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ARTICLE

Diversity and Distribution Patterns of Biofouling Macrobenthos Based on the Ship Navigation Type

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Abstract
Hull fouling by marine organisms is a known major pathway for introducing non-indigenous species, but information on this process is very limited. This study aimed to investigate variations in species diversity and distribution patterns based on navigation type (domestic–international and international) and attachment area. This study investigated the attached macroinvertebrates on six ships in 2021 and 2022. Quadrat sampling (15 × 15 cm) was conducted by scuba divers at eight ship attachment areas. Forty species from seven phyla were identified through qualitative and quantitative surveys, with 17 attached species, including 10 non-indigenous species (NIS). Dominant species included *Balanus trigonus*, *Amphibalanus amphitrite*, and *Bugula neritina*. Cluster and non-metric multidimensional scaling analyses (nMDS) revealed four distinct groups based on species density, with significant differences between domestic–international and international ships. Statistical analyses indicated significant differences in species number, density, richness, and diversity index among groups, with Group *D* showing the highest values. The study emphasized international ships as primary introducers of NIS. Unique findings included differences in biofouling based on ship shape, antifouling paint conditions, and speed, highlighting the need for tailored management strategies based on navigation type and attachment area. This study urges further research to explore differences in attachment areas and emphasizes the importance of obtaining more information about ships for effective management.

Keywords Biofouling · Hull fouling · Invasive alien species (IAS) · Macroinvertebrate · Non-indigenous species (NIS)

1 Introduction

The rapid growth of maritime transportation since the industrial revolution has increased the movement of marine organisms via ships, both in the ballast and when attached to the hull (Suk 2018). Several studies have suggested that biofouling introduces and spreads more organisms than those introduced through ballast water (Eldredge and Carlton 2002; Farrapeira et al. 2011).

In 2004, the International Maritime Organization (IMO) adopted the International Convention for the Control and Management of Ships' Ballast Water and Sediments in response to the challenges posed by the movement of organisms via ships. For organisms adhering to hulls, in 2011, the IMO introduced a guideline for the control and management of ship biofouling aimed at minimizing the transfer of invasive aquatic species. However, unlike the preventive measures targeting ballast water, in which the recommendation took the form of a resolution, the guideline is not legally enforceable (Suk 2018). In several countries, national laws regulating the management of hull-attached organisms have been enacted (Hyun et al. 2018; Park et al. 2022; Shin and Park 2020), but there are no clear guidelines in South Korea.

Biofouling on ships has increased, despite advances in antifouling paints (Lewis 2001). Biofouling of the hull causes a variety of economic and environmental problems, including increasing the cost of ship repair and maintenance (Schultz et al. 2011), and exerting drag,

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which reduces energy efficiency and, in turn, increases greenhouse gas emissions (Liu et al. 2023). In particular, biofouling of the hull is an important vector for the introduction of non-indigenous species (NIS). International ships are a major route for the introduction, spread, and settlement of NIS (Davidson et al. 2009), with negative effects on native species and human health (Georgiades et al. 2021; Shine et al. 2000). Information on biofouling species is needed to determine the impacts of NIS on marine ecosystems, but studies are very limited.

Ships have large underwater surface areas; this favors the growth of marine organisms (Liu et al. 2023), whose composition and density may differ depending on the attachment area. For example, niche areas are less affected by external factors than exposed areas and, due to their complex structure, are less likely to be coated with antifouling paint, thus providing a safe sheltering place for organisms (Davidson et al. 2009; Moser et al. 2017; Otani 2006; Ulman et al. 2019). Bulbous bows also increase biofouling due to hydrodynamic forces (Alamsyah et al. 2018). For such reasons, macroinvertebrates that attach to the hull may have regional specificity.

Several recent studies have reported that international ships are the main vector for introducing NIS (Çinar et al. 2014; Pinochet et al. 2023). However, while barnacles have been surveyed as an evaluation method for managing biofouling in South Korea (Park et al. 2022; Shin and Park 2020), only biofouling of international ships has been investigated (Park et al. 2022). No accurate species information has been obtained, and the number of studies is limited (Lee et al. 2010; Park et al. 2022). This study aimed to investigate and compare the species distribution patterns of attached macroinvertebrates on six ships with different navigation types (domestic–international and international) and attachment areas in 2021 and 2022.

2 Materials and Methods

Six ships (*A*–*F*) were assessed to investigate the management of attached macroinvertebrates. Ship type, size, construction date, main routes, average speed, type of antifouling paint used, and cleaning status were determined. Information on ship management was obtained directly from ship owners and inspectors. Additional operational information was obtained from TradLinx (www.tradlinx.com), the Integrated Port Management Information System (new.portmis.go.kr), a public database of ship operations (www.data.go.kr), and My Ship Tracking (www.myshiptracking.com).

Scuba divers collected quadrat samples (15 × 15 cm) from eight attachment areas (bottom, bow, hull, rudder, screw, shaft, stern, and thruster)on six ships (three each in 2021 and 2022) (Fig. 1a), and qualitative samples were collected from eight attachment areas (bottom, bow, hull, rudder, screw, shaft, stern, and thruster) where high concentrations of macroinvertebrates were randomly sampled (Fig. 1b). For qualitative analyses, sections within the eight areas with high concentrations of macroinvertebrates were randomly sampled. The samples were transported to the laboratory, where species identification was performed by sieving the organisms through a 1-mm mesh sieve, after which the densities and wet weights of the organisms were recorded. Once analyzed, the samples were fixed in 70% ethanol.

The number and wet weight (*g*) of individuals were measured, and the organisms were identified at the species level. Macroinvertebrate number and wet weight (*g*) were calculated per m^2, and the species number, density

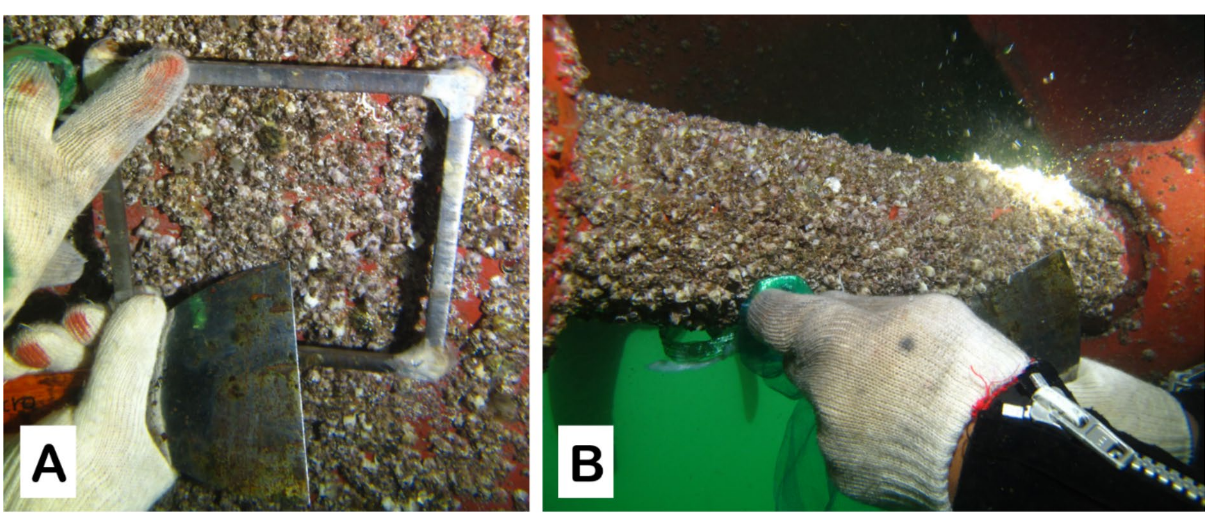

Fig. 1 Sample methods for attached macroinvertebrates: **a** Quantitative sampling; **b** Qualitative sampling

(individuals/m^2), and biomass (g/m^2) were analyzed. The Shannon–Weiner diversity index H ($\log_e$) (Colwell 2005) was calculated for the density data. Analysis of variance (ANOVA) was used to determine differences in density based on navigation type and attachment area (SigmaPlot 11; Systat Software Inc., San Jose, CA, USA). The results of cluster analysis of biofouling community structure were analyzed using the Bray–Curtis similarity index (Chapman 1998) on fourth-root-transformed species density data. A similarity profile permutation (SIMPROF) test was used to identify differences among species groups, and a similarity percentage (SIMPER) analysis was used to determine which species were the main drivers of the similarity and dissimilarity values of the groups. Permutational analysis of variance (PERMANOVA) was used to analyze differences in macroinvertebrate species similarity among attachment areas and navigation types. Community analyses were performed using PRIMER 7 (Systat Software Inc.).

3 Results

3.1 Ship Information

The six investigated ships were designated as *A*–*F* based on the date of the survey. Specific information on the ships is presented in Table 1. Three of the ships (*A*–*C*) were research ships that were operated both domestically and internationally. The other three ships (*D*–*F*) were full container ships that were operated only internationally. The container ships were larger than the research ships and were operated at higher speeds. The antifouling paint was oldest on ship *B* (February 2003), while the hulls of ships *D* and *F* had not been cleaned. Information on hull cleaning was not available for ship *C* (Table 1).

3.2 Species Composition

Forty species belonging to seven phyla were identified in the qualitative and quantitative surveys (Table 2). Based on navigation type, 21 species belonging to seven phyla appeared on domestic–international ships, and 22 species belonging to three phyla appeared on international ships. Among all species, 17 were attached, 10 of which were NIS; 7 attached NIS were on domestic–international ships, while 5 were on international ships (Table 2).

Ten dominant species were high ranking based on average density (> 2% average density); *Balanus trigonus* (Thecostraca) predominated (45.39%) (Table 3), followed by *Amphibalanus amphitrite* (Thecostraca) (9.22%), *Bugula neritina* (Gymnolaemata) (7.56%), *Magallana gigas* (Bivalvia) (6.18%), *Amphibalanus reticulatus* (Thecostraca) (4.66%), *Fistulobalanus kondakovi* (Thecostraca) (3.91%), *Pseudopotamilla occelata* (Polychaeta), *Actinia equina* (Anthozoa), *Megabalanus rosa* (Thecostraca), and *Monocorophium acherusicum* (Amphipoda) (Table 3). *A. amphitrite* had the highest frequency of appearance, at 81.82%, followed by *B. trigonus* (36.36%) and *M. acherusicum* (36.36%) (Table 3).

3.3 Distribution Patterns According to Navigation Type and Attachment Area

Cluster and non-metric multidimensional scaling analyses (nMDS) of species density revealed four groups (PERMANOVA, df = 3, $F = 5.919$, $p = 0.001$; Fig. 2). Groups *A* and *B* were domestic–international and differed significantly from groups *C* and *D*, which were international (PERMANOVA, df = 1, $F = 4.036$, $p = 0.005$). Group *A* was attached at the stern of domestic–international ships; based on SIMPER analysis, the average similarity was 50.63%, and the species that contributed to the community was *B. trigonus*. Group B was attached at the bow and midships of domestic–international ships; the average similarity was 54.95%, and the species that contributed to the community were *B. neritina*, *P. occelata*, *A. equina*, and *A. amphitrite*. Group *C* was attached to the midships and stern of international ships; the average similarity was 47.27%, and the species that contributed to the community was *A. amphitrite*. Group *D* was attached at the bow of international ships; the average similarity was 34.97%, and the species that contributed to the community were *M. rosa*, *A. amphitrite*, and *Ericthonius pugnax* (Table 4).

There were significant differences among groups in number of species (one-way ANOVA, df = 3, $p = 0.009$), species density (one-way ANOVA, df = 3, $p = 0.005$), species richness (one-way ANOVA, df = 3, $p = 0.01$), and diversity index (H') (One-way ANOVA, df = 3, $p = 0.05$) (Fig. 3), all four of which were highest in group *D*. Based on the SIMPER analysis, the average dissimilarity between groups ranged from 76.65% (*D* and *C*) to 100% (*A* and *C*) (Table 5). In addition to the previously mentioned species, *Hydroides elegans* and *Koinostylochus* sp. also contributed to the dissimilarity between communities (Table 5).

The effect of navigation type was significantly dependent on the attachment area (two-way ANOVA, df = 2, $F = 10.18$, $p = 0.02$; Table 6). On domestic–international vessels, there was a significant difference between midships and stern ($p = 0.004$) and bow and stern ($p = 0.03$); on international vessels, there was a significant difference between bow and midships ($p = 0.002$; Table 6).

Table 1 Ship information

Ship name	Survey date	Survey location	Type	Build	Size (m)[a]	Average speed (kn)	Navigation[b]	Clean	Type of WSA coating	Date of WSA coating	Operation date (day)	Operational Routes (*docking)
Ship *A*	September 2021	Gyeongsangnam-do	Government research	2016	99.8×18	12	D+I	YES	Antifouling	February 2019	235	South Korea (East Sea, South Sea, Yellow Sea)*-Northwest Pacific-Western Pacific
Ship *B*	October 2021	Gyeongsangnam-do	Government research	2001	70.6×12.3	11.5	D+I	No information	Antifouling	February 2003	No information	South Korea (jeju)*-Southeast Asia
Ship *C*	November 2021	Gyeongsangnam-do	Government research	1992	57.1×12	12.5	D+I	YES	Antifouling	December 2020	292	South Korea (Busan, Jeju, Tongyeong)*-Pacific Ocean
Ship *D*	June 2022	Gyeongsangnam-do	Full container	2020	399.9×61.5	22.3	I	NO	Antifouling	March 2020	120	South Korea*-China*-Singapore-Suez-Europe
Ship *E*	August 2022	Gyeongsangnam-do	Full container	2020	399×61	21.9	I	YES	Antifouling	December 2019	118	South Korea*-China*-Suez-Europe-Singapore
Ship *F*	September 2022	Busan	Full container	2013	365.5×48.4	23	I	NO	Antifouling	February 2020	96	South Korea*-Taiwan-Hong Kong-China-Panama-USA*

[a]Length Over All×Extreme Breadth

[b]*D:* domestic, *I*: International

Table 2 List of species detected on the seven studied ships: species name, non-indigenous species (NIS) classification, NIS origin (first recorded area), and appearance of macroinvertebrate by navigation type

Phylum	Species name	NIS classification	NIS origin (first record areas)	Navigation type
Annelida	*Pseudopotamila occelata*	Indigenous species		D+I
Annelida	*Nereis* sp.	Indigenous species		D+I
Annelida	*Lepidonutus* sp.	Indigenous species		D+I
Annelida	*Hydroides elegans*	NIS	Indo-Pacific (Çinar 2012)	D+I
Arthropoda	*Unidentified* sp.	Indigenous species		I
Arthropoda	*Stenothoe valida*	Indigenous species		D+I
Arthropoda	*Protomedeia* sp.	Indigenous species		I
Arthropoda	*Pareurystheus* sp.	Indigenous species		I
Arthropoda	*Monocorophium insidiosum*	Indigenous species		I
Arthropoda	*Monocorophium acherusicum*	Indigenous species		I
Arthropoda	*Melita hoshinoi*	Indigenous species		I
Arthropoda	*Megabalanus rosa*	NIS	Japan, Formosa (Carlton et al. 2011)	I
Arthropoda	*Lepas anatifera*	Indigenous species		I
Arthropoda	*Jassa slatteryi*	Indigenous species		I
Arthropoda	*Gnorimosphaeroma ovatum*	Indigenous species		D+I
Arthropoda	*Gnorimosphaeroma naktongense*	Indigenous species		I
Arthropoda	*Fistulobalanus kondakovi*	Indigenous species		I
Arthropoda	*Ericthonius pugnax*	Indigenous species		I
Arthropoda	*Crassicorophium crassicorne*	Indigenous species		I
Arthropoda	*Conchoderma auritum*	NIS	Cosmopolitan (Foster and Willan 2010)	D+I, I
Arthropoda	*Ceradocus* sp.	Indigenous species		D+I
Arthropoda	*Caprella scaura*	Indigenous species		D+I
Arthropoda	*Caprella penantis*	Indigenous species		D+I
Arthropoda	*Caprella equilibra*	Indigenous species		I
Arthropoda	*Caprella californica*	Indigenous species		I
Arthropoda	*Balanus trigonus*	Indigenous species		D+I, I
Arthropoda	*Apocorophium acutum*	Indigenous species		D+I
Arthropoda	*Anoplodactylus crassus*	Indigenous species		D+I
Arthropoda	*Amphibalanus reticulatus*	NIS	Indo-Pacific (Carlton et al. 2011)	I
Arthropoda	*Amphibalanus eburneus*	NIS	Northwest Atlantic (Carlton et al. 2011)	I
Arthropoda	*Amphibalanus amphitrite*	NIS	Indo-Pacific (Carlton et al. 2011)	D+I, I
Bryozoa	*Bugula neritina*	NIS	Pacific Coast (Robertson 1905)	D+I
Chordata	*Ciona intestinalis*	NIS	Europe (Park et al. 2018)	D+I
Cnidaria	*Plumularia setacea*	Indigenous species		I
Cnidaria	*Actinia equina*	Indigenous species		D+I
Mollusca	*Perna viridis*	NIS	Indo-Pacific (Siddall 1980)	D+I
Mollusca	*Mytilus galloprovincialis*	NIS	Mediterranean Sea (Siddall 1980)	D+I
Mollusca	*Magallana gigas*	Indigenous species		D+I
Mollusca	*Brachidontes mutabilis*	Indigenous species		I
Platyhelminthes	*Kinostylochus* sp.	Indigenous species		D+I

D domestic, *I* International

4 Discussion

Forty species were identified in qualitative and quantitative surveys of eight attachment areas on six ships (Table 2). *B. trigonus* was the most predominant species (Table 3), while *A. amphitrite* had the highest frequency of appearance (Table 3). *A. amphitrite*, *Amphibalanus eburneus*, *A. reticulatus*, *B. neritina*, *H. elegans*, *Ciona intestinalis*, *Conchoderma auritum*, *M. rosa*, *Mytilus galloprovincialis*, and *Perna viridis* were NIS identified in this study (Carlton et al. 2011; Çinar 2012; Foster and Willan 2010; Lee et al. 2010; Park et al. 2018; Siddall

Table 3 Dominant species ranking based on the density of macroinvertebrates as a result of quantitative survey

Taxa	Species	Average density (individuals/m^2)	% of total density	Frequency (%)
ACr	*Balanus trigonus*	1454.55	45.39	36.36
ACr	*Amphibalanus amphitrite*	295.62	9.22	81.82
BGy	*Bugula neritina*	242.42	7.56	27.27
MBi	*Magallana gigas*	197.98	6.18	18.18
ACr	*Amphibalanus reticulatus*	149.49	4.66	9.09
ACr	*Fistulobalanus kondakovi*	125.25	3.91	9.09
APo	*Pseudopotamila occelata*	123.23	3.85	27.27
CAn	*Actinia equina*	84.85	2.65	27.27
ACr	*Megabalanus rosa*	80.81	2.52	18.18
ACr	*Monocorophium acherusicum*	72.73	2.27	36.36

ACr Crustacea, *BGy* Gymnolaemata, *MBi* Bivalvia, *APo* Polychaeta, *CAn* Anthozoa

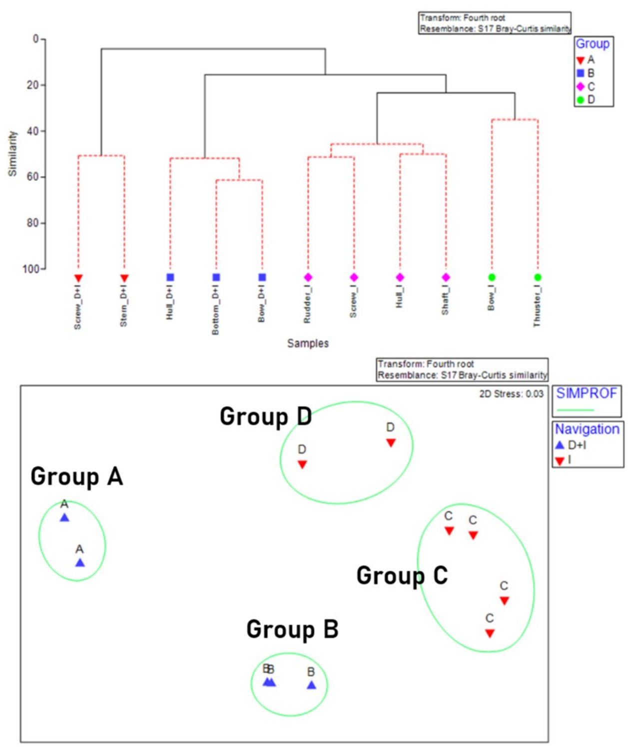

Fig. 2 Cluster analysis and non-metric multidimensional scaling (nMDS) using Bray–Curtis similarities, based on the fourth-root transformed abundance data

1980). In previous studies, only juvenile *P. viridis* were reported domestically (Lee et al. 2010) However, in this study, adults were also discovered. Thus, we anticipated that *P. viridis* would establish itself in Korea in the future. Additionally, *C. intestinalis* is a known biofouling organism and a designated NIS, and it is managed as a disturbance organism by the Ministry of Oceans and Fisheries (Park et al. 2018). *C. intestinalis* may decrease ecosystem diversity.

The species composition and distribution patterns differed between the navigation types (Table 2). Reported that international ships are the main factor of NIS, and the domestic–international navigation type acts as a secondary factor in spreading NIS in the country (Otani 2006). In this study, *A. reticulatus* and *M. rosa* appeared only on the international navigation type of ship (Table 1). This species was NIS with a low habitat density on domestic–international (Kim et al. 2019). Among the NIS, *A. amphitrite*, *A. eburneus*, *C. intestinalis*, and *M. galloprovincialis* are completely settled in country (Kim et al. 2019; Lee et al. 2010; Lee and Shin 2014), and *Hydroides eleganss* is a representative invasive species (Bagaveeva and Zvyagintsev 2000). In this study, *A. amphitrite* and *A. eburneus* were dense on international hulls, but *H. eleganss* was dense on the domestic and international sterns, and *C. intestinalis*, *H. eleganss* and *M. galloprovincialis* were dense on the mid and bow (Fig. 4). Previous studies concluded that ship speed is one of the most important determinants of the survival of biofouling organisms (Coutts et al. 2010; Davidson et al. 2009). The average speed of the domestic–international ships examined in this study was 12 kn, which is less than half that of international ships (29.7 kn) (Table 1). Species density was higher on the slower domestic–international ships (Fig. 2). International ships were the main contributor to NIS, and domestic–international vessels will spread such species into domestic waters, where they have not yet been introduced.

In this study, no clear trend emerged when comparing density, cleaning information, and operating period on each ship (Figure 5). However, the number and density of species on the examined attachment areas differed based on the navigation type (Figure 3). While previous studies showed differences in exposed and niche areas due to external environmental factors (Moser et al. 2017), this study found no such difference. However, a unique finding of this study was the difference in biofouling between bows, midships, and sterns depending on the navigation type (Figure 4). This

Table 4 SIMPER analysis of main characterizing species at each group (*A*–*D*) (Av. Abund, average abundance; Av. Diss, average dissimilarity; Contrib%, contribution%; Cum%, cumulative)

	Species	Av. Abund	Av. Sim	Contrib%	Cum.%
Group *A* Average similarity: 50.63	*Balanus trigonus*	9.09	50.63	100	100
Group *B* Average similarity: 54.95	*Bugula neritina*	5.46	13.88	25.27	25.27
	Pseudopotamila occelata	4.61	9.98	18.17	43.43
	Actinia equina	4.15	9.77	17.79	61.22
	Amphibalanus amphitrite	4.22	9.77	17.79	79.01
Group *C* Average similarity: 47.27	*Amphibalanus amphitrite*	4.32	36.79	77.83	77.83
Group *D* Average similarity: 34.97	*Megabalanus rosa*	5.01	10.74	30.7	30.7
	Amphibalanus amphitrite	5.62	10.21	29.2	59.9
	Ericthonius pugnax	4.36	7.01	20.05	79.95

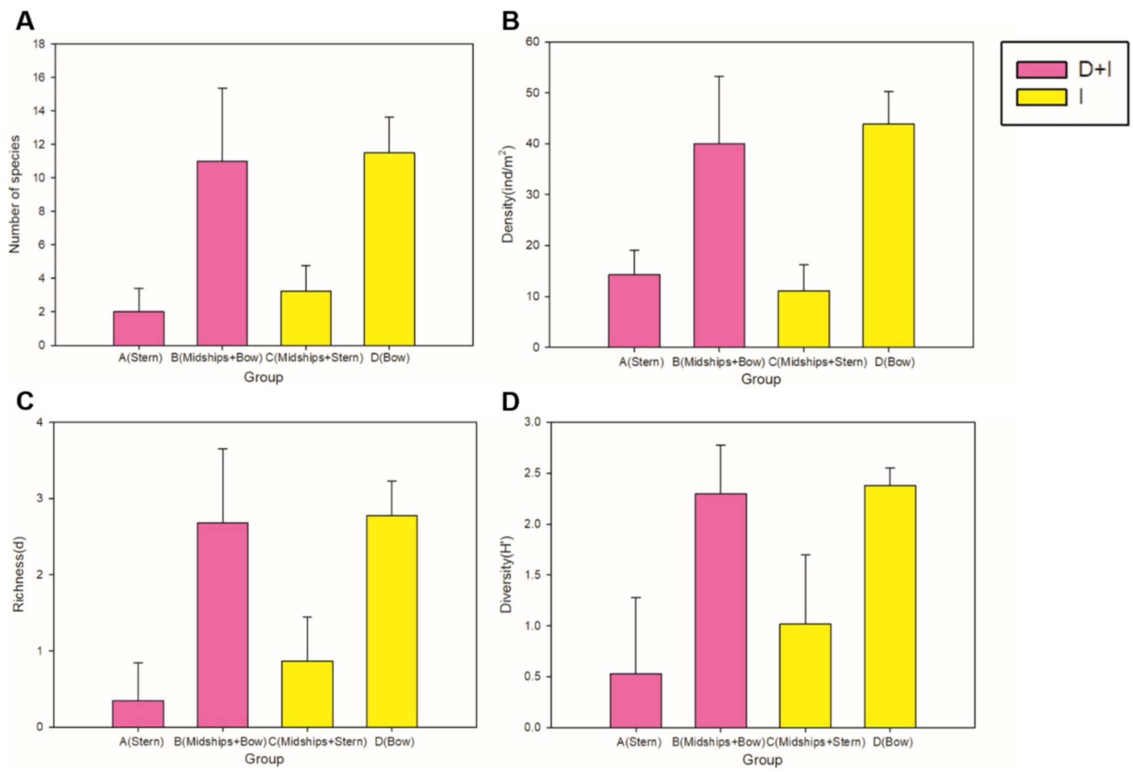

Fig. 3 The macroinvertebrate communities according to navigation type and groups: **a** Number of species (*S*); **b** Density (*N*); **c** Richness (*d*); **d** Diversity (H´)

difference can be attributed to several factors, such as the condition of the antifouling paint, the shape of the ship, and ship speed. Cargo ships, in particular, have a unique bow shape and may have a high rate of antifouling paint removal (Coutts and Taylor 2004), which can increased biofouling due to external factors, such as shear and pressure forces (Alamsyah et al. 2018). The international ships investigated in this study were also cargo ships (Table 1), and the occurrence of high biofouling in Group *D* (bow) was influenced by these factors. Group *B*, which showed high biofouling in midships and bows, appeared to have high biofouling even on the flat and wide midships due to low-speed operation (Coutts et al. 2010; Davidson et al. 2009). These results suggest that different management approaches are needed for each attached area depending on the navigation type.

Maritime transportation has brought significant benefits to humanity, but it has also caused many problems. Korea is surrounded by the sea on three sides, and its many ports, together with its oceanographic characteristics, provide a perfect environment for the settlement of NIS (Kim et al. 2020; Ubagan et al. 2021). However, only a few NIS have been surveyed to date, and their current status is unknown (Lee et al. 2010). The results of this study indicate that different management strategies are required depending on the

Table 5 SIMPER analysis of main characterizing species at each group (*A–D*; Av. Abund, average abundance; Av. Diss, average dissimilarity; Contrib%, contribution%; Cum%, cumulative%; 5 < Contrib%)

	Species	Av. Abund	Av. Abund	Av. Diss	Diss/SD	Contrib%	Cum.%
Groups *A* and *B* average dissimilarity = 92.09	*Balanus trigonus*	9.09	0.86	16.41	2.06	17.82	17.82
	Bugula neritina	0	5.46	10.58	3.75	11.49	29.31
	Pseudopotamila occelata	0	4.61	8.98	2.83	9.76	39.07
	Amphibalanus amphitrite	0	4.22	8.35	2.62	9.07	48.14
	Actinia equina	0	4.15	8.17	2.82	8.87	57.01
	Magallana gigas	3.4	0.86	6.21	0.99	6.74	63.75
Groups *A* and *C* average dissimilarity = 100.00	*Balanus trigonus*	9.09	0	38.94	2.24	38.94	38.94
	Amphibalanus amphitrite	0	4.32	17.7	4	17.7	56.64
	Magallana gigas	3.4	0	12.11	0.91	12.11	68.75
	Monocorophium acherusicum	0	1.97	6.92	0.91	6.92	75.67
Groups *A* and *D* average dissimilarity = 93.28	*Balanus trigonus*	9.09	2.1	12.61	1.79	13.52	13.52
	Amphibalanus amphitrite	0	5.62	9.6	6.19	10.29	23.82
	Megabalanus rosa	0	5.01	8.66	14.13	9.29	33.1
	Ericthonius pugnax	0	4.36	7.76	2.33	8.31	41.42
	Monocorophium acherusicum	0	3.36	5.88	4.96	6.3	47.72
	Fistulobalanus kondakovi	0	3.05	5.71	0.86	6.12	53.84
	Magallana gigas	3.4	0	5.56	0.86	5.96	59.8
	Amphibalanus reticulatus	0	3.18	5.1	0.86	5.47	65.26
Groups *B* and *D* average dissimilarity = 86.70	*Bugula neritina*	5.46	0	6.66	5.96	7.68	7.68
	Megabalanus rosa	0	5.01	6.09	6.45	7.02	14.7
	Pseudopotamila occelata	4.61	0	5.64	3.63	6.5	21.2
	Ericthonius pugnax	0	4.36	5.41	2.4	6.24	27.44
	Actinia equina	4.15	0	5.11	3.93	5.89	33.33
Groups *B* and *C* average dissimilarity = 83.54	*Bugula neritina*	5.46	0	11.38	3.44	13.63	13.63
	Pseudopotamila occelata	4.61	0	9.67	2.71	11.57	25.2
	Actinia equina	4.15	0	8.8	2.68	10.53	35.73
	Hydroides elegans	2.5	0	4.29	1.34	5.14	40.87
	Kinostylochus sp.	2.5	0	4.29	1.34	5.14	46.01
Groups *D* and *C* average dissimilarity = 76.65	*Megabalanus rosa*	5.01	0	9.2	10.38	12	12
	Ericthonius pugnax	4.36	0	8.25	2.44	10.77	22.77
	Fistulobalanus kondakovi	3.05	0	6.09	0.93	7.95	30.72
	Amphibalanus reticulatus	3.18	0	5.39	0.93	7.03	37.74
	Monocorophium acherusicum	3.36	1.97	3.92	1.25	5.12	42.86

Table 6 Results of statistical analysis of navigation and attachment area effects Shannon–Wiener diversity index (H′) of Two-Way ANOVA (*p*-values: *, < 0.05)

		DF	*F*	*P*
Navigation x attachment area		2	10.182	0.017
Navigation	Attachment area	Diff of means	*t*	*P*
Domestic–international	Midships versus Stern	1.647	3.775	0.038*
	Bow versus Stern	2.016	3.773	0.026*
	Bow versus Midships	0.369	0.691	0.52
International	Bow versus Midships	2.379	4.452	0.02*
	Stern versus Midships	1.359	2.698	0.084
	Bow versus Stern	1.02	2.56	0.051

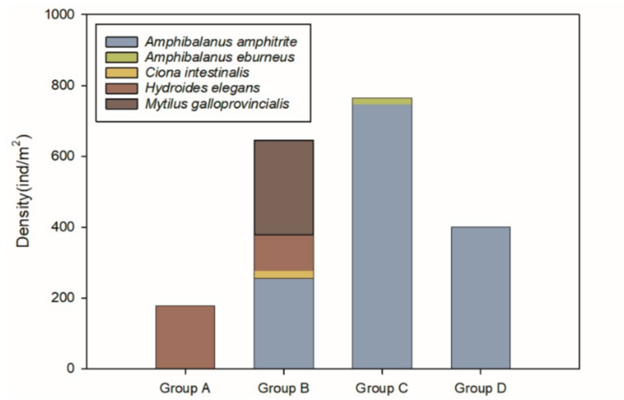

Fig. 4 The density of domestically settled non-indigenous species (NIS) by group

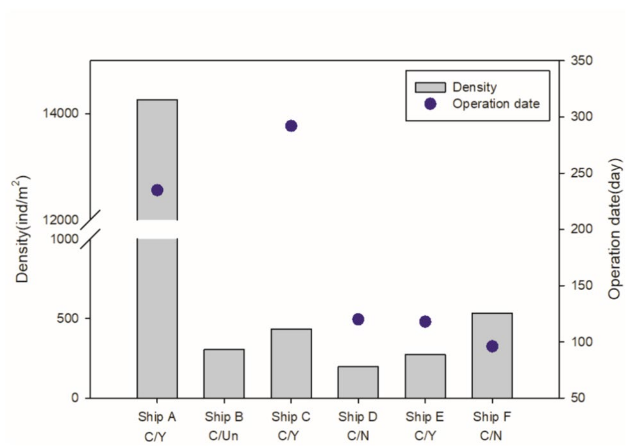

Fig. 5 The density, operating date, and cleaning information (*C*/*Y* = Cleaning/Yes, *C*/*N* = Cleaning/No and *C*/Un = Cleaning/Unknown) of each ship

type of ship and the location of the operation, as there were differences in species number and density between the navigation types and attachment areas. Future research should investigate the differences between attachment areas with by increasing sampling frequency. Close communication with ship owners and shipping companies is required to obtain more ship information.

5 Conclusion

This study investigated the diversity and distribution patterns of biofouling macroinvertebrates on different types of ships. We identified 40 species, among which *B. trigonus* was the most dominant in terms of density. Several NIS were identified, including *A. amphitrite*, *A. eburneus*, and *M. rosa*, and *P. viridis* could potentially settle in Korean waters in the future. Significant differences in species composition and density were found between navigation types, indicating that international ships play a major role in introducing NIS, while domestic–international ships contribute to their spread; ship speed was determined to be a crucial factor, with slower speeds associated with higher species densities. The variation in species diversity between navigation types and attachment areas underscores the need for tailored management strategies.

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Data availability The raw data that support the findings of this study are available from the corresponding authorupon reasonable request to corresponding author and with permission from Korea Institue of Ocean Science andTechnology (KIOST).

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