

INTEGRATING FIELD DATA AND NUMERICAL MODELING TO ASSESS MICROPLASTIC DISTRIBUTION IN THE AQUATIC ENVIRONMENT OF HA LONG BAY, VIETNAM

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ABSTRACT: This study aimed to investigate the microplastic distribution in the aquatic environment and sediments, and integrate field data and numerical modeling to simulate the spreading of microplastics to gain valuable insights into microplastic accumulation and infiltration into the sea. The study showed that the microplastic density in seawater was ranging from 0.01 to 0.69 particles/m³; the color of microplastics were white/transparent with 41.3%, blue 22.3% and yellow/orange 21.3%; the morphology of microplastics were thin, spherical and fibrous filaments, accounted for 96.9%, of which the size from 1-5mm accounted for 87.9%; the main types of microplastics were HDPE and PS accounting for 47.4% and 18.8%, respectively. The amount of microplastics found in the sedimentation was rather low, up to 12 particles/kilogram, was mostly found in the coast and in rivers. The spreading of microplastic modeling indicated that the high microplastic concentration areas were primarily located in the coastal regions of Ha Long and Cam Pha cities; and the microplastic generated from the inland did not affect Ha Long Bay due to the geomorphological structure with numerous islands that limited the dispersion of microplastics into the offshore. The zones with the highest microplastic concentrations coincide with areas of intensive human activity, including cruise tourism, coastal services, maritime transport, coal mining, and coastal industrial zones. Hence, the waste capture in estuaries and coastal areas and the limitation of single-use plastic products on cruise ships are needed to avoid microplastic movement to the sea.

Keywords: Microplastics, Ha Long Bay, Surface water, Sediment, Fate

1. INTRODUCTION

With the development of chemical engineering techniques, many convenient and useful products have come to human life, and plastic was one of the outstanding inventions. Plastic waste management and recycling capabilities would be far exceeded in the next two decades with the enormous increase in plastic production, which was foreseen to double at that time. Along with the need for plastic products, the volume of plastic litter has been steadily rising in recent years [1]. Plastic litters were primarily collected and recycled (9%), some was burned (12%), and the remaining 79% was untreated and dumped in oceans [2,3]. At least 8 million tons of plastic enter the ocean every year, according to the study [4], which showed that 20% plastic waste is generated from seafood and fishing vessels, and the other 80% originates from inland activities.

Microplastics, or plastic particles less than 5 mm in size, have been found in oceans [5] and might exist in marine ecosystems for hundreds of years [6]. Their presence has been found in lakes, streams, rivers, seawater, sandy beaches, and sediments [7]. Microplastics can enter the aqueous environment (e.g., fresh water and sea water) through the drainage

system and estuaries [8]. Microplastics also spread to the aqueous environment via wind, currents, waves, storms, anthropogenic (e.g., dam releases, emissions), and sediments [9]. Rivers are the potential sinks and important routes for microplastics to the ocean. Despite their importance, the mechanisms of microplastic movement and abundance in riverine and marine environments remain poorly understood [10].

Researchers have also been investigating methods to understand and predict the movement of microplastics in water bodies. Despite limitations in available data and monitoring capabilities [11], modeling approaches offered valuable insights into microplastic transport and transformation in the ocean [11]. Several mathematical models provided reliable predictions regarding the motion and behavior of microplastics in water, such as accumulation hotspots, transport pathways, and potential sources. The Lagrangian particle tracking models (PTMs) simulated the movement of discrete particles in water [12]. Numerous integrated mathematical models (e.g., TELEMAC) were simulated to study the movement of microplastics influenced by flow regimes and waves in estuaries and coastal areas, such as hydrodynamic processes,

currents, and wave dynamics [13]. Another powerful model was ROMS, which focused on simulating ocean circulation, temperature, and salinity. When coupled with microplastic tracking modules, ROMS enables the exploration of microplastic transport pathways over larger spatial scales [9]. Additionally, the comprehensive hydraulic model MIKE 21 played a crucial role in simulating hydrodynamics, waves, sediment transport, and water quality [14]. The recently mapped microplastic distribution revealed a deviation where plastic accumulates, generates, and infiltrates into the sea due to a lack of integrated features, microplastic data, waves, tides, wind, and sediment transport in coastal regions and estuaries. These findings highlight the need for further research into the effects of integrated microplastic distribution characteristic data and local hydrodynamic considerations on the microplastic distribution maps.

2. RESEARCH SIGNIFICANCE

We further (i) investigate the microplastics distribution characteristic (abundance, types, colors, sizes, and shapes) in the aquatic environment and sediment in order to better understand the fate and characteristics of microplastics; (ii) intergrade microplastics data and the MIKE 21 numerical modeling number establish the microplastics distribution map in offshore areas. This work provides crucial insights for developing effective intergrade methods for predicting microplastics movement from river to the ocean systems. Moreover, the study on the existence and characteristic of microplastics is necessary due to the current moving, affecting the waters, aquaculture and tourism activities. This research will offer baseline values for microplastics in coastal and marginal waters, which may assist the government in developing successful management strategies on plastic and microplastic pollution.

3. MATERIALS AND METHODS

3.1 Study Area

Ha Long bay has an area of 1,553 km² and contains 1,969 islands. UNESCO has twice designated Ha Long bay in Quang Ninh province as a World Natural Heritage site having outstanding values of natural beauty (1994) and geology (2000).

Ha Long bay was bordered by a 120 km long coastline from Quang Yen town, through Ha Long city, Cam Pha city and to Van Don island. The activities from residential areas, tourist areas, and inland waterway ports directly affected to the environmental quality in Ha Long bay. Ha Long Bay is also affected by currents and aquaculture and tourist activities, such as the Cua Luc estuary current, the Lan Ha Bay sea currents, the aquaculture

activities in Bai Tu Long Bay and Lan Ha Bay, and the cruise ship activities in the gulf [15].

3.2 Sampling Methods

3.2.1 Sampling location

The samples of water and sediment were collected following three groups of sampling locations, such as: (i) river estuaries and coastal areas (sampling point No. 1, 2, 3, 4, 7); (ii) tourism corridors (sampling point No. 8, 10, 11, 12, 13, 16, 17); (iii) aquaculture zones (sampling point No. 5, 6, 9, 14, 15, 18, 19, 20). The sampling locations in this study were given in Table 1 and Fig. 1.

Table 1. Sampling location

	No	X	Y	Location
Estuary and coastal area	1	20°54'26"N	106°57'45"E	Coastal area in Hoang Tan island commune
	2	20°55'35"N	106°56'59"E	The confluence of Hot River, Ben Giang River before flow into Ha Long bay
	3	20°56'57"N	107°03'48"E	Coastal area in Bai Chay ward, Ha Long city, adjacent to Cua Luc estuary
	4	20°56'02"N	107°07'19"E	Coastal area in Ha Phong ward, Ha Long city
Tourism corridor	7	20°55'10"N	107°00'10"E	Sea area near Tuan Chau island
	8	20°53'50"N	107°07'01"E	Coastal area in Hong Hai ward, Ha Long city
	10	20°52'25"N	107°13'19"E	Sea area near Cap La island, Ha Long bay
	11	20°54'34"N	107°14'19"E	Sea area near Hon Goi Dau island, Ha Long bay
	12	20°53'22"N	107°03'56"E	Sea area near Hon Van Boi island, Ha Long bay
	13	20°50'49"N	107°07'50"E	Sea area near Bu Xam island, Ha Long bay
	16	20°50'55"N	107°11'50"E	Sea area near Bo Hung island, Ha Long bay
	17	20°53'16"N	107°09'24"E	Sea area near Ong Mo island, Ha Long bay
	5	20°55'12"N	107°08'07"E	Coastal area in Hong Ha ward, Ha Long city
	6	20°55'55"N	107°12'30"E	Coastal area in Hong Ha ward, bordering Bai Tu Long bay
Aquaculture zone	9	20°52'25"N	107°13'19"E	Sea area near Hon Let port channel area, Ha Long bay
	14	20°49'02"N	107°09'34"E	Sea area near Hon Luoi Liem island, Ha Long bay
	15	20°45'15"N	107°10'00"E	Sea area near Dam Be island, bordering Lan Ha bay
	18	20°48'58"N	107°17'38"E	Sea area near Van Gio island, adjacent to Van Don bay and Lan Ha bay
	19	20°48'07"N	107°15'10"E	Sea area near bordering Lan Ha bay
	20	20°45'51"N	107°12'43"E	Sea area near bordering Lan Ha bay

3.2.2 Sampling method in seawater

Microplastic samples in the seawater were

obtained using a 50x50 cm Neuston net. A microorganism net had a 20 µm mesh size; it used buoys to keep 50% of the net floating and used a boat to tow the net across the water [16]. Triplicate field blanks were implemented by aspirating ambient air through a 20 µm mesh. A null result was obtained in all three replicate trials. Subsequent laboratory procedures were conducted within a HEPA-filtered laminar flow environment to ensure air quality and prevent sample compromise.

A flowmeter was used during sailing to gauge the velocity. The microplastic samples were pre-treated by eliminating non-plastic components and microplastics larger than 5 mm.

3.2.3 Sampling methods in sediment

The bucket sediment sampler Van Veen, with a capacity of 25 liters, was used to collect microplastics in the sediment. After taking the sample, the bucket sediment sampler was dropped vertically, opened the compartment to remove the layer of sediment with a thickness of 5-10 cm on the surface, and put it in the sample bottle. The samples were pre-treated by removing the microplastics > 5 mm and non-plastic components from the sample. Blank tests were carried out for vessels twice in a similar manner to those reported [17]. The Neuston net was washed by clean water before towing; it was hung with a crane and poured seawater from the outside of the net, then counted the microplastics in the cod end. The results of blank tests showed that no microplastic particles were observed in the net.

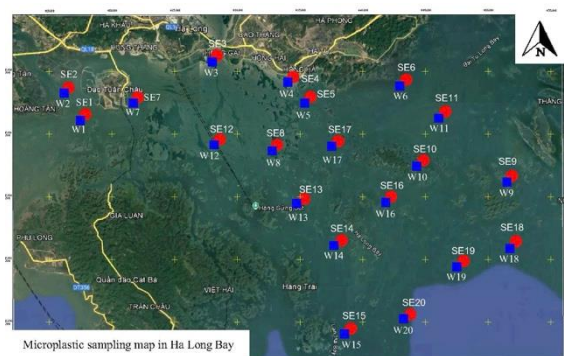


Fig. 1 Sampling locations in seawater and sediments in Ha Long bay

3.3 Microplastic Analysis Method

The microplastics samples in water and sediment were processed and analyzed at the Key Laboratory of Advanced Materials Applied in Green Development (KLAMAG), University of Science, Vietnam Nation University, Ha Noi (HUS – VNU).

The collected microplastic samples in seawater and sediment were chemically treated according to NOAA's process, used the Fenton reaction to remove organic matter. According to GESAMP 2019, this

was the effective and rapid method that did not affect the polymer structure of microplastics compared to other methods. This method could be used to analyze plastic debris in the form of suspended solids in water samples. After removing organic matters, the separation step was carried out based on the density difference between the samples (water or sediment samples) and the density of chemical compound (NaCl or NaI); as following: (i) for water samples, using NaCl with density 1.2 g/cm³ [18], (ii) for sediment samples, using NaI with density 1.6 g/cm³ [20]. Based on the density difference, the plastic debris were float to the surface of sample. After that, samples were filtered with 100 µm and dried in the air to get plastic debris [16]. Spiked recovery tests using relevant reference particles were used to assess extraction efficiency or loss in the digestion protocols or density separation [17].

The volume of water passing through the grid (V) at each sampling route is determined by the following formula:

$$V \text{ (m}^3\text{)} = S_{\text{net}} \text{ (m}^2\text{)} \times \text{Sampling line length (m)}$$

in which, the length of the sampling route and the area of the mouth of the net (S_{net}), and the measurement of the water flow velocity with the flowmeter,

The density of microplastics at the sampling points (C) was calculated by the formula:

$$C \text{ (particle/m}^3\text{)} = \frac{\text{particles at sampling point}}{V \text{ (m}^3\text{)}}$$

In this study, microplastic concentrations were expressed in terms of particle counts (particles/m³ for water and particles/kg for sediment). This approach follows regional and international standards, allowing for reliable comparison across studies (e.g., [21, 22]). Mass-based units (mg/kg) were not used, as microplastics differ widely in density, morphology, and porosity, and current analytical methods (FTIR, microscopic analysis) do not allow for accurate weight determination of individual particles.

3.4 Analytical Methods For Microplastic Determination

The microplastic sample was captured using a Terino HDMI-HD 1000X LCD Digital Microscope LCD microscope with a magnification of 50 times, and used GIMP software to process the images and moved to the particle size measurement step. In the size measurement step, dimensions were measured by using ImageJ software (Fiji) which was used to measure the sample according to the Feret diameter. The obtained results included the length of the diagonal and the area of the sample.

The chemical composition was determined by Fourier transform infrared (FTIR) spectroscopy using a JASCO FTIR Model 4600 instrument with ATR probe. The determination of the plastic types was based on comparison with standard FTIR spectra with an ATR probe in accordance with the Council of

Europe (EC) Guidelines for the Monitoring of Marine Waste in European.

3.5 Establish The Microplastics Movement Map

The spreading microplastics modeling in Ha Long bay was set up using MIKE 21 software which simulated microplastic movement. Based on the numerical solution of Reynolds averaged Navier-Stokes equations, the Hydrodynamic Module simulated water flow, currents, and turbulence [19]. It provided the foundation for understanding how microplastics move within the water column. By considering flow patterns, wind, and other factors, we could predict their dispersion and accumulation. Spectral Waves based on the wave action conservation equation, as described in e.g., helped to understand how waves affect microplastic transport and dispersion. This approach tracked the movement of individual particles and monitor changes in their mass over time, independently of any reference grid system [20].

3.5.1 Data Collection and Model Setup

Bathymetric data for this study were sourced from multiple datasets to ensure accurate and comprehensive representation of the modeling domain in MIKE 21. The regional seabed topography was derived from the General Bathymetric Chart of the Oceans (GEBCO) global dataset, which provides bathymetric data at a 15 arc-second resolution. For nearshore areas, higher-resolution bathymetric maps at scales of 1:50,000 and 1:25,000 (Fig. 2) were obtained from the Vietnamese Ministry of Natural Resources and Environment. These datasets were integrated to accurately represent the complex topography of the coastal zone. Recent in situ bathymetric surveys conducted in 2021 provided detailed topographic information around the target area, including the proposed microplastic dispersion modeling zones. This combination of global datasets and field measurements ensured a reliable and detailed representation of seabed morphology, which was essential for simulating hydrodynamic processes and predicting microplastic transport in coastal waters.

The WAVEWATCH III dataset, developed by NOAA/NCEP following the WAM model framework, was utilized to enhance our understanding of wave dynamics in the study area. This high-resolution, globally recognized dataset provides extensive spatial coverage and long-term records of key wave parameters, including significant wave height, wave period, and directional spectra, for the model's northern, eastern, and southern boundaries. The integration of WAVEWATCH III data with field measurements ensured a comprehensive and accurate representation of environmental conditions, crucial for modeling hydrodynamics and microplastics

dispersion in the coastal zone.

The wind data was employed the ERA5 dataset, the fifth-generation ECMWF reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 provided global, hourly estimates of wind parameters at a spatial resolution of 0.25 degrees, offering consistent and high-quality data for atmospheric forcing in the model (see Table 2)

Hourly water level data were collected from tide gauges deployed at Co To station, providing essential information on tidal fluctuations in the study area. These datasets were crucial for the calibration and validation of the MIKE 21 hydrodynamic model, ensuring an accurate representation of water level dynamics and improving the reliability of the simulation results.

Using tidal data for model calibration helped to minimize discrepancies between simulated and observed water levels, enhancing the model's ability to reproduce real-world hydrodynamic conditions. This process is critical for accurately modeling current patterns and tidal-driven processes, which play a significant role in the transport and dispersion of microplastics in the coastal zone. The combination of field measurements and model validation also ensured a more robust assessment of microplastic pathways and their interaction with local hydrodynamic forces.

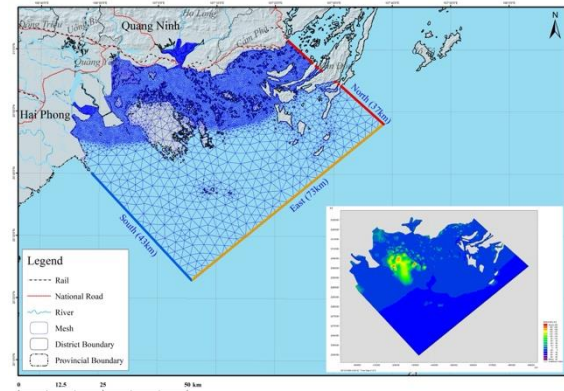


Fig. 2 Computation domain with finite element grids for (a) the whole domain and (b) the port site

Table 2. The data sources for setting up the model

No	Parameter	Source
1	Bathymetry	GEBCO
2	Water levels	Viet Nam Meteorological and hydrological Administration
3	Wave	WAVEWATCH III
4	Microplastic Data	Measurement

3.5.2 Computational domain

The computational domain, covering the coastal waters from Lan Ha bay to Bai Tu Long bay (Fig. 2), was modeled using a flexible mesh grid in MIKE 21. The grid was designed with variable resolution levels to accurately simulate hydrodynamic processes and

microplastic dispersion while ensuring computational efficiency. The nearshore zone represented the primary focus of the model, covering most of Lan Ha bay, Ha Long bay, and Bai Tu Long bay. This zone contains key microplastic emission sources, monitoring stations, and numerous limestone islands. To capture the complex topography and dynamic coastal processes, the grid resolution in this area was the most detailed, ranging from 100 to 300 meters. The offshore zone lied in the outermost part of the computational domain, where fewer small islands were present. As this area served primarily to provide boundary conditions, a coarser grid resolution of 600 to 800 meters was applied. This multi-resolution grid structure ensured a detailed representation of key nearshore areas while maintaining efficiency in simulating hydrodynamics and microplastic transport across the entire coastal zone.

3.5.3 Boundary conditions

Boundary conditions for the MIKE 21 model were established for the Hydrodynamic (HD), Spectral Waves (SW), and Particle Tracking (PT) modules used data from various sources to ensure reliable simulation of hydrodynamic processes and microplastic dispersion.

For the Hydrodynamic module, water level time series were derived from measurements collected at three oceanographic stations: Hon Dau for the northern boundary, Co To for the eastern boundary, and Cua Ong for the southern boundary. These time series provided accurate tidal and water level information along the open boundaries, improving the model's ability to reproduce local hydrodynamic conditions (Table 3).

Wave boundary conditions for the Spectral Waves (SW) module were specified using wave parameters from the globally validated WAVEWATCH III dataset. This ensured realistic representation of offshore wave conditions propagating toward the eastern boundary of the computational domain.

Boundary conditions for the Particle Tracking (PT) module were based on field surveys. These data were critical for simulating the transport and dispersion of microplastics within the coastal waters, ensuring consistency with the hydrodynamic and wave conditions in the model

3.5.4. Microplastic-specific transport parameters

The microplastic-specific transport parameters were determined as follows: (i) Density was derived from FTIR analysis to identify polymer types and compared with standard values reported in the literature [17, 18]; (ii) The shape factor was calculated from morphological analysis using ImageJ software, based on particle length, area, and aspect ratio, normalized following NOAA and GESAMP guidelines; (iii) Settling velocity was estimated using a modified Stokes' law, adjusted for polymer-specific

density and shape factor [25, 9]. These parameters were then used as input data for the MIKE 21 model to simulate the transport and distribution of microplastics in Ha Long Bay.

Table 3. The boundary data of the spreading microplastic modeling

Boundary	Hydrodynamic Module	Spectral Waves Module	Particle Tracking Module
Northern	Data collected at Hon Dau oceanographic station		
Eastern	Data collected at Co To oceanographic station	WAVEWATCH III	Survey
Southern	Data collected at Cua Ong oceanographic station		
Initial condition	The average data recorded at oceanographic stations during the simulation period		The minimum microplastic particle concentration was 0.02 particles/m ³

4. RESULTS AND DISCUSSION

4.1 Numerical Distribution Of Microplastics Abundance In Aquatic Environment In HaLong Bay

The abundance of microplastics was shown in Fig.3. The results showed that the density of microplastics in Ha Long bay was unevenly distributed and followed to the group of sampling locations. The density of microplastics found in the Ha Long bay area was only reach the level indicated “having microplastic pollution” and was consistent with earlier studies [21]. The highest microplastic density areas were measured at the coastal areas and estuaries such as Cua Luc estuary (W3) and Hot and Ben Giang rivers estuaries (W2), which were 0.69 particle/m³ and 0.4 particle/m³, respectively. This implied that the Cua Luc estuary was one of the most significant microplastic sources in Ha Long bay. This situation was caused by the plastic mismanagement, the microplastic debris from the coastal areas leaked to the river and passed into the sea through the estuaries. These marine microplastic debris were being considered as one of the most remarkable environment pollutants. The microplastic density in the tourist routes of cruise ship ranged from 0.17 – 0.33 particle/m³, lower than the sample locations in the coastal areas; because the main sources of plastic waste came from the take-away services for tourists. At the border locations (W18, W19, W20) between Ha Long bay and the Gulf of Tonkin, the presence of microplastics was very low density ranging from 0.01 – 0.02 particle/m³. The border locations such as W11, W9 had higher microplastic density due to the effect of using styrofoam buoy in aquaculture activities in

Bai Tu Long bay.

The microplastic pollution measured in Vietnam was lower than those measured in China, Philippines and Indonesia (Table 4). Hence, this clearly demonstrated that the Quang Ninh province committee had efforts in plastic management to protect the environment in Ha Long bay such as: waste management in the tourist, fishing and aquaculture activities in the Bay and using the ship picking up the trash within the Bay.

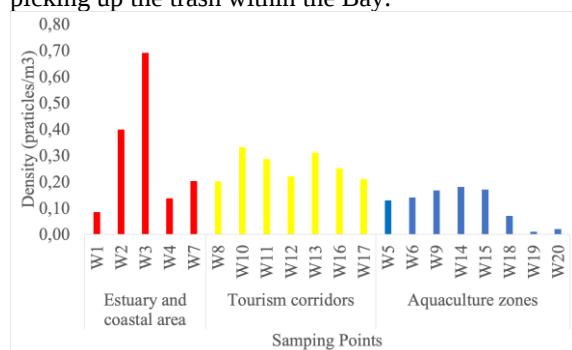


Fig. 3 Density of microplastics at seawater sampling sites in Ha Long bay, Quang Ninh province

Table 4. Density of microplastic distribution in the seawater of Ha Long bay and others

Research area			Density (Value/ Unit)		Ref.
Indonesia	North Surabaya		380-610	particle /m ³	[22]
Philippines	Macajalar Bay		2.95-33.65	particle /m ³	[23]
	Yangtze mouth	river	4.14		
China	Jiaojiang mouth	river	955.6	particle /m ³	[24]
	Oujiang mouth	river	680		
	Tien Giang, Can Gio and Ba Ria - Vung Tau		0.04-0.82	particle /m ³	[22]
Vietnam	Ha Long Bay		0.01-0.69	particle /m ³	This study

4.2. Distribution Of Microplastic Colors In Aquatic Environment In Ha Long Bay

The color distribution of microplastic in aqueous environment in Ha Long bay in Fig. 4 showed that the microplastics in Ha Long bay were found in a variety of colors, including white, green, blue, red, and black. However, with 41.3% of the total, white/transparent was the dominant color, followed by blue (22.3%) and yellow/orange (21.3%); the remaining colors account for 15.1%. White or transparent color accounted for a large proportion in the obtained microplastic samples, indicated that the main microplastics originated from the fragmentation of styrofoam buoy, plastic bags, canning boxes, plastic bottles, etc. Additionally, the plastic litters persisted

for a very long time in the water, where they gradually broke down into debris and lose their original color, turning milky or ivory white. Another significant chunk made up of blue, which were the color of fishing nets. Additionally, due to the presence of a rich alluvial (typical of the Quang Ninh region), microplastics partially attached to the surface of the alluvial precipitated and had an orange or yellow appearance.

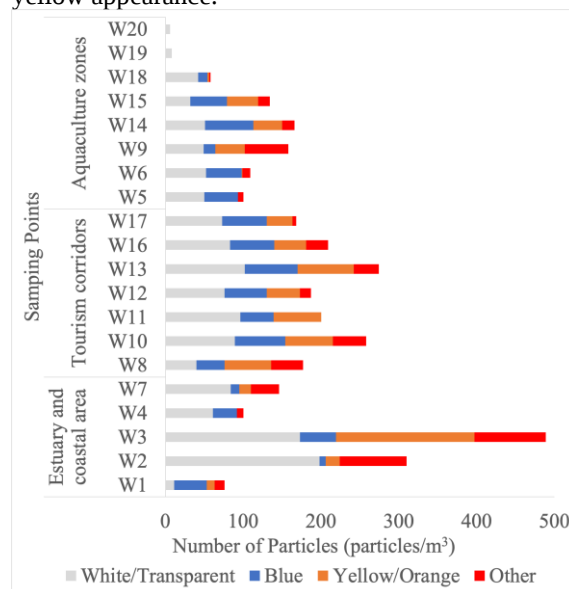


Fig. 4 Color distribution of microplastics in aquatic environment in Ha Long bay

4.3. Distribution Of Microplastic Shapes In Aquatic Environment In Ha Long Bay

Microplastic shapes' distribution was given in Fig. 6. In Ha Long bay, microplastics found in three primary shapes: fragments, pellets, and fibres. The fragments form made up 44.2%, followed by the pellets form (29%), and the fibers form (23.6%) (see Fig. 5).

The fragments form made up a significant portion of the morphology, especially in coastal seawater sample locations (W2, W3) and tourist routes of cruise ship (W8, W10, W11, W12, W13, W16, W17) with high levels of plastic wastes, such as bottles, plastic bags, and disposable cans. In addition, Ha Long bay also received more household appliance discharge (at location W2, W3), which resulted in higher levels of microplastics. This was also the most prevalent microplastic forms in other studies of Zhang [24] and Esquinas [23].

Due to extensive usage of polystyrene (PS) containers for aquaculture, the abundance of pellets microplastics in Ha Long bay was a unique characteristic that set apart from previous research conducted. Additionally, a significant portion of samples collected mostly from fishing lines and nets during aquaculture and fishing operations were

microfibre samples.

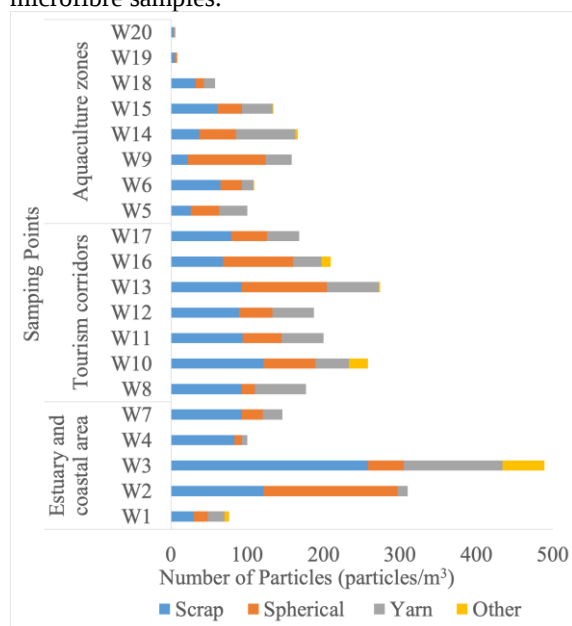


Fig. 5 Shape distribution of microplastics in seawater samples in Ha Long bay.

4.4. Distribution Of Microplastic Sizes In Aquatic Environment In Ha Long Bay

The analysis results showed that the size distribution was in the range of 1-5mm, accounting for 87.9% (see Fig. 6). The size 1-2 mm made up 35.2%, which was thought to be long-lasting in the marine environment yet vulnerable to weather and climatic influences that can cause to break down into fragments. Due to color loss from prolonged exposure to the environment, this became debris and also was similar to the primary hue of white or transparent microplastics. The concern was the significant amount (23.5%) of microplastics had a size of less than 1 mm; because at this size, they could be mistaken for food by large fish and entered the food chain.

4.5. Distribution Of Microplastic Chemical Properties In Aquatic Environment In Ha Long Bay

The microplastics chemical composition was given in Fig. 7. The FTIR measurement results showed that the main chemical compositions of the microplastic samples were HDPE (High Density Poly Ethylene), accounting for about 47.4%, followed by PS (Polystyren) accounted for 18.8% of the total water samples in Ha Long bay. In addition, some other plastics such as PET (Polyethylene Terephthalate), LDPE (Low Density Polyethylene), PP had lower rates of 11.4%, 8.3% and 6.9%, respectively (see Fig. 8).

Due to its high tensile strength, HDPE plastic was particularly popular in the consumer goods and

product packaging industries. It was also used extensively in agricultural applications, including ropes, fishing and sports nets, as well as industrial and decorative fabrics. Additionally recyclable, HDPE was appropriate for a variety of applications.

PS plastic was also one of the most widely used plastics in use nowadays including the production of food containers, plastic cups, and disposable plastic dining utensils, because of its affordability, practicality, short shelf life, ease of disposal, and variety of uses.

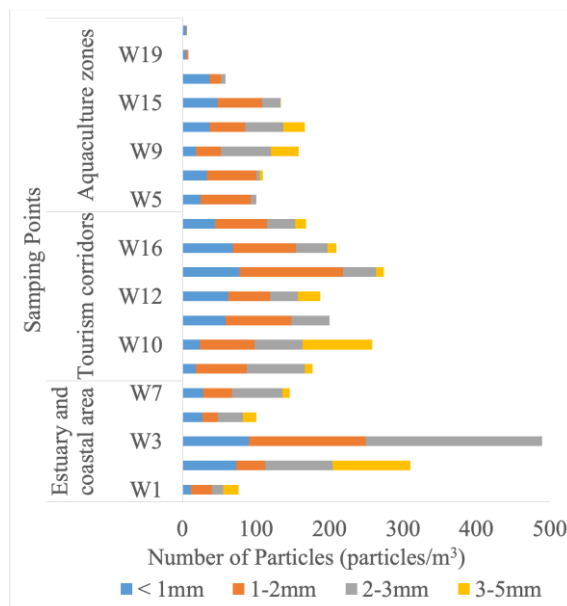


Fig. 6 Feret diameter of microplastics in seawater samples in Ha Long bay.

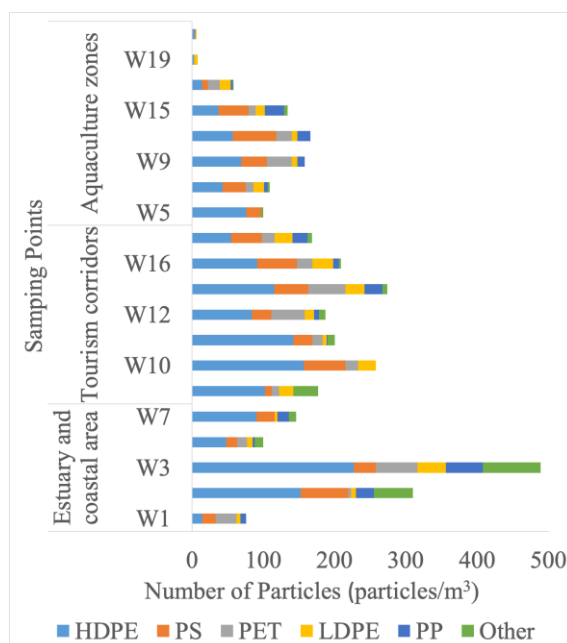


Fig. 7 Chemical composition of microplastics in seawater samples on Ha Long bay.

A significant fraction was made up of HDPE and PS plastic, indicating that microplastics may originated from the fragmentation of plastic debris from industrial and agricultural sources, including ropes, fishing nets, and single-use plastic goods.

The category 'Other polymers' refers to plastic types detected with low frequency or with FTIR spectra that did not match the reference library with >70% certainty (e.g., PVC, EVA, or polymer blends). To avoid over-interpretation, these were grouped into 'Other.' Non-plastic particles (e.g., organic fibers, sand, or cellulose) were removed during pre-treatment and confirmed by FTIR not to be included in the statistics.

4.6. Distribution Of Microplastic In Sediment In Ha Long Bay

The amount of microplastics found in sediment samples (see Fig. 8) ranged from 0 to 12 particles/kg. The highest density was about 12 particles/kg, which concentrated in coastal sediment samples and canal areas. The stratification and mixing between fresh water and seawater in estuaries might affect floating and deposition of microplastics that influenced microplastic transportation [25]. Moreover, due to poor water circulation, the plastics were suspended and deposited in estuaries. Hence, the Cua Luc estuaries (SE3) had highest microplastic concentration 12 particles/kg the Hot and Ben Giang rivers estuaries (SE2) had microplastic concentration 8 particles/kg. The microplastic levels in the sediment of rivers tended to decrease from the river mouth toward the open sea due to the increased distance [28]. Moreover, due to less aquaculture activities in Lan Ha bay, the microplastics were not found in SE18, SE19 and SE 20 samples. The microplastic density in Ha Long bay was extremely low when compared to certain other studies conducted (see Table 5). This was explained by the fact that aquaculture activities were restricted in Ha Long bay and environmental pollution control was strictly enforced. The majority of the microplastics were derived from microorganisms that naturally contain microplastics; as they died, these microplastics sank and mixed with the sediment at the bottom of the sample.

4.7.1. Model calibration and validation for microplastic dispersion

The dispersion of microplastic particles in the study area was primarily governed by hydrodynamic processes influenced by wave action and tidal currents. Model calibration and validation were conducted using water level data collected at Bai Chay station during the seawater sampling period. The Nash-Sutcliffe Efficiency (NSE) and Correlation Coefficient (R) were employed to assess the agreement between model predictions and observed data [30].

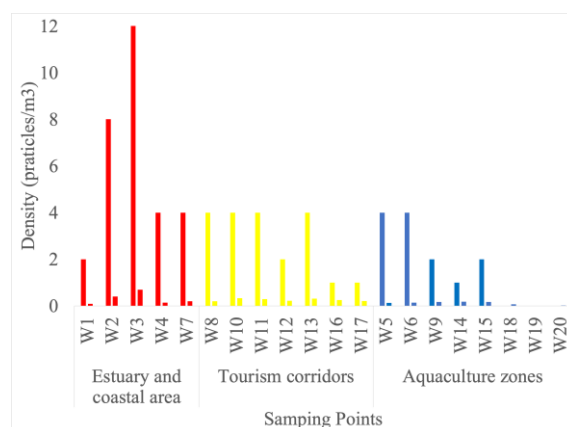


Fig.8 Density of microplastics in sediment samples in Ha Long bay.

Table 5. Comparison of the density of microplastics distribution in the sediments of Ha Long bay and other regions in the world.

Research areas	Size (mm)	Density (particles/kg)	Reference
Australia's East Coast	0.2-5	83-350	[5]
Hong Kong	0.1-5	44-458	[27]
Sishili Bay, Yellow Sea, China	<5	20-340	[7]
Sishili Bay, Yellow Sea, China	<5	140-1873	[24]
Coasts along Singapore	0.0016-5	0-16	[28]
Can Gio, Vietnam	0.3-5	0-666	[15]
Ba Lat, Vietnam	0.3-5	45-3.235	[29]
Ha Long bay	<5	0-12	This study

4.7. The sMicroplastics Movement Modeling In Offshore Ha Long Bay

The calibration results (Table 6, Fig. 9 and Fig. 10) indicated a high level of accuracy, with NSE values of 0.96 for calibration and 0.98 for validation, which fall into the 'very good' category based on [31] standards. The correlation coefficient (R) also demonstrated excellent agreement, with values of 0.98 and 0.99 for calibration and validation, respectively. These metrics confirm the model's strong performance in simulating the hydrodynamic processes within the study area. The results demonstrate that the model adequately simulates the hydrodynamic processes within the study area, with an average Manning's roughness coefficient of approximately 32 m^{1/3}/s and a dynamic viscosity coefficient of around 0.28.

Table 6. Model calibration and validation results

STT	Index	Calibration	Validation
1	NSE	0.96	0.98
2	Correlation coefficient	0.98	0.99

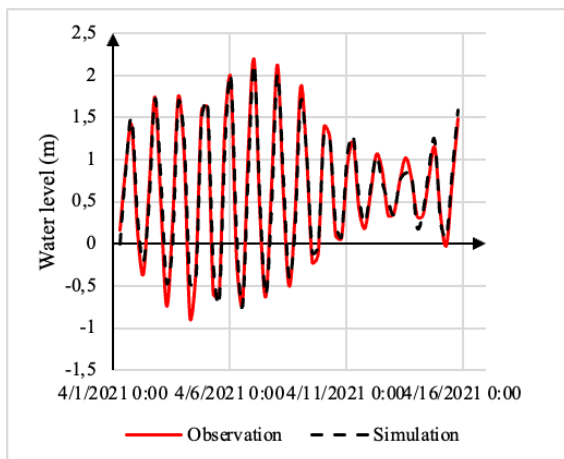


Fig.9 Correlation of calibrated water level at the Bai Chay station

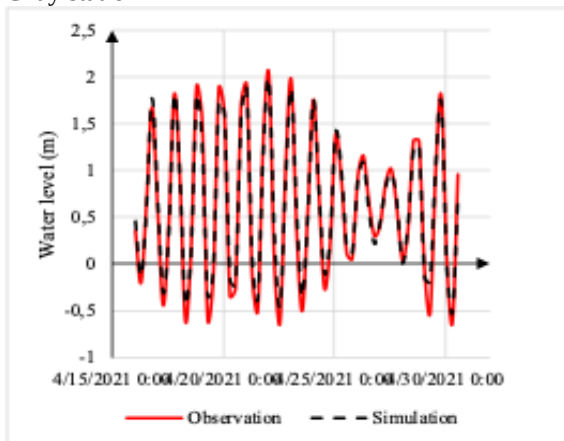


Fig. 10 Correlation of validated water level at the Bai Chay station

After calibrating the hydrodynamic processes based on observed water levels, the study proceeded to calibrate the Particle Tracking module using particle-specific parameters, including particle density, settling velocity, windage factor, and diffusivity (in Fig 11). For this calibration, 20 sampling sites were employed as initial conditions at source points of microplastic release, while the remaining 5 sites were reserved for independent validation against model simulations. The calibration results indicated that simulated microplastic concentrations at stations W4, W7, W17, and W9 were 13–26% higher than observations, whereas at W10, the model underestimated observed values by approximately 16%. These discrepancies highlight inherent uncertainties in particle dispersion modeling; however, an error range of 16–26% is considered acceptable for the PT module.

Following calibration, the PT parameters were determined as follows: the horizontal and vertical dispersion coefficients were estimated at 0.012 and 0.013 m/s, respectively. These coefficients represent transport processes driven by molecular diffusion as well as unresolved turbulence and eddies. The

settling velocity was established at 0.012 m/s, indicating prolonged surface residence times before particle deposition. The windage factor was estimated at approximately 3%, reflecting the drag effect of wind on buoyant microplastic particles at the water surface.

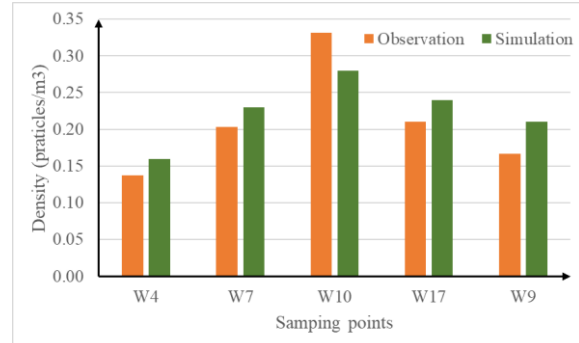


Fig. 11 Correlation of calibrated microplastic concentrations at sampling locations

4.7.2. Microplastic movement map in Ha Long bay

The results of microplastic modeling (refer to Fig. 12) indicated that areas with high concentrations of microplastic debris were primarily located in the coastal regions of Ha Long and Cam Pha cities, which were hubs of economic activities and services.

Microplastics from the coastal areas and estuaries dispersed into the sea through tidal and wave processes. Within a range of 15–30 kilometers from the inland, the distribution of microplastic particles reach 0.2–0.5 particles/m³. It was proven that due to efficiency waste management for pollution control in Ha Long bay, the microplastic generated from the inland was not affected to the sea. However, under monsoonal storms or seasonal floods conditions rivers, floodplains and the coastal seabed switch from sink to source, and the offshore flux of micro- and macro-plastics can rise by one to two orders of magnitude.

Regions with high microplastic concentrations (>1.0 particles/m³, shown in red) are prominently located along the coastal zones of Ha Long City and Cam Pha City (Quang Ninh province), extending toward the estuarine areas such as Cua Luc Bay and the coastal waters of Hai Phong.

Areas with moderate microplastic concentrations (0.5–1.0 particles/m³, shown in orange) surround the high-concentration zones, extending approximately 5–10 km offshore. These areas span the coastal stretch from Hai Phong to Quang Ninh, suggesting spatial connectivity between major urban centers, port systems, and coastal transport routes.

Lower concentration zones (0.2–0.5 particles/m³, shown in yellow) are distributed more widely, covering nearly the entire coastal region of Hai Phong and Ha Long, and reaching 20–30 km offshore. This widespread distribution reflects the role of coastal currents, waves, and tides in the diffusion of microplastics.

Areas with low microplastic concentrations (<0.1 particles/ m^3 , shown in dark blue) are mainly found in offshore regions, particularly in the open waters of Lan Ha Bay, where the direct influence of land-based human activities is minimal. This suggests that microplastic pollution is currently concentrated along the coast and has not yet spread extensively to offshore marine environments.

Within a range of 15–30 km from the coast, the model shows a significant decrease in microplastic concentrations, dropping to 0.2–0.5 particles/ m^3 . This indicates a dilution effect driven by waves, tides, and oceanic circulation. However, if land-based microplastic emissions are not effectively controlled, the risk of further dispersion—especially under the influence of storms or strong seasonal currents—will increase.

Based on the research findings, the spatial distribution of microplastic concentrations in Ha Long Bay can be preliminarily attributed to the following main factors:

Major rivers, such as the Cua Luc Bay, Bach Dang River, Hot River, and Ben Giang River, serve as primary pathways transporting microplastics from land to the marine environment. Estuarine zones—where freshwater mixes with seawater—typically exhibit reduced current velocities, creating favorable conditions for microplastic accumulation or deposition.

The geomorphological structure of Ha Long Bay, characterized by a semi-enclosed bay with numerous islands, limits the dispersion of microplastics into offshore waters and promotes their retention and accumulation in coastal areas.

The zones with the highest microplastic concentrations coincide with areas of intensive human activity, including cruise tourism, coastal services, maritime transport, coal mining, and coastal industrial zones. The waste-capture in estuaries and coastal area limitation of single-use plastic products in cruise ships were need to avoid spearding microplastic to the sea.

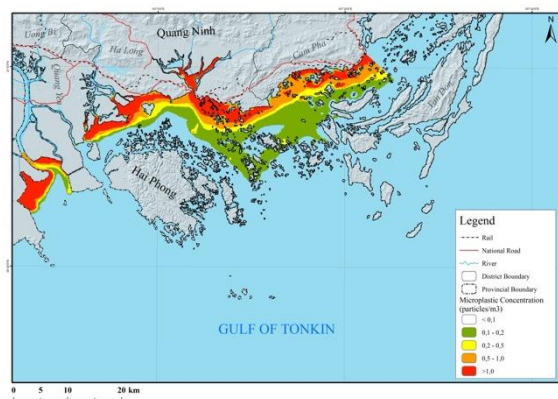


Fig. 12 The microplastics movement map in Ha Long bay

5. CONCLUSION

The research results had assessed the status of microplastic by monitoring some of the physical and chemical properties of the microplastics discovered in seawater and sediment samples taken from Ha Long bay, Quang Ninh province. Despite the presence of microplastic pollution in sea water in Ha Long bay, the density of the particles was still quite low (ranging from 0.01 to 0.69 particles/ m^3). Microplastics were more prevalent in coastal seawater areas, close to river estuarial areas, such as Cua Luc, Hot River, Ben Giang River, and along channels on Ha Long bay.

In aquatic environment, microplastics had different colors such as: white/transparent (41.3%), blue (22.3%) and yellow/orange (21.3%). There are three basic types of microplastics—fragments, pellets, and fibres distributed throughout Ha Long bay. 87.9% of seawater samples taken in Ha Long bay had a diameter (Ferret) D50 between 1 and 5 mm. The microplastics composition in seawater samples from Ha Long bay revealed that HDPE and PS were the predominant constituents, indicating that microplastics may have originated from the fragmentation of plastic debris from industrial and agricultural sources, including ropes, fishing nets, and single-use plastic goods.

The discovery of microplastics in marine sediments with concentrations between 0 and 12 particles/kg, emphasized the study's relevance. The spreading microplastic modeling was proven that due to efficiency waste management for pollution control in Ha Long bay, the microplastic generated from the inland was not affected to the sea.

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