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Heavy Metal Contamination and Benthic Foraminifers' Abundance in Sediments of Lagos Harbour, Gulf of Guinea Coastal Area, Southwest Nigeria

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Abstract
Five heavy metals and benthic foraminifera contents in sediments from Lagos Harbour (Nigeria) were investigated, to determine the degree of contamination and the corresponding impact on the abundance of the benthic species. Surface-sediment samples were analysed by adopting multi-acid digestion and employing inductively coupled plasma-emission spectrometer (ICP-MS: MA-300) for metal quantification. Standard preparation for the recovery of foraminifera was followed, and specimens were identified. The consensus-based empirical sediment quality guidelines (SQGs); and relevant indices of contamination were used to assess the extent of sediments' degradation. Results showed that concentrations of metals such as Cu, Pb, Ni and Zn which were below the threshold effects level (TEL) in sediments are expectedly favourable for benthic foraminifera. Meanwhile, the corresponding low population density of some species in response to moderate contamination by Zn, indicated that their microhabitats are impaired, despite the concentrations being below TEL. Four dominant species identified are *Hanzawaia boueana*, *Textularia sgittula*, *Florilus atlanticus* and *Melonis padanum* in decreasing order of abundance. Consequent upon the spurious impact of Zn and As contamination, *Textularia sagittula* which constituted over 94 % of the agglutinated forms, were implied to be most disadvantaged among the dominant species.

Keywords: *Heavy metals, benthic foraminifera, Hanzawaia boueana, Melonis padanum, agglutinated forms.*

Introduction

Lagos Harbour serves as a seaport, centre for recreational sailing, artisanal fishing and a sink for disposal of domestic and industrial wastes. These anthropogenic activities release various heavy metals of environmental concern which may be adsorbed unto the surface of the bottom sediments. Weathering of nearby rocks and soil, and erosion and transport of the residual particles may also contribute to the concentration of heavy metals in this environment. Such metals settled in sediments may be re-suspended and cause secondary contamination to the aquatic environment (Wardhani et al., 2017). However, heavy metals are regarded as harmful contaminants, if present in amounts exceeding natural concentrations (Sekabira et al., 2010; Bing et al., 2016). Intensive industrial and shipping activities resulting to discharge of untreated sewage, oil spills and wastes from repairs of ferry or high speed-boats are preponderant. Consequently, an accompanying deterioration of water and sediment qualities within this harbour is not unexpected (Filipkowska et al., 2005; Knox et al., 2014; Knox and Paller, 2017; Bamanga et al., 2019). This environment like similar aquatic systems, provides food and shelter for flora and fauna as well as act as a sink for a wide variety of pollutants (Swarnalatha et al., 2013). Heavy metals among other pollutants have been of great concern due to their abundance, persistence, toxicity and non-biodegradability (Yuen et al., 2012). Humans may be exposed to the deleterious impact of these metals through direct inhalation, consumption of aquatic organisms (ingestion) and dermal contact absorption (Chabukdhara, and Nema, 2013; Qing, 2015; Silva et al., 2017). Comparison of metal concentrations are usually done by using the consensus-based sediment quality guidelines (SQGs) which considers the threshold effect level (TEL) and probable effect level (PEL) suggested by MacDonald et al. (2000). Such comparisons between measured data and SQGs are useful to assess the potential biological effects of heavy metals on organisms, to maintain water quality and trigger possible remediation actions.

Although some publications exist on heavy metal pollution in the adjoining Lagos Lagoon (Don-Pedro et al., 2004; Olatunji and Abimbola, 2010; Amaeze et al., 2012; Alo et al., 2014 among others), dearth of information on Lagos Harbour persists. Of the few literature on pollution, Bamanga et al. (2019) seems to be the most relevant to this study as it emphasizes on sediments' contamination and the health of Lagos Harbour environment. These authors investigated and characterised the total concentrations of As, Cd, Cr, Cu, Co, Fe, Mn, Ni, Pb, Sn, V and Zn, and concluded that only Cu and Zn exceeded the TEL in surface sediments of Lagos Harbour. However, it has been clearly set down in writing that heavy metals in sediments are persistent in the environment, contaminate the food chains, and cause different health problems due to their toxicity.

Since, chronic exposure to heavy metals in the environment is undoubtedly, a real threat to living organisms, continuous monitoring through studies of this kind is therefore, pertinent (Wieczorek-Dąbrowska, 2013; Ali et al., 2019).

Foraminifera are eukaryotic unicellular microorganisms with records of huge success as inhabitants from deep oceans to brackish water lagoons, estuaries, and in few freshwater streams and lakes (Solai et al., 2012). They have been used as suitable bioindicators owing to their prompt response to subtle environmental changes arising from heavy metal contamination (Debenay et al., 2001; Burone et al., 2006; Martins et al., 2011; Vilela et al., 2011); hydrodynamic fluctuations (Debenay et al., 2006); and changes in salinity (Debenay et al., 2001), pH (Fatela et al., 2009), and Eh (Bernhard and Sen Gupta. 1999). Anthropogenic discharge of heavy metals generates environmental pressure that modifies the distribution and association of benthic communities (Martins et al., 2016; Musco et al., 2017; Tadir et al., 2017).

Numerous global studies of benthic foraminifera in marine-terrestrial transitional environments are known (Donnici et al., 2012; Martins et al., 2016; Dimiza et al., 2016; Paquette et al., 2016; Tadir et al., 2017 among others). Meanwhile, only few studies have compared baseline conditions to human activity impacts in coastal zones (Thomas et al., 2000; Tsujimoto et al., 2006; Carnahan et al., 2009; Martins et al., 2013). The last five decades recorded studies on Quaternary benthic foraminiferal assemblages and species diversity in southwest Nigeria sector of the Gulf of Guinea coast (e.g. Asseez et al., 1974; Adegoke et al., 1976; Salami, 1982; Dublin-Green, 1999; 2004; Okewole, 2007; Olayiwola and Odebode, 2011; Phillips et al., 2010; 2012). Based on the available literature, some of these authors worked extensively on the adjacent lagoon, beaches, continental shelf and river estuaries, but none discussed foraminiferal assemblages in Lagos Harbour. This study therefore intends to (a) assess the extent of contamination of Cu, Pb, Zn, Ni and As; (b) determine the abundance and distribution of benthic foraminifera, consequent upon their ecological dependence on change in environmental conditions, specifically heavy metal contamination; and (c) investigate the influence of heavy metal(s) of concern on abundance and distribution of species that are dominant and of common occurrence. In this sense, a study of benthic foraminiferal species and their relationship with degree of heavy metal contamination will help in the identification of the locations and extent of anthropogenic impacts. By logical inference, the health of the aquatic environment being investigated can therefore be inferred.

The Study Area

Lagos Harbour is situated at the centre of a system of marginal lagoons extending 124.6 km from Cotonou at the Republic of Benin to the entrance of Lagos Lagoon. Immense volume of fresh water passes through this harbour and out to the sea during rainy season. During the dry season, the flow of fresh water ceases, and the rivers become a series of isolated pools, and sea water enters the harbour, giving rise to marine conditions near the harbour mouth, and a brackish water extending about 20 miles up the adjacent lagoons and creeks (Hill and Webb, 1958). However, besides salinity changes arising from alternating ebb- and flood tides, many of the physical features of the area are comparatively stable. The tidal regime in this area is semi-diurnal with tidal heights that decrease inland from the Lagos Harbour into the Lagos lagoon system (Onyema and Popoola, 2013). Lagos Harbour which serves as the main channel through which Lagos Lagoon connects to the South Atlantic Ocean, is approximately 10 km long, and varies from 0.5 km to 1 km in width. It is the only natural break of any size with an extended barrier beach from the Volta River in Ghana to the River Niger, and has been established for decades. According to Egborge (1994), the Lagos harbour is Nigeria's most important sea-port and the first inlet from the Atlantic Ocean beyond the Republic of Benin. It is composed of three stone moles in the form of harbour break waters. It is a naturally protected basin equipped with docking and other facilities for the loading and unloading of cargo and usually with installations for the refuelling and repair of ships (Onyema, 2009). The investigated harbour lies within latitudes 6^{o} 23'N and 6^{o} 26'N and longitudes 3^{o} 23'E and 3^{o} 24'E (Fig. 1).

Materials and Methods

Sampling Technique

Sediments were collected on-board a boat with "Bruce anchor" from 14 sampled stations that were geo-referenced with hand-held "Global Positioning System" (GPS). The measured coordinates enabled comparison of heavy metal contamination; and abundance and distribution of foraminifera in these stations. The collection of surface sediments was done using van Veen grab that was well wrapped with polyethylene material around the stainless steel clamshell bucket to

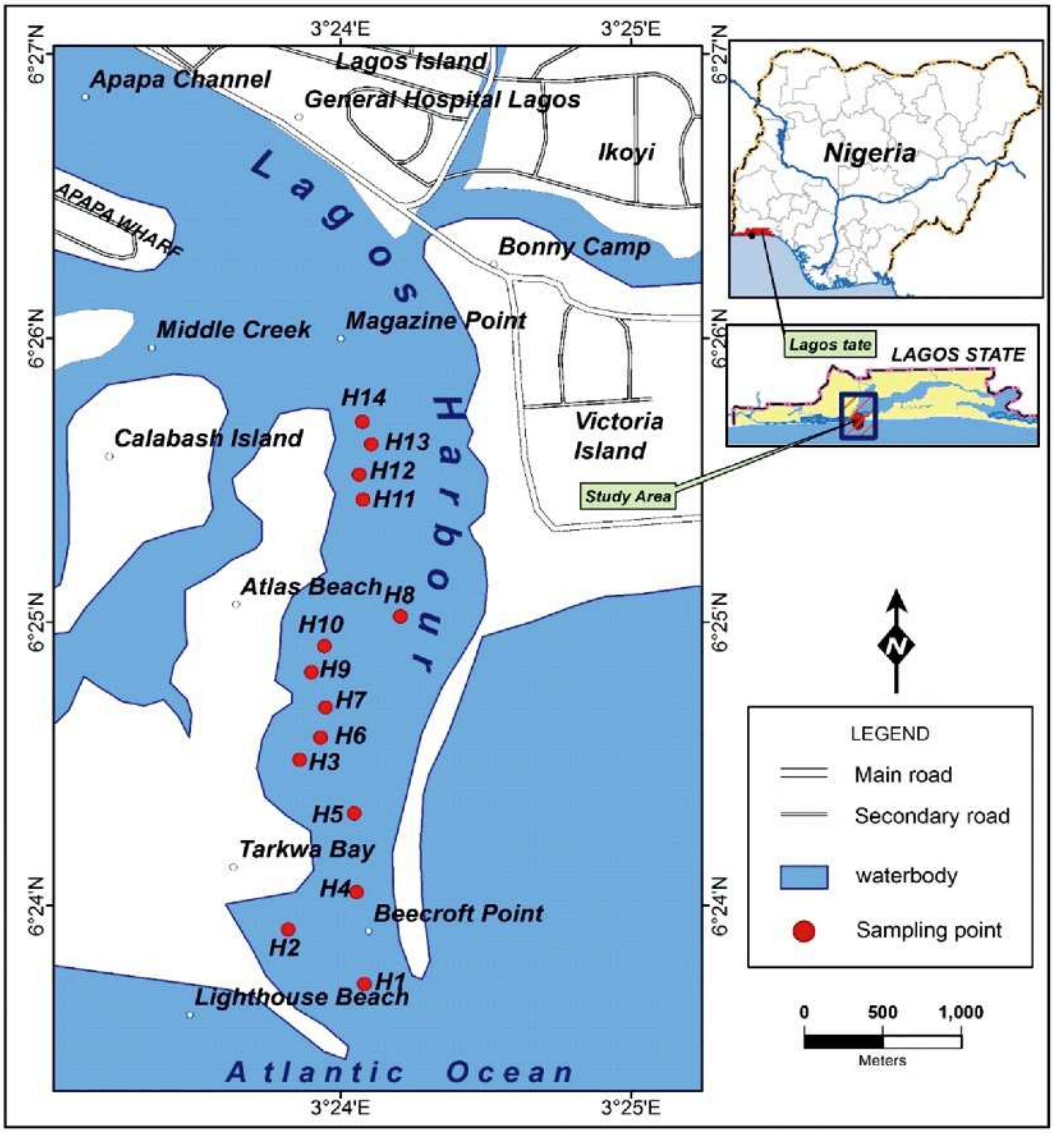


Fig. 1: The map of stations sampled in Lagos Harbour, Gulf of Guinea coastal area, southwest Nigeria.

avoid contamination. The bucket was washed with water immediately after every sampling. The upper sediment layer (2 cm) was scrapped using a plastic spatula and kept in the appropriate labelled cellophane bag for foraminiferal fauna, particle size, and heavy metal analyses.

Sample Preparation for Foraminifers' Specimens

A portion of the sample at each station was immediately kept in labelled plastic container and preserved with 5 % formalin-sea water for foraminifers' analysis. In order to remove mud particles and obtain a good representation of the species, each sample was washed over 63μm aperture sieve. In foraminifera preparation, rose-Bengal remains the stain of choice among paleoceanographers and benthic ecologists because it is cheap and convenient to use (Murray and Bowser, 2000) but the limitations may cause inaccurate interpretation of data. Such disadvantages are premised on the fact that a.) rose-Bengal staining in opaque specimens such as certain agglutinated or calcareous porcellaneous foraminifers is difficult to visualize (Bernhard, 2000); b.) the reaction of rose-Bengal with protein defines it as a non-vital stain; that is, it will adhere to dead as well as living cytoplasm (Bernhard, 1988) and; c.) Rose-Bengal can stain the organic lining of foraminiferal tests (Walker et al., 1974) or bacteria attached to or located inside the test (Martin and Steinker, 1973). Also, foraminiferal tests containing living cytoplasm do not always stain with Rose-Bengal, possibly because apertural blockage prevents stain penetration into the test cytoplasm (Martin and Steinker, 1973). Consequentially, total forаmininiferal assemblages in a thin surface interval which provides less biased ecological information was considered, hence, staining with rose-Bengal (2g/l: 2g in 1000ml of alcohol) for identification of live specimens is unnecessary. Each of the sediment samples was oven-dried, and 30g was measured for examination under a reflected-light binocular microscope for its foraminifer contents. Specimens were picked, stored in cellules, counted, and identified based on qualitative morphological characteristics from relevant literature (Loeblich and Tappan, 1964; 1987; and Debenay, et al., 2001).

Measurement of Water Characteristics

Bottom water was collected into labelled plastic bottles at various stations and temperature, pH and salinity were measured. The pH was measured with a pH meter (Hanna H 19625, Precision 0.01); Salinity with a conductimeter salinometer (WTWLF 325, Probe WTW Tetracon 325, Precision 0.1g/l); and temperature with a mercury thermometer. Dissolved oxygen meter with optical sensor was used to measure dissolved oxygen (DO) in the harbour water. Compensations were done by employing data logging software to avoid inaccurate measurement of DO, due to likely influence of temperature and salinity. At each station, the depth was measured using a hand lead (calibrated rope to the end of which a lead weight was attached).

***Particle Size Analysis* (PSA)**

The samples collected in the study area are unconsolidated loose sands, hence sand size granulometric analysis, following Folk and Ward, 1957 procedures was undertaken. Wet sieving using 63µm aperture sieve was done to separate the mud content which was calculated after drying and weighing of the residues. The > 63µm residues was sieved using a set of Endecott BS410 test sieves arranged in downward decreasing mesh diameter as follows: -1φ; 0φ; 0.8φ; 1.0φ; 2.0φ; 2.5φ; 3.0φ; 4.0φ. The phi (φ) values were obtained based on phi-millimeter conversion of Krumbein (1938) i.e. $\varphi = -\log_2 D$ where D is aperture diameter in mm). The sieves were mechanically vibrated for about 15 minutes using a Ro-tap shaker. The results from sieve analysis enabled the calculation of the statistical mean and, the average grain sizes defined.

Analytical Techniques

The air-dried samples for chemical analysis were pulverized using agate mortar and pestle, and the dried homogenized samples were sieved through 75 mm screen. The pulverized samples were sent to ACME analytical laboratory (now Bureau Veritas Commodities) in Vancouver, Canada, where samples were ignited at 500°C before aqua regia digestion. A 0.25 g split was heated in HNO_3, $HClO_4$ and HF to fuming and taken to dryness, and residue dissolved in HCl. Inductively Coupled Plasma-Emission Spectrometer (ICP-ES: MA300) was employed for trace metal quantification; and report submitted with certificate number VAN 13002288.1.

Assessment of Sediment Contamination

The degree of contamination of sediments by heavy metals could be evaluated by determining the contamination factor (CF), enrichment factor (EF) and geoaccumulation index (Igeo). Consequent upon the non-availability of background values for the study area, the mean concentrations of heavy metals were compared to the upper continental values documented by Taylor and McLennan (1995; 2001). Also, the unit of measurement of concentration was converted to part per million to allow direct comparison of values where necessary.

In order to improve on the determination of heavy metal contamination, sediment quality guidelines (SQGs) has since been developed for use in assessing sediment quality and the average contaminant concentrations that cause adverse effects (Thompson and Wasserman, 2015). The simplistic approach of comparison i.e. threshold effect level (TEL) and probable effect level (PEL) values were used to assess the ecotoxicological potential of heavy metal concentrations in sediments. Also, risk index (RI) was determined because, it has been proven as a highly effective tool for assessment of the extent of sediment contamination in aquatic ecosystem (Lin et al., 2013).

Contamination Factor (CF)

Contamination factor is a single index considered to be an effective tool in monitoring heavy metal contamination in sediments (Hakanson, 1980; Shen et al., 2019). The CF is the ratio obtained by dividing the concentration of each metal in the sediment by the baseline or background value (Syakti *et al*., 2015). Contamination factor is calculated using equation 1.

$$CF = C_s/C_{ref} \quad \text{.....(1)}$$

Where CF is contamination factor, C_s is concentration of element of interest in sample and C_{ref} is the concentration of sample element in reference sample or background value.

The four descriptive categories of sediment quality that CF has distinguished (Hakanson, 1980) are CF < 1 indicates low contamination; 1 < CF < 3 is moderate contamination; 3 < CF < 6 is considerable contamination; and CF > 6 is very high contamination.

***Enrichment Factor* (EF)**

This factor evaluates the normalized concentration of an element of interest with respect to a reference similarly normalized standard. Values are obtained from formula (eq. 2) suggested by Buat-Menard (1979), while classification of values is based on Faiz *et al*. (2009) and Sutherland (2000).

$$EF = \frac{\frac{C_i}{C_{i(s)}}}{\frac{B_i}{B_{ie(Rs)}}} \quad \text{...(2)}$$

Where Ci is the content of element in the sample of interest and Cie is content of immobile element in the sample (S) while Bi is the content of element in the selected reference sample and Bie is content of immobile element in the selected reference sample (RS). In this study, Al was used as the reference element for geochemical normalization, because it represents one of the most important constituents of aluminosilicate mineral fraction. It is the most abundant naturally occurring metal; highly immobile; not affected significantly by diagenetic processes and strong redox effects in sediments; and its content not generally influenced by anthropogenic sources (Charlesworth and Service, 2000; Ho et al., 2012). Consequentially, aluminium was used as the conservative tracer to differentiate natural from anthropogenic activities.

***Geoaccumulation Index* (I_{geo})**

The geoaccumulation index ($_{Igeo}$) has been widely applied to the assessment of sediment contamination (Islam *et al*., 2015). In order to characterize the level of pollution in the sediment, I_{geo} values were calculated using equation 3.

$$I_{geo} = \mathrm{Log}_2[Cn/(1.5bn)] \quad \text{...(3)}$$

C_n is the total content of the individual element n and b_n is its geochemical background concentration, and 1.5 is used because of possible variation in background values for a given metal in the environment, as well as very small anthropogenic influences. The geoaccumulation index was distinguished into seven classes by Muller (1969) as follows: Class 0 (practically uncontaminated): I_{geo} 0; Class 1 (uncontaminated to moderately uncontaminated): 0< I_{geo} < 1; Class 2 (moderately contaminated): 1 < I_{geo} < 2; Class 3 (moderately to heavily contaminated): 2 < I_{geo} < 3; Class 4 (heavily contaminated): 3 < I_{geo} < 4; Class 5 (heavily to extremely contaminated): 4 < I_{geo} < 5; Class 6 (extremely contaminated): 5 > I_{geo} < 6.

Ecological Risk Assessment

***Sediment Quality Guidelines* (SQGs)**

The consensus-based empirical sediment quality guidelines (SQGs) were used to assess the possible risks arising from heavy metal contamination of surface sediments on bottom-dwelling organisms in the study environment. This involved comparison of measured heavy metal concentrations in sediment samples with the consensus based threshold effect level (TEL) and probable effect level (PEL) values.

***Potential Ecological Risk Index* (PERI)**

The potential ecological risk that could be posed by metals in sediments was originally proposed by Hakanson (1980) who suggested the quantitative method using the procedure:

$$RI = \sum E_i$$
$$E_i = Tf_i$$
$$F_i = \frac{C_i}{C_b}$$

RI refers to index of comprehensive potential ecological risk at a sampling point and *Ei* is the monomial potential ecological risk factor for an individual heavy metal. Ti refers to the toxic response coefficient for potentially toxic element (PTE: e.g. As = 10, Cd = 30, Cu = Pb = Ni = 5, and Zn = 1), *Fi* refers to the metal contamination factor, Ci is the measured concentration of heavy metal in the sediment sample, and Cb is the background value of the reference metal. The RI values were categorized as follows: RI<150 indicates low ecological risk, 150=RI<300 indicates moderate ecological risk, 300=RI<600 indicates considerable ecological risk, and RI=600 indicates very high ecological risk for the sediment (Hakanson, 1980). Half the detection limit was used for heavy metals reported below the method detection limit.

Multivariate Statistics

Multivariate analyses including Pearson's correlation and cluster analysis (CA) were assigned to define the source apportionment of heavy metals using Paleontological Statistical Software of Hammer *et al.* (2007). The Pearson's correlation analysis was employed to determine the strength of interrelationship of contamination factors among metals of interest contained in the sediments investigated. Also, it was used to identify the relationship between variations in population of common foraminiferal species and contamination factors of heavy metal(s) of concern in the study area. Cluster analysis was performed using aluminium normalized enrichment factors (EF) to unveil the similarity in pattern of enrichment among the metals investigated. The hierarchical agglomerative cluster analysis was done by adopting the pair group method which considered Euclidean similarity measure.

Results

Water and Sediments' Characteristics

The average depths of 6.95 m (H1, H2, H4 and H5), 4.48 m (H11-H14) and 4.43 m (H3 and H5-H10) were recorded for sediment-water surface at the lower reach near the sea entrance, upper reach and middle reach in relative order (Table 1; Fig. 1). The pH of water which was similar to the average value for coastal waters, fell within a narrow range of 7.79-8.05. Temperature, salinity and dissolved oxygen were within the range of 23.7°C-24.1°C, 33.40 $^{0}/_{00}$ -34.80 $^{0}/_{00}$, and 5.90-6.51 mg/L respectively (Table 1).

Sediments from Lagos harbour were generally fine grained except stations H9 and H14 where medium grain particles predominated. There was prevalence of poorly sorted sand in 64.3 % of the sampled stations; and sediments were mostly fine skewed and more platykurtic than leptokurtic (Table 1). Sand-grade particles made up almost the entire composition of sediments in the study area except sample H6, which was characterized by clayey sand as evident from the ternary plot of sand-silt-clay distribution (Fig. 2). Based on individual particle size frequency plots, 50.0 % (Figs. 3a, 6a, 8a, 9a, 11a, 12a, and 15a); 42.9 % (Figs. 4a, 5a, 7a, 10a, 13a and 14a); and 7.1 % (Fig. 16a) of all samples indicated unimodal, bimodal and polymodal distributions in relative order. On the other hand, the cumulative frequency curves showed that grain sizes were distributed between 2 and 3 subpopulation (Figs. 3b-16b). Some of these subpopulations were not represented at the coarse terminal (Figs. 3b, 6b, 10b, 12b and 13b) rather distributed between the central and right portions. Two phases of transport by saltation (central portion) were noticed in stations H5, H6, H7, H9, H13 and H14. Sediment particles were mostly constituted by the suspension and saltation subpopulation.

Table 1: Water and sediments' characteristics in Lagos Harbour, Southwest Nigeria

S/No	Sample Stations	Depth (m), Sediment-Water Surface	pH	Salinity ($^{0}/_{00}$)	Temperature (^{0}C)	Dissolved Oxygen (mg/L)	Cooordinates Longitudes (East)	Latitudes (North)	Sediments' Description
1	H1	9.6	8.05	34.80	23.8	5.90	3° 24' 4.946"	6° 23' 43.395"	Fine sand, moderately sorted, strongly fine skewed, extremely very leptokurtic
2	H2	5.6	8.05	34.80	24.1	5.91	3° 23' 49.163"	6° 23' 54.905"	Fined sand, poorly sorted, strongly fine skewed, platykurtic
3	H3	4.9	7.99	34.10	23.9	5.91	3° 23' 51.553"	6° 24' 30.801"	Fine sand, moderately sorted, fine skewed, platykurtic
4	H4	5.6	8.05	34.80	23.7	5.89	3° 24' 3.268"	6° 24' 2.850"	Fine sand, moderately sorted, strongly fine skewed, Platykurtic
5	H5	7.0	7.89	34.30	23.8	5.94	3° 24' 2.791"	6° 24' 19.496"	Fine sand, moderately sorted, strongly fine skewed, platykurtic
6	H6	4.6	7.87	34.10	23.8	5.97	3° 23' 55.833"	6° 24' 35.534"	Fine sand, poorly sorted, strongly fine skewed, extremely very leptokurtic
7	H7	4.9	7.80	34.10	23.9	6.00	3° 23' 56.903"	6° 24' 41.907"	Fine sand, poorly sorted, fine skewed, very platykurtic
8	H8	4.2	7.89	34.00	23.8	5.99	3° 24' 12.333"	6° 25' 1.110"	Fine sand, poorly sorted, coarse skewed, platykurtic
9	H9	4.0	7.88	34.00	23.8	6.51	3° 23' 53.953"	6° 24' 49.313"	Medium sand, moderately well sorted, coarse skewed, very leptokurtic
10	H10	4.0	7.86	34.00	23.9	6.49	3° 23' 56.640"	6° 24' 54.836"	Fine sand, poorly sorted, strongly fine skewed, very leptokurtic
11	H11	4.0	7.87	33.90	24.1	6.51	3° 24' 4.596"	6° 25' 25.811"	Fine sand, poorly sorted, fine skewed, leptokurtic
12	H12	4.1	7.79	33.90	24.0	6.51	3° 24' 3.802"	6° 25' 31.130"	Fine sand, poorly sorted, fine skewed, very platykurtic
13	H13	4.9	7.80	33.90	24.0	6.50	3° 24' 6.317"	6° 25' 37.492"	Fine sand, poorly sorted, fine skewed, leptokurtic
14	H14	4.9	8.01	33.40	23.8	6.51	3° 24' 4.480"	6° 25' 42.278"	Medium sand, very poorly sorted, coarse skewed, very platykurtic

Sediment Contamination

The mean concentrations in part per million of heavy metals in sediments of Lagos Harbour were below the background provided for the study except Arsenic (Table 2). Arsenic (As) concentration in all stations was

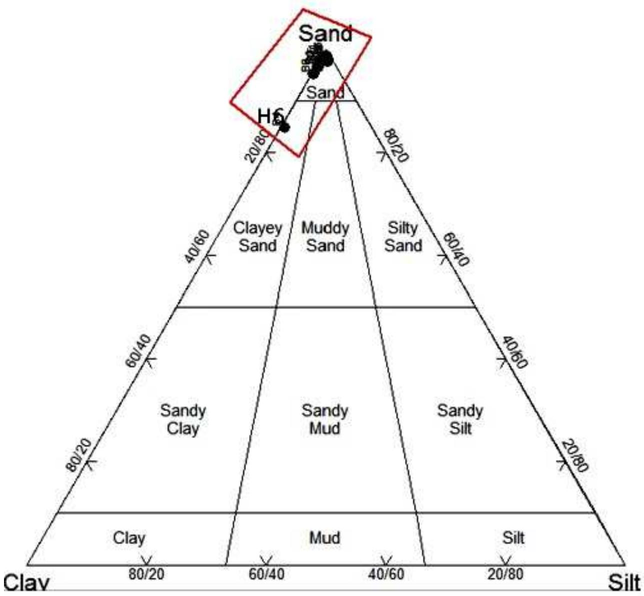


Fig. 2: Ternary plot of Sand-Silt-Clay distribution in sediments of Lagos Harbour, Southwest Nigeria.

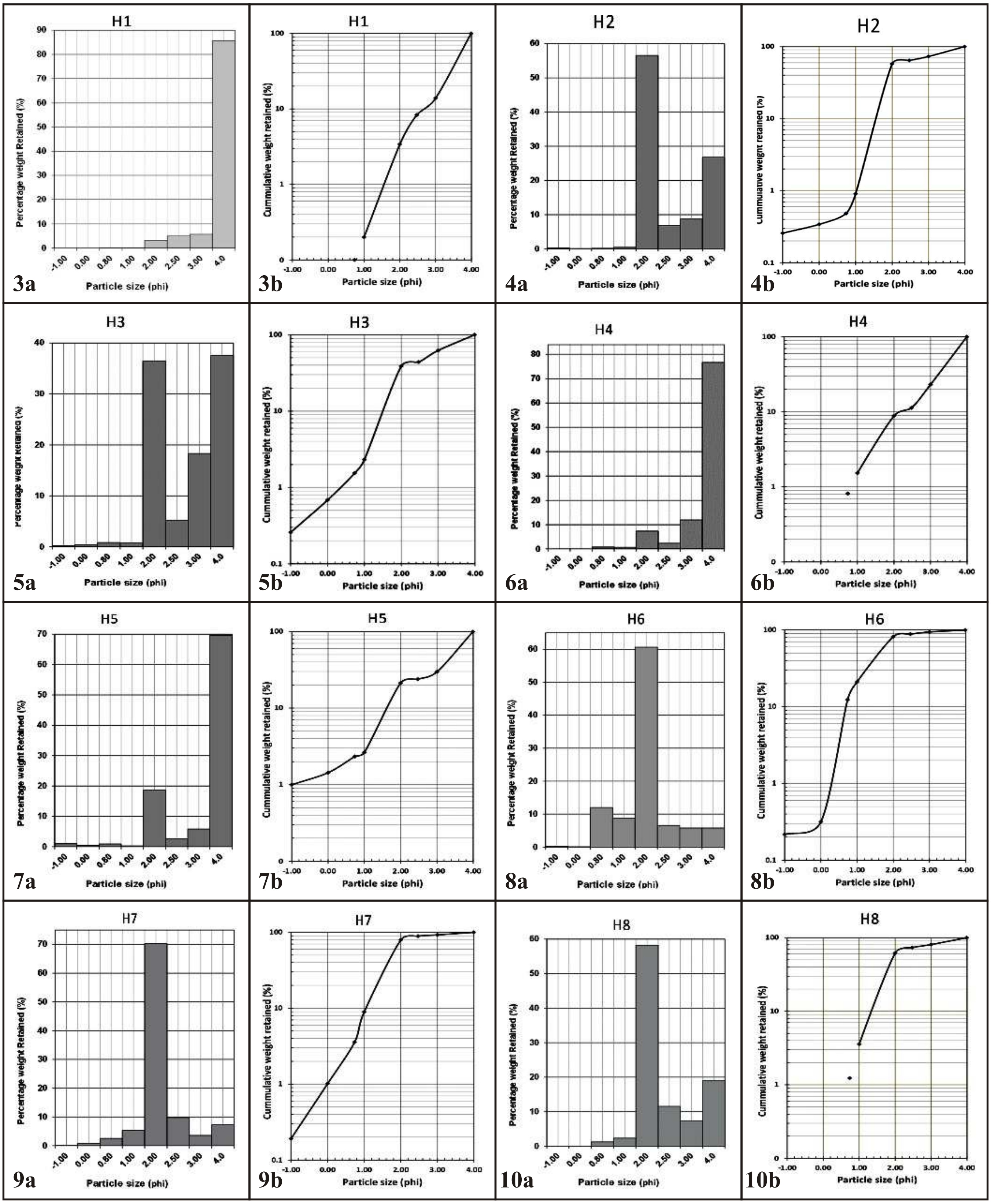
above the available background values; and the average concentration even surpassed the threshold effect concentration (TEL), though, below the probable effect concentration (PEL). Sediments in the study area were characterized by low contamination of Cu (0.04-0.20); Pb (0.09-0.53); Ni (0.09-0.27); and Zn in some places (0.18-0.66) and moderate contamination in few places (1.51-2.01). However, sediments' contamination with As varied from moderate contamination in few places (H11 and H12); considerable contamination in some stations (H1-H5, H10 and H14); and very high contamination in other stations (6.67-10.67). Generally, contamination with Zn was remarkable only at the middle reach (H6-H8) whereas, CF of As is of great environmental concern in the study area (Table 2). High concentrations of Zn in the harbour may have been a contribution from municipal waste water discharges, antifouling paints from boats, or secondary products of petroleum through leakage or during repairs of boats' engines (Phillips et al. 2020). Arsenic may contaminate this environment through wastes of insecticide and herbicide or wood preservatives as it has germicidal power (Nriagu and Azcue, 1990).

The EF of Cu, Pb and Ni showed sediments ranged from class 0 (uncontaminated) to class 3 i.e. significant contamination (Tables 3a and 3b). The EF of Zn varied from class 2 (moderate contamination) to class 5 (extreme contamination), whereas, As defined the sediments as extremely contaminated in all stations except station H11 with significant contamination (Table 3a). The geoaccumulation index for Cu (-5 to -3); Pb (-4 to -2); Ni (-4 to -3) and Zn (-3 to 0) showed that sediments were practically uncontaminated. The calculated Igeo values for Arsenic (As) range from 0-3, i.e. sediments were uncontaminated to extremely contaminated with As in the study area (Table 3a).

The monomial potential ecological risk factor for individual heavy metal *Ei* and potential ecological risk index (PERI or RI) for all stations are displayed in table 4. The average *Ei* for each heavy metal of concern increased in the order of Cu<Ni< Zn<Pb<As (Table 4). This order is directly influenced by the toxic response factor of the individual metal and its concentration in sediments. The risk index varied from 16.8 (station H12) to 111.79 (station H9). The Pearson's correlation based on contamination factors indicated that Cu and Pb (r= 0.3227); Ni and Cu (r= 0.3843); and Ni and Pb (r= 0.4241) had weak positive correlation. Arsenic and Zn (r= 0.8182) showed strong positive correlation, while other metals indicated negative correlation with these metals (Table 5). The resulting dendrogram from pair group cluster analysis which considered Euclidean similarity measure showed outlier of As with high values of contamination factors; one major cluster of Ni, Cu, Pb and Zn; and a minor cluster of Ni and Cu (Fig. 17).

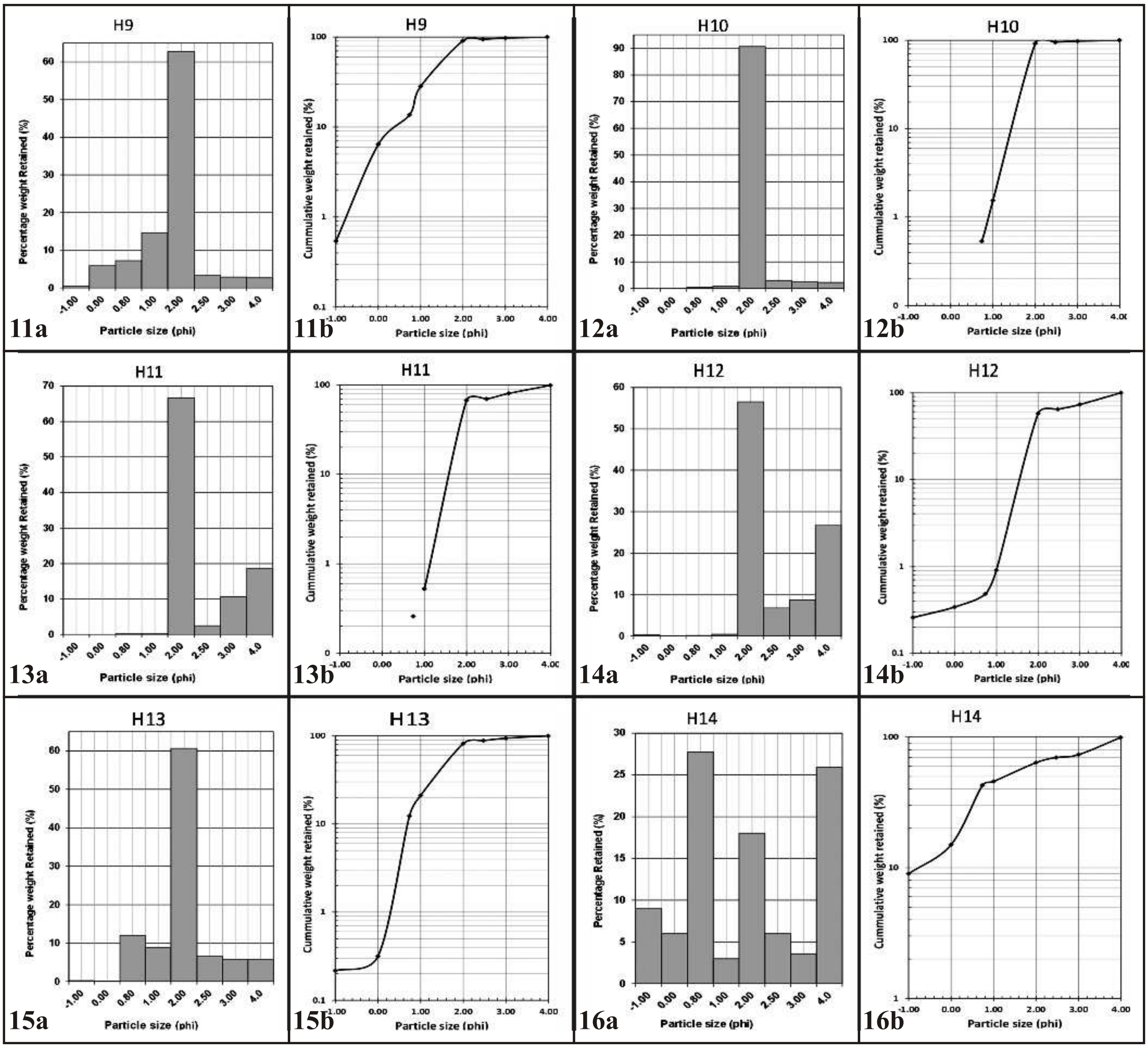
Foraminifera in Sediments

Twenty five benthic foraminiferal species were recovered from the sand enriched Lagos Harbour sediments. Of these species, 69.85 % of the assemblages were dominated by *Hanzawaia boueana* (26.89 %), *Textularia sagittula* (16.87 %), *Florilus atlanticus* (14.25 %) and *Melonis padanum* (11.84 %). There is none of the other species that accounted for 5 % of the total assemblages (Table 6). Only *Textularia sagittula* (94.3 %) and *Poritextularia panamensis* (5.7 %) made the total Textularids in the study area. Consequentially, the characteristic response of the suborder Textulariina was expectedly determined by the behaviour of *Textularia sagittula*. *Hanzawaia boueana* had the greatest relative abundance as it constituted 26.89 % of the total population and was present in 10 out of 12 foraminifera enriched stations (Table 6). Although, *Textularia sagittula* was the second most abundant species across all station, it was the third most frequently recovered species being represented in 9 stations next to *Hanzawaia boueana*. *Melonis padanum* which ranked the fourth most abundant was the most frequently recovered, as the specimens were found in 11 of 12 foraminifera enriched stations. The species with the lowest abundance were *Cribroelphidium*



<u>Note:</u> **Figs. 3a-10a:** The histogram for individual particle-size class distribution in stations of Lagos Harbour.

Figs. 3b-10b: Cumulative frequency curves for particle size distribution in Lagos Harbour.



+Note: Figs. 3a-16a: The histogram for individual particle-size class distribution in stations of Lagos Harbour.

Figs. 3b-16b: Cumulative frequency curves for particle size distribution in Lagos Harbour

semistriatum (0.05 %), *Nodosaria raphanus* (0.12 %), *Nonion depressulum* (0.14 %) and *Amphicoryna scalaris* (0.17 %).

The calcareous hyaline forms (Rotalids) were the most abundant in all the sampled sites and ranged from 40.83-97.05 % (Table 7). Miliolids (4.85 %-38.89 %) and Textularids (0.00-36.75 %) also had significant abundance in all samples except H6, H7 and H9 that were without representative specimens of Textularids. The population density measured as total foraminiferal number per gram of sample analysed for each station ranged from $0.6g^{-1}$-$45.8g^{-1}$ (Table 7). There was no recovery of any agglutinated form, and least foraminiferal population density (0.6 g^{1-}) was recorded where the combined highest contamination of As and second highest contamination of Zn were recorded in the area (Table 7). The highest three values of contamination factors for Zn have corresponding value of zero for the recovery of agglutinated foraminifera (H6, H7 and H9).

In this study, Zn and As were the heavy metals of great concern due to moderate contamination of sediments with Zn in few places; and significant to very high contamination with As in all sampled sites. Consequent

Table 2: Heavy metal concentrations (ppm) and contamination factors (CF) in sediments of Lagos Harbour, southwest Nigeria.

Selected Metals →	Cu		Pb		Zn		Ni		As		Al, %	Fe, %
MDL (ppm) →	1		3		1		1		2		0.01	0.01
Sampled stations	Concentration	CF	Concentration	CF	Concentration	CF	Concentration	CF	Concentration	CF		
H1	3	0.12	9	0.53	24	0.34	11	0.25	6	4.00	0.70	2.43
H2	1	0.04	4	0.24	19	0.27	4	0.09	9	6.00	0.25	0.98
H3	5	0.20	8	0.47	13	0.18	10	0.23	6	4.00	0.25	0.98
H5	5	0.20	8	0.47	17	0.27	8	0.18	6	4.00	0.34	1.02
H6	2	0.08	<3	0.09	143	2.01	9	0.20	11	7.33	0.49	1.88
H7	1	0.04	7	0.41	123	1.73	5	0.11	10	6.67	0.25	1.04
H8	2	0.08	<3	0.09	107	1.51	5	0.11	14	9.33	0.80	2.65
H9	1	0.04	8	0.47	141	1.99	5	0.11	16	10.67	0.34	1.08
H10	2	0.08	4	0.24	47	0.66	5	0.11	6	4.00	0.19	0.87
H11	1	0.04	7	0.41	29	0.41	11	0.25	2	1.33	0.80	2.64
H12	2	0.08	5	0.41	13	0.18	8	0.18	2	1.33	0.16	0.67
H14	2	0.08	5	0.41	13	0.18	12	0.27	6	4.0	0.37	1.55
Average concentration for Study area	2.25		5.67		57.42		7.75		7.83		0.41	1.48
Background values	25[a]		17[a]		71[a]		44[a]		1.5[a]		7.1[b]	4.0[b]
Background (Buchman, 1999)	10-25		4-17		7-38		9.9		1.1		0.26	0.99-1.8
TEL: McDonald *et al.* 1996 (Canadian ISQs and TELs, 2000)	18.7		30.2		124.0		15.9		7.24		-	-
PEL: McDonald *et al.* 1996 (Canadian ISQs and PELs, 2000)	108.0		112.0		271.0		42.0		41.6		-	-

Note: 1. In ppm, Cadmium and Hg are less than the method detection limits (MDLs) of 0.5 and 1 respectively in the study area.
2. [a] Background values (Taylor & McLennan, 1995); [b] Background values (Taylor & McLennan, 2001).

Table 3a: Enrichment factors (EF) and geoaccumulation index (Igeo) of selected metals in sediments of Lagos Harbour, southwest Nigeria.

Selected Metals →	Cu		Pb		Zn		Ni		As	
Sampled Stations	EF	Igeo	EF	Igeo	EF	Igeo	EF	Igeo	EF	Igeo
H1	1.21	-4	5.35	-2	3.43	-2	2.53	-3	40.40	1
H2	1.14	-5	6.86	-3	7.71	-2	2.57	-4	171.40	2
H3	5.71	-3	13.43	-2	5.14	-3	6.57	-3	114.30	1
H5	4.17	-3	9.79	-2	5.63	-2	3.75	-3	83.33	1
H6	1.16	-4	1.30	-4	29.1	0	2.90	-3	106.20	2
H7	1.14	-5	11.71	-2	49.43	0	3.14	-4	190.57	2
H8	0.73	-4	0.82	-4	13.73	0	1.00	-4	84.82	3
H9	0.83	-5	9.79	-2	41.46	0	2.91	-4	222.29	3
H10	2.96	-4	8.89	-3	24.44	-1	4.07	-4	148.10	1
H11	0.37	-5	3.73	-2	3.73	-2	2.27	-3	12.07	0
H12	3.64	-4	18.64	-2	8.18	-3	8.18	-3	60.45	0
H14	1.54	-4	7.88	-2	3.46	-3	5.19	-3	76.92	1

Table 3b: Sutherland's (2000) classification of Enrichment factors

EF values	EF class	Designation of element quality
<1	0	Uncontaminated
1-2	1	Depletion to minimally contaminated
2-5	2	Moderately contaminated
5-20	3	Significantly contaminated
20-40	4	Strongly contaminated
>40	5	Extremely contaminated

upon this, bivariate plots of contamination factors of Zn versus foraminiferal density, As versus density, Zn versus abundance of Textularids, Zn vs Miliolids and Zn vs Rotalids were done. Contamination factors of As were also plotted in the same manner to understand the relationship between foraminiferal distribution and the two heavy metals of great concern (Figs. 18-25). *Textularia sagittula* (94.31 %) and *Poritextularia panamensis* (5.69 %) made up the entire population of the agglutinated forms recovered in the area. Here, the

Table 4: The potential ecological risk indices (RI) of trace metals in surface sediments of Lagos Harbour, Southwest Nigeria

Sampling Stations	Monomial ecological risk factor for individual heavy metal (Ei)					
	Cu	Pb	Zn	Ni	As	Risk Index (RI)
H1	0.60	2.65	0.34	1.25	40.00	44.84
H2	0.20	1.20	0.27	0.45	60.00	62.12
H3	1.00	2.35	0.18	1.15	40.00	44.68
H5	1.00	2.35	0.27	0.90	40.00	44.52
H6	0.40	0.45	2.01	1.00	73.30	77.16
H7	0.20	2.05	1.73	0.55	66.70	71.23
H8	0.40	0.45	1.51	0.55	93.30	96.21
H9	0.20	2.35	1.99	0.55	106.70	111.79
H10	0.40	1.20	0.66	0.55	40.00	42.81
H11	0.20	2.05	0.41	1.25	13.30	17.21
H12	0.40	2.05	0.18	0.90	13.30	16.83
H14	0.40	2.05	0.18	1.35	40.00	43.98

Table 5: Pearson's correlation matrix based on Contamination Factors of heavy metals

Heavy metal	Cu	Pb	Zn	Ni	As
Cu	1				
Pb	0.3227	1			
Zn	-0.4328	-0.4341	1		
Ni	0.3843	0.4241	-0.4742	1	
As	-0.2734	-0.3938	**0.8182**	-0.5920	1

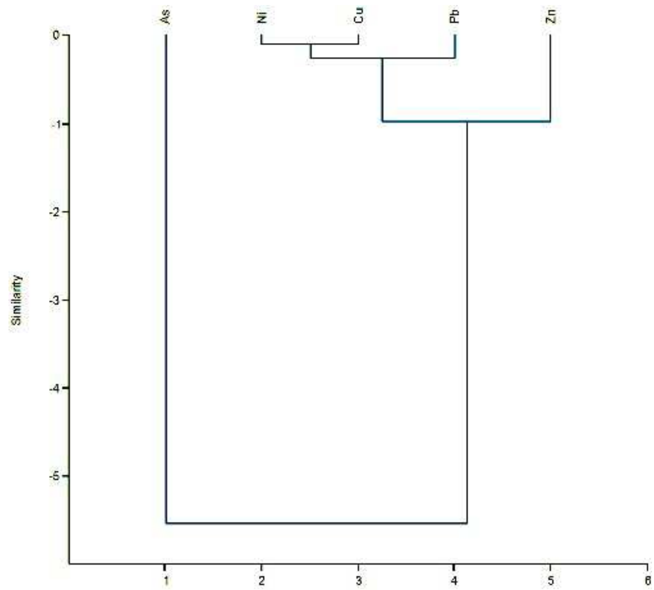


Fig. 17: Dendrogram showing clustering of enrichment factors for the heavy metals in sediments of Lagos Harbour, Southwest Nigeria

characteristic response of textularids to variation in the degree of contamination of As and Zn, could be regarded as same for the largely overwhelming *Textularia sagittula* in the composition of the agglutinated forms. However, the other 3 dominant species were considered for separate plots because of significant species diversity and abundances of other

Table 6: Absolute number and distribution of total benthic foraminiferal species identified in sediments of Lagos harbour, Southwest Nigeria

Species	Sample Stations →											
	H1	H2	H3	H5	H6	H7	H8	H9	H10	H11	H12	H14
Textularia sagittula	179	290	99	510	-	-	30	-	94	47	40	20
Poritextularia panamensis	16	40	14	-	-	-	4	-	-	-	-	5
Tubinella inornata	-	-	-	17	-	-	5	-	41	39	-	-
Amphicoryna scalaris	-	-	-	-	—	-	-	-	-	13	-	-
Sigmoilopsis schlumbergeri	-	-	-	7	1	-	-	-	14	-	-	-
Cruciloculina triangularis	27	11	-	3	3	-	-	-	1	-	1	-
Quinqueloculina vulgaris	6	4	-	26	1	-	7	-	-	-	-	-
Quinqueloculina oblonga	-	45	-	56	-	-	-	-	51	18	14	-
Quinqueloculina padana	26	41	31	13	-	-	42	-	-	-	22	33
Quinqueloculina bicarinata	11	1	-	-	-	-	-	7	11	4	7	5
Quinqueloculina seminulum	38	77	27	91		5	11	-	26	23	16	11
Quinqueloculina sp	-	-	-	90	-	-	22	-	6	22	-	-
Nodosaria raphanus	-	-	-	10	-	-	-	-	-	-	-	-
Cancris auriculus	23	22	-	-	-	-	-	-	8	-	31	-
Eponides cribrorepandus	10	54	23	-	-	-	127	-	1	-	-	114
Nonion depressulum	-	10	-	-	-	-	-	-	-	-	-	-
Zeaflorilus parri	39	-	-	-	-	-	-	-	37	-	-	-
Florilus boueanum	18	43	-	15	-	-	-	-	63	94	100	-
Florilus atlanticus	372	184	48	2	-	35	-	-	79	283	96	-
Melonis padanum	126	223	67	83	11	19	2	-	87	49	221	22
Hanzawaia boueana	293	263	55	434	87	78	19	-	280	403	157	-
Ammonia beccarii	-	21	-	19	-	33	13	11	-	-	-	-
Cribroelphidium decipiens	35	23	3	-	-	-	-	-	23	39	1	-
Cribroelphidium semistriatum	1	3	-	-	-	-	-	-	-	-	-	-
Elphidium advenum	14	-	-	-	-	-	-	-	-	-	17	5
Total foraminifera per 30g of sample	1234	1355	365	1374	103	170	282	18	820	1034	723	215

Table 7: Summary of foraminiferal density, percentage composition of suborders and contamination factors of Zn and As in various stations.

Stations	TFN per gram of sample (g^{-1})	Percentage of Agglutinated forms (Textularids)	Percentage of calcareous Porcellaneous Forms (Miliolids)	Percentage of Calcareous Hyaline forms (Rotalids)	CF for Zn	CF for As
H1	41.1	15.98	8.60	75.43	0.34	4.00
H2	45.1	24.15	13.29	62.56	0.27	6.00
H3	12.2	30.68	15.89	53.42	0.18	4.00
H5	45.8	36.75	22.42	40.83	0.27	4.00
H6	3.4	0	4.85	95.15	2.01	7.33
H7	5.7	0	2.95	97.05	1.73	6.67
H8	9.4	12.41	30.50	57.09	1.51	9.33
H9	0.6	0	38.89	61.11	1.99	10.67
H10	27.3	11.34	18.29	70.37	0.66	4.00
H11	34.5	4.45	10.25	85.30	0.41	1.33
H12	24.1	5.40	8.58	86.03	0.18	1.33
H14	7.2	10.65	23.15	66.20	0.18	4.0

species recorded for the calcareous hyaline forms (Figs. 26-31). Foraminifera density was highest where contamination factors for Zn was lowest (H2 and H5), and lowest population density recorded where the CF was highest (H9 and H8). The same inverse relationship was observed between As and density; Zn and Textularids; As and Textularids; As and Rotalids; Zn and *Melonis padanum*; Zn and *Florilus atlanticus*; As and *Melonis padanum*; As and *Florilus atlanticus*; and As and *Hanzawaia boueana* (Figs. 18-20, 23, 25-27 and 29-31). However, direct relationship was shown in the binary plots of Zn vs Miliolids, Zn vs Rotalids, As vs Miliolids and Zn vs *Hanzawaia boueana* (Figs. 21, 22, 24, and 28). The only four species that constituted above 5 % of the total foraminiferal population in sediments of this harbour are described in figures 32-35.

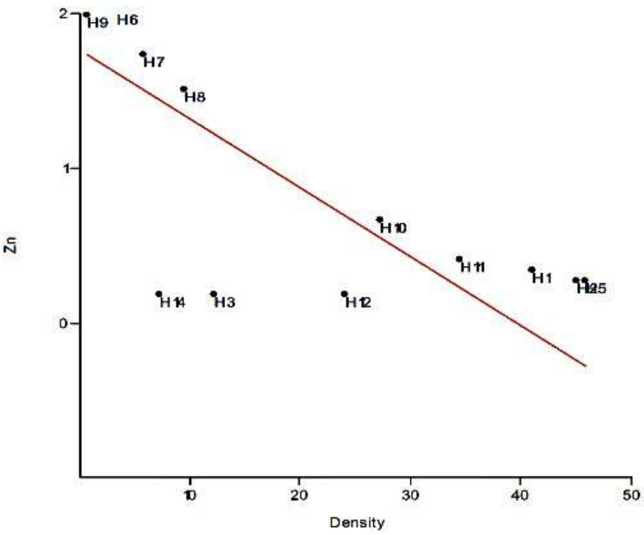


Fig. 18: The bivariate diagram of foraminiferal density versus contamination factor of zinc in various stations

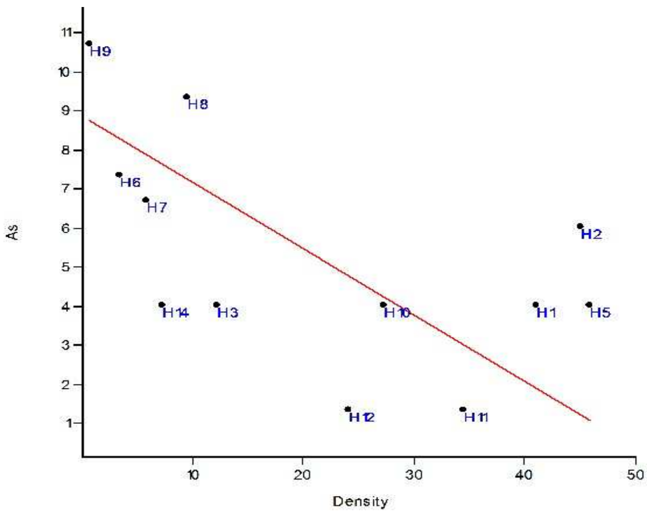


Fig. 19: The bivariate diagram of foraminiferal density versus contamination factor of Arsenic in various stations

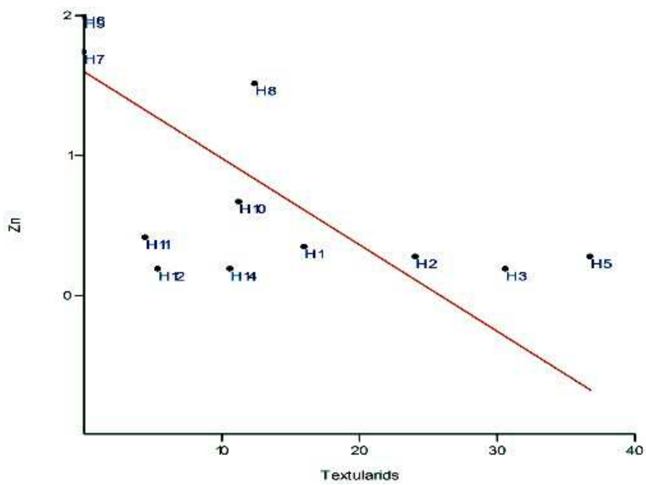


Fig. 20: The bivariate diagram of frequency of abundance of Textularids versus contamination factor of zinc in various stations

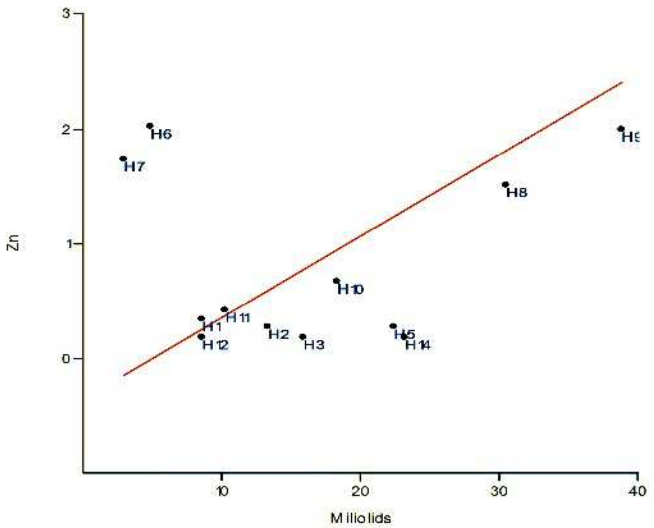


Fig. 21: The bivariate diagram of frequency of abundance of *Miliolids* versus contamination factor of zinc in various stations

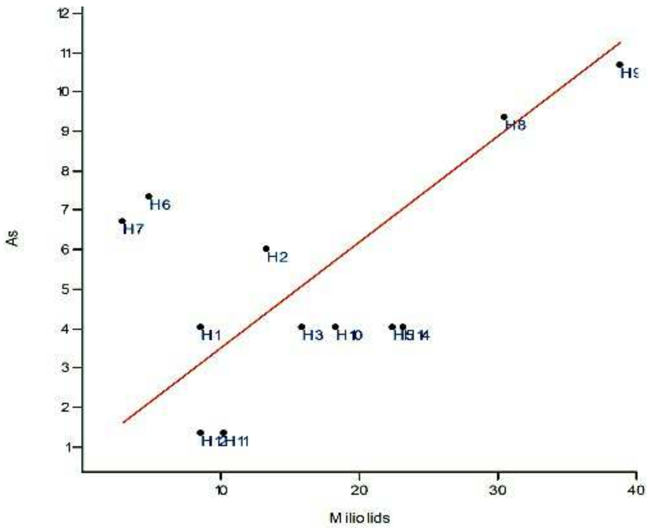


Fig. 24: The bivariate diagram of frequency of abundance of *Miliolids* versus contamination factor of arsenic in various stations

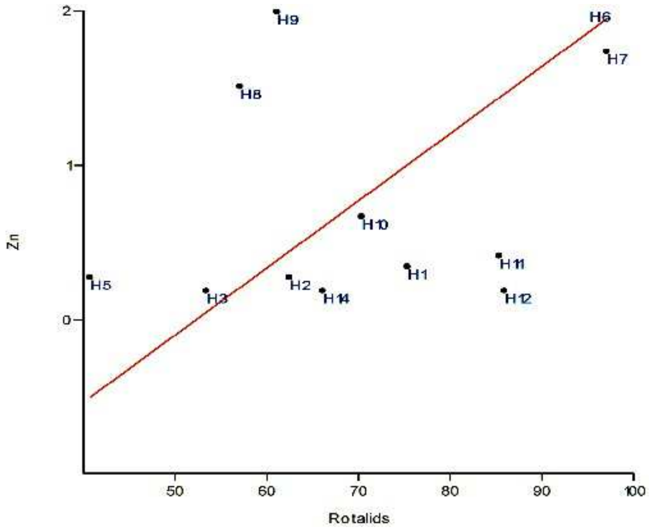


Fig. 22: The bivariate diagram of frequency of abundance of *Rotalids* versus contamination factor of zinc in various stations

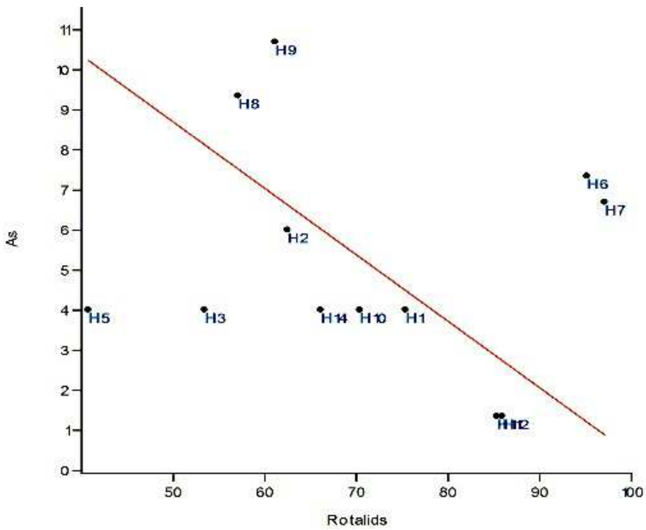


Fig. 25: The bivariate diagram of frequency of abundance of *Rotalids* versus contamination factor of arsenic in various stations

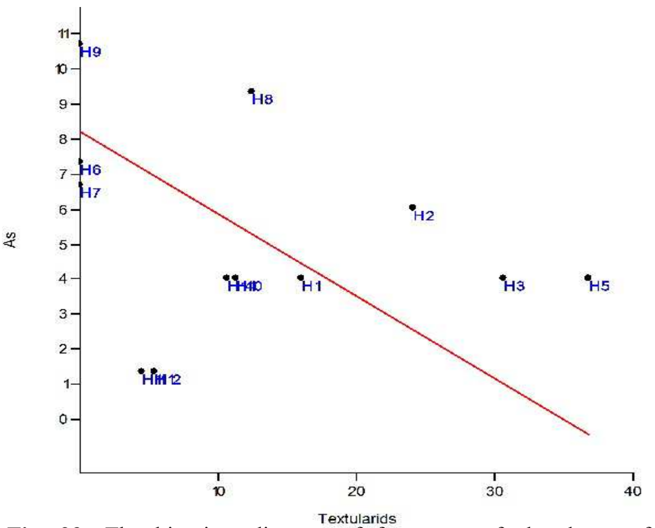


Fig. 23: The bivariate diagram of frequency of abundance of *Textularids* versus contamination factor of arsenic in various stations

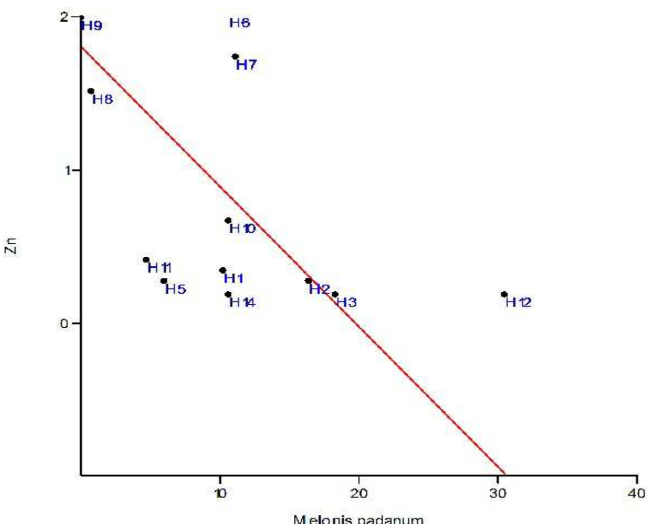


Fig. 26: The bivariate plot of frequency of abundance of *Melonis padanum* against contamination factor of zinc in various stations

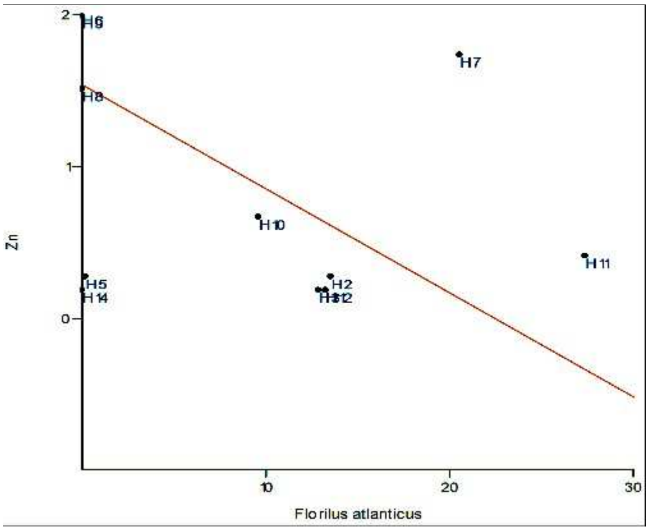


Fig. 27: The bivariate plot of frequency of abundance of *Florilus atlanticus* against contamination factor of zinc in various stations

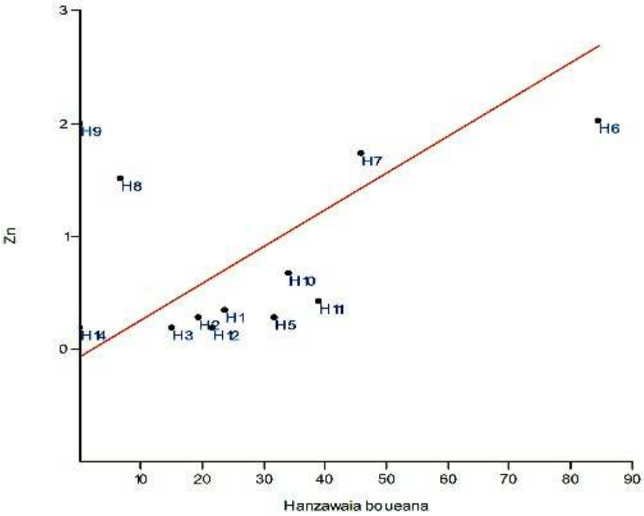


Fig. 28: The bivariate plot of frequency of abundance of *Hanzawaia boueana* against contamination factor of zinc in various stations

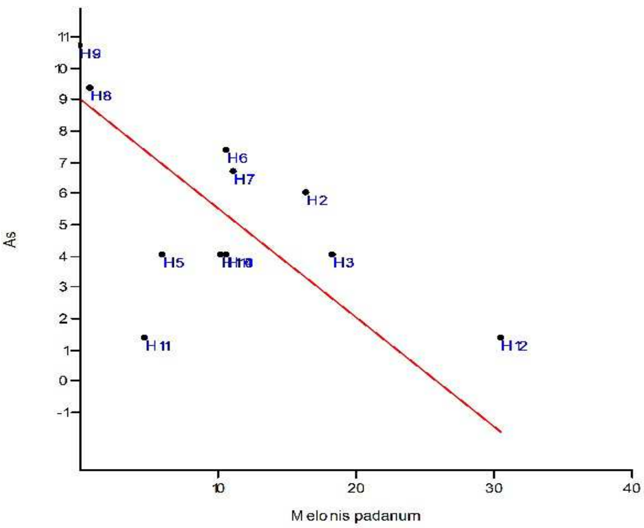


Fig. 29: The bivariate plot of frequency of abundance of *Melonis padanum* against contamination factor of arsenic in various stations

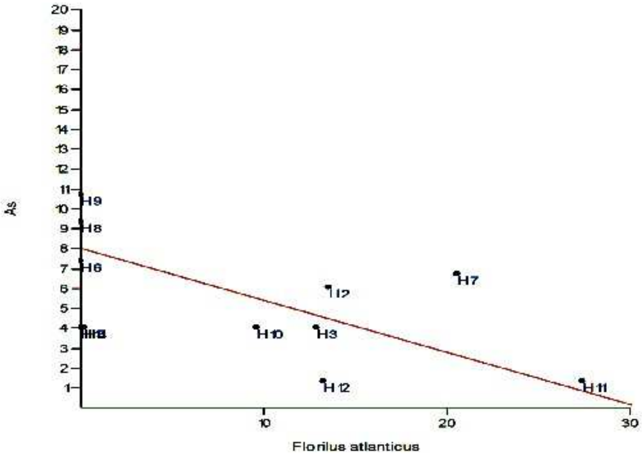


Fig. 30: The bivariate plot of frequency of abundance of *Florilus atlanticus* against contamination factor of arsenic in various stations.

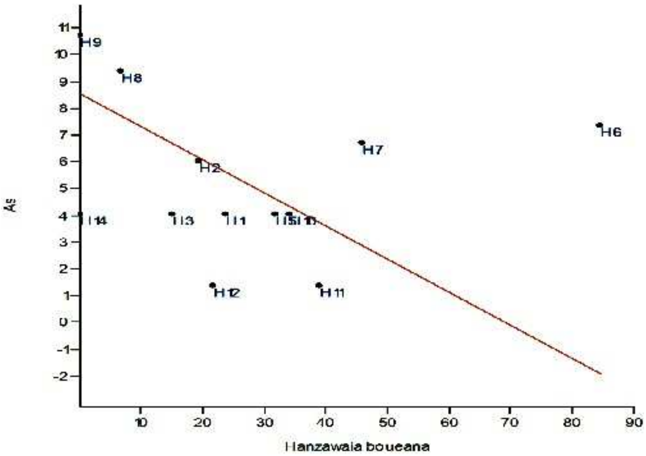
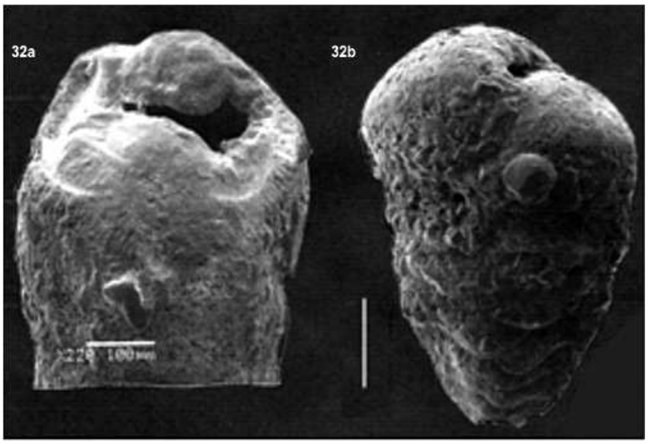


Fig. 31: The bivariate plot of frequency of abundance of *Hanzawaia boueana* against contamination factor of arsenic in various stations



Figs. 32a-b: The scanning electron micrograph (SEM) photographs of *Textularia sagittula*.

Description: a. *Textularia sagittula* (Defrance), apertural view (x 220; scale 100µm), b. lateral view (x 230; scale 100µm). The test is free, wall agglutinated with biserially arranged elongated and conical outline. The aperture is a single, low arch at the base of last chamber. Dimension: 400µm x 300µm at the longer section; 350µm x 300µm at the lower longitudinal section; aperture diameter width 200µm; longitudinal apertural section 12.5µm at one end and 87.5µm at the other end.

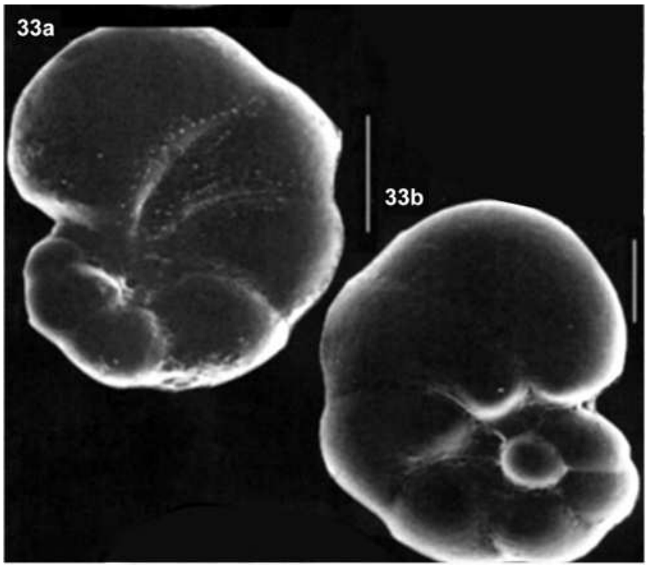


Fig. 33a-b: The scanning electron micrograph (SEM) photographs of *Hanzawaia boueana*

Description: a. *Hanzawaia boueana* (d'Orbigny), ventral view (x 180; scale 100µm), b. dorsal view (x180; scale 100µm). the test is free, planoconvex, few chambers, thickened sutures. The convex side is involute with clear central umbilical boss, the flattened side is partially evolute and aperture is interiomarginal. Dimension 315.4 µm x 292.3 µm.

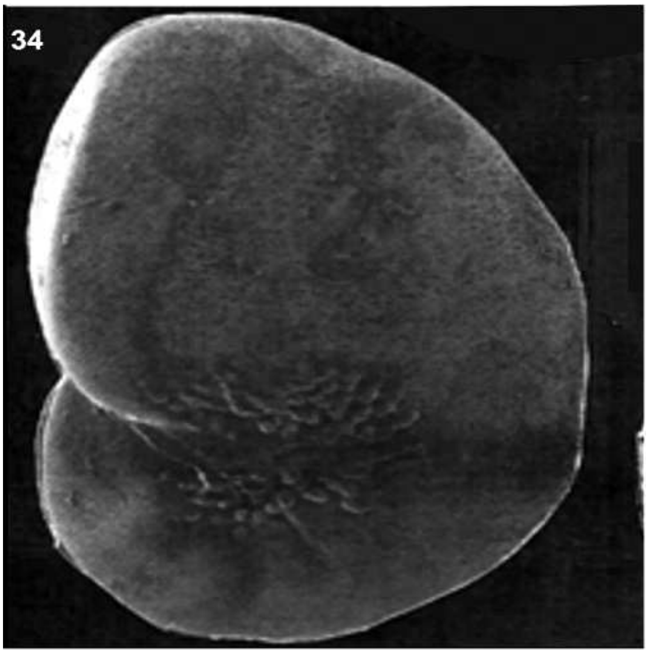


Fig. 34: The scanning electron micrograph (SEM) photograph of *Fluorilus atlanticus*

Description: Florilus atlanticus (d'Orbigny), umbilical view (x 220; scale 100 µm). Test auriculate in outline, six to seven chambers widening rapidly as added, radial sutures, coiling planispiral, interiomarginal aperture. Ventral side is involute with closed umbilicus. The cross section is 600µm x 428µm.

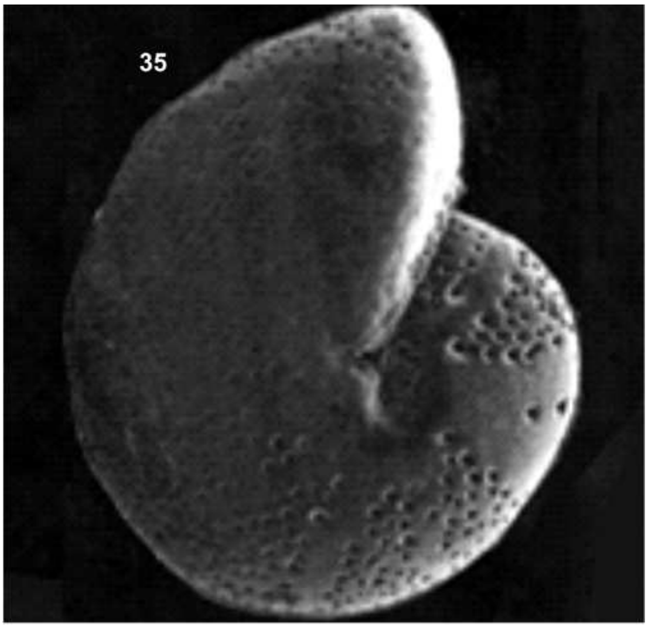


Fig. 35: The scanning electron micrograph (SEM) photograph of *Melonis padanum*.

Description: Melonis padanum (Perconig), dorsal view (x180; scale 100µm). The test is planispiral and symmetrical, involute, biumbilicate, looks robust. The aperture is interiomarginal with an equatorial slit. Specimen's cross-section: 500µm x 650µm; Apertural slit width = 187.5µm.

Discussion

Acidic water containing heavy metals in an aquatic environment seems to be more toxic as it could make these metals to be more available to the biota, whereas, an alkaline condition would make them less available, hence, less toxic (Simpson et al., 2004). For example when pH decreases in sediment, hydrogen ion and the dissolved heavy metals will significantly compete for ligands (e.g. OH^-, CO_3^{2-}, SO_4^{2-}, Cl^-, S^{2-}) and adsorption abilities and availabilities of metals subsequently decrease in sediments (Borma et al., 2003). Consequently, the mobility of these heavy metals increase and the metals are readily available to the aquatic organisms. The pH of an aquatic ecosystem is therefore very important. In this study, the pH measured was similar to that of coastal waters, highly habitable to aquatic organisms (slightly alkaline) and adsorption of metals by sediments may be relatively more than desorption. Generally, physicochemical factors such as temperature, salinity, dissolved oxygen, pH and even turbulence accompanying water column, influence the bioavailability of metals in surface sediments (Christophoridis et al., 2020). The ocean salinity is around 35 $^0/_{00}$ (Antonov et al, 2006), whereas most estuaries are usually between 5 and 30 $^0/_{00}$ depending on whether sea or fluvial influence was more. Salinity is important because various aquatic organisms have specific range they can tolerate before they experience stress (Montagna et al., 2013).The period of sampling for this research was marked dominantly by seawater penetration (transgressive phase) which overwhelmed the influence of the surrounding rivers, fluvial creeks and lagoons. The resulting euhaline condition (salinity: 33.40-34.80 $^{0}/_{00}$) is favourable for habitation by foraminifera. Consequent upon the salinity that characterized this harbour, the comparison of heavy metal concentrations with the standard sediment quality guidelines was done based on values provided for marine environments. The stations near the entrance of the seawater have relatively low concentrations of dissolved oxygen than those with lower salinities at the upper end of the harbour. Meanwhile, there is no significant order of influence of temperature on the DO. However, the average dissolved oxygen in this environment was within the moderate concentrations (5.0-6.6 mg/L) required for warm water biota (Brewer and Rees, 1990). The measured water temperature between 23.7 and 24.1°C was within the permissible limits for aquatic ecology (WHO, 2004).

The sediments were transported mostly as suspended particles from either single source (unimodal) or two sources (bimodal). The only sample showing polymodal peaks (H14) may be due to sediments' transport from Badagry creek on the west, weak tidal current from the south, and Lagos Lagoon through its outlets from Victoria Island and Lagos Island. The two phases of saltation discerned, may be a result of relative reduction in the kinetic energy of transport characterizing the depositing medium. This period could represent a threshold for the onset of transport of the suspension subpopulation by low velocity water current.

The average concentrations of Cu, Pb and Ni in sediments are below the background values presented by Taylor and McLennan (1995; 2001) and Buchman (1999), except Zn and As. Concentrations of heavy metals in sediments may be low and still produce harmful effects on organisms. Such example is found in arsenic, if more than 41.6 ppm (>PEL), it will always produce harmful effects on aquatic organisms (MacDonald et al., 1996), and could even define sediment as heavily polluted when concentration is just above 8 ppm (Pazi, 2011). In this study, 41.7 % of the entire stations have their arsenic concentrations much above the effects range low (ERL) of 8.2 ppm (Grecco et al., 2011; Hu et al., 2013; and Dimitrakakis et al., 2014). This implies that at concentrations above 8.2 ppm small percentage of biota will be affected. The calculated indices of contamination such as CF, EF and Igeo also described such stations as being very high to extremely contaminated with As. It is also interesting to note that, despite the potentially considerable contamination sources in this harbour, sediments were practically uncontaminated with Cu, Pb and Ni in all stations; and Zn in some places. The risk index ranked (RI) highest in sediments from station H9 where the monomial ecological risk factor (Ei) for As was highest. Also, the lowest values of risk index were obtained in stations H11 and H12 with the least Ei for As. This direct relationship implies that toxicity was most influenced by the degree of contamination of arsenic in sediments. As a result of the calculated values of potential ecological risk factor (RI) of < 150, the sediments were classified as having low ecological risk as at the time of this investigation. The resulting agglomerative cluster exhibited arsenic as outlier inferred source activities different from the other heavy metals. Although, Zn is a component of the major cluster (Ni-Cu-Pb-Zn) believed to have been sourced from lithogenic activities, its contribution from anthropogenic sources was also implied by the cluster of As and Zn. The strong positive correlation between As and Zn gave evidence of moderate contamination by Zn in few stations; and moderate to very high contamination in most stations by As. It is widely believed that, strong positive correlation between specific heavy metals in sediments indicate similar trend in degree of contamination, release of contaminants from same source(s) and identical behaviour during transport (Suresh et al., 2012; Jiang et al., 2014). However, dissimilarity arising from non-contamination by Cu, Pb and Ni in all sediments, clarified the negative correlation between this trio and As and Zn. Bamanga et al. (2019) documented that except Cu and Zn which exceeded TEL, concentrations of most metals in Lagos Harbour sediments were below some well documented standard values. Although, this study agrees with the low concentrations of most metals, strong contrasts exist with the concentrations of Cu and As which are below, and in exceedance of, these background values respectively.

Notwithstanding, benthic foraminifera are known to have tolerance limit which is very wide and quite distinct for different species, a threshold exists where they are adversely impacted. Upon this, brackish and hypersaline environments are known to be habitable to only few tolerant species. Usually calcareous porcellaneous forms dominate hypersaline environment, while low salinity conditions favour preponderance of agglutinated foraminifers (Murray, 1973). It has also been set down in writing that sandy environment favours the proliferation of agglutinated forms most especially *Textularia sagittula* (Phillips et al., 2020). In this study, highly significant seawater penetration, moderate concentration of dissolved oxygen, pH, moderately warm temperature and very low turbidity conditions favoured the high species variation identified in some stations. Though, the agglutinated and calcareous porcellaneous forms significantly contributed to the foraminiferal population, the calcareous hyaline forms had the highest population density.

Foraminifera are very sensitive to subtle change in environmental conditions, hence are expected to respond in abundance and distribution to variation in the degree of contamination of Zn and As, which were the heavy metals of concern in the area. Foraminiferal density decreased with increase in the degree of contamination of Zn and As in sediments (Figs. 18 and 19). In spite of their abundance in a favourable fine grained sandy substrate, moderate contamination of Zn above CF > 1.51 in sediments evidently resulted in non-recovery of agglutinated species (Textularids). Generally, stations with CF of Zn > 1 were marked by very low abundance of the agglutinated forms, lending credence to the negative relationship exhibited in figure 20. Meanwhile, moderate contamination of Zn seemed not to influence the abundance and distribution of the calcareous porcellaneous and hyaline forms (Figs. 21 and 22). Although, inverse relationship was exhibited between abundance of textularids and CF of As, the moderate to extremely high contamination of As seemed to produce lesser impact in comparison to Zn. Arsenic contamination shared similarity with Zn, producing insignificant influence in the population of the porcellaneous forms (Miliolids) based on fairly direct relationship between the contamination factors of As and miliolids' abundance. However, the calcareous hyaline forms showed significant response to As contamination as their abundance decreased with increased degree of contamination.

Where there was moderate contamination of Zn (CF > 1 <3), there was either no specimen of *Melonis padanum* recovered (H9) or the least recovery recorded (Fig. 26). Similar relationship was displayed in the bivariate plot of CF of Zn and abundance of *Florilus atlanticus* (Fig. 27), whereas, significant negative influence on the abundance of *Hanzawaia boueana* was not discernible (Fig. 28). On the contrary, *Melonis padanum*, *Florilus atlanticus* and *Hanzawaia boueana* negatively responded to increase in the degree of contamination of arsenic which resulted into attendant decimation of these calcareous hyaline forms (Figs. 29-31). Arising from the spurious impact of Zn (Fig. 20) and As (Fig. 23) contamination, *Textularia sagittula* which constituted over 94 % of the textularids, were implied to be most disadvantaged among the dominant species. Zinc with just moderate contamination was found to be more negatively impactful on species' abundance than arsenic with high to very high contamination in sediments. Consequently, this study has made it obvious that foraminiferal species are more sensitive to zinc contamination than arsenic. This dissimilarity in response of foraminifera to heavy metal contamination was also documented by Price et al. (2019), wherein, Zn was the only heavy metal that produced abundant aberrant test morphologies.

Conclusions

The study agrees with the low concentrations of most metals in literature, but differs in the concentrations of Cu and As which are lower, and much higher than their background values respectively. The mean concentrations of Cu, Pb, Ni and Zn were below the threshold effects level (TEL) and may not always produce harmful effect on the aquatic organisms. Results determined from indices of contamination (CF, EF, Igeo and RI), revealed that sediments were uncontaminated with heavy metals, except, Zn in few segments and As in all segments of the area. The resulting low population density of some species due to moderate contamination by Zn, indicated that their microhabitats are impaired, despite the concentrations being below TEL. Foraminiferal population decreased as the degree of contamination of Zn and As in sediments increased. However, the decimation was highest for the agglutinated forms, for instance, no specimen was recovered where contamination factor for Zn was greater than 1.51, making them the most impacted.

The abundance of calcareous hyaline forms was more negatively influenced by arsenic than zinc contamination, whereas, the agglutinated forms are more impacted by Zn. Nonetheless, As shared similarity with Zn by producing insignificant influence on the abundance of calcareous porcellaneous forms. The four dominant species identified are *Hanzawaia boueana*, *Textularia sgittula*, *Florilus atlanticus* and *Melonis padanum* in decreasing order of abundance. The population of these species decreased as the level of contamination increased in Zn and As, except *Hanzawaia boueana* which showed no significant reduction in their abundance with increasing level of As contamination. Arising from the spurious impact of Zn and As contamination, *Textularia sagittula* which constituted over 94 % of the textularids, were implied to be most disadvantaged among the dominant species. In this study, Zn with moderate contamination was found to be more negatively impactful on species' abundance than arsenic with high to very high contamination. This research also serves as complement to the fact that foraminifera are veritable tool for identifying heavy metal contamination in aquatic environments.

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