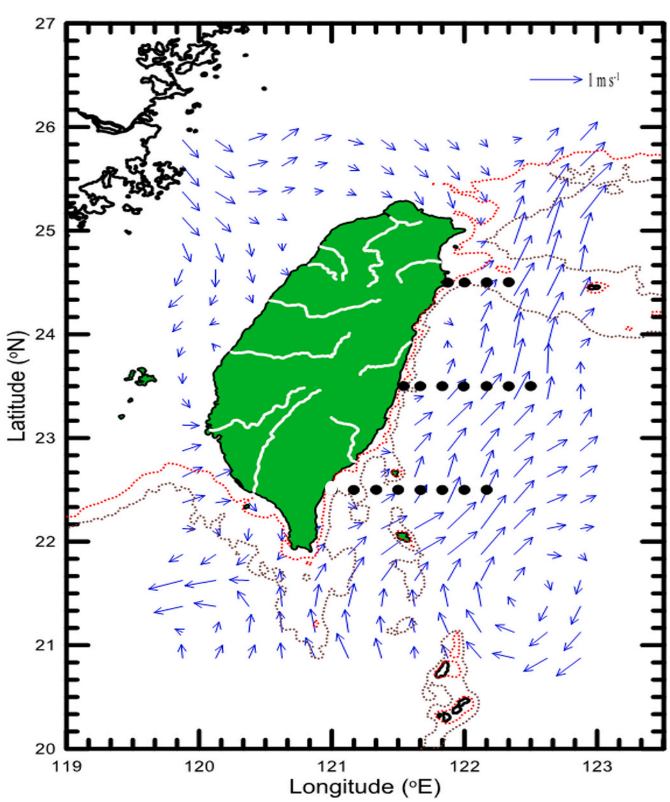

Fig. 2. Maps of geostrophic currents derived from the satellite altimetry data of absolute dynamic topography obtained from Archiving Validation and Interpretation of Satellite Oceanographic data (AVISO) website (https://www.aviso.altimetry.fr/en/home.html).

have been applied in previous studies. Inconsistency in the sampling methods, extraction techniques, and reporting units (e.g., items km^{-2}, items m^{-3}, etc.) complicate any comparisons with the worldwide MP data reported in the literature (Cai et al., 2018; Liu et al., 2021; Pan et al., 2019). In the Pacific, our values were comparable to the concentration level reported for waters from the South Pacific Subtropical Gyre, Northwestern Pacific, and Bering Sea (Doyle et al., 2011; Mu et al., 2019; Ory et al., 2017). Our observed MP abundance is at least one order of magnitude smaller than that reported for the southwest coast of Taiwan by Chen et al. (2020). This may reflect the fact that these places are higher population density and close to indusial harbors, so it receives more plastic debris from the land (Fig. S1). The MP levels in the East Asian sea around China, Korea, Japan are higher than the levels we observed in the Northwest Pacific (Kang et al., 2015; Liu et al., 2020; Zhao et al., 2014). This may reflect the proximity of the East Asian seas to highly industrialized and urbanized land (Lebreton et al., 2017; Isobe et al., 2015).

3.2. Chemical composition

The distinct micro-Raman spectral characteristics for selected samples of MPs with various shapes and for standard polymers are shown in Fig. 3. The polymer types of the MPs were determined by matching the characteristic peaks of the recorded spectra with the peaks in reference spectra of the standard plastics. The spectral results indicate that fourteen traditional plastic polymers were detected in our collected samples (Fig. 4a). The majority of MPs were PP (~26%), followed by PE (16%), PS (15%), and PET (13%), while PVA, nylon, and EVE each accounted for approximately 5%. PP, PE, and PET are dominant compositions of MPs and are the most commonly found plastics in surface oceans because these polymers are commercially desirable for many applications, including the aquaculture industry, other fishery activities, and commercial products worldwide (Hidalgo-Ruz et al., 2012; Schwarz et al., 2019). The dominant plastic types similar with global plastic production and the results of other studies. Some studies also have identified that PE, PP, PS were the most dominant of MPs in rivers, sands, and coastal waters in Taiwan and other area (Chen et al., 2020; Kunz et al., 2016; Wong et al., 2020). PP, PE, PS, and nylon were also found predominantly in surface waters, according to the literature, in the western Pacific area (Li et al., 2020; Liu et al., 2021). In addition, PP, and PE are the most commonly found plastics in surface oceans due to their lower densities than seawater. A possible explanation for the higher density of MPs (e.g., PET and PVC) in the surface ocean is that the floating and sinking behavior of MPs is affected by the polymer densities, but it is also influenced by other complex environmental factors, including particle size and shape, ocean circulation, and sediment resuspension. (Bergmann et al., 2017; Li et al., 2020; Waldschläger and Schüttrumpf, 2019). The chemical weathering, physical breaking, biodegradation and sea state also probably altered the transport of the plastics, causing a higher density MP that could float for a longer time on the water surface (Kooi et al., 2016; Kooi and Koelmans, 2019). Fig. 4b also shows that a greater complexity of MPs occurred in the nearby estuary area in locations 1–3 and 11–13 (Fig. 4b), indicating that estuary zones and river outlets may receive more plastic sources. The origin of plastics is difficult to fully identify, but specific types of manmade plastics can be used to speculate their possible sources. For instance, more PP and PE were distributed in the estuary and fishing ground areas, and these MPs mainly come from gear used in fishery and human activities, such as fishing nets, fishing lines, food packaging, and housewares. As shown in Fig. 4b, locations 1–3 had higher percentages of PS in the fishing ground areas, and these were mainly derived from PS used in aquaculture tools or other fishery products. The data suggests possible sources of plastic wastes that cab be strengthened the management of those sources. For example, mandatory control and recycling of discarded, housewares, fishing tools, and polystyrene foam should be implemented.

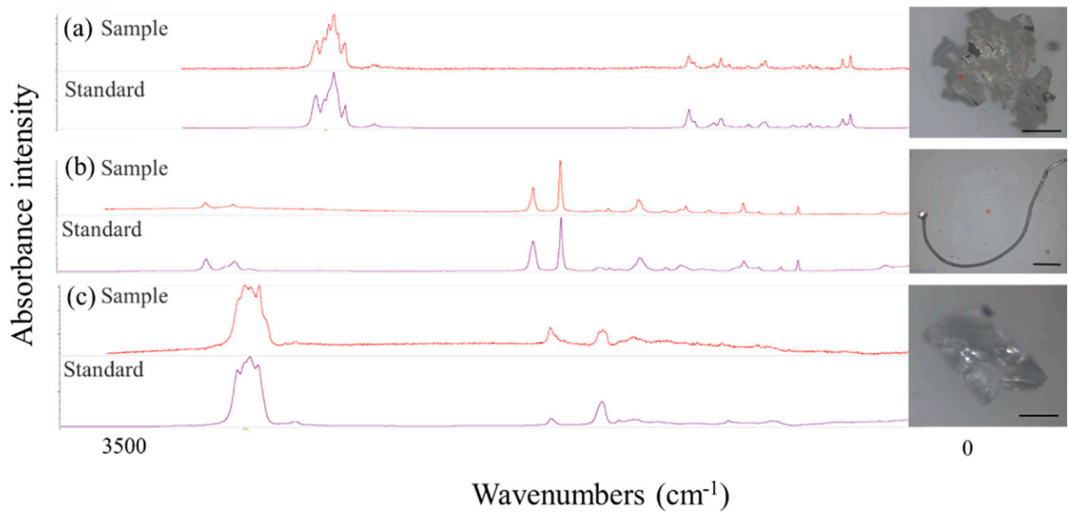

Fig. 3. Micro-Raman spectra of selected microplastic (MP) samples including (a) polypropylene fragment at site 1; (b) polyethylene terephthalate fiber at site 8; (c) polybutene sheet at site 12. Standard spectra were obtained from a micro-Raman library. Scale bar = 100 μm.

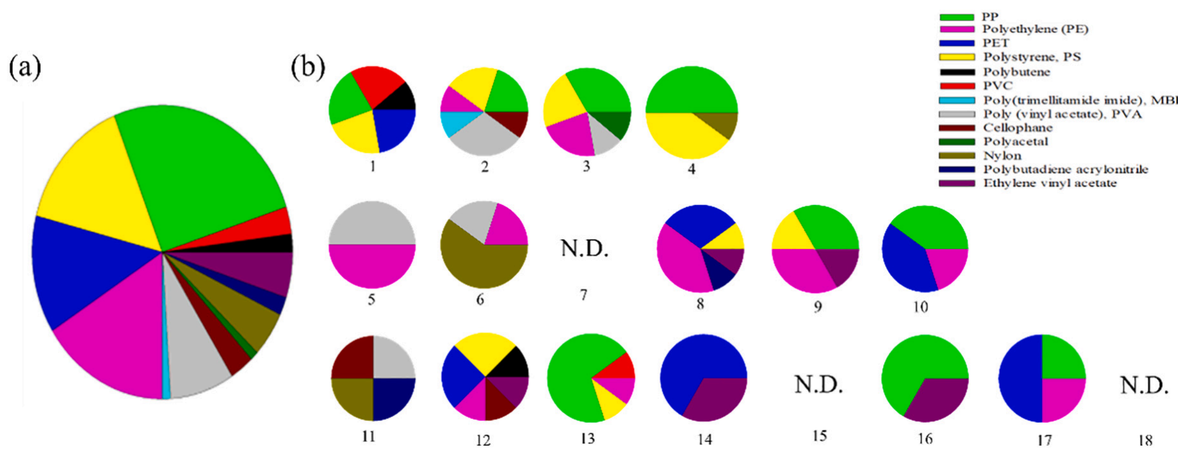

Fig. 4. Relative proportions of different polymer types of all collected microplastics (MPs) (a). Relative proportions of MPs at each sampling site (b), numbers represent sampling sites.

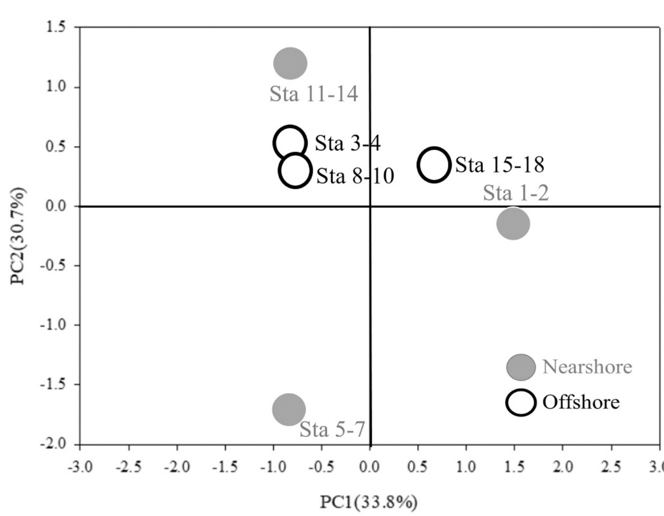

Fig. 5. Score plots of the three principal components (component 1 versus component 2) for microplastic types in the surface waters.

Principal component analysis (PCA) was further used to extract the chemical composition of MPs at nearshore and offshore sampling stations. Fig. 5 and table S2 show 8 polymer types (i.e., 8 variables) that describe the spatial distribution of the sampling sites. PC1 explained 33.8% of the total variance in the data matrix. The major positive loading polymers of component 1 were polybutene, PVC, and cellophane; high negative loadings included PE. All four loadings were related to commercial products. While PP, PS, and PET were heavily weighted in the positive loading polymers of PC2 (explained 30.7% of the total variance), nylon was the major negative loading polymer of component 2. These polymers in PC2 could be major components from fishing, net, and floating applications. The data showed that the distribution pattern of the samples on the score plot was based on regional differences, reflecting compositional differences between the nearshore and offshore. The MPs from offshore sites were located in the middle of the plot, indicating a high diversity of polymers in the ocean area. The diverse patterns observed in the nearshore area may represent multiple MP sources, such as coastal and riverine inputs from land, the Kuroshio intrusion, and other local currents (Liu et al., 2021). By contrast, samples from the nearshore sites indicate unique patterns of chemical polymers and may directly reflect local sources and activities.

Additionally, in plastic production, many monomers and other additional agents are used to improve the freshness and maintain the

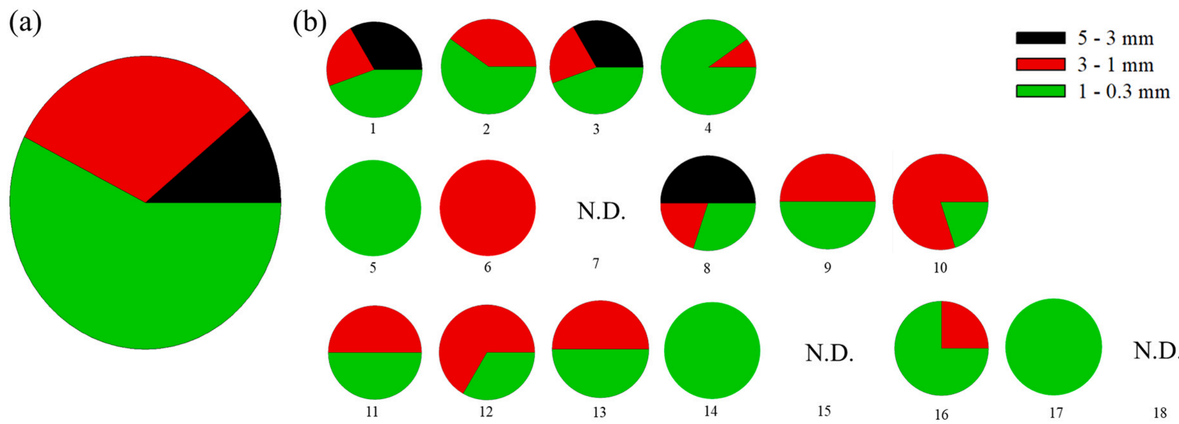

Fig. 6. Relative proportions of sizes of all collected microplastics (MPs) (a). Relative proportions of MPs at each sampling site (b), numbers represent sampling sites.

functionality of plastic products (OECD, 2004). These unreacted residual monomers and intrinsic plasticizers are carcinogenic, so their release into the environment poses an environmental risk to marine organism health (Chagas et al., 2021). Lithner et al. (2011) assessed the environmental and health hazard scores of MPs based on their chemical properties. PVC, polyurethane, and styrene acrylonitrile were considered highly harmful polymers, whereas PE and PS showed less ecological toxicity and PP exhibited the lowest hazard score. In the present study, PVC accounted for <3% of the total MPs, while MPs with higher hazard scores, such as polyurethane and styrene acrylonitrile, were not found in our sampling sites. The adsorption behavior of environmental pollutants is also related to the properties of MPs (Holmes et al., 2014; Rochman et al., 2013).

3.3. Physical properties

The identification of MP characteristics in marine and coastal environments is essential for understanding the transport of MPs and its ecological impacts, since aspects related to size and shape interfere with the behavior and fate of MPs in the environment (GESAMP, 2019). The MPs in the surface water off the Kuroshio have a broad size range and irregular shapes that include fragments, fibers, sheets, spheres, and films (Fig. 6). The sizes of ~60% of the detected MPs spanned from 0.3 to 1 mm; 31.6% of MPs were medium sized (1–3 mm), while 10.1% of MPs were large sized (3–5 mm). Our observations are consistent with the recent findings that relatively small-sized particles (smaller than 1 mm) dominate the MP populations (Eo et al., 2018). Interestingly, the relative proportion of MPs increases in size with decreasing plastic sizes, suggesting that plastic breaks off from large plastic debris to form smaller fragments via aging, weathering, mechanical fragmentation, chemical (oxidative and thermal) degradation, and biodegradation (Enders et al., 2015; Tekman et al., 2020; Isobe et al., 2019). The relative proportions of the MP sizes at each sampling site are shown in Fig. 6b, the MP size components, including large-sized MPs, had a higher complexity in the near shores of northern Taiwan (station 1 and 3) with densely populated coastlines and complex local currents; therefore, this area received large-sized plastic debris. By contrast, the less contaminated stations (locations 15–18) exhibited MPs mostly in the size range of 0.3 to 1 mm. This may indicate that the majority of MPs pervasive in the remote ocean are smaller sized plastic items (Cózar et al., 2014). This may indicate that larger marine plastic debris can be broken down into small MPs through various environmental processes (Auta et al., 2017). In fact, the MP size distributions significantly affect their transport and ecological consequences. For example, small-sized plastics spread widely and rapidly in natural systems and are easily transferred to the inner oceans and seafloors via food webs and aggregation processes with microorganisms (Lusher, 2015; Shiu et al., 2020a). Increasing evidence now indicates that a wide range of marine organisms, including bivalves, mussels, shrimp, oysters, copepods, and lugworms, can ingest or take up plastic particles, further disturbing their fertility and metabolism (Andrady, 2017; Lusher, 2015; Picó and Barceló, 2019). Shiu et al. (2020b) also indicated that the toxicity of plastics to marine algae is related to plastic size, and that the survival rates of algae decrease with decreasing plastic sizes. Chemically, smaller plastics have a high surface area and porosity that allow efficient adsorption and accumulation of several organic pollutants and heavy metals from surrounding water. The plastics therefore act as carrier vehicles for the transboundary transport of pollutants (Alimi et al., 2018).

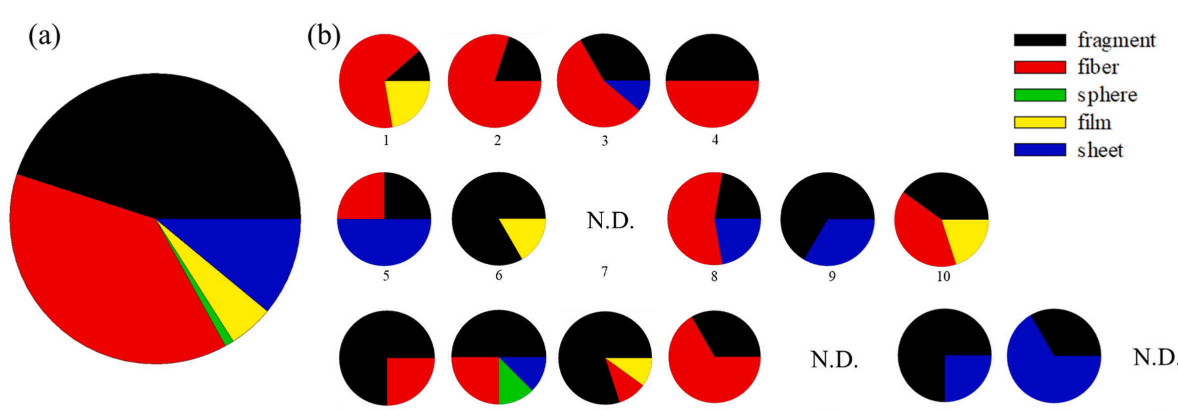

Fig. 7. Relative proportions of shapes of all collected microplastics (MPs) (a). Relative proportions of MPs at each sampling site (b), numbers represent sampling sites.

Fragments, fibers, sheets, films, and spheres in sampling sites accounted for 45%, 38%, 11%, 5%, and 1% of the MPs, respectively (Fig. 7a). Fragment-type plastics were the main form observed in our field survey results, in agreement with other studies conducted in different parts of the world, such as in the Northwestern Pacific region (Pan et al., 2019). Plastic shapes also can be used as indicators of the origins and pathways of MPs. For instance, fibers are an indication of sewage and fishery sources (Depledge et al., 2013) and prevail near the shore, river outlets, and fishing grounds (Cózar et al., 2014). The higher diversity of shapes especially in fragments and fibers observed in our field survey may infer that the study area is located near the shore (Fig. 7b). Primary microplastics, such as spheres, were rarely observed in our water samples, suggesting that the major sources of MPs in this environment are secondary and that the MPs arise from the fragmentation of larger plastic wastes. The less contaminated sites, such as locations 15–18, exhibited the majority of different MP shapes in the ocean, including fragments and sheets. The relatively low content of fibers also observed during our survey reflected the fact that our study area was located in the pelagic zone, far away from land.

4. Conclusions

Field observations of MPs were conducted for the first time in the Kuroshio east of Taiwan to investigate the abundance, chemical composition, spatial pattern, and shape of MPs. The results help us to understand the MP contribution from the east coast of Taiwan to the Kuroshio and Northwest Pacific, and further identify their possible sources and transport pathways. The level of MPs in the study area ranged from N.D. to 0.15 items m^{-3}, with an average concentration of 0.05 ± 0.03 items m^{-3}. The highest abundance of MPs appeared in river outlets and locations with more complexity of local currents. Interestingly, high concentrations of MPs were also detected in the Kuroshio stations, revealing that MPs have contaminated the relatively "ultra-oligotrophic" and "pristine" Kuroshio water and even the Northwest Pacific. The observed currents determined by vessel-mounted satellite altimetry data indicated that the spatial distribution of MPs can be attributed to the effects of river inputs and coastal circulation. Furthermore, the major MPs, which comprised PP, PE, PET, and PS, were distributed in the coastal zone and fishing ground areas. These MPs were mainly released from gears used in fishery and human activities. The background concentration of the Kuroshio (location 17 and 18) was ranged from N.D. to 0.001 items m^{-3} and found unique physical characteristics of MPs such as smaller sizes, fragments, and sheets. Our data have identified the presence of transport pathways, and further modelling studies will allow us to resolve the importance of these routes and the level of dispersal from local sources. This study also offers much-needed information about the MP contribution by Taiwan's coast to the western boundary current of the North Pacific Ocean to facilitate the legislation of waste and water quality control strategies.

CRediT authorship contribution statement

Ruei-Feng Shiu: Conceptualization, Investigation, Funding acquisition, Supervision, Resources, Formal analysis, Project administration, Methodology, Writing – original draft. **Gwo-Ching Gong:** Conceptualization, Investigation, Funding acquisition, Project administration, Supervision, Resources, Writing – review & editing. **Meng-Der Fang:** Methodology, Writing – review & editing. **Chun-Hoe Chow:** Methodology, Writing – review & editing. **Wei-Chun Chin:** Investigation, Supervision, Resources, Writing – review & editing.

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

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