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Understanding Role of Foraminifera in Environmental Studies: A Review

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ABSTRACT

Foraminifers can be found in all marine ecosystems, from the shallows to the deep oceans. They are environmentally sensitive and can reflect the health of the habitat in which they inhabit. Microfossils, notably foraminifera, have emerged as a critical source for addressing environmental challenges in recent decades. They give an indication of natural conditions by serving as indicator species. Dramatic variations in diversity of foram species are frequently used to identify stressed environments. Several foram species exhibit sensitivity to changes in environmental conditions with morphological abnormalities. *Ammonia sp.* has been identified as potential bio-indicator. Oil industry with the help of micropaleontological, biostratigraphy and paleoenvironmental studies have surely flourished all across glob. The purpose of this review is to provide a wide aspect of foraminiferan taxonomy, ecology and applications. This review evaluates current research work on modern foraminifers.

Key words: Foram, Diversity index, Sediment, Fossil, Indicator species, Ecological quality statuses

INTRODUCTION

All aspects of human well-being and livelihood rely on the ocean. The great oceans and their connecting seas cover over 70% of the earth's surface. The ocean is home to a diverse range of ecosystems, from bacteria to marine animals, which constitute a vast range of ecosystems in open pelagic and coastal oceans (Bindoff et al. 2019). Coastal ecosystems occur where land meets sea and contain a variety of habitats such as mangroves, coral reefs, seagrass beds, estuaries, and backwaters (NCCR 2019). Foraminifera may be found in all marine settings, from the intertidal zone to the deepest ocean trenches.

Foraminifera are calcareous microfossils that date back 4,00,000 years (Bilal et al. 1998) and they are recognised from the Paleozoic to the Present. They are classified into three types: planktonics, smaller benthics and larger benthics. The study of benthic foraminiferal assemblages preserved in coastal and marine sediments provides chances to investigate how coastal zones respond to human impacts. Many foraminiferal species secrete a carbonate shell that is easily maintained, allowing morphological and geochemical evidence of environmental conditions to be recorded. The purpose of this work is to offer an overview of role of foraminifera in environmental studies.

The Foraminifera

Foraminifera were discovered in the fifth century BC and were thought to be minute molluscs. They are members of the Phylum Protozoa and are classified as Sarcodina, which have mineralized shells and utilise pseudopodia as locomotory structure. Food is absorbed by extended pseudopodia surfaces, digested into useful chemicals and reabsorbed into the endoplasm. Planktonic foraminifera feed on diatoms, silicoflagellates, copepods and other microplanktons, whereas benthic foraminifera eat on diatoms, algae, bacteria and particulate organic compounds. The four primary foraminiferal groups are distinguished by the construction of their test walls. Group 1 is made up of an organic outer membrane, Group 2 is made up of agglutinated tests, Group 3 is made up of secreted calcium carbonate, and Group 4 is made up of silica (Fig. 1) (Gupta et al. 2003).

Joseph August Cushman published "The Classification and Economic Use of Foraminifera," one of the field's most important works. D'Orbigny in 1826 developed the order Foraminifera and offered the first taxonomic system based on the growth plan of foraminiferal tests. Later Carpenter was recognized for developing concepts like internal structures, canal networks, shell architecture, and wall texture (Cifelli et al. 1990). Wall features was the primary criterion for distinguishing higher-level

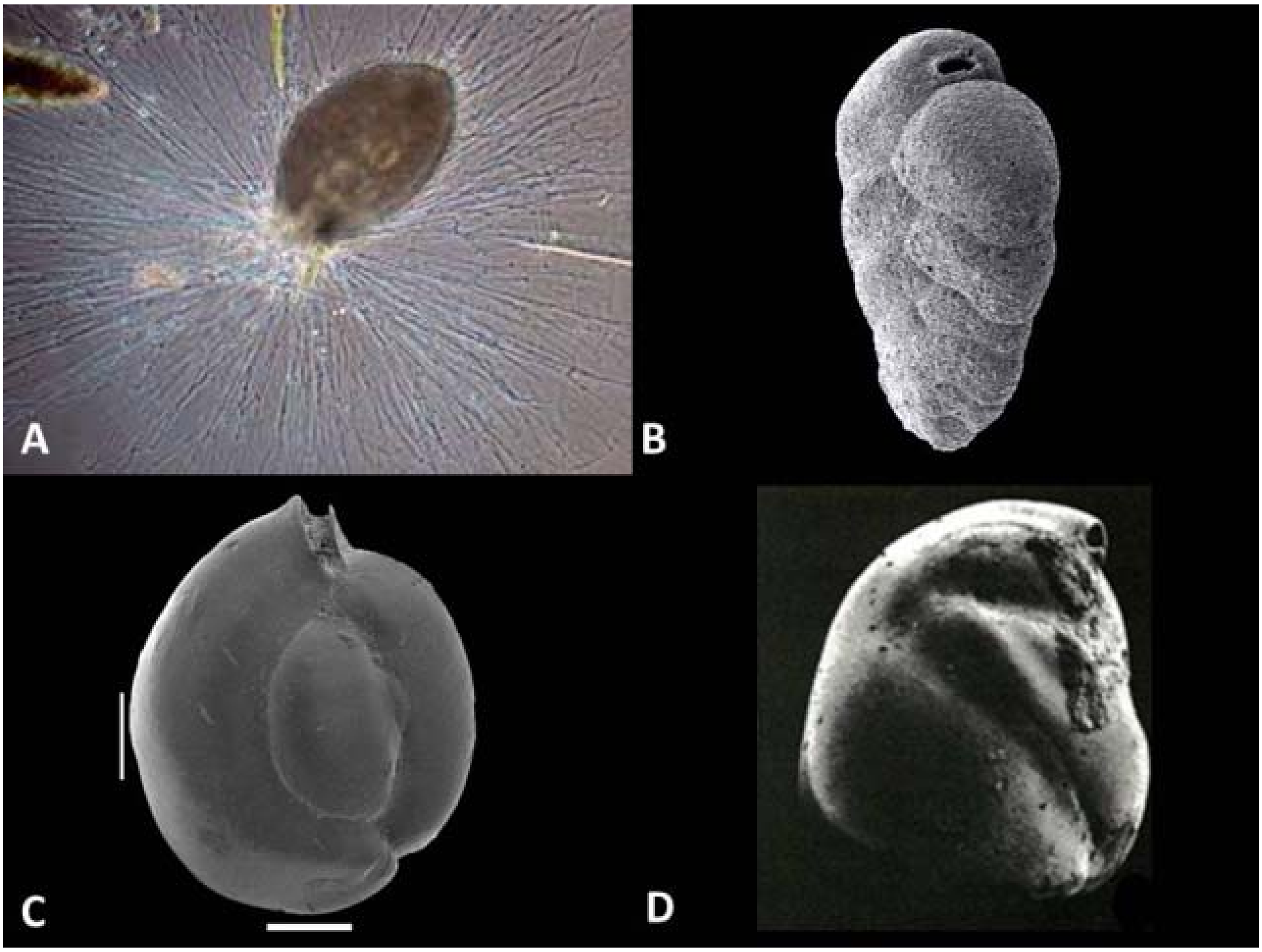

Figure 1. Representative genera. **A.** *Allogromia* with outer membrane made of organic material, **B.** *Siphotextularia* with agglutinated test, **C.** *Miliolinella* with wall made of secreted calcium carbonate, **D.** *Miliammellus* with wall made of silica (Source: Penard Labs: http://penard.de/, WoRMS: https://www.marinespecies.org/, Hesemann et al. 2023: https://foraminifera.eu/)

groupings in foraminifera in the twentieth century. Later, advanced microscopic techniques like scanning electron microscopy (SEM) was utilized to improve understanding of shell surface morphology and reveal structural details. In the preparation of SEM, gold coating of microfossils is utilized to improved shadow contrast of optical microscopic image, under high magnification for identification (Spezzaferri et al. 2007). Websites including World Foraminifera Database (Hayward et al. 2023) and Foraminifera.eu (Hesemann et al. 2023) help us in identifying various species.

Foraminifera and Ecological Correlations

Physicochemical parameters

Benthic foraminifera are the dominant marine biota in near-shore habitat and their susceptibility to environmental conditions is well documented. In the following section, we summarize current understanding of foraminifera and ecological parameters. Many environmental factors such as food, oxygen, temperature, pH, salinity and substrate influence species abundance and composition of foraminifera (Suokhrie et al. 2021). According to Martins (2016), environmental stress is mostly induced due to variations in physicochemical parameters, rather than metal contamination and organic matter enrichment.

Salinity: It is the most important element controlling benthic foraminiferal assemblage. Foraminifera are more common and diversified in brackish or saline environments (Guerra et al. 2019). The general pattern of foraminiferal species diversity decreases with decreasing salinity in brackish waters. In natural marine settings, the saturation state of calcium carbonate is primarily influenced by pH and salinity. The pH shift caused by salt, impacts calcification in the benthic foraminifera *Rosalina globularis*, where pH below a crucial level (7.5) significantly limits *R. globularis*'s capacity to secrete calcite (Saraswat et al. 2011). According to Kumar and Manivannan (2001) healthy foraminifera population, is present in salinities ranging from 33.6 to 35.2 ‰. The planktonic foraminifera *Neogloboquadrina incompta*, was able to withstand prolonged chronic exposure from 35 to 28 practical salinity unit (PSU) in culture, however at 25 PSU, extended rhizopods were absent (Greco et al. 2020).

pH: Because various benthic foraminiferal species are adapted to diverse environments, the pH tolerance range is likely to vary from species to species. Many tidal pools with acidic pH lack benthic foraminifera (Guerra et al. 2019). When examining the impacts and consequences of coastal ocean acidification, it is important to remember that pH is lower and more variable around the coastlines than in the open ocean (Charrieau et al. 2018). Changes in coastal pH induced by rising ocean acidification, eutrophication and other environmental conditions have a significant detrimental impact on foraminifera in the southern Baltic Sea (Charrieau et al. 2018). The acidification of the seas is thought to harm marine calcifiers through changes in seawater carbonate chemistry and associated calcification reductions (Müller et al. 2010). Dong (2019) cultured foraminifera from the Yellow Sea's continental shelf at 8.3, 7.8, and 7.3 pH gradients, finding that decreasing pH had an adverse effect on benthic foraminiferal communities, resulting in a significant decrease in community abundance, species richness, and variety. Dong (2019) discovered that the foraminiferal community in the Yellow Sea's center region was more vulnerable to falling pH than the near-shore population. The existing 0.1 unit lower pH of the ocean surface will result in a rise in aqueous [CO_2] concentrations and a reduction in carbonate ion concentrations [CO_3^{2-}], making it more difficult for marine calcifying organisms to generate biogenic calcium carbonate [$CaCO_3$] (Orr et al. 2005). *Marginopora vertebralis* calcification rates were negative under elevated CO_2 conditions at both optimum and elevated temperature treatments [pH 7.7, 28 °C and pH 7.7, 32 °C] (Sinutok et al. 2014).

Temperature: The large-scale distribution of foraminiferal taxa on inner shelves reflects a biogeographic zonation in which temperature is the critical factor that promotes proliferation of certain species (Eichler et al. 2008). In a laboratory culture experiment with samples collected from Qingdao, Yellow Sea, China foraminifera showed positive correlation up to 18°C - 24°C, but becomes negative when temperature increases to 30°C, with dominant species reducing in their length-width ratio (Li et al. 2019). Wukovits (2017) has observed temperature has significant negative effect on carbon retention behavior of *Haynesina germanica* and *Ammonia tepida* showed higher carbon uptake rate and tolerance to higher temperature 30°C. *H. germanica* showed a change in the behavior and the metabolism induced due to hyper-thermic stress occurred by marine heat-wave (Deldicq et al. 2021).

Oxygen: One of the primary factors influencing the spatial and in-sediment distribution of benthic foraminifera is oxygen (Jorissen et al. 1995). The quantity and distribution of most benthic foraminiferal morphotypes are thought to be influenced by dissolved oxygen levels and organic carbon input (Enge et al. 2016). Thick walls and large tests are common morphologic traits of benthic organisms in oxic environments (Kaiho et al. 1994). Miliolids are rare or absent in oxygen-deficient situations, according to Dulk (2000) and can thus be considered sensitive oxygen monitors. In oxygen-depleted environments, foraminiferal assemblages are modest in diversity and dominated by species with high stress tolerance, which benefit from adaptations such as increased pore density (Glock et al. 2011), denitrification (Ochoa et al 2010) and bacterial endobionts (Nomaki et al. 2014). Singh (2021) discovered that oxygen deficiency waters reduce foraminiferal variety and richness in the southern Arabian Sea, where *Bolivina obscuranta*, *Bulimina arabiensis* and *Bulimina pseudoaffinis* represent an assemblage that define oxygen deficient zone.

Phosphate: It has long been recognized as a calcite formation inhibitor, adsorbing onto the calcite surface, obstructing active crystal growth sites, and preventing calcite precipitation (Aldridge et al. 2011). Phosphorus-containing ions have been researched for their ability to inhibit calcium carbonate crystallization in supersaturated conditions (Reddy et al. 1977). Dadar's high nitrite concentration indicates that the aquatic ecosystem is under stress from pollution (Ingole and Kadam 2003). When *Amphisorus hemprichii* species from Okinawa Prefecture, Japan were tested with nitrogen-phosphate nutrients in a culture experiment, their development was better when the medium was changed regularly as the developing foraminifera eliminated nitrate and phosphate from media (Lee et al. 1991).

Substratum: Marine sediment is any deposit of insoluble material, such as rock and soil particles, remains of marine organisms that accumulate on the seafloor. Sediment is a key component that controls ecological functions, food production and many other processes at the Earth's surface. Benthic foraminifera are sensitive to changes in sediment texture (Zallesa et al. 2014, Abu-zied et al. 2016) and organic carbon content (Cappelli et al. 2019). Foraminiferal densities increased towards the deeper continental shelf zones, correlated with an increase in fine-grained sediment and total organic matter, according to Martins (2019), whereas low density of foraminifera is found in shallow stations due to sediment instability and lack of food quality associated with organic matter. The abrasion effect on foraminifera is influenced by grain size, with the most rapid abrasion occurring in very coarse sand, less in fine sand and least in medium sand (Post et al. 2007). The richest standing crop of foraminifera is supported by fine sand mixed with shelly fragments and silt or clay (Chaturvedi et al. 2000). Murray (2014) reported the substrate preference of various species and according to him *Ammonia* sp. prefers muddy sand, *Bolivina* sp. and *Bulimina* sp. mud to fine sand and *Nonion sp.* is supported by mud and silt. Magno (2012) has observed that *Elphidium crispum*, *Textularia truncata* had positive correlation with gravel and *Ammonia inflate*, *Lobatula lobatula* had positive correlation with coarse/medium sediment fractions. Many epiphytic foraminifera species have been observed above the depth limit of 100m in the sea, according to Jorissen (1987). According to his observations, shallow water species (*Rosalina bradyi*, *Elphidium crispum*, 50m) can adapt to a sandy substratum with vegetation, but intermediate water depth species (*Bulimina marginata*, *Nonion barleeanum*, 25-90m) are adapted to a clayey substratum with tolerant taxa dominance. Kitazato (1995) revealed the preference of foraminifera for natural and artificial substrates in a laboratory experiment. He discovered that both shallow and deep infaunal species colonized the defaunated mud, but only shallow infaunal species (*Triloculina* sp., *Uvigerina peregrine*, *Bulimina aculeata*) repopulated the artificial sediment. Because defaunated mud offered a 15-mm-thick organic-rich and oxygenated layer for both species to live, but artificial sediment only provided a 7-mm-thick layer for surface dwelling species. In a study conducted in the Gulf of Gabes, Mediterranean Sea, it found that species *Planorbulina mediterranensis* and *Rosalina macropora* acted as sensitive species, living in *Posidonia oceanica* seagrass meadows or clinging to coarse substratum to avoid polluted sites (Kateb et al. 2020).

Organic matter: Many factors influence the organic matter content of marine sediments, including water productivity, oxygen content, grain size, water depth, sedimentation rates, lateral transport of surface waters, bacterial degradation and sediment mixing (Khan et al. 2012). Foraminiferal density increases at sites where the substrate is fine-grained sediment enriched in organic matter (Martins et al. 2015). Food sources such as phytodetritus can be found in a low-degraded state on the sea floor and such high-quality sources have been observed at 4000 m depth in the Arabian Sea (Pfannkuche et al. 2000). Such phytodetritus is an important source of food for benthic foraminifera in the deep sea (Enge et al. 2016). Uneven food distribution around the sediment-water interface is a critical factor for foraminiferal distribution, with *Gyroidina sp.* extruding pseudopodia along the sediment surface to trap organic detritus and *Paracassidulina miuraensis* feeding on bacterial films or benthic diatoms attached to the top of sand grains (Kitazato et al. 1994). In his research on the Portuguese continental shelf, Dessandier (2016) discovered a link between organic matter (OM) quality, water depth, and foraminifera. He discovered that Group 1 *Ammonia beccarii* and *Quinqueloculina seminula* at depths of 20 and 50 m could tolerate low organic matter content. At 100 m depth, Group 2 *Nonion scaphum* is by far the dominant species in suboxic to anoxic sediments associated with organic matter. Group 3 *Melonis barleeanus*, *Hoeglundina elegans* and *Bigenerina nodosaria* living between 500 and 2000 m depth associated with low organic matter quality resulting from increased degradation of OM before reaching sediments. At Northern Iberian shelf station (Dessandier et al. 2015) observed high faunal density of *Nonion scaphum*, *Cancris auriculus*, *Uvigerina bifurcata* suggesting that elevated quantity and quality of total organic carbon responsible for maximum benthic foraminiferal abundance. In study carried out at Mazandaran state of Southern Caspian Sea station B4 had highest abundance of benthic foraminifera which can be related to the fine structure of sediment particles with high concentration of total organic matter (Sadough et al. 2013). Current energy and water depth influence grain size distribution and sediment sorting (Lidz et al. 1965). Cappelli (2019) found that the small size fraction (63-

150mm) has the most diagnostic species and the greatest species diversity and richness, providing a more robust statistical foundation for high-resolution environmental reconstructions. Under oxygenated conditions, a group of foraminifera including *Caronia silvestrii*, *Epistominella vitrea* and *Acostata mariae* were strongly affected by labile organic matter in samples collected from the Po river outlet, northern Adriatic Sea, demonstrating habitat distribution by migration towards the sediment-water interface (Ernst et al. 2005).

Calcium carbonate: The content of $CaCO_3$ and temperature of sea water are directly proportional to each other; hence at greater depths solubility of calcium carbonate increases leading to occurrence of small-sized specimens. Large benthic foraminifera (LBF) represent 3.9 to 5.4% of the global carbonate reef budget and produce an estimated 34 million tonnes of $CaCO_3$ per year (Narayan et al. 2022). Depth and undersaturation of calcium carbonate level play a crucial role in foraminifer dissolution in deep sea (306m to 5590m) benthic foraminifera. According to Corliss (1981), *Amphistegina* sp. is the most susceptible to carbonate dissolution, whereas *Epistominel umbonifera* is least susceptible even at 978 m deep. Agglutinating foraminifera in the Barents Sea exhibited a positive correlation with low amount of calcium carbonate, which is associated with calcium carbonate solubility. Where carbonate solubility increasing with decreasing temperature and increasing salinity and CO_2 concentration (Steinsund et al. 1994). *Quinqueloculina complanata* and *Quinqueloculina reticulata* revealed a significant positive correlation with $CaCO_3$ in a CCA (Canonical correlation analysis) study from the northern Taiwan Strait. They described this as imperforate foraminifera require more $CaCO_3$ to develop their thicker tests than hyaline foraminifera (Li et al. 2015). Jacob (2017) saw planktonic foraminifers *Orbulina universa* and *Neogloboquadrina dutertrei* mineralization using high-resolution transmission electron microscopy (HR-TEM) in his foraminiferal calcite mineralization experiment. This demonstrated that these foraminifera use a non-classical crystallization process including the transformation of metastable vaterite into calcite.

Illumination: Light intensity has been proven to be an important factor in foraminiferal biogeography and habitat dispersion. Light and nutrients are linked, as increased nutrient supply can result in increased plankton production (algal bloom) and decreased light availability. Turbidity is also an essential component since it determines the penetration of light into the water mass. *Amphistegina* spp. and *Calcarina hispida* exhibited notable rises with distance from the mainland in the Great Barrier Reef (GBR) study. Total suspended particles in the water column decrease as distance from the landmass advances, enhancing light availability for the benthic fauna (Uthicke et al. 2008). In a laboratory experiment on *Cribroelphidium selseyense* it is observed that, its activity and food absorption increases as light intensity increased (Lintner et al. 2022). *Globigerinoides sacculifer* favors warmer water and is more common at shallower depths with higher light intensity, according to a research done off the coast of Japan, as its development and survival is dependent on photosynthesis controlled by light (Kuroyanagi et al. 2004). A research conducted in the Whitsunday Islands, Central Great Barrier Reef (GBR), discovered that symbiotic foraminifera *Amphistegina* spp. and *Calcarina* sp. may flourish in both high and low light conditions, in shallow waters ranging in depth from 10 to 20m (Nobes et al. 2008). Ambient light levels impacted the distribution of symbiont-bearing species (*Neogloboquadrina dutertre*), which increased in abundance as water turbidity decreased, as shown by samples obtained from Northern California Currents. However, asymbiotic species (*Globigerin bulloides*) reaches maximum abundance in turbid waters when food is abundant (Ortiz et al. 1995).

Anthropogenic factors: Natural and anthropogenic factors influence sediment physicochemical qualities at different spatial and temporal scales (Parth et al. 2011). However, increased urbanization and industrialization have resulted in an increase in marine discharges transporting heavy metals to coastal metropolitan areas. Metals on the other hand, occur naturally and may enter the aquatic system through rock leaching, airborne dust, forest fires and plants (Jayasiri et al. 2014). Jayaraju (2011) showed a greater variance in the density and variety of foraminifera in the study location due to the iron ore dust element suspended in the water. Metal contamination decreased foraminiferal diversity and evenness (Martins et al. 2016). Zinc (Zn) caused deformed tests in a study of live forams from Sapelo Island, Georgia, by interacting with the cytoskeleton or inhibiting calcification, whereas lead(Pb) had the most acute influence on overall abundance (Price et al. 2019). Dimiza (2019) discovered that different contaminant levels in the surface sediments of the Drapetsona-

Keratsini coastal zone have a significant impact on foraminiferal assemblages; however, assessing the impacts on foraminiferal species distribution was complicated because the combination of several stressors can have unexpected effects on foraminiferal assemblage composition and abundance. The toxic element concentration patterns compared with the distribution of benthic foraminifera revealed a possible control of the chemical system on benthic foram, as *Ammonia tepida*, dominant in the Levante dock, acted as an important chemical stress, whereas *Quinqueloculina* sp., acted as a benthic species very sensitive to pollution with heavy metal (Ferraro et al. 2006). Heavy metal concentrations were higher in the sediments of Dadar and Versova beaches, which can be linked to the areas anthropogenic activities and geomorphology (Jayasiri et al. 2014). The deterioration was most noticeable near Dadar, where the effect of highly contaminated flows through Mahim Creek is thought to be the primary cause (Ingole and Kadam 2003).

Indicator species

These unicellular animals are useful environmental indicators because they respond fast to modest environmental changes and retain the change in their tests. In modern contexts, *Ammonia tepida* and *Haynesina germanica* are useful bio-indicators for Zn, Cd, and Pb; *Ovammina opaca* and *Psammophaga sapela* are also great bio-indicators in anthropogenically stressed habitats (Price et al. 2019). Taxa that are sensitive in Biscayne Bay, Florida *Miliolinella* sp. and symbiont-bearing miliolids linked negatively with Cu and Zn, while stress-tolerant taxa *Ammonia sp.* and *Cribroelphidium sp.* correlated favorably with Cu and Zn (Carnahan et al. 2008). Gandhi (2013) found *Ammonia beccarii* as an indicator species with a worldwide range that is well suited to variable salinity concentrations off the coast of Karaikal, India's south-east coast.

Morphological variation

Reddy (2016) correlated abnormalities in test morphology as indicators of pollution from heavy metals released by industrial effluents such as Cd, Cr, Cu, Pb, and Zn. According to Jayaraju (2008), heavy metal pollution has a greater negative impact on foraminiferal test morphology than agricultural and aquacultural wastes. He discovered that trace metal levels were associated with corrosion, cavity development, broken peripheries and a reduction in test growth. Coccioni discovered enrichment in Cr, Ni, Zn, Pb and As in sediments from Goro Lagoon, Italy, as indicated by foraminifera with smaller test sizes and a decrease in benthic species richness (Frontalini and Coccioni 2011). Lei (2015) discussed the effect of an oil spill in the Bohai Sea, PR China, where he observed a decrease in overall foraminiferal diversity with the presence of an oil-philic foraminiferal community. Wide salinity fluctuations, oxygen depletion, increased terrigenous input, stratification, and high energy hydrodynamics were used as stressors in planktonic foraminiferal tests for morphological abnormalities and aberrant characters in coastal, Aegean Sea, and open marine, Levantine Sea environments (Antonarakou et al. 2018). Geslin (2002) investigates the foraminiferal population on the southern Brazilian coast for anomalies. He stated that in a non-stressed population, the rate of abnormal tests is about 1%, as observed in laboratory cultures of *Ammonia sp.* under normal conditions. According to him high proportions of abnormal tests maybe induced by environmental stress resulting from natural factors such as hypersalinity, periodical acidification or regeneration of test after damage. *Ammonia tepida*, *Elphidium oceanensis* and *Haynesina germanica* were among the most abundant abnormal specimens, indicating that the Santa Gilla lagoon is heavily polluted with trace elements (Cd, Ni, Pb, Zn, and Hg) (Buosi et al. 2010). The largest percentages of foraminiferal test deformations occurred in Abu-Qir Bay at sites S1-S3, owing to high pollution levels of heavy metals and, at S1, to turbulence related with port activity. Forams such as *Miliolinella* sp. and *Peneroplis planatus* show abnormal growth, *Astrononion stelligerum* showed discontinuity of growth, *Quinqueloculina* sp. showed various combinations of last chamber division and *Cibicides lobatulus* and *Cibicides refulgens* typically show abnormal chamber enlargement and aberrant chamber shape and size (Elshanawany et al. 2011). High percentages of abnormalities were found in *Elphidium gunteri* and *Haynesina germanica* from the western basin (Marano) where the highest concentrations of nutrients, as well as the highest variations in salinity, were reported in studies from Marano and Grado Lagoon, Italy (Melis and Covelli 2013). Test abnormalities are over-represented in *Ammonia beccarii* and under-represented in *Elphidium excavatum* in the western Baltic Sea and they have been linked to intrusions of salt-rich bottom waters from the Baltic Sea and high levels of heavy metals in the inner fjords (Polovodova and

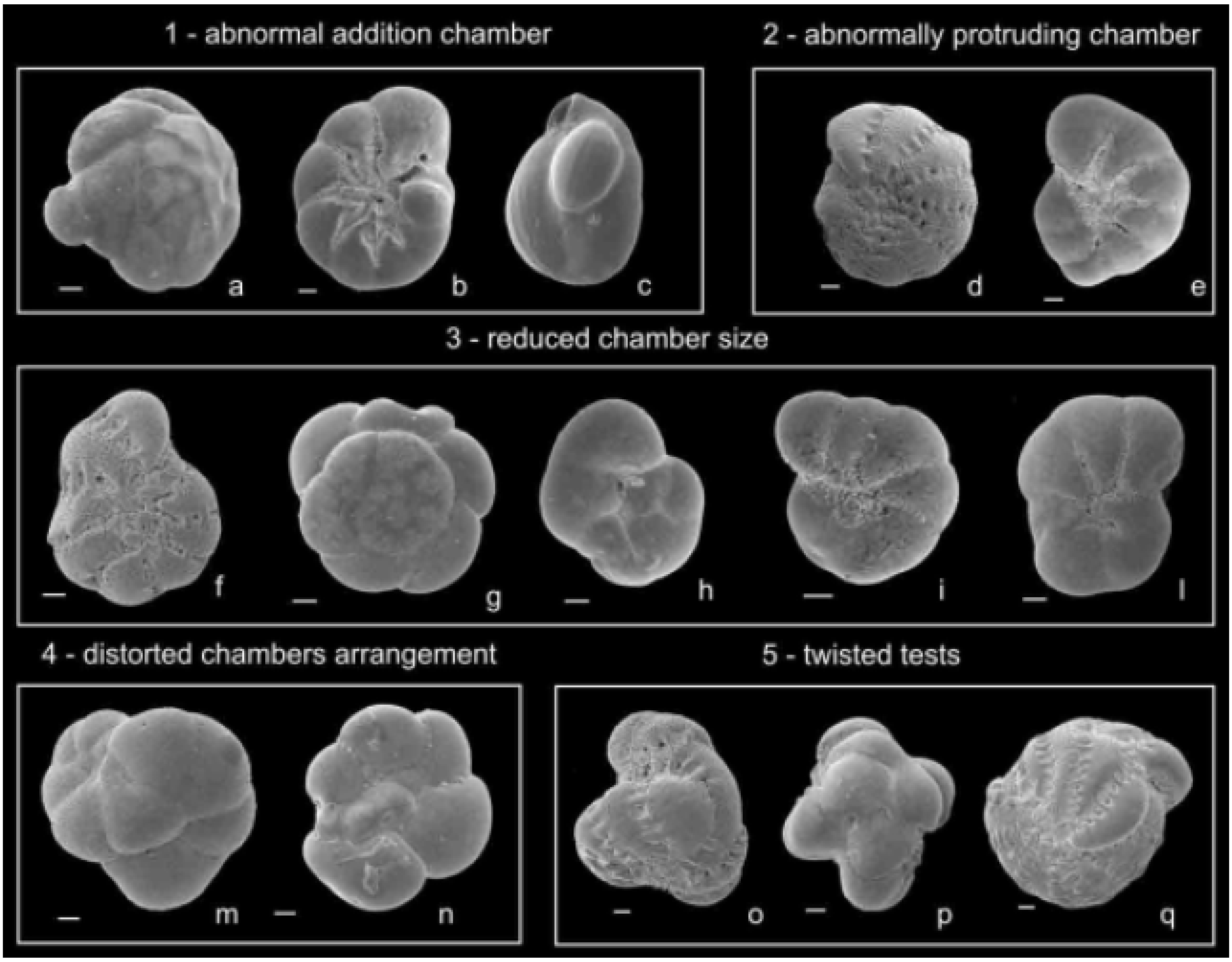

Figure 2. SEM photomicrographs of abnormal benthic foraminifera (Source: Melis and Covelli 2013)

Schönfeld 2008). *Sorites marginalis* and *Peneroplis planatus* in the Red Sea coastal area of Jeddah displayed abnormalities in their coiling, general shape of chambers, and apertures with concentrations of Cr, Fe, Mn, Ni, Zn, Cd, Pb and Cu in live individual tests, presenting heavy metals as one of the factors responsible for abnormal tests (Youssef et al. 2015). This suggests that environmental conditions, mechanical damage and pollution have an impact on foraminiferal morphological variations and abnormalities (Fig. 2).

Foraminifera Ecology and Diversity Indices

A diversity index is a quantitative measure that reflects the number of different species that exist in a community, as well as their relationship with ecology with respect to types, such as richness, variations and evenness. According to a study from Chilka Lake, Orissa foram species number (S), Shannon-Wiener index H(S) and Margalef's index (d) were lowest for the outer channel during the post-monsoon season (November) as there was a large river discharge into the lake. In contrast, a greater number of species and diversity was found in the lake's outer channel during the summer (May), when there was a significant oceanic influence, no river discharge and a big inflow from the Bay of Bengal (Jayalakshmy et al. 2006). According to Nagendra (2019), a study from the Uppanar Estuary on the Tamil Nadu Coast found a correlation between ecological stress indicators including FORAM Index (FI), Foram Stress Index (FSI), and Ammonia-Elphidium Index (AEI) that, they are positively correlates with foraminifera-ecological relationship in assessing the pollution impacts. Lower ecological index values of Shannon Index H(S), Equitability Index (E), and Foraminiferal Density (FD) at Torrecillas lagoon, Puerto Rico, indicated stressed environmental conditions with the presence of *Ammonia*

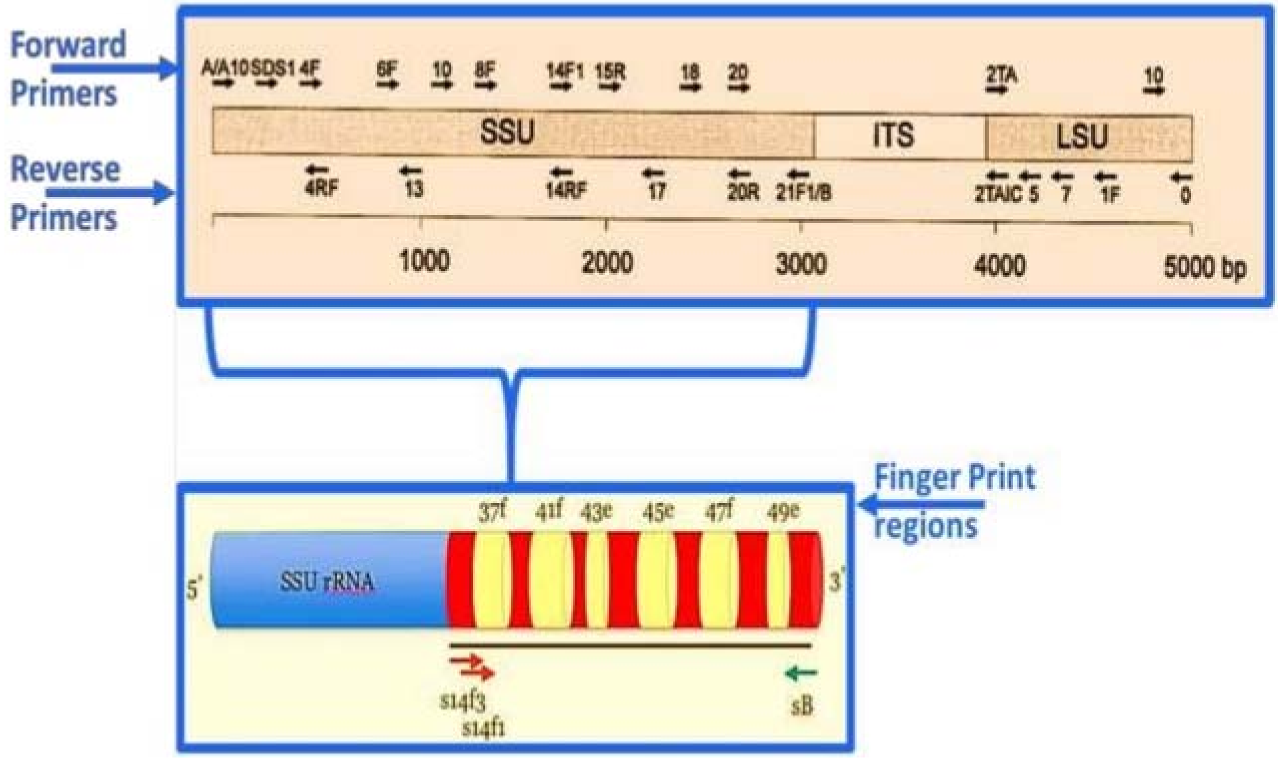

Figure 3. Schematic representation of foraminifera ribosomal DNA and its fingerprint region (Source: Prajapati and Trivedi 2022)

beccarii and *Triloculina oblonga* as indicator species (Colón et al. 2018). Ecological diversity statistics (foram abundance, species richness, margalef index) in the high intertidal zone were all smaller than those in the low intertidal zone, indicating a seaward preference of the foram community in a Yellow Sea intertidal zone, PR China (Lei et al. 2017). Singh (2021) discovered that oxygen deficient waters reduce foraminiferal diversity and abundance, whereas organic matter or food supply with just enough dissolved oxygen sustains increased species diversity (H) and richness (d).

Foram Genetic Era

Molecular research on foraminiferal species has revealed their phylogeny. It is now widely used to identify species diversity in a range of habitats, quantify environmental impact and explore Foraminifera ecology (Fig. 3) (Macher et al. 2022, Prajapati and Trivedi 2022). For molecular identification SSU rDNA, LSU rDNA sequencing (Bhatt and Trivedi 2018) and nuclear 18S rRNA sequencing with mitochondrial cytochrome c oxidase subunit I (COI) gene sequences (Macher et al. 2022) approaches are used. *Ammonia* and *Elphidium* species are major benthic foraminiferal fauna and their abundance allows them to be used in a wide range of studies including molecular analysis. The genetic data collected from *Ammonia sp.* populations taken in several locations Northern Atlantic, North Sea, Mediterranean Sea, Red Sea, and Pacific reveals the presence of ten distinct genotypes belonging to various species (Pawlowski and Holzmann 2008). Roberts (2016) demonstrated how a small subunit ribosomal RNA gene sequence assisted in reclassifying *Polystomella umbilicatula* specimens as *Elphidium williamsoni*. The analysis of rDNA sequences corresponding to the 3' segment of the SSU rRNA and the 5' fragment of the LSU rRNA genes in *Elphidium sp.* specimens from the Kiel Fjord, SW Baltic Sea, aided in the identification and differentiation of *Elphidium excavatum excavatum* and *Elphidium excavatum clavatum* (Schweizer et al. 2011). Using the SSU rRNA gene amplification method, seventeen distinct Elphidiid genetic types were discovered in the Northeast Atlantic, revealing a substantial number of Elphidiid genetic types within a Boreal-Lusitanian region known as a diversification hotspot (Darling et al. 2016). Twenty-six species and two subspecies of *Ammonia sp.* taxa were identified by DNA sequencing utilizing SSU rDNA genes from samples collected throughout the world, and they were morphologically distinct from one another (Hayward et al. 2021). As a result, these genetic investigations will help us in identifying specific species, which may be associated to species environment systems and anthropogenic effects.

Foram Ecological Applications

Ecology quality analysis

Ecological indices are significant in investigating information about ecosystems and the influence of nature and human activity on them. According to study conducted by El Kateb to calculated Ecological quality statuses (EcoQs) using different diversity and sensitivity indices "diversity index Exp(H'_{bc})" demonstrated expected $EcoQ_S$ values as compared to others (O'Brien et al. 2021). In the study from Rade de Cherbourg, France diversity index Exp(H'_{bc}) for foraminifera from salmon fish farm cages was considerably lower compared to the sites outside. Here EcoQs indicated moderate degradation of environmental conditions in cage area, with EcoQs status changing from excellent outside cage to poor in cages for foraminifera (Bouchet et al. 2020). For the Beypore estuary site on India's southwest coast, the FORAM index (FI) identified two functional groups: pollution-tolerant opportunistic foraminifera (*Ammonia tepida*, *Nonion scaphum*) and heterotrophic foraminifera (*Haplophragmoides* sp., *Quinqueloculina* sp.), with FI < 1.5 indicating environmental conditions that supported substantial populations of stress-tolerant species (Sreenivasulu et al. 2019). A research conducted along the Norwegian Skagerrak coast in the North Sea showed an association between the diversity index Exp(H'bc), community analysis (Redundancy analysis, Procrustes analysis) and live benthic foraminifera. Bottom-water dissolved oxygen content ($[O2]_{tos}$) was shown to be the key environmental component controlling variance in diversity, acting as an efficient bio-monitoring tool (Bouchet et al. 2012). In a study from central Adriatic Sea, diversity index Exp(H'_{bc}) was more suitable for predication of data and provided lower EcoQS scores for predication. Where in polluted sites with higher Cr and Zn concentrations, higher Foram-AMBI index values indicated an assemblage dominated by opportunistic species (Ammonia tepida, Rosalina bradyi) (Franzo et al. 2023).

Pollution monitors

Over the centuries, marginal marine ecosystems have been damaged by land reclamation, dumping garbage, channel dredging and other civil-engineering operations (Murray et al. 2006). The foraminifera offered cost-effective pollution monitoring in the Balearic Archipelago, Spain, with morphological and geochemical studies indicating a localized but long-lasting influence on tests (Khokhlova et al. 2022). Polycyclic aromatic hydrocarbons and heavy metals released by fishing boat engines affected the density and species richness along France's Atlantic coast (Châtelet et al. 2004). The Ammonia-Elphidium Index (AEI) revealed hypoxic and stressed environmental conditions induced by heavy meats from effluents of aqua ponds, farmland and urban sewage at Swarnamukhi estuary, India (Jayaraju et al. 2021). Many studies have shown how foraminifera respond to natural and anthropogenic factors with abnormal testing. According to Boehnert (2020), increasing abnormal tests in the North Atlantic region are linked to environmental stress factors such as polycyclic aromatic hydrocarbons (PAHs) and components in crude oil from marine areas. Yümün (2017) has linked test aberrations in the northeast Aegean Sea area by calculating Pollution Index (PI) and employing Scanning electron microscopy (SEM) for elemental surface analysis.

Palaeoecological applications

Sequence stratigraphy is an attempt to split the geological record into genetically linked, often stratigraphy constrained rock units or sequences. The fossil record provides a relative chronology (biostratigraphy) as well as an interpretation of depositional conditions i.e. paleoecology (Murray et al. 2006). Paleoecological studies has been studied well in areas including Pacific Ocean, Gulf of Aqaba, Japan, however here we are discussing work from Indian subcontinent. Foraminiferal evidence from lignite mines in Kutch, India, indicated that the lignite's maximum age limit is early Bartonian, with a lower age limit of late Lutetian (Saraswati et al. 2014). The existence of lignite in the early Bartonian, which corresponds to the middle Eocene climatic optimum (MECO), implies that the climate was humid at that time. The Krishna-Godavari Basin in India was studied to identify the time of the first incursion. From 2782 to 2785 m depth, foraminiferal evidence includes *Hedbergella aptiana*, *Hedbergella gorbachikae* and *Microhedbergella miniglobularis* implying a late Barremian to early Aptian age for the transgression event (Mishra et al. 2020). The biostratigraphy of the Jaisalmer basin in western Rajasthan, India, revealed the existence of fossil foraminifera in places such as Parh, Pariwar, and Baisakhi, showing their previous interaction with marine environments (Zadan and Arbab 2015).

Paleoecology is the study of ancient ecosystem composition and distribution for time periods spanning from decades to hundreds of millions of years (Webb et al. 2017). With the first appearance of foraminifera from earlier Cambrian period to present period foraminifers have turned into one of the most useful group for ancient sea environment interpretation. The Bathonian period of the Middle Jurassic represents an outer neritic depth with higher carbonate production in a healthy ecosystem dominated by carbonate shells with limited terrigenous influx in an arid climate. While the Callovian period of the Middle Jurassic represents a gradual shift towards a more humid climate with increased terrigenous input in a relatively shallower setup (Jain et al. 2019). According to Valchev (2003), tiny benthic foraminifera have tremendous potential in paleoecological interpretation of data. This data is obtained from the taxonomic composition and organization of foraminiferal assemblages. When the earth's climate was undergoing large-scale revolutions due to the growing severity of glacial-interglacial cycles the study of deep-sea benthic foraminiferal distribution in the south-west Indian Ocean indicated significant variability in tropical deep-sea settings (Jayaraju et al. 2010). Báldi (2008) used stable isotope records (^{18}O and ^{13}C) to confirm results from a foraminifera-based paleoenvironmental study. Correlation to bottom core depth revealed increasing inbenthic percentages linked with a slightly decreasing oxyphylic number and decreasing diversity, which interpreted as lower oxygen levels and higher food sources.

Petroleum exploration

Petroleum exploration relies heavily on micropaleontology, primarily foraminifera. The three most important components in oil exploration are petroleum source rocks, reservoir rocks and cap rocks/traps (Jones et al 2014). The major petroliferous basins of the Indian subcontinent are the Indus basin, Cambay basin, Mumbai basin, Cauvery basin, Krishna-Godavari basin, Assam basin and Surma basin (Sircar et al. 2017). Large benthic foraminifers from the Oligocene-Miocene age characterize the shallow water carbonate reservoir from the Mumbai High field in the offshore Mumbai basin on India's west coast (Cotton et al. 2019). When combined to create paleogeographic maps, seismic profiles and other geologic data sets, marker species of foraminifera with their First Appearance Datum (FAD) and Last Appearance Datum (LAD) are used as tools in the quest for hydrocarbons (O'Neill et al. 1996). Planktonic foraminifera are used to determining the particular geological period when organic matter degraded in marine rock under anaerobic conditions; usually petroleum formation occurs in such typical environments. These assemblages are good predictors of certain environmental conditions and help in the identification of the oil-bearing horizon (Sijinkumar and Nath 2012). Dam (2020) research at Cat Ba Island and the northern Song Hong Basin in Vietnam reveals the stratigraphic relationship that exists between the carbonate formations on Cat Ba Island and the basement rock in the northern Song Hong Basin. This provides chronostratigraphic data that can be used in hydrocarbon exploration geological models. Matsunaga (1955) mentioned a marker species *Spirosigmoilincela compressa*, which was discovered at a depth of 844.8 metres at the Teikoku Oil Company's Yahiko R-2, Niigata Prefecture, Japan**.**

CONCLUSIONS

This article summarizes research from the previous two decades on the expanding area of foraminifera and its applications in environmental studies. It also discusses its significance in ecological parameter correlations, molecular characteristics, paleoecology, and application as a potential bioindicator in marine pollution investigations. Paleoecological research may provide predictions about the climatic conditions of that era by detecting and analyzing various features of foraminifera from different strata. Previous research has more focused on susceptible changes in physicochemical parameters such as pH, salinity and organic carbon in benthic foraminifera. Substratum studies have identified groups of forams that thrive in diverse habitats, such as epiphytic and shallow water foraminifera. Calcium carbonate studies have found a link between test size of various species and water temperature. Light intensity has been found to be an important element in foraminiferal biogeography and dispersion. Contaminants in the water have a direct impact on foraminiferal diversity and density as urbanization progresses, making particular species, such as *Ammonia* sp. and *Elphidium* sp., bioindicators of specific environmental conditions. Lower ecological index values have been associated with considerable pollution effect in ecological studies, with the diversity index Exp(H'bc) providing expected EcoQS values, than other indices. Changes in the physicochemical properties of water, as well as an increase in contaminants, cause asymmetrical or abnormal tests. These indicator species and abnormal tests help in the identification as well as understanding of certain ecosystems and niches that have formed along coastlines and in the open ocean. With the advancement of molecular technology and the use of polymerase chain reaction tools, we can now identify forams at the gene level, allowing us to differentiate between two physically identical species that correspond to specific ecosystems. Furthermore, the effects of human activities may be evaluated at multiple levels utilizing these molecular instruments. However, there are still questions to be addressed. Nonetheless, we now understand enough about foraminifera to acknowledge their potential contribution to our understanding of marine ecosystems.

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