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Spatial and Seasonal Studies of Sedimentological and Neoichnological Characteristics from Mangrove areas of Karachi, Pakistan

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Abstract. The purpose of this study is to appraise the physicochemical properties of mangrove sediments and their influence on neoichnological properties produced by different crab species from Korangi Creek (S1) and Sandspit backwater areas (S2 and S3), Karachi. The significant spatial, seasonal and tidal differences ($p < 0.05$) were examined in %moisture, %porosity and sorting coefficient Φ.The significant spatial and seasonal variations were observed in total organic matter, mean Φ, skewness Φ and kurtosis Φ of sediment. Neoichnological properties (burrow number, diameter and total burrow opening area) were observed with significant differences among the macrohabitat (stations) and microhabitat (tidal levels). The correlation analysis indicated that the neoichnological properties are strongly linked with sedimentological properties such as water contents, total organic matter and textural parameters. This study could be employed to distinguish between different paleoenvironmental controlling factors, predicated on similar paleoichnological features made by similar fossil organisms in a mangrove environment.

Keywords: Mangrove sediment, grain size composition, ichnology, Karachi, Pakistan.

Introduction

Mangrove ecosystems are the environment of great complexity and respond actively to coastal processes, transportation of sediment and considered as the best geo-indicators for the recognition of modification in coastal zone dynamics (Morton, 2002; Cunha-Lignon et al., 2009). Sediment analysis provides good quantification for soil sciences and transmits information concerning the weathering, transportation, deposition, sedimentary sources and bio-geochemistry (Kranck and Milligan, 1985; Balagurunathan et al., 2001). The structure of the sediments plays a major role in the distribution of the organisms that live in or on them in the intertidal zone (Barnes and Hughes, 1988; Adakole and Anunne, 2003; Ikomi et al., 2005; George et al., 2010). The diversity of organisms in intertidal areas ranged from bacteria to large, mobile, mega-fauna mainly associated with the sediments. These organisms are also diverse in life style and are directly affected by the intertidal sediment structure (Adekole and Anunne, 2003; Ikomi et al., 2005; Jamabo, 2011).

Crabs are key bioturbators among the macro benthic fauna, therefore, they actively induce significant alterations in their habitat features, i.e. micro topography, sediment chemistry, drainage, reduction processes through their burrowing activities (Teal, 1958; Bertness and Miller, 1984; Warren and Underwood, 1986; Saher and Qureshi, 2010; Rodríguez Tovar et al., 2014). The burrowing activities and the resulting burrow features are affected by a large number of substrate variables, including grain size, pore-water oxygenation conditions, organic matter concentrations, salinity, vegetation cover and sediment stability (Teal, 1958; Warren and Underwood, 1986; Rodríguez-Tovar et al., 2014). Burrows and other traces of fauna have been studied as part of their ecology, auto-ecology, bio-geochemistry, sediment-ology and animal-habitat relationships for investigating species in tidal marine environments (Frey, 1975; Carney, 1981; Unno and Semeniuk, 2008).

Ichnology is the study of animal traces and it has been subdivided into neo ichnology (the study of modern traces and palaeoichnology (the study of fossil traces) (Garrison et al., 2007; Unno and Semeniuk, 2008; Rodríguez-Tovar et al., 2014). Many neoichnological aspects have been successfully applied to trace fossil records, therefore, it is revealed as a useful tool to understand the paleoichnology in different marine habitats (shallow, deep sea and continental margins). These aspects include the influence of ecological variables on trace producers, their interactions between the producer and the biogenic structures, the behavioral studies of trace producers, sedimentological alteration due to bioturbatory processes (Gingras et al., 2002; Rodríguez-Tovar and Delgado, 2006; Wetzel, 2008; Smith and Hasiotis, 2008; Rodríguez-Tovar et al., 2014).

The current study designed (1) to consider the spatial and seasonal variations in the physico chemical properties of mangrove sediments (2) to assess neoichnological properties (burrow number, diameter and the total burrow opening area) produced by different crab species (3) to appraise the interactions concerning sedimentological and neoichnological features from the mangrove areas of Karachi, Pakistan.

Materials and Methods

Site description

The Pakistan coastline extends over 990 kilometers alongwith the Balochistan province in the West and Sindh in the East (Qureshi and Saher, 2012). Two mangrove sites, i.e. Korangi Creek and Sandspit were selected along the Karachi coast (Fig. 1). The first station was located at Korangi Creek mangrove area (24°79' N, 67°20' E) from East of Karachi. It is the furthermost creek situated on the northern side of the Indus delta, adjacent to Ibrahim Hyedri and dominated by mangrove species *Avicennia marina.* At North-East, it is connected to Phitti and Kadiro creeks and at south-west to Gizri creek and the Arabian sea. The second and third station (a distance of 3km) was located in the Sandspit backwater mangrove area (24°50' N, 66°56'E) from the south-west of Karachi. The Sandspit shoreline is separated by a dry stripe of the area, on its northern side mud flats and mangrove vegetation are placed and at southern side the sandy coast is directly connected to the Arabian Sea. The dense vegetation is composed of mangrove species *Avicennia marina*.

Sediment Sampling

The regular monthly sampling was scheduled from March, 2001 to February, 2002 at three selected stations during the low tide time. Two parallel transects (5–10 m) were organized from low (LTL), mid (MTL) and high (HTL) tidal levels. On each transect, 0.25 m^{-2} quadrat was placed at equidistance (5 to 10 m apart) at three tidal levels. Neoichnological properties (burrow density and diameter) were evaluated inside the each quadrat, which were later used to calculate the total burrow opening area. Burrow density was measured by counting the number of all burrows. For determining burrow diameter, approximately all size ranges (small, medium and large) of burrow opening were randomly selected (N=10) and the opening was measured by vernier caliper (correction 0.01 mm). Sediment core (20 cm long) was collected from each level between two transects through PVC core (diameter 5.6 cm) to analyze the structure and composition of sediment.

Fig. 1 Map of study sites along the coastal areas of Pakistan (Google Map).

Laboratory Analysis

Sediment samples were mixed and homogenized and two replicates of 2–5 g of a sample was taken from it and then dried for 24 hours at 70°C in an oven to scrutinize the porosity and moisture. The organic contents were examined gravimetrically after loss on ignition at 450 °C for 4 hours (Saher and Qureshi, 2010; Qureshi and Saher, 2012). Grain size, composition was carried out using the standard dry sieving technique (Folk, 1974). About 100 grams of the sediment was dried at 70°C then was disaggregated and homogenized. The samples were mechanically sorted into a set of US mesh sieves (2.00, 1.00, 0.71, 0.50, 0.35, 0.25, 0.177, 0.125, 0.088, 0.0625 and 0.044 mm) by using a mechanical shaker. Samples were passed through a set of sieves arranged consecutively finer downwards and sieving time standardized 15 min for each sample for sorting of different grain size

Table 1. Seasonal pattern of hydrographic properties among the monitoring areas. Different lowercase and uppercase indicate significant differences (p <0.05) among the seasons and monitoring areas respectively.

Stations	Seasons	Temperature		Salinity		pH	
S1	NEM	$26.00^a \pm 3.94$	A	$39.39^a \pm 2.98$	A	$7.65^a \pm 0.13$	A
	POM	$28.11^a \pm 1.69$		$39.11^a \pm 1.54$		$7.52^a \pm 0.28$	
	PRM	$28.12^a \pm 4.16$		$40.67^a \pm 5.10$		$8.07^a \pm 0.74$	
	SWM	$29.73^a \pm 3.67$		$39.44^a \pm 2.79$		$7.86^a \pm 0.52$	
S2	NEM	$22.08^b \pm 2.72$	A	$39.06^a \pm 1.21$	A	$5.0^b \pm 3.76$	A
	POM	$30.25^a \pm 4.33$		$40.0^a \pm 1.41$		$8.15^a \pm 0.53$	
	PRM	$30.49^a \pm 2.92$		$42.28^a \pm 4.02$		$8.45^a \pm 1.79$	
	SWM	$31.33^a \pm 3.59$		$40.89^a \pm 2.45$		$8.71^a \pm 1.37$	
S3	NEM	$21.92^b \pm 2.37$	A	$39.22^a \pm 1.25$	A	$4.07^b \pm 3.86$	A
	POM	$30.71^a \pm 2.15$		$39.89^a \pm 3.90$		$7.59^a \pm 1.82$	
	PRM	$30.15^a \pm 1.71$		$41.0^a \pm 3.21$		$8.15^a \pm 1.36$	
	SWM	$31.59^a \pm 4.44$		$40.89^a \pm 1.98$		$9.37^a \pm 1.73$	

classes. The sediments retained on each sieve were collected in separate pre-weighed crucibles and the data were used to calculate the heterogeneity (Percent grain size composition) in the samples. According to Wentworth size class, sediments were classified as gravel (G), very coarse sand (VCS), coarse sand (CS), medium sand (MS), fine sand (FS), very fine sand (VFS) and mud (M).

Data Analyses

The textural parameters used to describe a grain size distribution fall into four principal groups: (a) the mean size (b) the spread (sorting) of the sizes around the average (c) the symmetry or preferential spread (skewness) to one side of the average and (d) the degree of concentration of the grains relative to the average (kurtosis). All textural parameters were calculated for each sample by plotting the cumulative percentages of grain size against the equivalent phi values (Folk and Ward, 1957; Folk, 1974; Okeyode and Jibri, 2013). Total burrow opening area ($cm^2\ m^{-2}$) was calculated by following equation (Wang et al., 2009).

$$\text{Total burrow opening area} = \sum N \pi (D / 2)^2$$

Where N is the number of burrows and D is the mean opening diameter of burrows (cm) within the each quadrat.

All variables were tested for the level of significant differences among the stations, seasons and tidal levels by means of analysis of variance (ANOVA). Pearson's correlation matrix has been subjected to correlation analysis for elucidating the relationships between neoichnological properties with sedimentological properties of sediments. The data were statistically analyzed using Minitab (Version 17.0).

Results and Discussion

Hydrological Properties

The variations in temperature, salinity and pH of pit water are shown in Table 1. The temperature ranged from 18.5 to 36.7°C and no seasonal variations were observed at S1. However, a typical decreasing trend was observed in NEM at S2 and S3 (Table 1). The seasonal variations in temperature were quite similar to previous studies from Sandspit and tidal creeks (Sultana and Mustaquim, 2003). The salinity varied from 34.5 to 48‰, having no significant differences among the seasons and tidal variations among the stations. Salinity is directly related to the exposure time of the area between the two tidal cycles, seasonal changes and low tide time in the intertidal areas. The pH ranged from 7.2–8.86, 7.22–12.18 and 3.44–12.48 at S1, S2 and S3 respectively. The neutral to alkaline pH was observed at S1 and showed no significant variations according to seasons. The significant differences (<0.005) were observed at S2 and S3 according to the seasons and acidic pH were observed in NEM at S2 and S3 (Table 1). The present results were also comparable with the previous studies (Sultana and Mustaquim, 2003).

Physical Properties of Sediments

The seasonal pattern of moisture, porosity and organic matter at three stations was presented in Figure 2. The moisture ranged from 13.18–22.60%, 11.73–24.64% and 10.86–40.71% at S1, S2 and S3 respectively. The significant differences were observed in moisture according to stations (F = 13.67; p = 0.000), tidal level (F = 6.12; p = 0.003) and seasons (F = 5.04; p = 0.003). Porosity was observed 46.4±5.1%, 43.01±7.14% and 53.7±14.4% at S1, S2 and S3 respectively (Fig. 2b). The significant differences were observed in porosity according to stations (F = 13.81; p

= 0.000), tidal levels (F = 6.63; p = 0.002) and seasons (F = 5.04; p = 0.003). The porosity and moisture contents were observed highest at the S1 as compared to S2 and S3 due to additional interstitial spaces (porosity) accessible to water and organics in the Korangi Creek area more than Sandspit backwater areas (Figs. 2a, b). Compact soils have low porosity, which may vary due to compaction induced by the hydrodynamic regime (Qureshi and Sultana, 2001) while in unfastened soils with greater organic content, the porosity is usually high (Miller et al., 1990; George et al., 2010).

The total organic matter (TOM) ranged between 1.01–5.87%, 0.87–3.56% and 0.98–3.05% at S1, S2 and S3 respectively (Fig. 2c). According to Marin et al. (2008), TOM ecological quality status is classified into three levels: less than 5% (good), 5 to 10% (moderate) and greater than 10% (bad). TOM content at all stations was within the range and presented good to moderate quality of sediments at S1 and good quality at S2 and S3 in the current study (Fig. 2c). The significant differences were observed according to stations (F = 36.22; p = 0.000) and seasons (F = 6.17; p = 0.001) but not for the tidal levels.

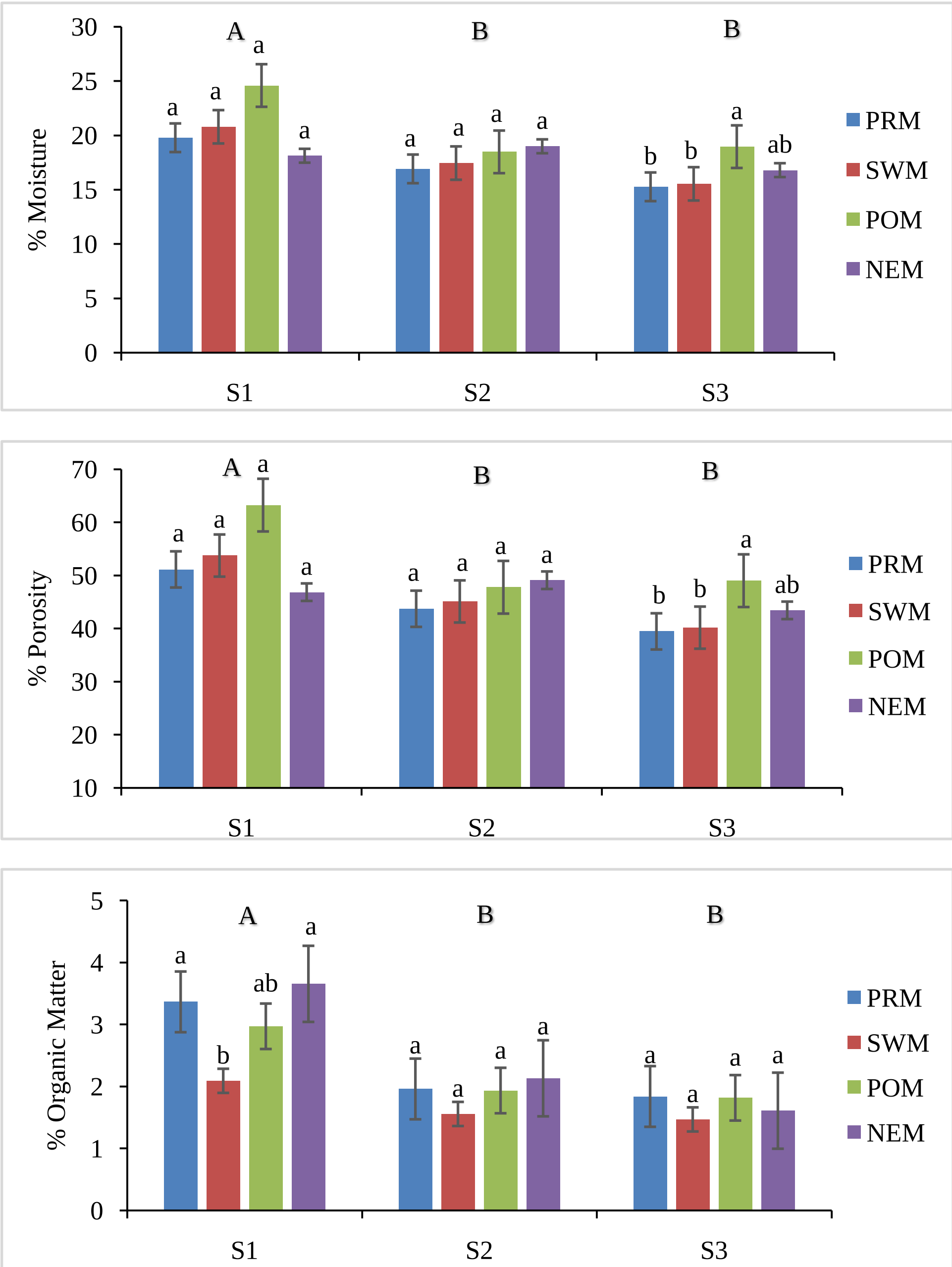

Fig. 2 Seasonal pattern of physical properties of sediment among the monitoring stations. Different lowercase and uppercase indicate significant differences (p < 0.05) among the seasons and stations respectively.

Correlation analysis showed a significant correlation of porosity with moisture (r = 0.928; p <0.001) and TOM (r = 0.194; p <0.05). It has definite ecological significance that a portion of the soil is not occupied or isolated by solid material and it provides a space available for fauna (Qureshi and Sultana, 2001). It is influenced by critical aspects of almost everything (the movement of water, air, and other fluids, the transport and the reaction of chemicals and the residence of roots and other biota) that occur in the soil (Nimmo, 2004).

Grain size Composition

The sediment composition showed different proportions of very coarse sand to silt and clay for study sites (Fig. 3). Sediment particles were dominated by fine sand (43%), medium sand (42%) and coarse sand (47%) at S1, S2 and S3, respectively. The mean percentage of sand was 97.54 ± 0.72, 96.78 ± 1.09 and 98.10 ± 1.01 for S1, S2 and S3 correspondingly. Particle size distribution in S1 was significantly changed as compared to S2 and S3. Fine sand dominated in S1 followed by 19% medium sand and 16% very fine sand (Fig. 2). At S2 medium sand dominated throughout the year, followed by coarse sand (30%) and fine sand (15%), while at S3 coarse sand dominated (47%) followed by 35% medium sand and 8% fine sand. The distinct variation in silt and clay

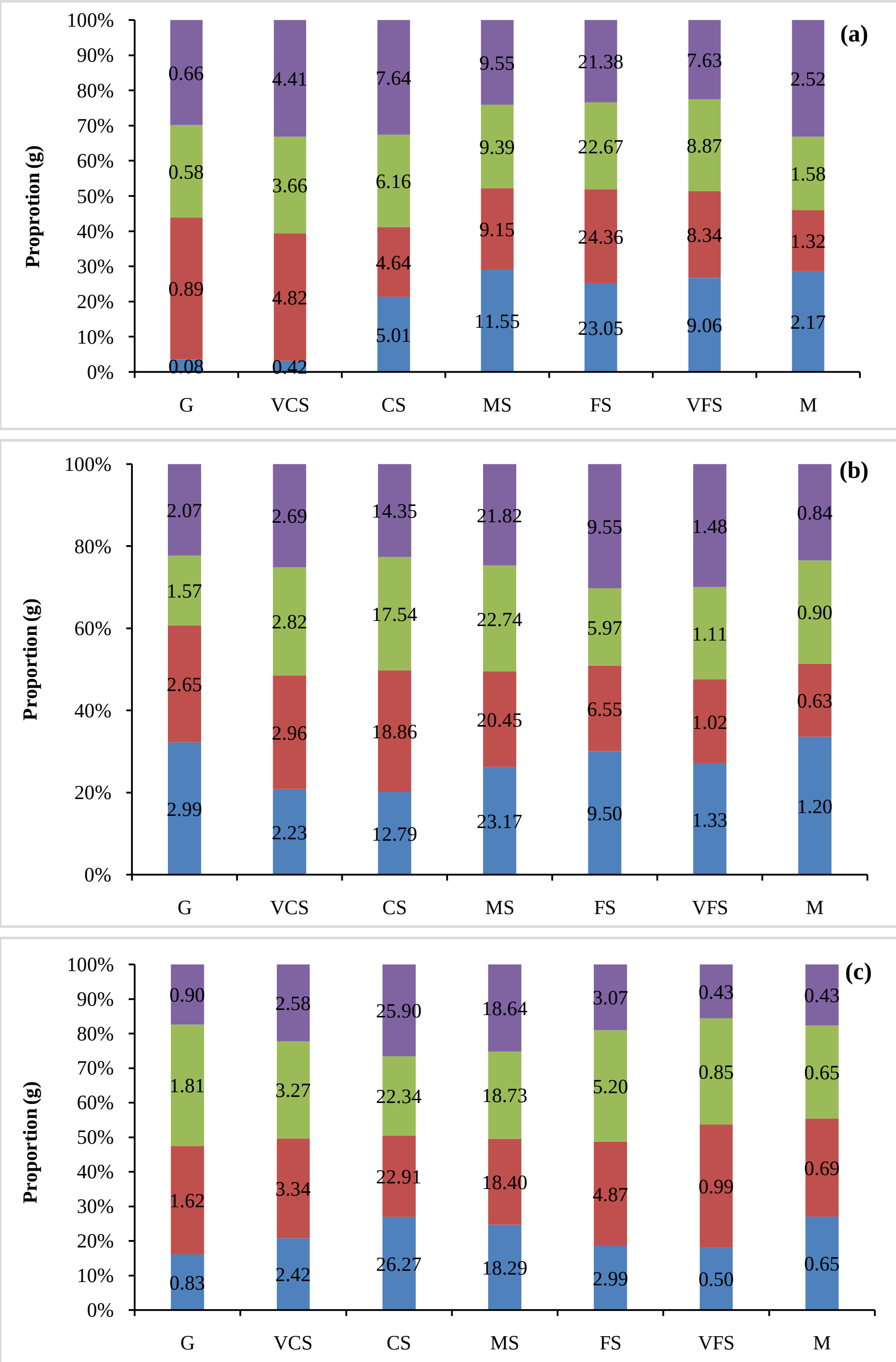

Fig. 3 Seasonal distribution of grain size composition at (a) S1 (b) S2 and (c) S3.

composition was observed for both the sites and extended from 0.27 to 3.13 percent. The highest mean percentage 1.89 ± 0.69 of silt content was recorded for S1, while the lowest value of 0.60 ± 0.25 was obtained for S3.

The high sand percentage could be attributed to tidal influence and wave actions experienced in the intertidal zones and influx of the water from the sea as well. The sediments usually become finer when they deposited under the low energy environment as well as with a decrease in the energy of the transporting medium (Folk, 1974). The sandy substratum usually observed an area of abundance for crabs and their burrowing activities (Warner, 1977; George et al., 2010) as observed during the present study. Sand was observed comparatively higher in PRM and NEM at S3 backwater area, which may be due to the strong wave action. In NEM and PRM, coarse sand affect and alter the distribution pattern of organisms in the intertidal area. Furthermore, distribution of sediments was also influenced by the NEM season, with a stronger wave and wind energy recorded in comparison to other seasons.

Textural Characteristics

Heterogeneity in the sediment structure has been regarded as direct consequence of granulometric properties i.e., mean, sorting, skewness and kurtosis (Table 2).

Graphic Mean (phi Φ)

The mean (Φ) distribution varied from 0.995–2.308 Φ pointed toward the coarse sand to fine sand. Seasonal distribution of mean phi showed the least value (1.99 ± 0.08) in NEM and highest (2.30 ± 0.05) in the PRM

Table 2. Seasonal pattern of textural parameters of mangrove sediment. Different lowercase and uppercase indicate significant differences ($p < 0.05$) among the seasons and monitoring areas, respectively.

Stations	Seasons	Mean		Sorting		Skewness		Kurtosis	
	PRM	2.31[a]		0.99[b]		0.02[a]		1.26[ab]	
		2.25–2.36		0.92–1.08		0.002–0.06		1.15–1.38	
	SWM	2.17[a]		1.14[ab]		-0.16[b]		1.36[a]	
		2.06–2.24		1.07–1.26		-0.26–0.11		1.25–1.42	
S1	POM	2.19[a]	A	1.16[ab]	A	-0.12[b]	C	1.18[ab]	A
		2.16–2.23		1.02–1.13		-0.15–0.09		1.02–1.28	
	NEM	1.99[b]		1.27[a]		-0.18[b]		1.14[ab]	
		1.92–1.08		1.12–1.36		-0.23–0.12		0.97–1.25	
	PRM	1.41[a]		0.82[a]		0.09[a]		0.98[a]	
		1.36–1.45		0.79–0.86		0.08-0.11		0.83-1.08	
	SWM	1.34[a]		0.84[a]		0.09[a]		1.18[a]	
		1.31–1.38		0.71–0.03		0.02–0.15		0.97–1.45	
S2	POM	1.39[a]	B	0.81[a]	B	0.01[a]	B	1.13[a]	A
		1.33–1.45		0.78–0.87		-0.02–0.06		1.09–1.17	
	NEM	1.39[a]		0.82[a]		0.10[a]		1.07[a]	
		1.28–1.45		0.81–0.84		0.09–0.12		1.01–1.18	
	PRM	1.03[a]		0.60[a]		0.22[a]		1.21[a]	
		0.94–1.07		0.57–0.61		0.21–0.23		1.18–1.27	
	SWM	0.99[a]		0.63[a]		0.19[a]		1.31[a]	
		0.98–0.01		0.58–0.68		0.16–0.22		1.17–1.45	
S3	POM	1.01[a]	C	0.61[a]	C	0.24[a]	A	1.26[a]	B
		0.98–0.03		0.60–0.63		0.22–0.27		0.19–1.36	
	NEM	1.02[a]		0.60[a]		0.21[a]		1.22[a]	
		1.02–1.03		0.58–0.63		0.18–0.22		1.18–1.27	

dominated (50%) and the fine sand ratio was observed to decrease at S3, possibly indicating a high tidal influence in monsoon season. According to Yaccob and Mustapa (2010), tides with some degree of current velocity are in the main hydrodynamic factors that indicating medium to fine sand particle distribution at S1, which is located at Korangi creek (Table 2). The highest mean Φ was observed in PRM and lowest in the SWM, which indicated coarse sand to medium sand at S2 and S3, located in the Sandspit backwater area. It showed a significant difference between the stations (F = 894.99; p = 0.000), seasons (F = 4.53; p = 0.005) but not for tidal levels (Table 2). Mean Φ is influenced by the source of supply, transporting medium and the energy conditions of the depositing environment (Folk and Ward 1957; Trivedi et al. 2012). (It indicates that medium sand dominated at Sandspit at the same time as in Korangi creek area, fine sand dominated. The presence of fine sand at Korangi creek area revealed the lower energy environment, whereas medium sand deposits dominated under moderately high energy conditions during the monsoon season at both stations of Sandspit.

Sorting Coefficient (Φ)

Mean spread of sorting coefficient (Φ) was 0.59–1.16 Φ, indicate poorly to moderate well-sorted sediment particles from S1 to S3 (Table 2). It was observed highest in POM and lowest in the PRM which suggested poorly to moderately sorted sediment particles at S1, whereas at S2, it was highest (0.84 ± 0.16) in SWM and was low (0.081 ± 0.04) in the POM indicating the moderately sorted particles. However, sorting coefficient ranged in between 0.59 ± 0.02 to 0.63 ± 0.04 in PRM and SWM respectively at S3 back water areas implying moderately well-sorted sediment particles (Table 2). The significant differences were observed between the stations (F = 202.3; p = 0.000), seasons (F = 3.64; p = 0.015) and levels (F = 6.16; p = 0.003). The sorting coefficient is useful property that gives an indication of the effectiveness of the depositional medium in separating grains of different classes. It measures the organization of sediments and indicates the fluctuations in kinetic energy or velocity conditions of depositing agent (Jol and Smith, 1991; Trivedi et al., 2012). Its variation reflects the continuous addition of fine and coarse materials in various proportions. The poorly sorted sediments can be related to the disturbance of sediments with the season, especially monsoon season, where due to high tidal amplitude, sediments are re-suspended and washed over from the sandy beach and disperse and resettle in the backwaters of mangrove area (Hussain and Samad 1995, Qureshi and Sultana, 2001). However, fine and poorly sorted sediments may be a reason of low energy condition with mild wave action at Korangi Creek area.

Skewness (Φ)

Skewness (Φ) ranged between 0.184–0.241 Φ, which signifies the presence of the particle population from coarse to fine skewed. It was observed from -0.184 ± 0.07 and 0.023 ± 0.06 in NEM and PRM respectively. It is evident from slightly skewed pattern of particles at S1 (Table 1). The skewness was low (0.014 ± 0.14) in POM and was highest (0.103 ± 0.05) in the NEM showing nearly symmetrical skewed to fine skewed at S2, while, the minimum (0.192 ± 0.19) in SWM and maximum (0.241 ± 0.12) in POM is a sign of fine skewed at S3. A significant difference was observed between the sites (F = 115.0; p = 0.000) and seasons (F = 3.97; p = 0.010) but not for tidal levels. Skewness is a reflection of the deposition process and simply a measure of the symmetry of the distribution as well as the sign whether a curve has an asymmetrical tail on the left or right (Folk, 1974; Okeyode and Jibiri 2013). Sandspit areas were positively skewed particles while negatively skewed particles were observed at Korangi Creek. Skewness is useful in environmental diagnosis because it is directly related to the fine and coarse tails of the size distribution and hence suggestive of energy of deposition (Okeyode and Jibiri, 2013). Those with an excess fine material (a tail to the right) have positive skewness and those with an excess coarse material (a tail to the left) have negative skewness (Folk, 1974). Skewness values were noted to decrease as the grain size increased. The negatively skewed areas were probably associated with sediments deposited in an environment dominated by strong current action and might also result from the accumulation of coarse grains in these areas (Buller and McManus 1979; Yacoob and Mustapa, 2010). At Korangi Creek, skewness has negative values, which can be caused by the accumulation of sediment particles.

Kurtosis (Φ)

Kurtosis (Φ) ranged in between 0.983–1.358 Φ showed mesokurtic to a leptokurtic behavior of particle population. It was observed highest (1.13 ± 0.14) in NEM and lowest (1.35 ± 0.09) in the SWM, which suggested the leptokurtic pattern of sediment particles at S1 (Table 2). However, it was observed highest (1.18 ± 0.24 at S2 and 1.30 ± 0.13 at S3) in SWM and lowest (0.98 ± 0.13 at S2 and 1.21 ± 0.05 at S3) in PRM, indicated as mesokurtic to leptokurtic manner at both stations of Sandspit. It showed significant differences between the stations (F = 7.71; p = 0.001) and seasons (F = 3.11; p = 0.030) but not for tidal levels. Variations in kurtosis reveal a consideration of flow characteristics of depositing medium (Kumar et al., 2010). At S1 and S3, a leptokurtic behavior of particles was investigated throughout the year, although from S2 mesokurtic curve was observed during the NEM and PRM. Kurtosis measures the ratio between the sorting in the tails of the curve and the sorting in the central portion. If the central portion is better sorted than tails, the curve is said to be excessively peaked or leptokurtic (Folk, 1974). The sediment samples of the study sites are predominantly leptokurtic, the central portions were better sorted at the tails.

Neoichnological Characteristics

Mean burrow density ranged between 5.5–568.5, 8.50–82.50 and 5.50–68.50 m^2 at S1, S2 and S3 respectively (Fig. 4a). Burrow density showed significant differences among the stations (F = 62.56; p = 0.000) and levels (F = 19.89; p = 0.000) but not for the seasons. The lowest burrow density was observed at high tide level in S2 and highest at low tide level in S1. The average burrow diameter was observed widest (10.68 ± 2.31) at S2 and narrowest (7.73±2.37) at S1 (Fig. 4b) and it showed significant differences among the stations ($F = 23.71$; $p = 0.000$), seasons ($F = 5.53$; $p = 0.001$) and levels ($F = 20.42$; $p = 0.000$). The small sized crab species were recorded (*Ilyoplax frater*, *Opusia indica*, and juveniles of *Macropthalmus dentipes*, *M. depressus*) at low and mid tide level in the S1 (Korangi creek), which were responsible for high burrow density and smaller burrow diameter. However, the S2 and S3 (Sandspit) were dominated by comparatively large sized crabs such as *Uca iranica*, *U. sindensis*, *U. urvillie*, *Macropthalmus depressus*, that is why these areas have low density with wider burrow diameter.

The total burrow opening area ranged between 6.1–401.8, 10.84–126.37 and 4.43–109.73cm^2 m^{-2} at S1, S2 and S3 respectively. The largest range of burrow opening area was recorded at S1 and the smallest observed at S3 (Fig. 4). The burrow opening area showed significant differences among the stations ($F = 47.34$; $p = 0.000$) and levels ($F = 9.48$; $p = 0.000$). In general, small size crabs and juvenile preferred low to mid tide zone, where they easily maintained their burrows. Hence, these areas are characterized by high

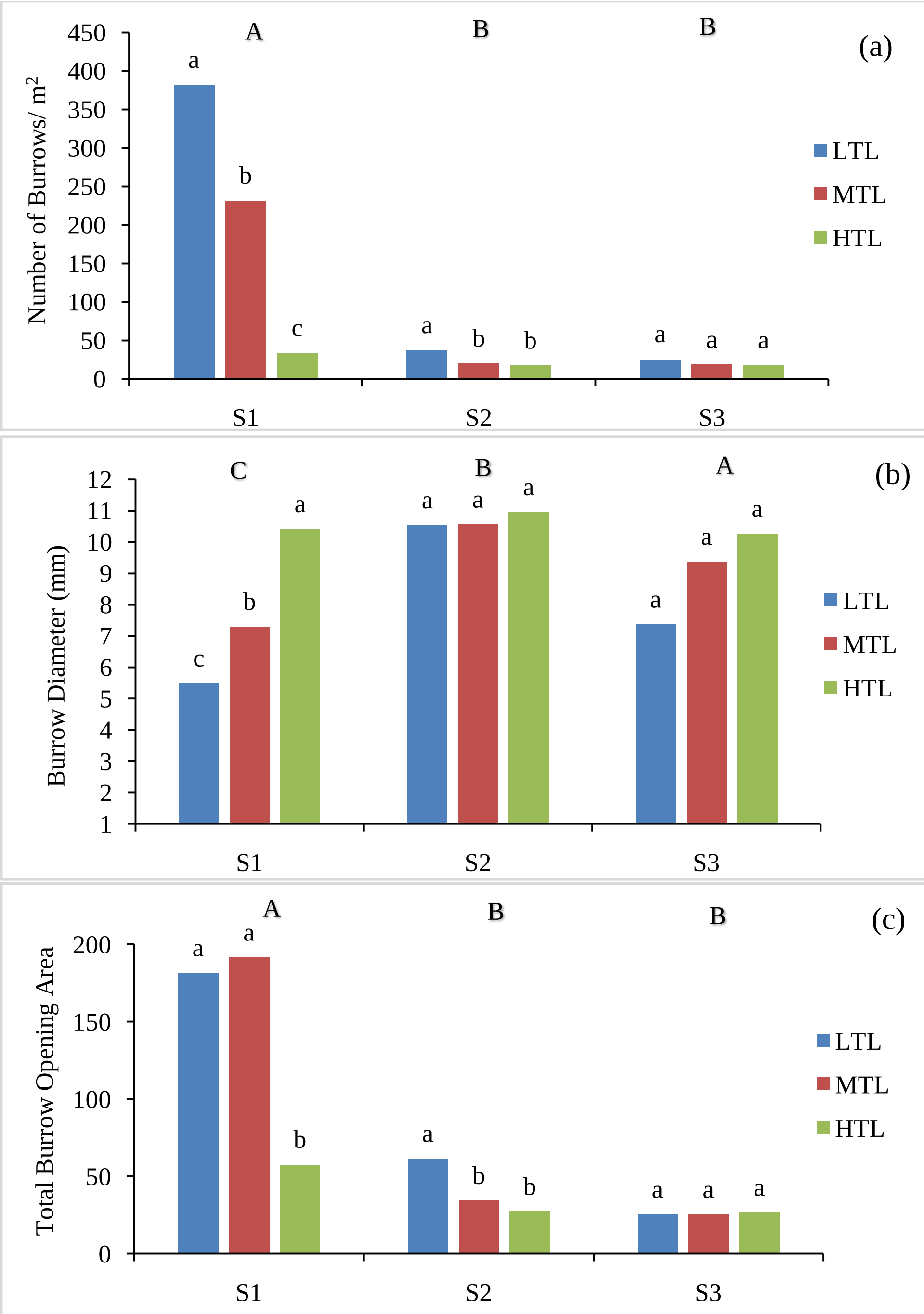

Fig. 4 Tidal variations in neoichnological properties (a) number of burrows/ m^2, (b) burrow diameter and (c) total burrow opening area (cm^2 m^{-2}) among the monitoring stations. Different lowercase and uppercase indicate significant differences ($p < 0.05$) among the tidal levels and stations respectively.

density with small diameter, whereas, high tide levels are characterized by low density with wider diameter.

Relationship between sedimentological and neoichnological properties

The Pearson correlation analysis used to determine the relationship between sedimentological and bioturbatory activities of crabs (Table 3). The ichnological features of crab burrows had no strong relationship with hydrographical properties (temperature and pH) except the total burrow opening area, which was negatively correlated with salinity, suggesting that it may be acting as controlling factor on total area occupied by crab populations. The burrow density and total burrow opening area were positively correlated with porosity, moisture, TOM, mean Φ and sorting Φ (Table 3). However, burrow diameter was showing a negative correlation with the above mentioned properties. The results indicate that crabs selected fine sediments to burrow with good sorting and water content because highly cohesive particles present in fine sediments provide the stability and support to the burrow structures as well as enhance the burrow density. Burrowing activities of crabs depend on the cohesiveness of the substratum, its firmness, the presence of roots, grain-size and moisture content (Bertness and Miller, 1984; Morrisey et al., 1999). Organic matter was correlated with burrow density and area, but showed no correlation with burrow diameter. Environmental conditions (salinity, availability of water and food etc.) affect the physiological activities of crabs and determine their selection of habitats (Ashton *et al*., 2003). Skewness Φ shows negative correlation with burrow density and area, suggesting that crab species may prefer the coarse skewed particles (negative skewed) that was observed at S1 with a high density of crab burrows.

Table 3 Pearson correlation “r” between neoichnological properties with hydrographic and sediment properties.

Variables	Burrow density	Burrow Diameter	Burrow Opening Area
Temperature	-0.037^{ns}	0.013^{ns}	-0.046^{ns}
Salinity	-0.120^{ns}	0.057^{ns}	-0.194*
pH	0.046^{ns}	-0.137^{ns}	0.052^{ns}
%Porosity	0.545***	-0.276*	0.435***
%Moisture	0.505***	-0.291*	0.413***
%Organic matter	0.446***	-0.150^{ns}	0.412***
Mean Φ	0.653***	-0.293*	0.637***
Sorting Φ	0.702***	-0.337***	0.651***
Skewness Φ	-0.446***	0.092^{ns}	-0.485***
Kurtosis Φ	-0.020^{ns}	-0.215*	0.051^{ns}

“***” = $p < 0.001$, “*” = $p < 0.05$ and “ns” = not significant $p > 0.05$

Conclusion

1. The substratum of Korangi creek (S1) dominated by fine sand with poorly sorted grains revealed that the sediments deposited under a low energy environment with somewhat influence of river input. Most of the samples were coarse skewed to nearly symmetrical skewed with leptokurtic behavior.
2. The Sandspit backwater mangrove areas (S2, S3) were dominated by the medium sand with moderately sorted to moderately well-sorted grains, indicating high energy environment during the monsoon season. Most of the samples were nearly symmetrical to fine skewed with leptokurtic behavior.
3. The results of the present study can be applied on paleoichnological and paleoenvironmental records that occupied and dominated by burrowing crab fossils for the identification and interpretation of trace structures in marine environments.
4. The sedimentological properties (such as water and organic supply, sediment texture and grain size) directly impact on neoichnological features of crabs. The results could be applied to differentiate between the different paleoenvironmental limiting factors based on similar paleoichnological features produced by similar fossil organisms in mangrove environment.

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