Evaluation of the edaphic and water properties of Diu coast (Saurashtra, Gujarat, India) in relation to the population density of *Avicennia marina*

Varsha V. Patale1 · Jigna G. Tank1

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Abstract
The Diu Island is the natural habitat dominated by *Avicennia marina* mangrove species in the southeast coast of Saurashtra in Gujarat State of India. Since it is a famous industrial and tourism place, survival of these mangrove species is threatened due to anthropogenic activities. Therefore, to conserve the natural habitat of *Avicennia marina*, it is necessary to evaluate the influence of water quality and edaphic factors on growth of *Avicennia marina* species in this region. In order to study the quality of soil and water, samples were collected from the sediments of five different habitats during each season (summer, winter and monsoon) and physicochemical parameters were measured. The quality of water and soil was influenced by seasonal changes due to change in temperature, pH, macroelements (carbon, oxygen, nitrogen, phosphate, sulfur, potassium, calcium and magnesium) and microelements (zinc, iron, manganese, copper, boron and nickel) content which in turn increases TDS, TSS, TS, alkalinity, COD and BOD of water. These parameters were correlated with the population density of plants growing in the sediments to observe its effect on growth of plants in each habitat. Hence, it was concluded that there was significant influence of seasonal changes on the physicochemical parameters of water and soil which in turn changed the density of plants (site:3 > site:1 > site:2 > site:5 > site:4) at all five sites. Multivariate cluster analysis, MDS and PCA, identified spatial and temporal characteristics of five habitats and suggested that site-4 and site-5 are more polluted as compared to other sites and require restoration and conservation.

Keywords Anthropogenic activities · Heavy metals · Sediments · Mangroves · Conservation · Restoration

Introduction
Mangroves protect the shoreline from erosions caused by wind, water currents, heavy hurricanes and rainstorms. They are referred as shelter providers for fishermen during strong wind and water currents (Das and Crépin 2013; McIvor et al. 2012; Das and Vincent 2009). They are the major producers of intertidal areas and most important carbon sinks in coastal and intertidal regions. They provide shelter and habitat to many marine organisms through slow water flow (Nagelkerken et al. 2008). They enhance sediments deposition and act as sink for variety of heavy trace metals. The removal of mangroves disturbs these underlying sediments and develops trace metal contamination in seawaters (Brander et al. 2012; de Groot et al. 2012; Malik et al. 2015; Cooper et al. 2009; Samonte-Tan et al. 2007; Sathirathai and Barbier 2001). They possess complicated salt filtration mechanism and root system which help them to adapt against salty water wave actions. They can survive in low-oxygen environment of waterlogged soils. The root system of mangroves is efficient in dispersing wave energy (Mazda et al. 1997a, b; Kathiresan and Rajendran 2005; Dadhouh-Guebas et al. 2005). Hence, it is necessary to conserve the natural habitats of mangroves for the socioeconomic security of coastal areas with well-developed and healthy mangrove cover.

The economic resources of mangroves have been studied by various researchers. In past ancient days, mangroves were used in countless ways to support major part of coastal population in all over the world. These ecosystems meet all the basic needs of human beings who used to build their resident of mangrove areas. Nowadays changing structure of human society and increased population density has limited
the use of mangrove resource which changed the pattern of their use according to the need of supplements. A major common use of mangroves was with emphasis on medicinal value (Bandaranayake 1998). The mangrove forests were beneficial to the humans who settle their life nearby seashores. They were used in a very numerous ways directly and indirectly. Various scientists have depicted the utilization of mangroves by human being in the literature (MacNae 1969; Amarasinghe and Balasubramanium 1992; Untawale 1984).

Some of the mangrove species commonly used in ethnobotany are Avicennia alba, Excoecaria agallocha and Ceriops decandra. The traditional uses of mangroves are to capture fishes, medicines, fuel, fodder, tannery, honey collection and other minor ones (Sathe et al. 2012). Soe tribes used R. mucronata fruit as edible as well as to prepare fermented light wine. Sonneratia fruit has been reported to be as edible fruit. Sonneratia fruits have been found in Maharashtra their main use was for fuel, fishery and coastal stabilization. Occasionally they could be used in other ways also. The fire wood could also be collected from area by local people who live near mangrove forests this aspect has been dealt with separately under energy. The wood logs of A. officinalis, R. mucronata and alba could be used for fencing and frames (Sathe et al. 2012). The wood of different species is also used for these craft articles. Members of family Avicenniaceae, Rhizophoraceae, Sonneratiaceae, Malvaceae and Palmae are widely used for craft industries. Wood logs of A. officinalis were reported as used for small cabinet work. The wood trunks of A. marina were reported as used for boat fittings, masts, bedsteads, chairs as well as lime burning. In some other studies it was found that the wood logs of Avicennia were used for poles, fencing and to very limited extent for carpentry; observed in coastal Maharashtra. For this purpose wood from B. gymnorrhiza and R. mucronata also reported for use in same manner. B. gymnorrhiza, R. mucronata and R. mangle wood were widely used for furniture, house posts due to its quality (Burkill 1935).

In India, mangrove forests are present in three union territories and nine states. Among the nine states, Gujarat has the longest coastline with two gulfs out of the three major gulfs of India. The mangrove forests of the Gujarat are represented by 15 mangrove species viz. Avicennia marina, Avicennia officinalis, Avicennia alba, Acanthus ilicifolius, Aegiceras corniculatum, Bruguiera cylindrica, Bruguiera gymnorrhiza, Ceriops tagal, Ceriops decandra, Excoecaria agallocha, Kandelia candel, Lumnitzera racemosa, Rhizophora mucronata, Rhizophora apiculata and Sonneratia apetala. It represents about 97% of the total mangrove cover of the Gujarat State. The three species namely, Bruguiera gymnorrhiza, Lumnitzera racemosa and Kandelia candel are represented by only a single population in South Gujarat. Even though Kachchh has the highest mangrove cover, the highest floristic diversity of mangroves has been reported from South Gujarat region owing to better freshwater inflow. In fact, many mangrove species are found only in South Gujarat region (Singh 2020).

Among the fifteen species of mangroves, Avicennia marina is the most dominant species distributed throughout the coast of Gujarat. They cover the whole Saurashtra coast of Gujarat from Dwarka to Rajula. They are confined to soil flats and creeks present at Dwarka, Diu, Porbandar, Jafarabad, Mahuva, Bhutharai, Pipavavbandar and Narera bet (Bahuguna et al. 2013). Among these places, Diu is a union territory of India, which is situated on an island in the Gulf of Kachhbat of the Arabian Sea in the southeastern Gujarat State. It is located at 20.71˚ N and 70.98˚ E, covering an area of 38.8 km². The climate of this region is extremely warm and humid, with an average annual rainfall of 1500 mm. The coastal wetland of the Diu with numerous creeks and channels is associated with shoals and vast tidal flats have one of the richest zone for mangroves along the west coast of India. The coastal region of Diu is the natural habitat of Avicennia marina in the Gulf of Kachchbat toward the southeastern coast of Saurashtra in Gujarat State of India. Conservation of this natural habitat of Avicennia marina is important as it is the only island dominated by these plants. Avicennia marina species are distributed sparsely in these regions in the form of patches. Since Diu is a famous tourism place and industrial zone of Gujarat, the survival of these mangrove patches is significantly threatened due to anthropogenic activities such as intense deforestation activities, plastic and domestic waste disposal, flow of industrial effluents, fishing activities and construction of tourism sites.

In order to conserve the natural habitat of these species, it is necessary to assess the effect of edaphic and water properties which influence the growth of Avicennia marina species. Soil and water quality provides basic scientific information about spatial quality parameters and ecologically relevant toxicological threshold values. These are important to understand critical physical and chemical parameters influencing the aquatic environment. Physical and chemical variables like temperature, rainfall, pH, salinity, dissolved oxygen and carbon dioxide, concentration of macronutrients and micronutrients, total suspended and dissolved solids, total alkalinity, acidity and heavy metal contaminants are limiting factors for the growth of mangroves (Zhang et al. 2001). The tides in mangrove forest are semi-diurnal and vary in amplitude from about 15–100 cm in different regions, reaching maximum during monsoon and post-monsoon and a minimum during summer. The rise and fall of the tidal water are through a direct connection with the sea and also through the two adjacent estuaries (Kumar and Kumar 2010). Das et al. (2019) studied the physicochemical properties of sediments and water collected from seven sites of mangroves (Poshitra, Khijadiya, Dedeka-Mundeka, Kalubhar, Pirotan, Sikka and Jodiya) in the southern Gulf of Kachchh and determined its
influences on natural regeneration of four species (*Avicennia marina, Ceriops tagal, Aegiceras corniculatum, Rhizophora mucronata*) of mangroves. However, studies on the physicochemical parameters of water and sediments at Diu coast in natural habitat of *Avicennia marina* are not reported till date. Hence, the present studies show the influence of water and sediments quality on growth of *Avicennia marina* and spatial variation in the species density at its natural habitats situated at Diu coast.

**Materials and methods**

**Geographical locations of the study area**

Diu is a union territory of India, which is situated on an island in the Gulf of Kambhat of the Arabian Sea in the southeastern Gujarat State. It is located at 20.71° N and 70.98° E, covering an area of 38.8 km². The climate of this region is extremely warm and humid, with an average annual rainfall of 1500 mm. The coastal wetland of the Diu with numerous creeks and channels is associated with shoals and vast tidal flats have one of the richest zone for mangroves along the west coast of India. Present research work was carried out at the five natural habitats of *Avicennia marina* at the coastal region of Diu. The sites were located at the following geographical locations: (1) site-1 was near Goghala bridge (GPS 20°43′46.66″N 70°59′17.52″E) (2) site-2 was opposite to the Jethibai Bus Station) (GPS 20°43′7.31″N 70°58′52.16″E) (3) site-3 was at Airport road, Diu (GPS 20°42′51.90″N 70°57′28.26″E) (4) site-4 was behind Goa Industrial Development Corporation area (GPS 20°42′57.40″N 70°56′59.87″E) (5) site-5 was near Taad village bridge (GPS 20°44′7.35″N 70°55′48.07″E). These five natural habitats were selected for this research on the basis of the geographical dominance of *Avicennia marina* species, the anthropogenic activities, aggregation of fishing community, industrial activities and sewage pollution in the regions. The site-1 near Goghala bridge was close to the fishing port and fishing activities were observed in the region. The site-2 was opposite to the Jethibai Bus Station where tourist activities were observed. The site-3 was at Airport road where least anthropological activities were observed. The site-4 was behind Goa Industrial Development Corporation area where industrial waste disposal was observed. The site-5 was near Taad village bridge where plastic and domestic waste disposal was observed (Fig. 1).

**Water samples collection and its physico-chemical analysis**

Seawater was collected from five different sampling sites (site 1, 2, 3, 4 and 5) in the plastic sample bottles. Temperature, pH and Electrical Conductivity (EC) were recorded on the site using portable thermometer, pH meter and EC meter. For dissolved oxygen and biological oxygen demand analysis, water was collected from 0.5 m depth in the 125 ml stoppered glass bottles without trapping air bubbles and fixed immediately with manganese chloride (Winkler A) followed by alkaline potassium iodide (Winkler B) solution. Surface water was collected from all the five sites in clean polythene containers, kept in an ice box and transported as early as possible to the laboratory to analyze the physicochemical parameters such as total solids, total dissolved solids, total suspended solids, alkalinity, dissolved oxygen, chemical oxygen demand, biological oxygen demand by following the standard methods described by Baird et al. (2017).

**Determination of alkalinity**

Alkalinity in collected seawater was determined by titrimetric method as per IS 3025-Part 23: 1986 (BIS 2008).

**Soil samples collection from sediments**

Soil samples from the sediments were collected using random sampling method in the plastic samples containers during the low tide. Samples were collected from all the five natural habitats of *Avicennia marina* during each season (summer, winter and monsoon). pH and EC of soil were determined on the site by using portable pH and EC meter.

**Macroelements analysis from water and soil samples**

Total organic carbon, organic matter and nitrogen were measured by following the method described by Jackson (1958). Phosphorus was estimated from water samples by using the method described by Olsen (1954). Calcium (Ca), sodium (Na), potassium (K) and lithium (Li) were estimated from water and soil samples by using flame photometers following the method described by Jackson (1958).

**Microelements and heavy metals analysis from soil samples**

Soil samples were dried in an oven at 70 °C and then grinded using mechanical grinder. The powder of samples was passed through 0.3 mm size sieves. Further dry ash oxidation method was used to digest the powder samples of soil and leaves. The well-grinded dry powder of each sample was filled in crucible of muffle furnish. In Muffle furnish, ash of each sample powder was prepared by incubating the crucible for 5 h. at 550 °C. Then, after cooling ash was dissolved in 5 ml of 25% HCl. The mixture was filtered using acid
wash filter paper and final volume of 50 ml was prepared using distilled water. Concentration of all microelements (Mg, S, B, Fe, Zn, Cu, Mn, Ni) and heavy metals (As, Cd, Cr, Pd, Hg, Se) were determined from this digested sample solution using ICP-MS (ICAP Q Thermo Fisher Scientific, Waltham, MA, USA). Samples were analyzed in triplicate.
using the following operation conditions of instrument:
Power = 1550 W, cool gas flow = 14.1 L/min, nebulizer gas flow = 0.94 L/min, auxiliary gas flow = 0.79 L/min, dwell time = 0.01 s, peristaltic pump speed = 40 rpm, total time for each sample measurement = 3 min.

**Determination of Avicennia marina species density**

Density is an expression of the numerical strength of a species, where the total number of individuals of each species in all the belts is divided by the total number of belts studied (Greig 1964). Density was calculated by the following equation:

\[
\text{Density} = \frac{\text{Total no. of individuals of a species in all belts}}{\text{Total no. of belts studied}}
\]

**Statistical analysis**

Multivariate cluster analysis was performed to construct a dendrogram based on the similarity matrix data using the paired group (UPGMA) method with arithmetic averages and Bray–Curtis similarity index. All the measured parameters were also subjected to Principle component analysis to determine significant relationship of one component with another. Non-metric multidimensional scaling was done to group all the five habitats on the basis of similarity in physicochemical parameters of soil and water. Pearson’s correlation coefficient analyses were done to assess the associations between different parameters. Comparison and similarity groupings of all measured parameters were done by using two-way ANOVA to determine significant variation between means. These analysis were performed using PAST: Palaeontological Statistics software package version 4.05 (Hammer et al. 2001).

**Results**

**Physicochemical analysis of water**

It was observed that there was no significant variation in the temperature of water at all the five habitats of *Avicennia marina* but remarkable influence of seasons on water temperature was observed (Table 1). During summer, temperature remained 32–39.2 °C at all the five sites. During monsoon, temperature remained 28–29 °C and during winter, temperature remained 20 °C at all the five habitats. Among all habitats, site-4 (behind Goa Industrial Development Corporation area) and site-5 (Taad village bridge) had higher temperature as compared to other sites. There was positive correlation of temperature with TSS, TDS and alkalinity as well as TDS and alkalinity with COD during summer season. This suggests that high temperature increases TDS and alkalinity of water which in turn increases chemical oxygen

| Physico-chemical parameters of Water | Site | Season |
|-------------------------------------|------|--------|
| Temperature (°C)                    | df   | F      | P-value | df | F      | P-value |
| pH                                  | 4    | 1.24411 | 0.366052 | 2  | 151.317 | 4.3991E-07 |
| Electrical Conductivity (ms/cm)     | 4    | 4.004504 | 0.045144 | 2  | 1.258733 | 0.334746145 |
| TDS (mg/L)                          | 4    | 3.254584 | 0.072985 | 2  | 0.632382 | 0.55932903 |
| TSS (mg/L)                          | 4    | 1.783149 | 0.225375 | 2  | 5.482791 | 0.031658862 |
| TS (mg/L)                           | 4    | 2.315186 | 0.145175 | 2  | 230.9433 | 8.4021E-08 |
| Alkalinity (mg/L)                   | 4    | 1.778912 | 0.226202 | 2  | 8.517138 | 0.01042845 |
| BOD (mg/L)                          | 4    | 10.44146 | 0.00291  | 2  | 5.045359 | 0.038241666 |
| COD (mg/L)                          | 4    | 0.859149 | 0.52721  | 2  | 1.822792 | 0.22270685 |
| Organic carbon (%)                  | 4    | 0.332561 | 0.848728 | 2  | 3.014881 | 0.105720384 |
| Organic matter (%)                  | 4    | 1.335207 | 0.336378 | 2  | 5.054966 | 0.038079623 |
| Nitrogen (%)                        | 4    | 1.335212 | 0.336376 | 2  | 5.054955 | 0.038079812 |
| Na (mg/L)                           | 4    | 5.463895 | 0.020251 | 2  | 5.781182 | 0.027968854 |
| K (mg/L)                            | 4    | 7.064982 | 0.009756 | 2  | 39.53791 | 7.12475E-05 |
| P (mg/L)                            | 4    | 2.016242 | 0.184983 | 2  | 5.729858 | 0.02856367 |
| Ca (mg/L)                           | 4    | 10.2963  | 0.003044 | 2  | 29.08642 | 0.000213619 |

*P* value highlighted in yellow color indicates significant variation, *P* value highlighted in blue color indicates nonsignificant variation
demand of water. Hence, TDS, alkalinity and COD remained high at site-4 and site-5 as compared to other sites during summer season. There was positive correlation of temperature with biological oxygen demand during winter season but negative correlation during summer season. There was significant variation ($p$ value < 0.01) in TDS, TSS and Total solids (TS) of water at all five habitats of *Avicennia marina* due to seasonal changes. There was remarkably high TDS during summer season at site-4 and site-5 as compared to winter and monsoon. However, TSS was high at site-2 and site-3 during winter season. Total solids were high during summer season at site-4 and site-5 and during winter season at site-2 and site-4. During monsoon season, there was positive correlation of pH and alkalinity with TDS. pH of water at all the five habitats remained basic in range of 7.6–8.6. There was no significant variation ($p$ value > 0.01) in pH of water at all the five habitats and even there was no major influence of seasonal changes on pH of water at the natural habitat of *Avicennia marina*. Lower pH (7.6) was observed at site-2 and higher pH (8.5) was observed at site-4. EC (Electrical Conductivity) of water at all the five sites remained in range of 12.65–33.7 ms/cm. There was significant variation in EC of water at all the five habitats of *Avicennia marina* but it was not influenced by seasonal changes at 0.01 level $p$ value. The highest EC was observed at site-5 and lowest EC was observed at site-3. Alkalinity of water at all the five habitats of *Avicennia marina* remained in range of 80–162 mg/L. There was significant variation ($p$ value < 0.01) in alkalinity of water at all the five habitat but it was not influenced by seasonal changes. Alkalinity of water was high at site-4 and site-5 but low at site-1. There was no significant variation ($p$ value > 0.01) in BOD and COD of water at all the five habitats of *Avicennia marina* and even it was not influenced by seasonal changes. There was no significant variation ($p$ value > 0.01) of organic carbon, organic matter and nitrogen content of water at all the five habitats of *Avicennia marina* due to seasonal changes. There was no significant variation of phosphorus and sodium content of water at all five habitats due to seasonal changes. There was remarkable variation ($p$ value < 0.01) in potassium and calcium content of water at all five habitats due to seasonal changes. Potassium and calcium content were high during summer season and low during monsoon season. Highest potassium and calcium level was observed at site-4 and site-5 whereas lowest was observed at site-2 and site-3 (Fig. 2, Table 1).

**Physicochemical analysis of sediments**

It was observed that there was no significant variation ($p$ > 0.01) in pH of soil at all the five habitats and it was not influenced by seasonal changes. There was no significant variation ($p$ > 0.01) in electrical conductivity of soils at all five habitats of *A. marina* but they were altered by seasonal changes. EC of water was high at all five habitats during summer and low during monsoon season. There was significant variation ($p$ < 0.01) in sodium content of soil at all five habitats and it was also altered by seasonal changes. Highest sodium content was observed at site-4 and site-5 during summer and winter season. Lowest sodium content was observed at site-2 during all the seasons. There was no significant variation ($p$ > 0.01) in calcium content of soil at all five habitat but it was altered by seasonal changes. There was remarkable high calcium content at site-4 and site-5 during summer season and low at site-2 and site-3 during monsoon season. There was significant variation ($p$ < 0.01) in lithium content of soil at all five habitats and it was also altered by seasonal changes. Higher lithium content of soil was observed at site-4 during summer and winter season whereas lower lithium content was observed at site-2 during all seasons. There was significant variation ($p$ < 0.01) in potassium content of soil at five habitats and it was not altered by seasonal changes. Higher potassium content was observed at site-4 and lowest potassium content was observed at site-2. There was no significant variation ($p$ > 0.01) in phosphorus content of soil but it was altered by seasonal changes. Phosphorus content was high during summer season in all five habitats as compared to winter and monsoon season. There was no significant variation ($p$ < 0.01) in organic carbon, organic matter and nitrogen content of soil at all five habitats of *Avicennia marina*.

However, nitrogen content of soil was altered by seasonal changes. Higher nitrogen content was observed during summer season whereas lower nitrogen content was observed during monsoon season. There was significant variation ($p$ < 0.01) in magnesium content of soil at all five habitats but it was not altered by seasonal changes. Higher magnesium content was observed at site-1, -2 and -3 whereas lower magnesium content was observed at site-4 and -5. There was no significant variation ($p$ > 0.01) in organic carbon, organic matter and nitrogen content of soil at all five habitats of *Avicennia marina* during seasonal changes. There was no significant variation ($p$ > 0.01) in iron content of soil at all five habitats but it was altered by seasonal changes. Higher iron content was observed during summer and lower was observed during monsoon season. There was significant variation ($p$ < 0.01) in the sulfur content of soil at all five habitats and it was also altered by seasonal changes. Highest sulfur content was observed at site-4 and site-5 during summer season and lowest content was observed at site-2 and site-3 during winter season. There was no significant variation of manganese content of soil at all the five habitats but its content was altered by seasonal changes. Higher manganese content was observed during summer season as compared to winter and monsoon at all five habitats. There was no significant variation ($p$ > 0.01) in boron, zinc, copper, nickel, chromium, lead and cadmium content of soil at all five habitats.
Fig. 2 Physico-chemical analysis of water samples collected from five different natural habitats of *Avicennia marina*
Fig. 3 Physico-chemical analysis of soil samples collected from five different natural habitats of *Avicennia marina*
all five habitats and it was not altered by seasonal changes. Arsenic, mercury and selenium were not detected at all the five habitats of *Avicennia marina* for all the three seasons (Fig. 3, Table 2).

**Table 2** The ANOVA table of physicochemical parameters measured from waterlogged soil collected from five habitats of *Avicennia marina* at Diu coast

| Physico-chemical parameters of Water-logged soil | Site | Season |
|-----------------------------------------------|------|--------|
| | df | F | P-value | df | F | P-value |
| pH | 4 | 4 | 0.045267 | 2 | 1.084746 | 0.382968 |
| Electrical Conductivity (ms/cm) | 4 | 5.487192 | 0.020017 | 2 | 55.57 | 2.61E-09 |
| Na (mg/L) | 4 | 25.16348 | 0.000138 | 2 | 21.31306 | 0.000624 |
| Ca (mg/L) | 4 | 4.002145 | 0.045209 | 2 | 8.198784 | 0.01156 |
| Li (mg/L) | 4 | 25.63901 | 0.000129 | 2 | 11.71749 | 0.004195 |
| K (mg/L) | 4 | 21.48387 | 0.000245 | 2 | 3.184751 | 0.096071 |
| P (mg/L) | 4 | 0.956582 | 0.480382 | 2 | 2.248447 | 0.167939 |
| OC (%) | 4 | 0.923714 | 0.495689 | 2 | 14.91554 | 0.002 |
| OM (%) | 4 | 0.967596 | 0.475361 | 2 | 14.15387 | 0.002357 |
| N (%) | 4 | 0.925478 | 0.494855 | 2 | 15.04295 | 0.001947 |
| Mg (mg/L) | 4 | 6.343051 | 0.013345 | 2 | 4.979667 | 0.039373 |
| Fe (mg/L) | 4 | 1.13603 | 0.494855 | 2 | 19.45869 | 0.001947 |
| S (mg/L) | 4 | 137.6027 | 2.08E-07 | 2 | 174.3562 | 2.53E-07 |
| Bo (mg/L) | 4 | 1.265348 | 0.358879 | 2 | 2.202277 | 0.172996 |
| Zn (mg/L) | 4 | 0.486407 | 0.746212 | 2 | 1.253653 | 0.336043 |
| Mn (mg/L) | 4 | 2.131282 | 0.16827 | 2 | 53.08169 | 2.41E-05 |
| Cu (mg/L) | 4 | 3.046612 | 0.084233 | 2 | 4.873277 | 0.041296 |
| Ni (mg/L) | 4 | 0.182553 | 0.941026 | 2 | 2.25391 | 0.167353 |
| Cd (mg/L) | 4 | 1.182981 | 0.387611 | 2 | 2.226158 | 0.170357 |
| Cr (mg/L) | 4 | 0.650019 | 0.64275 | 2 | 5.024431 | 0.038598 |
| Pb (mg/L) | 4 | 0.508627 | 0.731636 | 2 | 0.022211 | 0.978094 |

*P* value highlighted in yellow color indicates significant variation, *P* value highlighted in blue color indicates nonsignificant variation

**Spatial variation in the species density of *Avicennia marina***

The density of plants at all the five habitats was in the following order: site-3 > site-1 > site-2 > site-5 > site-4. The density of plants during summer was high as compared...
to monsoon and winter season. The change in density of Avicennia marina plants at all the five habitats was due to the significant variation ($p < 0.01$) in the physicochemical parameters of water and soil. There was no significant variation ($p > 0.01$) in pH, EC, TSS, TDS, BOD, COD, OC, OM, N, Na and P content of water. However, there was significant variation ($p < 0.01$) in alkalinity, K, Ca content in water samples. Alkalinity, potassium and calcium content were high at site-4 and site-5 as compared to other sites which affected the growth of plants at these habitats. There was no significant variation in pH, EC, Ca, P, OC, OM, N, Fe, Br, Zn, Mn, Cu, Ni, Cd, Cr and Pb content in soil collected from all the five habitats. However, there was significant variation in Na, Li, K, Mg and sulfur S content of soil. Sodium, potassium, Lithium and sulfur were high at site-4 and site-5 which affected the physiological growth of plants whereas Magnesium was high at site-1, site-2 and site-3 which promoted the growth of plants. With respect to seasonal (summer, winter and monsoon) changes, there was significant variation in temperature, TSS, potassium and calcium content in water. Even, there was significant variation in physicochemical parameters of soil such as EC, Na, Ca, Li, OC, OM, N, Fe, S and Mn. However, there was no significant influence of seasonal changes on parameters such as pH, K, P, Mg, Br, Zn, Cu, Ni, Cd, Cr and Pb. The EC, Na, Ca, Li, OC, OM, N, Fe, S and Mn remained high at site-4 and site-5 as compared to other sites during summer season which reduced the growth of plants in these habitats. During summer season density of plants was high at site-1 and site-3 as compared to site-2, site-4 and site-5 is due to the positive correlation of density with high temperature, low TSS, low TDS, low alkalinity, low COD, low Na, low K, Low Ca and high phosphorus content of water and soil. The density of plants during monsoon season was high at site-1, site-2 and site-3 was due to the positive correlation of density with low TDS of water, low alkalinity of water and high phosphorus content of soil. The density of plants during winter season was low at site-4 and site-5 was due to the positive correlation of density with high TDS of water and low phosphorus and manganese content in soil (Table 3, Supplementary Tables 4, 5, 6, 7, 8 & 9).

### Multivariate statistical analysis of edaphic and water quality at five habitats of Avicennia marina

Multivariate cluster analysis was used to detect the similarity between the five habitats during three seasons. Cluster analysis grouped the five habitats in to three groups on the basis of its physicochemical characteristics of water during three seasons. Group A included site-2, group B included site-1 and site-3, and group C included site-4 and site-5 (Figs. 4, 5). Group A corresponds to low EC, TS, alkalinity, OC, OM, K, Ca and Na as compared to group B and group C which suggests low pollution in group A, moderate pollution in group B and high pollution in group C. Similar clusters were also formed by non-metric multi-dimensional scaling (MDS) (Fig. 8) which supported the

Table 3 The ANOVA table of density of plants available during different seasons at five natural habitats of Avicennia marina at Diu coast

| Source of Variation | SS       | df | MS          | F         | P-value   | F crit  |
|---------------------|----------|----|-------------|-----------|-----------|---------|
| Site                | 1672.191 | 4  | 418.0478    | 15.06112  | 0.000856  | 7.006077|
| Season              | 5826.099 | 2  | 2913.05     | 104.9492  | 1.82E-06  | 8.649111|
| Error               | 222.054  | 8  | 27.75675    |           |           |         |
| Total               | 7720.344 | 14 |             |           |           |         |

*P* value highlighted in yellow color indicates significant variation in density of plants at all five natural habitats and also during different seasons.
The first two principle components explained 60.861% and 38.726% of variance in the water properties, respectively. However, third and fourth principle component explained only 0.27573 and 0.13721% of the variance, respectively. This suggests that cluster A which includes site-2 has less polluted water, cluster B which includes site-3 and site-1 has moderately polluted water and cluster 3 which includes site-4 and site-5 has highly polluted water (Fig. 6). On the basis of physicochemical characteristics of soil during three seasons, cluster analysis grouped the five habitats in to three groups. Group A included site-2, group B included site-3 and group C included site-1, site-4 and site-5 (Fig. 5). Group A corresponds to low Ca, Li, Na, K as compared to group B and group C which suggests low soil pollution in group A, moderate soil pollution in group B and high soil pollution in group C. Similar clusters were also formed by non-metric multidimensional scaling (MDS) (Fig. 9) which supported the results of multivariate cluster analysis. From the Principle component analysis, it was observed that 100% total variations were retained on the basis of the eigenvalue greater than one rule. The first two principle components explained 59.998% and 38.32% of variance in the soil properties, respectively. However, third and fourth principle component explained only 1.114% and 0.567% of the variance, respectively. This suggests that cluster A which includes site-2 has less polluted soil, cluster B which includes site-3 has moderately polluted soil and cluster 3 which includes site-1, site-4 and site-5 has highly polluted soil (Fig. 7).
Discussion

Water temperature is the most important limiting factor for the sustenance of aquatic flora and fauna in coastal regions (Bindoff et al. 2019). It regulates the biological activities such as photosynthetic rates, physiological metabolism, growth and reproduction of plants (Hossain et al. 2007; Shah et al. 2008). In present studies, there was no significant variation ($p > 0.01$) in temperature of water at all the five habitats of *Avicennia marina* at Diu coast but it was significantly ($p < 0.01$) influenced by seasonal changes. The high temperature during summer season was due to hot air and high evaporation level through solar radiation (Satpathy and Nair 1990; Richardson et al. 2000; Ashok Prabu et al. 2008). There was no significant variation in pH of water (7.6–8.5) and soil (8–8.5) at all the five habitats and it was not much influenced by seasonal changes. The basic pH observed during summer season might be due to the penetration of seawater and high biological activity (Saravanakumar et al. 2008). Even Ramanathan et al. (1999) observed the pH range of 7.71–7.82 while working on Pichavaram mangroves. Even Prabhu et al. (2008) reported the pH range of 7.2–8.2 at natural habitat of Pichavaram mangroves. There was no significant variation in electrical conductivity (EC) of water and soil.
soil at all five habitats, but EC of soil was influenced by seasonal changes. As EC is an indication of the amount of salt dissolved in water, the number of positive and negative ions in water and the water’s ability to pass an electrical current. It is a useful indicator of the salinity and total salt content of water (Chaudhuri et al. 2009). The electric conductivity (EC) of water and soil were higher during summer due to the decrease in freshwater flow and high evaporation rate. It remained low during monsoon due to more in flow of water. Present studies were in accordance with the reports given by Kathiresan (2000) on Pichavaram mangroves habitat, Kumara and Kumar (2020) on Kundapur mangroves habitat and Vilas and Ashwinova (2015) on Sundarbans mangroves habitat. Alkalinity ranged between 80 and 162 mg/l as it was marine water. Maximum alkalinity values were observed during summer and minimum values were observed during monsoon due to the low water influx, high evaporation rate, accumulation of domestic waste and the absence of high tidal action that have had flushing and diluting effect on dissolved constituents which increases alkalinity levels during summer. Even, Islam et al. (2004) reported that alkalinity in the range of 74–180 mg/L along the shrimp farms of the Sundarbans mangrove forest. Raj et al. (2013) reported the average total alkalinity of 81 mg/L along the coastal zone of Muttukadu.

Dissolved oxygen is an important characteristic of water and its concentration in water is an indicator of prevailing water quality, trophic status and the ability of water to support a well-balanced aquatic life (Sánchez et al. 2007). It is essential for the respiratory metabolism of the entire aerobic aquatic life in the mangrove ecosystem (Prasad et al. 2014). Dissolved oxygen content ranged between 5 and 24.6 mg/L. Prabu et al. (2008) observed DO ranging from 2.4 to 5.0 mg/L at the Pichavaram mangroves site. Srilatha et al. (2013) reported DO from 3.92 to 5.22 mg/L and 3.97 to 5.33 mg/L at Calimere and Muthupettai mangroves sites, respectively. Srinivasan et al. (2013) reported DO in the range of 5.5–6.4 mg/L at Vedaranayam mangroves sites. There was no significant variation in BOD and COD of water at all five habitats of Avicennia marina and even, it was not influenced by seasonal changes. BOD is the measure of the extent of organic pollution in the water body; its value provides information regarding the quality of water. BOD values varied from 2.38 to 15.4 mg/L, higher BOD values were observed during winter season due to microbial demand for oxygen in the decomposition of suspended organic matter (Murugan and Ayyakkannu 1991) accumulated in mangrove leaf litter. The plentiful decaying organic matter in the mangroves habitat results in very high BOD during winter than summer and monsoon season. Kumar and Kumara (2011) reported BOD values in the range of 0.1 to 6.51 mg/L while working on Kundapura mangroves. Kavitha (2012) noticed BOD values ranging from 1.0 to 2.7 mg/L in selected fishing grounds of Gulf of Mannar. COD varied from 40 to 354 mg/L, higher COD was observed during monsoon as compared to summer and winter season. COD is the amount of oxygen required for oxidizing dissolved and particulate matter, which is a practical measure of organic contamination (Ogawa and Ogura 1990).

During the study period TSS content varied from 0.46 to 1.980 g/L, high TSS was observed during winter and summer season as compared to monsoon season. The high concentration of TSS increases turbidity in water which restricts light penetration and hinders photosynthetic activity. The observed higher TSS values during summer and winter is due to the degradation of organic matter accumulated in mangrove habitat. Islam et al. (2004) observed TSS varying between 0.24 and 1.22 g/L along the shrimp farms of the Sundarbans mangrove forest. Anand and Kumarasamy (2013) observed TSS varying between 0.38 and 1.48 g/L at Kottakudi Mangrove Estuary. Rahman et al. (2016) observed TSS as 0.39 ± 0.03 g/L along the Coastal water around the Tioman Island. Total Dissolved Solids (TDS) is a measurement of inorganic salts, organic matter and other dissolved materials in water (Weber-Scannell et al. 2007). TDS varied from 1.28 to 8.48 g/L. TDS values were high during summer and winter season because the parameter TDS shows positive correlation with water temperature and not exceeding the standard level (Shinde et al. 2008). So the TDS value of sea water at mangroves habitat is not harmful for aquatic life. Akther et al. (2018) observed the values of TDS ranging from 5.04 to 12.65 ppt. in the study area of Sundarbans mangrove forest river. Water with total dissolved solids concentration within 0.1 ppt to 20 ppt is considered as suitable for aquatic life (Akhter et al. 2018). The sum of TSS and TDS represents total solids. During the study period, high TS concentration was observed during summer season as compared to winter and monsoon. The higher levels of total solids during the summer season was due to the higher level of TSS and TDS which shows positive correlation with high organic matter and high temperature at mangrove habitats.

The determination of organic carbon (OC) is an essential part of any site characterization or ecological assessment since its presence or absence can markedly influence as to how chemicals will react in the soil or sediment. Kumary et al. (2001) reported that the organic carbon content in sediments was a reliable index of nutrient regeneration and the productivity of a water body. There was no significant variation in organic carbon, organic matter and nitrogen percentage at all the five habitats but it was influenced by seasonal changes. The percentage of organic carbon, organic matter and nitrogen remained high during summer as compared to winter and monsoon season. The amount of organic carbon ranged from 0.32 to 2.5%, organic matter ranged from 0.56 to 4.32%, which indicates that it was sufficient for nutrients generation and
productivity of water body. Ranjan et al. (2011) have suggested that the organic matter content remains higher in the mangrove sediments in comparison to adjacent estuaries. Hossain and Nuruddin (2016) have suggested that less than one percent of organic carbon indicates the poor nutritional conditions of the mangrove soils. Sandy soil holds very less organic matter as compared to the clay soil. Sites which were coasts have invariably sandy beaches and thus soil of such sites remains less in organic carbon and organic matter content.

Macro- and microelements were estimated from the soil and water collected from five natural habitats of *Avicennia marina* because nutrient availability varies greatly at different mangrove forests (Feller et al. 2003). Ukpong (1997) showed that nutrient availability is the major factor influencing growth of mangrove vegetation in Africa. The availability of nutrients in mangrove forest is controlled by a variety of biotic and abiotic factors such as redox status, tidal inundation, elevation in the tidal frame, soil type, microbial activities in soils, decomposition of organic matter and litter production. The delivery of nutrients in sediments and water during tidal inundation and sporadically in flood waters associated with cyclones and hurricanes provides significant sources of nutrients for mangroves (Lugo and Snedaker 1974; Davis et al. 2003; Reef et al. 2010). In present studies, there was no significant variation in Ca, P, N, Fe, Bo, Zn, Mn, Cu, Ni, Cd, Cr and Pb content of soil. However, there was significant variation in Na, Li, K, Mg and S content of soil at all five habitats. There was remarkable high Na, K, Li and sulfur content at site-4 and site-5 as compared to other sites. There was significant influence of seasonal changes on physicochemical parameters of soil such as EC, Na, Ca, Li, OC, OM, N, Fe, S and Mn content. However, there was no significant influence of seasonal changes on parameters such as K, P, Mg, B, Zn, Cu, Ni, Cd, Cr and Pb content of soil. The amount of cadmium (0.005–0.009 mg/kg) and lead (0.024–0.095 mg/kg) in marine sediments were diminutive which are not hazardous to aquatic flora and fauna (Supplementary Table 10). There was significant increase in density of *Avicennia marina* plants during summer season than winter and monsoon is due to the presence of high amount of macro- and microelements in sediments. There was remarkable change in the density of *Avicennia marina* plants in five different habitats, in the following order: site:3 > site:1 > site:2 > site:5 > site:4. Hence, it is concluded from the analysis that site-1 (Near Goghala bridge), site-3 (Airport road, Diu) and site-2 (Opposite Jethibai Bus Station) are not influenced by water quality and edaphic factors but site-5 (Taad village bridge) and site-4 (behind industrial zone Goa area) are influenced by soil and water pollution which requires restoration and conservation.

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**Declarations**

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