



The Occurrence and Distribution of Benthic Foraminifera in Tropical Waters Along the Strait of Malacca

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Foraminifera are shelled single-celled protists that are found in all marine environments. Benthic foraminifera either live in sediments or attach to surfaces on the seafloor. Understanding the distribution and ecological response of benthic foraminifera is crucial, as they can indicate past and current ocean conditions. However, the benthic foraminifera distribution along the busy Strait of Malacca, which connects the Indian Ocean (north) to the Java Sea (south), is undersampled. In this study, we collected 24 surface samples from the northern Strait of Malacca to understand the distribution of foraminifera assemblages in shallow tropical waters. A total of 49 species of benthic foraminifera were identified. Calcareous hyaline species dominated the assemblages, with an extremely low occurrence of calcareous porcelaneous species. The common calcareous hyaline taxa were *Asterorotalia pulchella*, *Pseudorotalia schroeteriana*, *Discorbinella bertheloti*, *Ammonia tepida*, and *Heterolepa praecincta*. Cluster analysis categorised the foraminiferal assemblages into three major groups. The first cluster (Group A) consisted of a more diverse assemblage of hyaline and agglutinated species that inhabited a mean water depth of 45 m. The second cluster represented a population that inhabited deeper water environments (average water depth of 59 m). Finally, the third cluster (Group C) consisted of a foraminifera assemblage that inhabited shallow coastal environments (average depth of 22 m) with higher organic matter enrichment. The multivariate canonical correspondence analysis (CCA) showed that the foraminiferal assemblages reflected the shallow to deep water transition in the Malacca Strait. Water depth, which defines the depositional environment, had a greater influence on foraminifera distribution here than organic matter and salinity.

Keywords: *Asterorotalia*, organic matter, monitoring, water depth, LIMA scientific expedition

INTRODUCTION

The Strait of Malacca is a shallow water passage between peninsular Malaysia and Sumatra that connects the Indian and Pacific Oceans. It is also a global shipping marine route, with more than 120,000 ships passing through the straits annually. The narrow Strait of Malacca was a savannah corridor during the Last Glacial Maximum when the sea level was much lower than the present day. Today, the shallow strait receives freshwater runoff from both peninsular Malaysia and Sumatra, resulting in more hyposaline environments closer to the coastline. These characteristics have endowed the region with abundant non-renewable and renewable resources, including profitable coastal ecosystems, aquaculture, coastal tourism, extensive capture fisheries, valuable natural gas reserves, and mining (Evers and Gerke, 2006). However, the region is also repeatedly threatened by the overexploitation of living resources and the introduction of harmful domestic and industrial waste (Chua et al., 2000). With growing maritime and coastal activities, key stakeholders are under increasing pressure to minimise the future impact on environmental services along the Malacca Strait.

Foraminifera can help monitor the environmental status of both sandy and soft-bottom marine ecosystems (Hallock et al., 2003; Sreenivasulu et al., 2019; Sousa et al., 2020). Due to their widespread distribution, modern benthic foraminifera have been used to assess the ecological health of lagoon environments (Culver et al., 2012; Bouchet et al., 2018), estuaries (Nagendra and Reddy, 2019; Sreenivasulu et al., 2019), coral reefs (Nurruhwati et al., 2020; Prazeres et al., 2020), and modern harbours (Dijkstra et al., 2017). Moreover, foraminiferal assemblages are influenced by their immediate environment and have often served as modern and past analogues to characterise paleoenvironments (Rao et al., 2013; Benito et al., 2016; Minhat et al., 2016; Kemp et al., 2018). Therefore, documenting and understanding the regional distribution of foraminifera are essential. This study documented the distribution of benthic foraminifera species

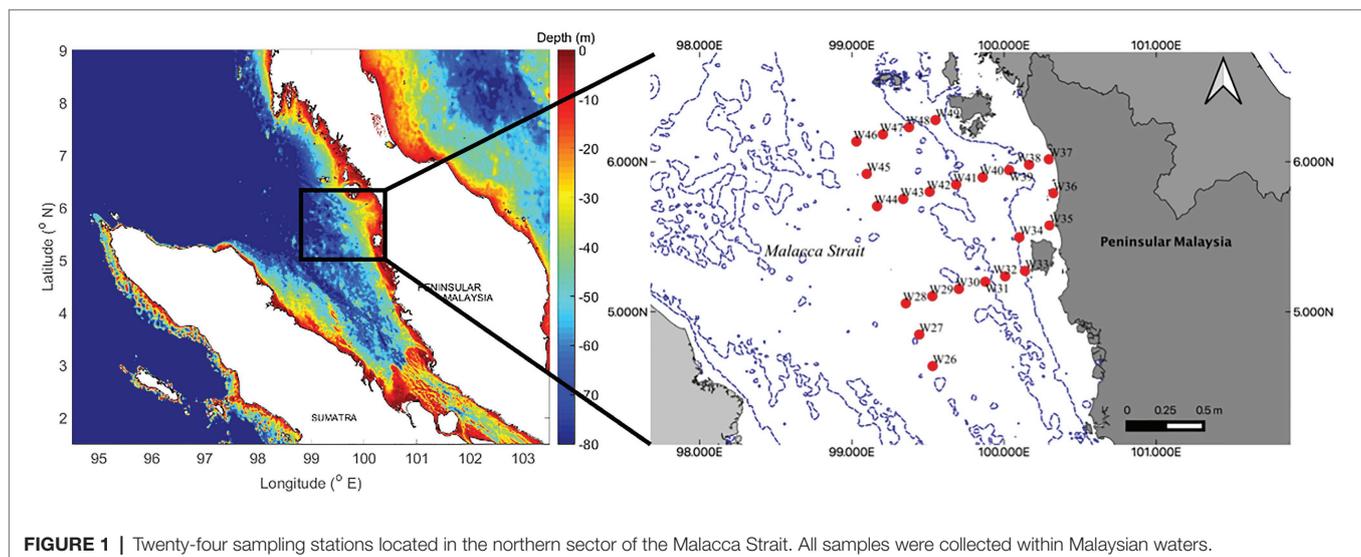
in the Malacca Strait. We also assessed the dominant environmental factors influencing benthic foraminifera distribution in one of the world's busiest shipping lanes.

STUDY AREA

The northern region of the Strait connects with the deeper Andaman Sea and is more saline (>34 PSU) than the middle and southern sectors of the strait (Amiruddin et al., 2011). Major rivers from Sumatra and peninsular Malaysia discharge approximately $19 \times 10^{10} \text{ m}^3$ of freshwater annually to both sites of the strait, creating hyposaline conditions along most parts of the strait (Hii et al., 2006; Amiruddin et al., 2011). Numerous ecosystems have been reported along the strait, including mangroves, coral reefs, seagrass, and extended mudflats (Yasin et al., 2019). Two tropical monsoon seasons influence the weather along the Strait of Malacca. These monsoon winds create wetter conditions during the northeast monsoon period and drier conditions during the southwest monsoon period (Hii et al., 2006; Amiruddin et al., 2011).

SAMPLE COLLECTION

A total of 24 surface sediment samples were collected using a Smith McIntyre grab onboard the UMT RV Discovery (15 × 5 m) during the UMT Scientific Expedition Voyage LIMA'19 from 13 to 23 March, 2019. These samples were collected along the northern regions of the Malacca Strait within Malaysian waters (Figure 1). We collected sub-samples from the bulk sediments for both sediment (~40 g) and foraminifera analyses (10 cm³; 10 cm² × 1 cm; Scott and Medioli, 1980; Minhat et al., 2020). Ethanol solution (>70%) was used to preserve the foraminifera samples. We recorded the coordinates of each station, and water depth and bottom water salinity were measured using a Conductivity, Temperature,



Depth (CTD) castaway profiler. We obtained salinity records for all stations except W35, as the depth was too shallow for CTD deployment.

LABORATORY ANALYSIS

Foraminifera Analyses

Sediment samples were passed through 63 μm sieves under running tap water (Schönfeld et al., 2012). The residues on the sieve were decanted into labelled boats and left to dry overnight in an oven at 50°C. The dried foraminifera samples were then transferred and stored in plastic bags until analysed.

Prior to sorting, the samples were equally divided into aliquots using a microsampler. A total of 300 foraminifera specimens were randomly picked from a gridded picking tray using a fine artist brush and then sorted on micropalaeontology slides. During the picking process, foraminiferal tests that were discoloured, broken, or poorly preserved (Yordanova and Hohenegger, 2002) were excluded. The sorted specimens were identified at the species level based on Loeblich and Tappan (1988, 1994) and regional taxonomic references (Szarek, 2001; Martin et al., 2018; Minhat et al., 2020).

Sediment and Organic Matter Analyses

The sediment grain size was determined *via* the dry sieving method (Folk, 1980), and the organic matter composition was determined *via* the loss-on-ignition method (Heiri et al., 2001).

Computation of Diversity Indices and Statistical Analyses

To compare our results with previous work by Minhat et al. (2020), Fisher's alpha diversity and Pielou's evenness indices (Pielou, 1969) were calculated using PRIMER v.6 software (Clarke and Gorley, 2006). To avoid using reworked specimens, only foraminiferal taxa with a relative abundance of >2% in at least one sample were used to determine the foraminiferal zonation and fauna-environment relationship. The Q-mode hierarchical cluster analysis based on the Euclidean distance similarity measure was used to understand the biozonation of foraminiferal assemblages (Mello and Buzas, 1968; Culver et al., 2012; Azmi et al., 2020). Multivariate canonical correspondence analysis (CCA) was calculated using XLSTAT software to determine the influence of environmental variables, water depth, and sediment characteristics on foraminiferal assemblages. The CCA was performed on all 49 foraminifera species with >2% relative abundance.

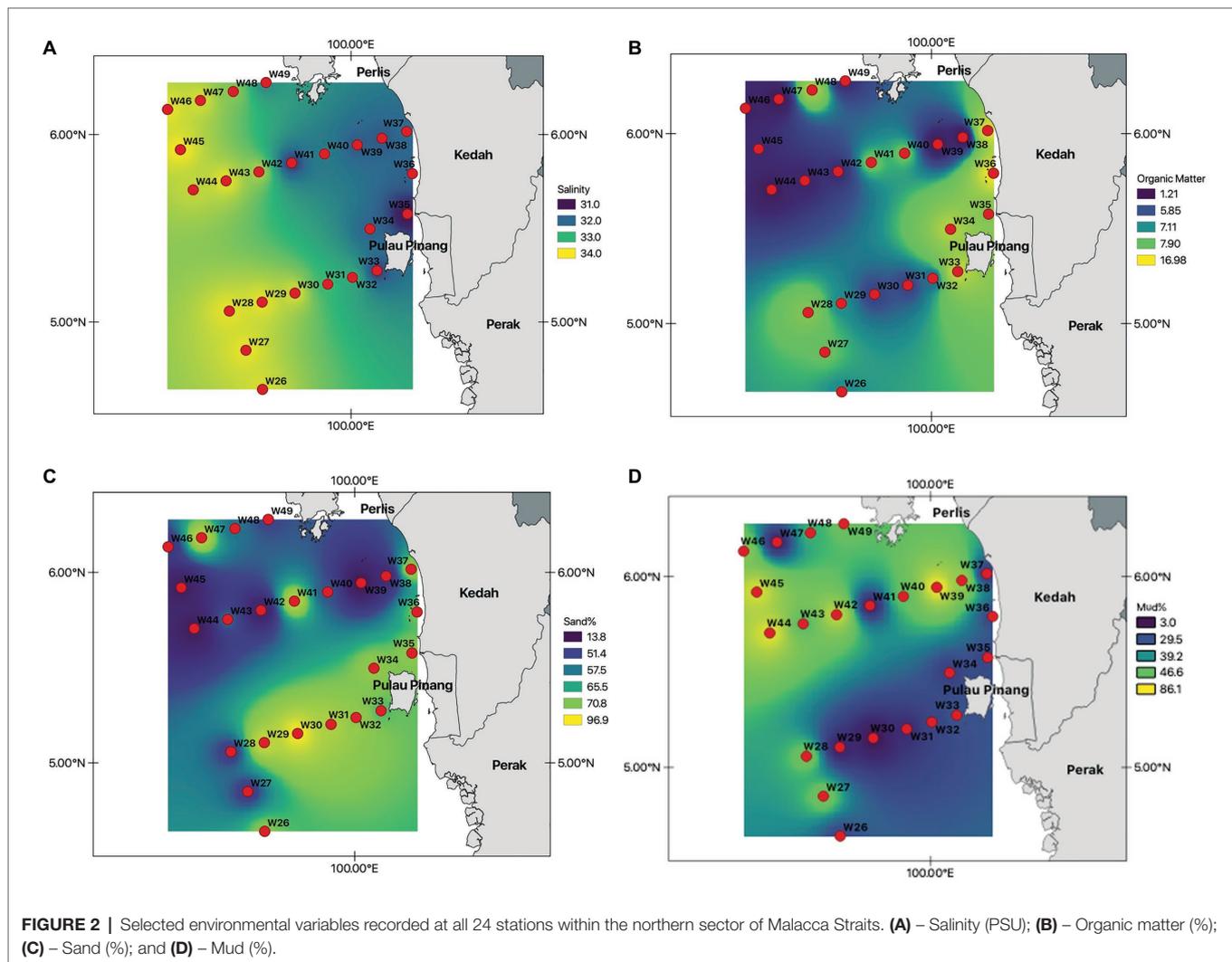
RESULTS

Environmental Conditions Along the Northern Sector of the Malacca Strait

The water depth of the study area ranged from 9 to 86 m, with recorded salinities of 32–34 PSU (Table 1; Figure 2A). The average proportion of organic matter in this study was 7.1%, with the highest organic matter content recorded at station W36 (17%; Figure 2B). Most stations were predominantly sandy, with a sand composition of 97% at W30. Moreover, stations with deeper water depths (>60 m) had relatively high mud compositions (mud >60%; Figures 2C,D).

TABLE 1 | List of 24 stations within the Malacca Straits with station coordinates, water depth, salinity, organic matter, and sand and mud compositions.

Stations	Longitude	Latitude	Water depth (m)	Salinity (PSU)	Organic matter (%)	Sand (%)	Mud (%)
W26	99.53160	4.63997	60.0	34.0	7.0	72.0	27.0
W27	99.44375	4.84896	68.0	34.1	8.0	48.0	51.0
W28	99.35590	5.05796	68.0	34.1	10.0	48.0	51.0
W29	99.52960	5.10588	71.0	34.1	7.0	87.0	13.0
W30	99.70329	5.15380	63.0	34.0	5.0	97.0	3.0
W31	99.87698	5.20172	55.0	33.2	5.0	82.0	17.0
W32	100.00724	5.23766	46.0	33.0	6.0	76.0	25.0
W33	100.13751	5.27361	24.0	31.7	14.0	68.0	30.0
W34	100.10020	5.49654	25.0	32.0	13.0	76.0	23.0
W35	100.29854	5.57636	9.2	n/a	10.0	74.0	26.0
W36	100.32448	5.79165	10.3	32.0	17.0	71.0	27.0
W37	100.29401	6.01648	10.0	32.1	16.0	77.0	22.0
W38	100.16374	5.98053	21.0	31.9	1.2	37.4	62.6
W39	100.03348	5.94459	27.0	31.9	1.5	13.8	86.2
W40	99.85979	5.89667	38.0	32.3	8.2	53.3	46.7
W41	99.68610	5.84875	52.0	31.6	8.3	85.3	14.7
W42	99.51240	5.80083	57.0	33.8	3.6	27.9	72.1
W43	99.33871	5.75291	71.0	34.1	3.0	55.4	44.6
W44	99.16502	5.70499	62.0	33.9	1.9	20.1	79.9
W45	99.09714	5.91949	86.0	34.2	3.6	22.2	77.8
W46	99.02926	6.13399	68.0	34.1	2.4	44.2	55.8
W47	99.20295	6.18191	63.0	34.0	1.5	85.6	14.4
W48	99.37664	6.22984	57.0	33.6	12.4	56.4	43.6
W49	99.55034	6.27776	46.0	32.5	3.6	51.0	49.0



Foraminiferal Assemblages

A total of 90 foraminifera species were identified from the 24 stations in the northern region of the Strait of Malacca. However, only 49 species had >2% relative abundance, and 20 species had >10% relative abundance in at least one station (Supplementary Table S1). On average, the calcareous hyaline (86%) group dominated the total foraminifera assemblages in the study area. In comparison, the agglutinated group and porcelaneous group accounted for 13 and <1% of the total assemblages, respectively (Table 2). The common calcareous hyaline species identified were *Asterorotalia pulchella*, *Pseudorotalia schroeteriana*, *Discorbinella bertheloti*, *Ammonia tepida*, and *Heterolepa praecincta* (Figure 3). Of these, *A. pulchella* was recorded at all sampling stations and was therefore the most common species in the study area (Table 2). Moreover, four other species (*P. schroeteriana*, *D. bertheloti*, *A. tepida*, and *H. praecincta*) were recorded at more than 15 stations.

The assemblage diversity, measured by Fisher's alpha (α), ranged between 1.11 (W37) and 7.56 (W30 and W31), and

the number of species present at each station was between $S = 5$ and $S = 20$ (Table 2). The species distribution was the most evenly distributed [Pielou evenness (J') = 0.82] at W29 and the least evenly distributed ($J' = 0.25$) at W34. The latter site was dominated by *A. pulchella* (76%).

Cluster Analysis

The Q-mode hierarchical cluster analysis based on the 24 stations produced three distinct groups (Figure 4). The first cluster (Group A) included samples from eight stations with an average water depth of 45 m. The foraminiferal assemblage within this group was dominated by *A. pulchella* (19%), followed by *D. bertheloti* (8%), and *Elphidium advenum* (7%). Agglutinated taxa, such as *Agglutinella agglutinans* (3%) and *Textularia* spp. (1–4%), were also relatively higher in Group A than in the other groups. The second cluster (Group B) contained half of the sampling stations that were generally located at deeper water depths (average water depth = 59 m). This group was co-dominated by *A. pulchella* (16%) and *Bolivina glutinata* (15%). Moreover, the porcelaneous species *Quinqueloculina*

TABLE 2 | Distribution of hyaline, agglutinated, and porcelaneous foraminifera groups within the Malacca Straits. The computed diversity indices and Fisher alpha (α) are also included.

Site	Hyaline (5%)	Agglutinated (%)	Porcelaneous (%)	No. of species	Fisher alpha (α)	Evenness (J')
W26	58	42	0	17	5.94	0.74
W27	85	15	0	18	6.41	0.64
W28	69	31	0	18	6.47	0.72
W29	46	54	0	19	6.95	0.82
W30	51	49	0	20	7.56	0.80
W31	65	35	0	20	7.56	0.75
W32	53	47	0	18	6.41	0.74
W33	100	0	0	10	2.77	0.34
W34	99	1	0	12	3.56	0.25
W35	83	17	0	12	3.56	0.67
W36	100	0	0	6	1.40	0.56
W37	97	3	0	5	1.11	0.55
W38	100	0	0	9	2.40	0.54
W39	95	5	0	11	3.17	0.58
W40	96	3	1	17	5.94	0.57
W41	98	2	0	19	7.03	0.63
W42	99	1	0	13	3.99	0.56
W43	97	0	0	14	4.51	0.60
W44	100	0	0	13	4.02	0.66
W45	92	4	4	15	4.94	0.77
W46	99	1	0	16	5.38	0.59
W47	100	0	0	12	3.56	0.65
W48	99	0	1	14	4.47	0.74
W49	100	0	0	20	7.48	0.69

crassicarinata was only recorded in Group B. Finally, the third cluster (Group C) consisted of a foraminiferal assemblage from shallow coastal waters (average water depth = 23 m) and was dominated by three species: *A. pulchella* (27%), *Ammonia convexa* (26%), and *A. tepida* (21%). Agglutinated species were absent in Group C, except for *Trochammina* sp. 1, which had very low abundance (1%).

Species-Environment Relationship

The total variance calculated by CCA between species and the environmental parameters was 70.1% for both axis-1 (eigenvalue: 0.61) and axis-2 (eigenvalue: 0.33; **Figure 5**). The results of the Monte Carlo permutation test ($p < 0.0001$; 500 permutation reduced model) suggest that these variables (i.e., water depth, salinity, organic matter content, and percentage of sand and mud) significantly influenced the foraminiferal distribution in the Malacca Strait. CCA axis-1 showed that water depth and organic matter content were the two most significant variables influencing foraminiferal distribution. This axis also reflects the shallow to deep water transition in the Malacca Strait.

DISCUSSION

Species Composition

The most common species recorded at all stations was *A. pulchella*, with a relative abundance of 1–76%. This species, which was identified as *Asterorotalia trispinosa* by Panchang and Nigam (2012) along the Myanmar shelf, prefers low salinity and fine-grained sediment. In this study, the relative

abundance of *A. pulchella* was >10% in stations with a salinity of 32 PSU or less. In addition, the relatively higher abundance of *A. pulchella* (>40%) in the Malacca Strait was associated with a water depth of 21–25 m. *Pseudorotalia schroeteriana* was also common in the Malacca Strait (present in 20 out of the 24 stations) but in low relative abundances (<10%). Moreover, the distribution of *D. bertheloti* was observed at 50–60 m water depth at relative abundances of >15%. A similar finding was reported by Azmi et al. (2020) in the southern region of the South China Sea, where *D. bertheloti* represented 20% of the foraminiferal assemblages at ~56 m depth. We, therefore, confirm that this species represents depths of 50–60 m in sandy tropical waters. *Heterolepa praecineta* is another common species that contributed >10% to the foraminiferal assemblages in deep-water environments (57–71 m water depth). Both *D. bertheloti* and *H. praecineta* were absent in samples from stations W36 and W37, where *A. tepida* (37–40%) appears to dominate. The higher organic matter composition (>15%) allowed stress tolerance taxa, such as *A. tepida*, to flourish.

Foraminifera Species-Environment Relationship

The CCA results suggest that the distribution of benthic foraminifera within the Malacca Strait varies with water depth (**Figure 5**). The cluster analysis produced three groups of foraminifera assemblages (**Figure 4**), which represented the transition from shallow to deep water environments (**Figure 5**). The Group A assemblage represented samples obtained from locations with varying magnitudes of environmental gradients; agglutinated foraminifera were also present in these samples.

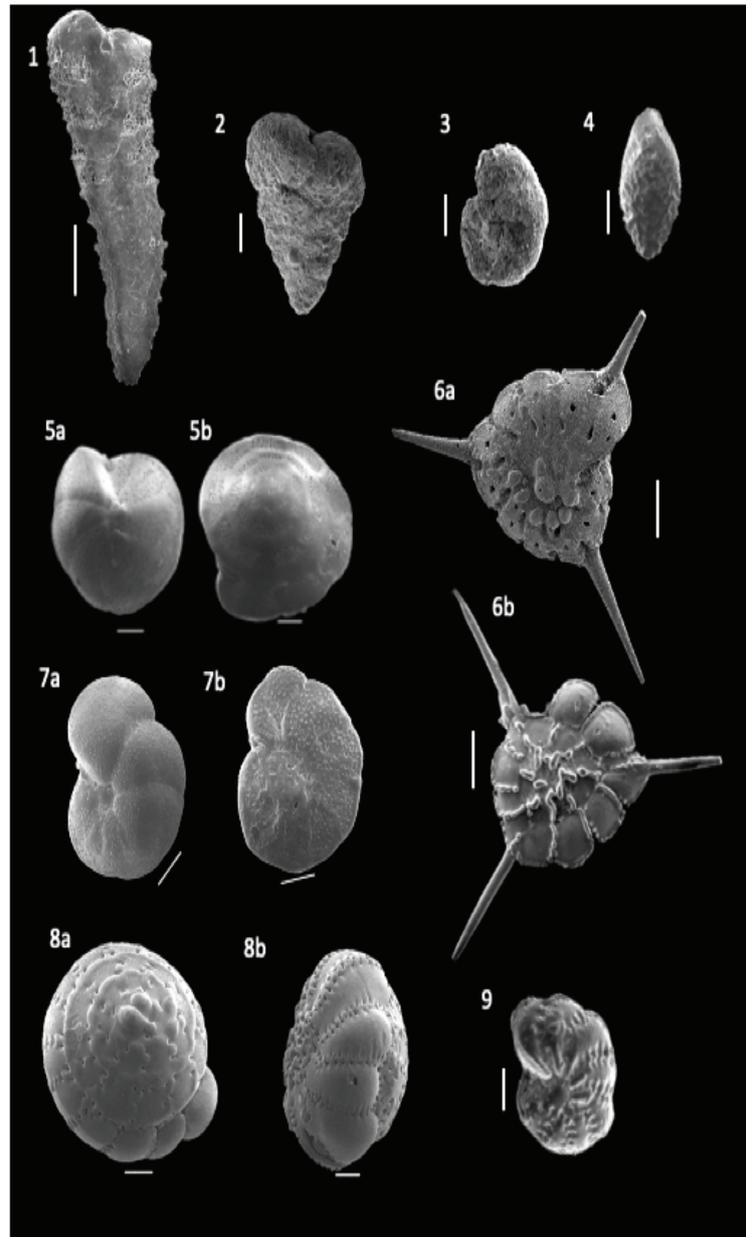


FIGURE 3 | Scanning Electron Microscope images of among the benthic foraminifera identified from Malacca Straits. **(1)** *Textularia fistula* (magnification- x70; scale bar = 200 μm). **(2)** *Textularia fistula* (magnification- x150; scale bar = 100 μm). **(3)** *Trochammina* sp. 1 (magnification- x150; scale bar = 100 μm). **(4)** *Bolivina glutinata* (magnification- x250; scale bar = 100 μm). **(5a)** *Heterolepa praecincta* (magnification- x150; scale bar = 100 μm). **(5b)** *Heterolepa praecincta* (magnification- x140; scale bar = 100 μm). **(6a)** *Asterorotalia pulchella* (magnification- x70; scale bar = 200 μm). **(6b)** *Asterorotalia pulchella* (magnification- x85; scale bar = 200 μm). **(7a)** *Discorbinella berteloti* (magnification- x100; scale bar = 100 μm). **(7b)** *Discorbinella berteloti* (magnification- x180; scale bar = 100 μm). **(8a)** *Pseudorotalia indopacifica* (magnification- x60; scale bar = 200 μm). **(8b)** *Pseudorotalia indopacifica* (magnification- x55; scale bar = 200 μm). **(9)** *Elphidium advenum* (magnification- x200; scale bar = 100 μm).

This group can be further divided into subgroups A1 and A2. The foraminifera assemblages of A1, which correlated with deeper water and sandy substrates, showed a more diverse species distribution (average Fisher's alpha = 6.43; **Table 2**). The abundance of agglutinated foraminifera was also higher in A1 than in other groups. For example, *Textularia* spp.

(13–24%) and *A. agglutinans* (4–9%) showed relatively higher abundances at water depths of 55–71 m (stations W29–31). In contrast, the relative abundance of agglutinated foraminifera was lower in Group A2 and was correlated with higher percentages of mud. Within Group A2 assemblages, *A. pulchella* and *E. advenum* were more abundant in the

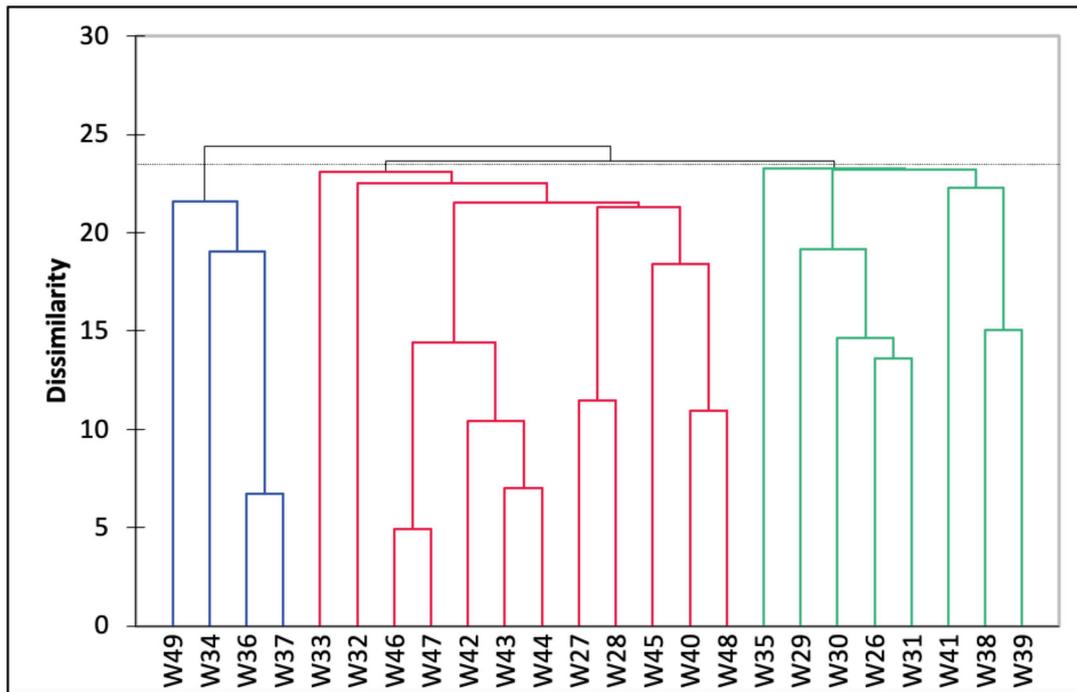


FIGURE 4 | Dendrogram based on hierarchical cluster analysis on all 24 samples collected in the study area, Malacca Straits. The clusters were defined into three major clusters (i.e., Groups A–C) based on the dissimilarity between cluster groups.

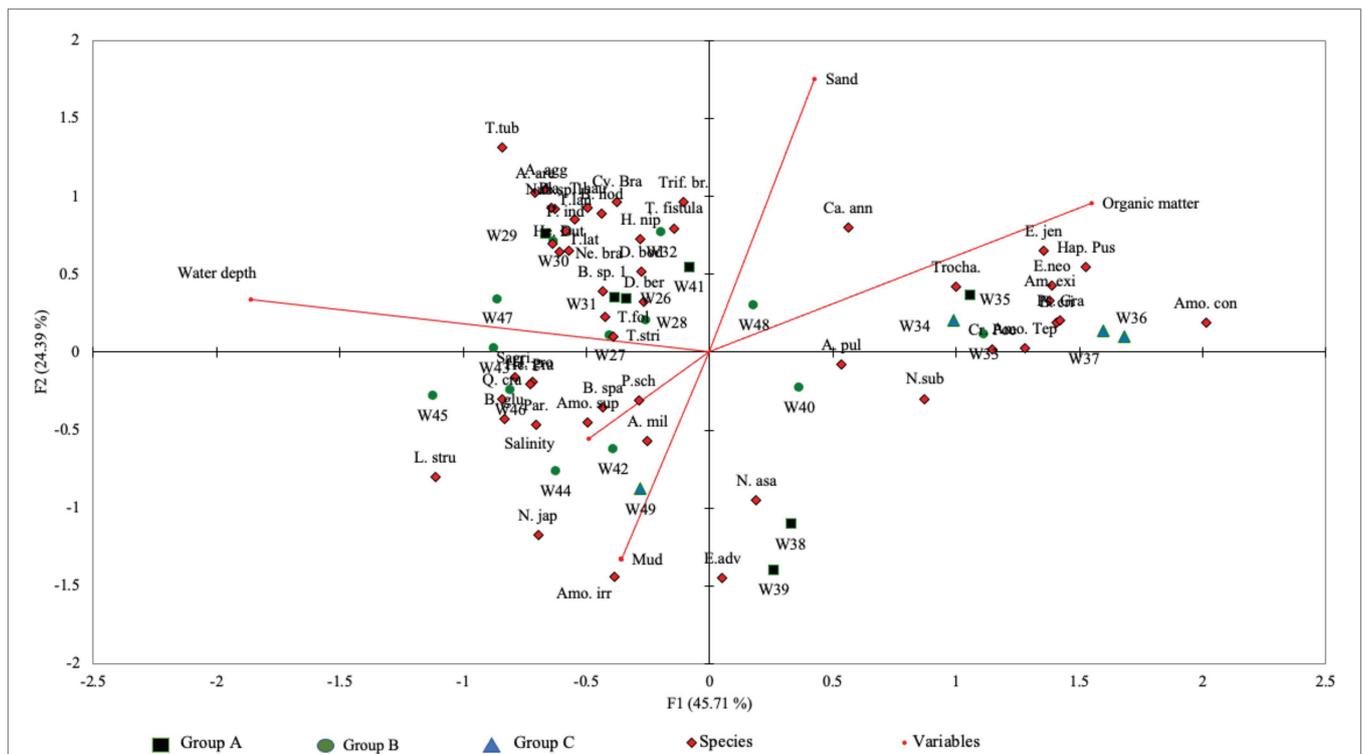


FIGURE 5 | Canonical correspondence analysis (CCA) triplot based on species–environmental relationship along the Malacca Straits. The total variances of both axes were 70.1%.

muddy substrate. In addition, *E. advenum* only showed >15% relative abundance at stations W38 and W39, which belong to the Group A2 assemblages. Similar species have been reported in the muddy substrates of the Andaman Sea at water depths of 4–20 m (Gandhi et al., 2016). This explains the maximum abundance of this species at similar water depths within the Malacca Strait.

Group B was characterised by open marine foraminiferal assemblages. Most of the stations belonged to this group and had water depths of >40 m. Although *A. pulchella* was the dominant species in Group B, its relative abundance was much lower than that of the other cluster groups. Instead, *Bolivina* spp. had a higher relative abundance in Group B assemblages, and the maximum abundance of *B. glutinata* (38%) was observed at station W42. *Bolivina* spp. is opportunistic taxa that may tolerate low oxygen conditions and prefer substrates with higher organic matter content (Murray, 2006; Eichler et al., 2012). The Group B assemblages were associated with muddy substrates, with an average sediment organic matter content of 6%. Group C represented foraminifera assemblages from shallow water, with a much higher sediment organic matter (average 11.5%) content than other cluster assemblages. Similar to previous reports in organic-rich sediments, *Ammonia* spp. had higher relative abundances in Group C (Melis and Violanti, 2006; Minhat et al., 2014, 2020; Martins et al., 2015). In this study, *A. tepida* and *A. convexa* together represented >80% of the total foraminiferal assemblage at stations W36 and W37, which had organic matter contents of >15%. In addition, the much higher organic matter content in Group C may be the reason for the absence of agglutinated species, except for *Textularia* spp. *Ammobaculites exiguus*, and *Trochammina* sp. 1.

This study documented the distribution and ecological preferences of foraminifera species along the busy Malacca Strait. Based on our findings, species such as *A. pulchella* were found to be useful for paleo-salinity interpretations. Moreover, understanding the distribution of *H. praecincta* and *D. bertheloti* and their correlation with water depth can help to determine past depositional environments. The Malacca Strait is one of the busiest shipping regions in the world, as it connects several major shipping ports in East and West Asia (Cheng et al., 2019). As a result, it is affected by land-based pollution from littoral states and marine-based pollution from maritime activities (Yasin et al., 2019). Malaysia is a dominant littoral state in the Malacca Strait and therefore plays a major role in monitoring and governing marine health in the region. The benthic foraminifera data reported in this study are thus highly useful for monitoring the marine conditions in the region. Despite the high volume of terrestrial discharge from various rivers to the Malacca Strait, this study reported predominantly sandy substrates in most stations, similar to those reported by Keller and Richards (1967). In addition, we found that stations located closer to the coastlines experienced hyposaline conditions and organic matter enrichment. Similar to other shallow water environments around peninsular Malaysia (Minhat et al., 2016; Martin et al., 2018; Suriadi et al., 2019), the foraminifera assemblages in the Malacca Strait are dominated by calcareous hyaline groups. The extremely low relative abundance or absence of porcelaneous groups could be attributed to the low concentration of calcium carbonate along the strait (Keller and Richards, 1967).

CONCLUSION

The benthic foraminifera along the Malacca Strait were dominated by calcareous hyaline species with extremely low numbers of porcelaneous species. *Asterorotalia pulchella* was the most common and dominant species in this study because of the relatively low salinity along the strait. According to the CCA and cluster analysis, foraminifera assemblages correspond to the transition from shallow coastal water to deeper marine environments. Depth was, therefore, the major factor influencing foraminifera species along the Malacca Strait.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

FM has proposed this study, funded the laboratory analysis, and contributed in major revision of the manuscript including statistical interpretation and writing the discussion. SG has contributed in critical revision of the manuscript with input on language and the flow of the manuscript. NA, NH, OM, and SS have involved in field samples collection, laboratory analysis of sediment foraminifera and organic matter content. LL, MAk, and MAb have contributed in the revision of the manuscript and research funding for field works. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2021.647531/full#supplementary-material>

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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