Chapter 4

Results and Discussion

4.1 Comprehensive hydrochemistry of coastal water

One of the most important factors that might affect the marine environment is said to be the physico-chemical parameters, which vary greatly in both space and time. Different seasonal patterns for pre-monsoon (PRM), monsoon (M), post-monsoon (POM) was seen in all of the physico-chemical properties, which are typical of the tropical marine environment. To understand the variation in data with their study, the current study results were compared with those of earlier studies carried out on the Gujarat coast (Table 4.1). Figures 4.1 and 4.2 show the physico-chemical seasonal fluctuation of the coastal water for all sampling sites along the Bhavnagar coast, Gulf of Khambhat. Every site under study found temperature fluctuations ranging from 27°C to 33°C. During PRM, M, and POM, the average temperature of coastal water varied by 33.3 ± 0.5 ºC, 29.24 ± 0.4 ºC, and 27.7 ± 0.3 ºC, respectively (Figure 4.1). Numerous studies on the Gujarat coast have similarly documented a similar trend in the temperature of surface water (Table 4.1). Surface water temperature is influenced by a number of factors, including air circulation, evaporation, insolation, freshwater mixing, solar radiation intensity, and water currents (Cronin *et al.*, 2019).

The viability of water for aquatic life is largely dependent on its pH. All of the stations had pH values between 8.04 and 8.74. The average pH values for PRM, M, and POM were 8.58 ± 0.04, 8.38 ± 0.17, and 8.29 ± 0.15, respectively, indicating that seasonal change was not significant. The pH during current research has an alkaline nature, which is characteristic of the coastal marine environment. According to USEPA (1989), current study pH is suitable for marine biota. Similarly, Sharma *et al.* (2021) reported the pH range of 7.59 to 8.24 from the Gujarat coastal area of Saurashtra. Similar pH ranges of 5.4 - 9.16 were also found by Pandit and Fulekar (2017) from the Gulf of Kutch in Gujarat, India.

Tidal action has a major impact on the movement of fronts and suspended sediments. Due to the vast tidal range of the Gulf of Khambhat, there are powerful tidal currents and a mechanism for the transportation of suspended sediments (Gosai & Mankodi, 2023). Total suspended solids (TSS) determine the suspended solids condition. TSS levels were found to be between 1813 and 2950 mg/L at all research location in the current investigation. During PRM, M, and POM, the average TSS of the coastal water samples ranged from 2528.0 ± 130.5 mg/L, 2250.8 ± 178.2 mg/L, and 2294.1 ± 379.1 mg/L, respectively. Researchers along the Gujarat coast also found comparable results: Patel *et al.* (2014) recorded a TSS level of 4000 – 70000

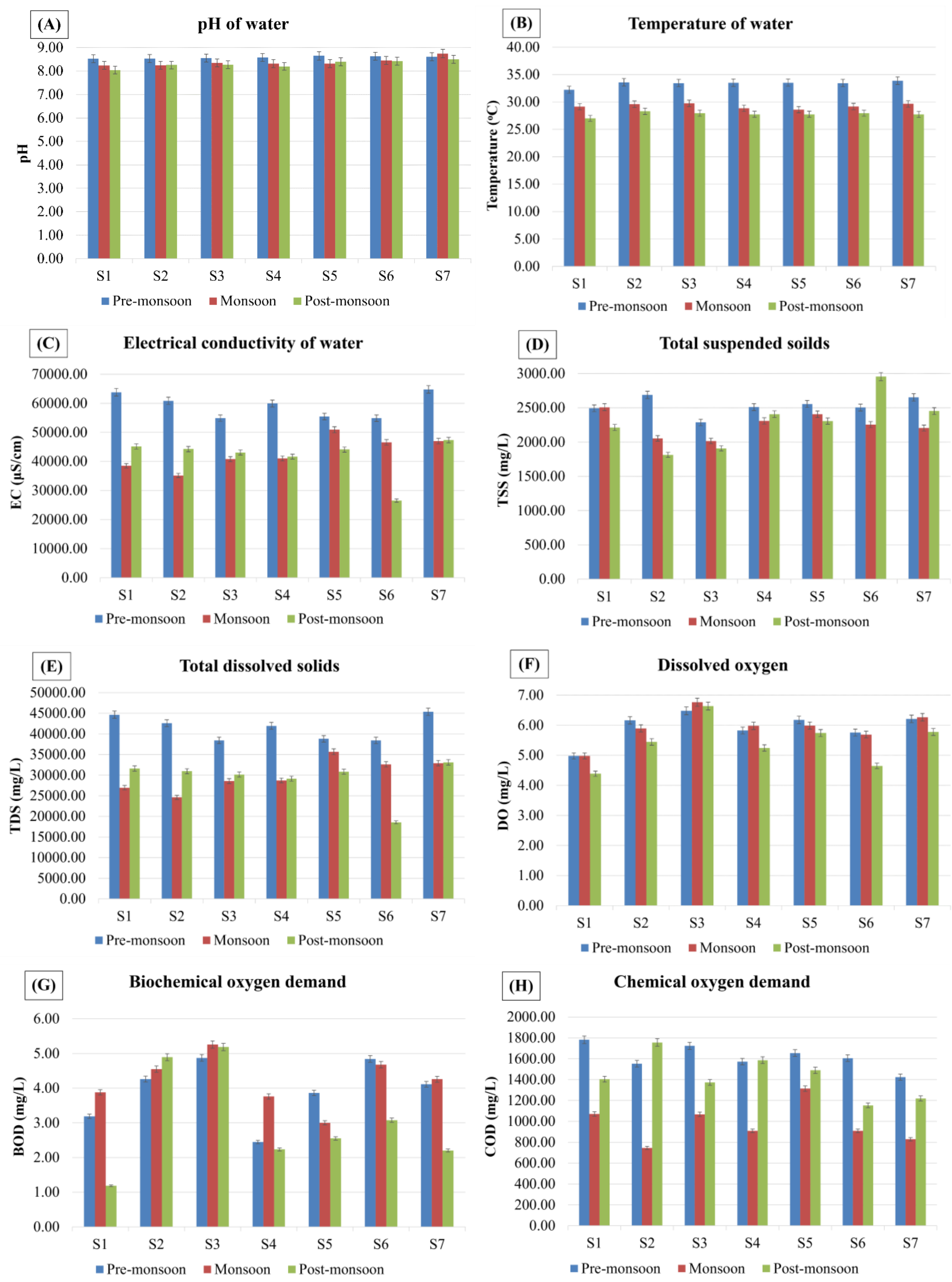

Figure 4.1 A pH, **B** Temperature, **C** EC, **D** TSS**, E** TDS, **F** DO, **G** BOD and **H** COD at study sites

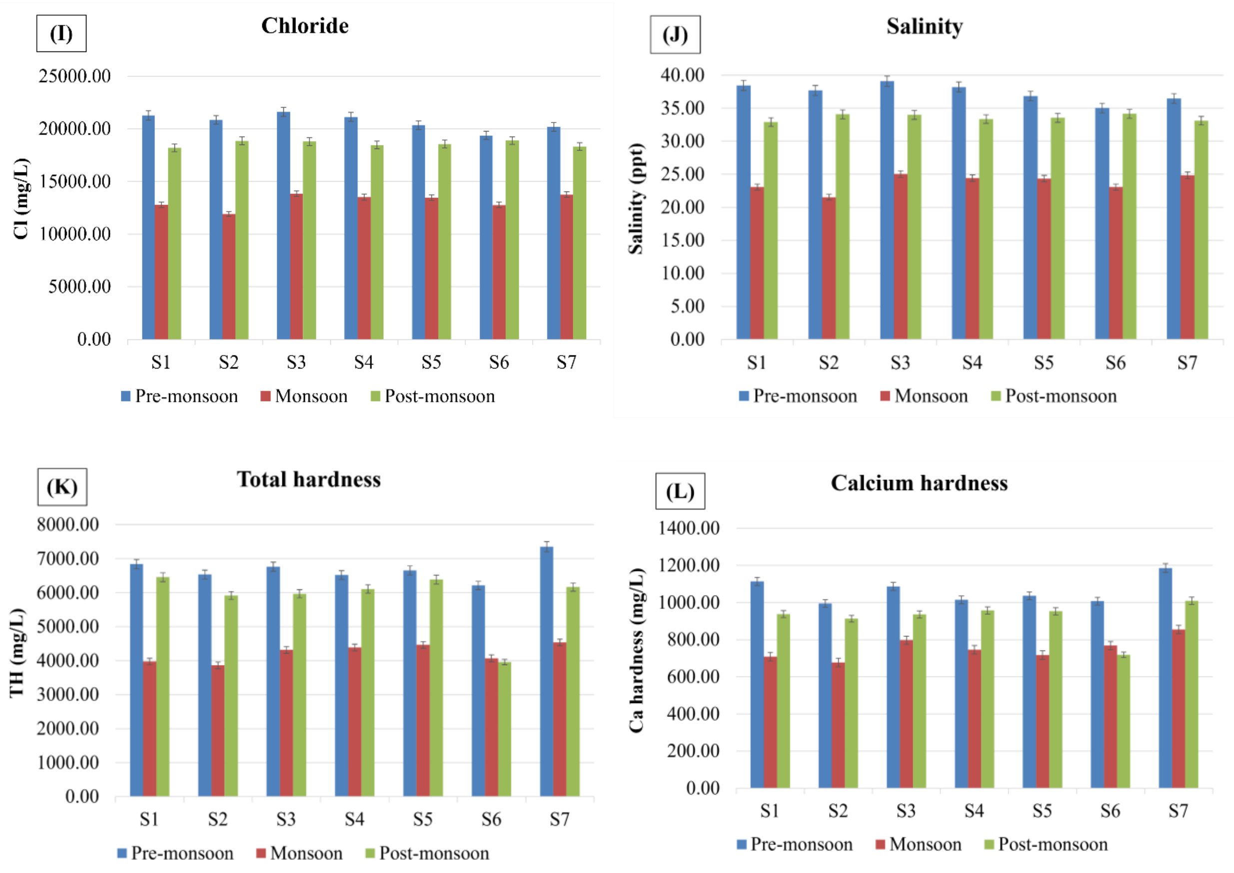

Figure 4.2 Seasonal variation of coastal water parameters **I** Chloride, **J** Salinity, **K** TH, **L** Ca hardness at study

mg/L at the ASSBY coast of Bhavnagar, while Patale and Tank (2022) noted 400 – 2500 mg/L at the Diu coast. Total dissolved solids (TDS) concentrations varied between 18000 and 45000 mg/L at every research station. The PRM, M, and POM average TDS readings were 41460.4 ± 2957.9 mg/L, 30002.0 ± 3856.8 mg/L, and 29207.5 ± 4852.7 mg/L, respectively. The tidal action near the shore might cause a change in TDS. Sharma *et al.* (2021) found 37900 mg/L TDS level at the Somnath coast and 38800 mg/L at the Dwarka coast on the Saurashtra coastal region of Gujarat coast. The direct effect of seawater may be the cause of the increased TDS in samples of coastal water.

Variations in salinity and TDS significantly impact the electrical conductivity (EC) of water (Maliki *et al.*, 2020). The EC readings ranged from 26000 to 64000 µS/cm. During PRM, M, and POM, the average electrical conductivity values along the coast of Bhavnagar were 59229.2 ± 4225.6 µS/cm, 42860.0 ± 5510.8 µS/cm, and 41725 ± 6932.5 µS/cm, respectively. In most research sites, PRM exhibited the highest average conductivity levels, whereas POM had the lowest average conductivity values across all of them. The high conductivity levels might be attributed to increased human activities during the PRM season (Clifford *et al.*, 2021). Research from Dahej, Diu, and Dumas of Gujarat coasts showed similar findings (Table 4.1). Zheng *et al.* (2018) found that the conductivity range for seawater was 30000 – 60000 µS/cm, whereas Tyler *et al.* (2017) found that the EC was 33100 ± 2300 µS/cm.

Total hardness (TH) is the ability of water to separate insoluble calcium and magnesium salts of various acidity from solutions. According to Boyd (2015), the most common cations that result in hardness include calcium, magnesium bicarbonate, carbonate, chloride, and sulphates. At every sampling location, the TH levels varied between 3800 and 7100 mg/L. During PRM, M, and POM the average TH levels were 6697.3 ± 353.9 mg/L, 4231.0 ± 261.5 mg/L, and 5851.8 ± 857.4 mg/L, respectively. The range of the calcium content was 677 mg/L to 1185 mg/L. The average calcium concentration was 1062.7 ± 69.4 mg/L during the PRM, 752.7 ± 60.1 mg/L during the M, and 917.69 ± 92.7 mg/L during the POM.

The diluting effect caused by stream discharge into the ocean is linked to lower concentrations during the monsoon season (Harrison & Elsworth, 1958). Similar studies of the Dwarka coastline water from the Gulf of Kutch, Gujarat revealed TH of 5702.5 mg/L and calcium hardness of 422.5 mg/L, respectively, by Bhadja and Kundu (2012). Patale and Tank (2022) discovered 3-11 mg/L of calcium hardness in Diu coastal water of Gujarat. High evaporation during the summer may cause temperatures to rise, which might lead to an increase in the concentration of calcium, magnesium, and other minerals and cause the surface water to become harder (Jayakumar *et al.*, 2013).

In Gujarat state, India, the Bhavnagar district is widely recognized for contributing to salt production (Rakhasiya *et al.*, 2023). The present study recorded chloride levels ranged from 11913 to 21625 mg/L at each location. For the PRM, M, and POM periods, the average chloride levels were 20692.2 ± 765.7 mg/L, 13150.3 ± 697.8 mg/L, and 18591.4 ± 276.3 mg/L, respectively. There are noticeable seasonal changes in the amounts of chloride, which might be explained by natural processes including water passing through naturally occurring salt deposits in the earth, formations weathering, and pollution from domestic usage (Abbasnia *et al.*, 2019; Allan, 1995).

Table 4.1 Comparison of physico–chemical parameters with other studies in the Gujarat region

Parameters	Bhavnagar coast	Gulf of Kutch	Dahej coast	Dumas coast	Diu coast	Gulf of Kutch	ASSBY coast
pH	8.04 – 8.74	7.90 – 8.79	7.88 – 7.97	7.71 – 7.87	7 – 9	7.9 – 8.6	–
Temp (°C)	27.73 – 33.88	32.70 – 34.10	29.42 – 30.74	26.40 – 30.58	22 – 37	24.7 – 33.9	22 – 40
EC (µS/cm)	26512 – 64807	6300 – 9900	38630 – 39740	38800 – 40200	13000 – 34000	3300 – 9700	–
TSS (ppm)	1813 – 2955	1880 – 6980	–	–	400 – 2300	400 – 5200	4000 – 70000
TDS (ppm)	18558 – 45365	48520 – 74520	22970 – 28680	24000 – 25360	1500 – 8200	45300 – 71600	34000 – 42000
Ca (mg/L)	677 – 1185	–	–	–	3 – 11	–	–
Cl (mg/L)	11913 – 21625	–	24960 – 28260	6800 – 10810	–	–	–
Salinity (ppt)	21.52 – 39.07	36 – 51	23.22 – 26.94	15.42– 25.48	–	36.5 – 52	–
DO (mg/L)	4.39 – 6.76	2.43 – 6.91	4.42 – 6.25	3.29 – 7.23	5 – 22	3 – 11.7	–
BOD (mg/L)	1.18 – 5.26	1.63 – 4.49	10.17 – 12.93	3.11 – 15.25	2 – 15	1.8 – 7.3	870 – 3160
COD (mg/L)	745 – 1782	–	107 – 317	92 – 354	40 – 350	–	1690 – 7000
Reference	*	a	b	b	c	d	e

[*] Present study, [a] Panseriya *et al.* (2023), [b] Singh *et al.* (2022), [c] Patale and Tank (2022), [d] Panseriya *et al.* (2021), [e] Patel *et al.* (2014)

The salinity ranged from 28 to 39 ppt. PRM salinity levels were 37.3 ± 1.3 ppt, M salinity levels were 23.7 ± 1.2 ppt, and POM salinity levels were 33.59 ± 0.4 ppt, respectively. Significant salinity was seen during the pre-monsoon season, in contrast to the monsoon and post-monsoon seasons. The monsoon season sees a large amount of freshwater infiltration, which reduces the salinity of coastal water. In a similar manner, Sharma *et al.* (2021) earlier study indicated that the salinity of the coastal water at Okha Port from Saurashtra coastline area of Gujarat ranged from 32.3 to 35.5 ppt.

Dissolved oxygen (DO) is the conventional and extensively utilized indicator for the condition of the aquatic environment. The seven sites had DO ranging from 4.39 to 6.76 mg/L. The average DO seasonal fluctuation was not significant; the average DO values for the PRM, M, and POM were 5.9 ± 0.4 mg/L, 5.8 ± 0.5 mg/L, and 5.4 ± 0.7 mg/L, respectively. By Akkajit *et al.* (2018), marine organism development may be supported by oxygen concentrations between 1 - 6 mg/L. A greater concentration of DO in coastal water may be caused by phytoplankton photosynthetic activities or freshwater incursion from heavy rainfall (Hammer *et al.*, 2019).

Similar DO content ranges (4.21 – 6.56 mg/L) were recorded by Singh *et al.* (2022) in coastal water in the Gulf of Khambhat area of Gujarat. In the Tapi area, Gulf of Khambhat, Gujarat, DO was found to range from 0.1 to 12.3 mg/L in previous research conducted by George *et al.* (2012). Numerous factors, including as pH, temperature, salinity, chemical composition, incubation time, and oxygen availability, affect BOD (Chaudhuri *et al.*, 1992). Biochemical oxygen demand (BOD) concentrations were 1.18 mg/L to 5.89 mg/L in all areas that were looked into. For the PRM, M, and POM periods, the average BOD values were 3.9 ± 0.8 mg/L, 4.2 ± 0.7 mg/L, and 3.0 ± 1.4 mg/L, respectively. Pandya *et al.* (2022), who reported a 4.8 mg/L BOD value from the Zanzmer coast, Gulf of Khambhat, Gujarat provide evidence in favour of this claim.

For every site, the chemical oxygen demands (COD) varied substantially between 745.44 mg/L and 1782.04 mg/L. For the PRM, M, and POM periods, the average COD values were 1616.3 ± 118.0 mg/L, 977.9 ± 189.4 mg/L, and 1426.1 ± 207.6 mg/L, respectively. This is supported by Patel *et al.* (2014), who found that COD levels in coastal water from ASSBY, on the Gujarati coast of Bhavnagar, ranged from 1690 to 7000 mg/L. In a similar way, Patale and

Tank (2022) investigation revealed 40–350 mg/L of COD in the coastal water of Diu, Saurashtra area, Gujarat. The challenging tidal dynamics of the Gulf of Khambhat and the possible growth of several sectors, including textile, fertilizer, tanning, chemical, cement, steel, gas, oil, and shipbreaking, may be to blame for the elevated COD levels. Huge volumes of treated wastewater are dumped into the sea by companies on both sides of the Gulf of Khambhat (Gosai & Mankodi, 2023). The lower concentration of COD during the monsoon season as opposed to the PRM and POM periods may be caused by the dilution effect of ions brought on by high seasonal rainfall.

4.2 Distribution of dissolved heavy metal content in coastal water

Figure 4.3 illustrates the trend of seasonal dissolved heavy metal i.e., lead (Pb), chromium (Cr), nickel (Ni), cobalt (Co), iron (Fe), cadmium (Cd), manganese (Mn), copper (Cu), zinc (Zn) concentrations in coastal water. The site average dissolved heavy metal concentrations were found to be in decreasing order as follows: Pb > Cr > Ni > Co > Fe > Cd > Mn > Cu > Zn. The dry season pre-monsoon (PRM) and post-monsoon (POM) showed greater levels of dissolved heavy metal in the coastal water than did the monsoon (M) season. During the dry season, anthropogenic activities rise, leading to a greater accumulation of heavy metals in water. But during the monsoon season, there is less heavy metal due to the diluted effect of freshwater invasion during the rainy season (Zhang *et al.*, 2010).

The concentration of lead (Pb) varied between 0.34 and 0.66 mg/L at the sample locations. During PRM, M, and POM the average Pb concentrations were, respectively, 0.54 ± 0.03 mg/L, 0.46 ± 0.09 mg/L, and 0.41 ± 0.14 mg/L. The permissible limit for Pb concentration is exceeded as compared with Bureau of Indian Standard (BIS). For both plants and animals Pb is an unnecessary component. It is a contamination that builds up within living things. Pb can be transported through waterborne sediments and precipitates in these sediments. Pb can be dangerous for the majority of living organism (USEPA, 1986). The paint and ship repair activities along the shore, as well as the discharge of industrial waste, may be the cause of the elevated Pb content in the coastal water.

Taking into account chromium (Cr), the dissolved Cr content in the water varied from 0.09 to 0.86 mg/L, exceeding the BIS permitted limits in each location. For the PRM, M, and POM periods, the average concentration of Cr was 0.72 ± 0.12 mg/L, 0.25 ± 0.03 mg/L, and

0.12 ± 0.02 mg/L, respectively. In the shipbreaking region between the coasts of S4 and S5, we saw waste materials throughout the sample period, including metal ceramics, chrome plating, glossy finishes in paint and dye, etc. Particulate (aerosols and suspended solids from rivers) makes up the majority of Cr into the oceans. The water column experiences chromium cycling as a function of nutrient biogeochemistry (Richard & Bourg, 1991).

The range of nickel (Ni) concentrations in the water across all locations was 0.14 to 0.39 mg/L. For the PRM, M, and POM periods, the average concentration of Ni was 0.35 ± 0.02 mg/L, 0.19 ± 0.03 mg/L, and 0.25 ± 0.03 mg/L, respectively. The levels of Ni exceeded BIS guidelines. According to research by Tokatli (2019) and Aydin *et al.* (2021), Ni may be connected to industrial effluents, paint and dyes, old batteries degrading, sewage sludge, and fertilizer use. Among the research sites, the cobalt (Co) content in coastal water was found to range from 0.011 to 0.275 mg/L. For PRM, M, and POM, the average concentrations of Co were 0.25 ± 0.02 mg/L, 0.17 ± 0.02 mg/L, and 0.07 ± 0.07 mg/L, in that order. Co is a naturally occurring element in the crust of the Earth that fish and other aquatic life depend on (Blust, 2011).

Coastal water samples showed levels of cadmium (Cd) ranging from 0.026 to 0.090 mg/L, exceeding BIS permissible limits across all study locations. For PRM, M and POM, the average values of Cd were 0.05 ± 0.004 mg/L, 0.03 ± 0.004 mg/L, and 0.08 ± 0.006 mg/L, respectively. Cd is released into soil and aquatic systems by sewage sludge, ship repair, weathering of crust, agricultural runoff, and industrial effluent (Hutton, 1983; Sheppard *et al.*, 2009). The range for copper (Cu) was 0.02 mg/L - 0.05 mg/L. For PRM, M, and POM season the Cu average values were 0.04 ± 0.003 mg/L, 0.04 ± 0.006 mg/L, and 0.02 ± 0.002 mg/L, respectively. At sites S2 through S7, the concentration of Cu in the water was found to be within the permissible range. On the other hand, during the POM, Cu concentration was observed to be somewhat greater at the S1 location. Elevated Cu may be connected to the painting work and the electrical work being done to break the ships at the coast. Although Cu is a widespread element in the environment, living things are hazardous to it (Fatoki *et al.*, 2002).

For the majority of living organisms zinc (Zn), manganese (Mn), and iron (Fe) are the three necessary micronutrients. These micronutrients are important in cellular and metabolic processes and are present in the crust of the Earth (Hänsch & Mendel, 2009). Throughout the investigation, these micronutrients' ranges fluctuated in the following ways: Among all the locations under investigation, the values for Zn were 0.01 - 0.11 mg/L; Mn were 0.01 - 0.11 mg/L and Fe were 0.06 - 0.29 mg/L, respectively. For PRM, M, and POM, the average Zn concentrations were 0.04 ± 0.03 mg/L, 0.02 ± 0.01 mg/L, and 0.02 ± 0.01 mg/L, respectively. For PRM, M, and POM, the average values of Mn were 0.08 ± 0.01 mg/L, 0.04 ± 0.004 mg/L, and 0.024 ± 0.009 mg/L, respectively. In PRM, M, and POM the Fe average values were 0.25 ± 0.03 mg/L, 0.11 ± 0.02 mg/L, and 0.07 ± 0.002 mg/L, respectively. In every area under investigation, the amounts of Zn, Mn, and Fe were shown to be within allowable bounds. We saw boat operations, fishing landing hubs, tourist activity, shrimp pond farms, and the shipbreaking industry while doing our field assessment. Consequently, the investigated region exhibits an enhanced content of heavy metals. The higher levels of heavy metal in the study regions may be related to sewage, painting, shipbreaking, chemical manufacturing, and runoff from agriculture (Ali *et al.*, 2022; Basha *et al.*, 2007; Hasan *et al.*, 2023).

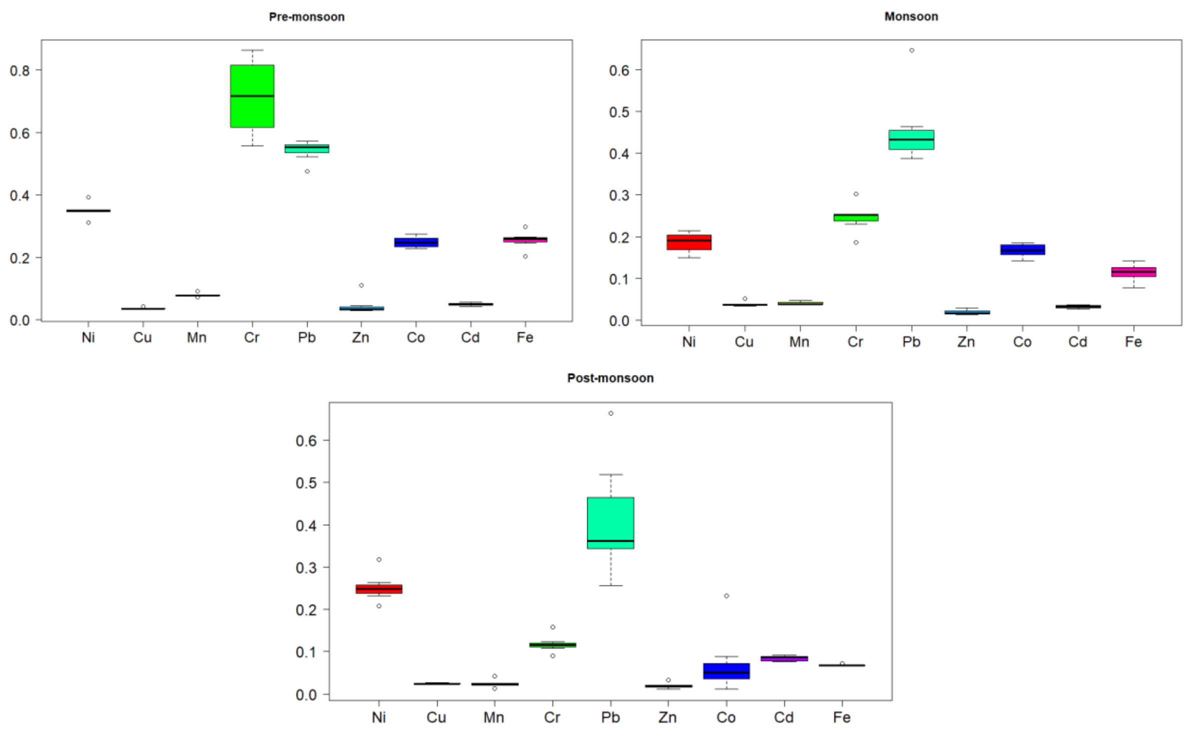

Figure 4.3 Seasonal variation of dissolved heavy metal concentration in coastal surface water (mg/L)

4.3 Physico-chemical variation in coastal sediments

Seasonal variations in the physico-chemical properties of sediment can be associated with dynamic environmental variables such as rainfall, river runoff, and marine activities. The texture, character, and nutritional content of the sediments may change as a result of this transformation, which may have an impact on the organisms that rely on them for habitat and food (Pandion *et al.*, 2023). Understanding how seasonal variations affect the aquatic ecosystem's features and the surrounding marine environment is essential for managing and maintaining it. It may help assess potential effects on ecosystems and marine species, identify critical periods for sediment disturbance or enrichment, and assist in developing practical plans for sustainable coastal development (Pandion *et al.*, 2023).

However, some adsorption, desorption, transport, transformation, and biological activities at the sediment-water interface tightly control the availability of phosphorus, nitrogen, and carbon (Eyre, 1993). In general, nutrients from runoff can be absorbed by sediment and buried in it (Furukawa *et al.*, 1997). The distribution of nutrients in sediments is governed by the sediment texture, which is closely linked to the biogeochemical processes occurring in the sediments of mangrove forests (Prasad & Ramanathan, 2008). Significant supplies of nutrients are provided by the external supply of bioavailable nutrients during tidal inundation, in addition to the in-situ recycling of organic matter through microbial decomposition. Additionally, the sediment physio-chemical characteristics, oxidation state, and nutrient availability are ultimately influenced by topographic parameters including elevation and the length of tidal inundation (Reddy *et al.*, 2021).

A critical physico-chemical factor affecting several biogeochemical processes and the overall wellbeing of coastal ecosystems is the pH of sediment. A coastal environment would be destroyed by anything exceedingly basic or acidic. Because marine organisms are sensitive to pH fluctuations, biotic activity involves pH mechanisms or monitoring. The pH ranged from 8.5 – 9.5. The average value of pH was 9.4 ± 0.11, 8.8 ± 0.20, and 9.1 ± 0.12 for PRM, M, and POM, respectively.

Interactions among the iron, sulphur, and phosphorus cycles might significantly impact the availability of PO_4^{3-} in salinity gradients. PO_4^{3-} combines with several cations, including Fe^{3+} and Ca^{2+}, in aerobic circumstances to generate somewhat insoluble compounds that precipitate out of the water column and into the sediments (Gireeshkumar *et al.*, 2013). Throughout the study period, the total available phosphorus (TAP) ranged from 125.6 – 279.1 mg/kg. The average value of TAP was 246.1 ± 29.41 mg/kg, 179.7 ± 40.62 mg/kg, and 194.3 ± 13.65 for PRM, M, and POM, respectively.

The sulphate ranged from 146.2 – 219 mg/kg. The average value of sulphate was 204.1 ± 17.11 mg/kg, 152 ± 5.54 mg/kg, and 175.9 ± 9.92 for PRM, M, and POM, respectively. Although sulphur is widely distributed throughout the crust of the earth, with an average concentration of 0.1%, environmental pollution by sulphur compounds has risen in parallel with human usage of fossil fuels and metal sulphide deposits. There isn't any disagreement that human activity is increasing the amount of sulphur budget in the atmosphere on a global scale. Furthermore, there is an increased input of sulphur into the environment due to the weathering of sulphide rocks and the observed rise in sulphur content of precipitation water and the atmosphere (Brown, 1982).

The available nitrogen ranged from 100.3 – 181.8 mg/kg. The average value available nitrogen was 171.4 ± 7.4 mg/kg, 108.6 ± 7.4 mg/kg, and 194.3 ± 137.8 mg/kg for PRM, M, and POM, respectively. One significant process that provides available nitrogen in the organically rich mangrove sediments is the release of ammonia from the breakdown of organic compounds and dissimilatory nitrate reduction to ammonium. By adhering to the clay particles in the sediments, a significant portion of this available nitrogen pool is fixed. Silty and clayey particles predominantly affect the sediments around the shore, maybe as a result of geomorphological features (Reddy *et al.*, 2021).

The highest TOC level was often found in sediments with high clay and silt content and low redox potential values. Indeed, a number of factors, including the type of organic matter terrestrial or marine determine the quantity of organic carbon buried and preserved in marine sediments, as terrestrial organic matter is more refractory. However, because of global warming, scientists have highlighted the significance of coastal ecosystems for buffering and protecting the shoreline as well as managing "Blue Carbon" functions. Coastal sediment is a significant source of organic carbon trapped in marine ecosystems and is biologically significant to the global biogeochemical carbon cycle (Pandion *et al.*, 2023). The average total organic carbon (TOC) ranged from 0.06 – 2.40%. The average value of TOC was 1.81 ± 0.39

%, 0.54 ± 0.29 %, and 0.50 ± 0.32 % for PRM, M, and POM, respectively. The geographical distinction between organic and inorganic content is influenced by a multitude of elements on a broad scale, such as topography, climate, and land-use patterns (Zhao *et al.*, 2023).

The average organic matter (OM) ranged from 0.10 % - 4.13 %. The average value of OM was 3.12 ± 0.68 %, 0.93 ± 0.50 %, and 0.87 ± 0.56 % for PRM, M, and POM, respectively. Research has indicated that substantial amounts of organic matter are added to the sediment by marsh plants. However, rather than being primarily influenced by the vegetation, the organic matter in the surface sediments of the current research was mostly determined by the chemical makeup of the suspended particulate matter (Wang *et al.*, 2003).

Table 4.2 Physico-chemical characteristics of coastal sediments

Sampling site	Season	pH	Available nitrogen (mg/kg)	Phosphate (mg/kg)	Sulphate (mg/kg)	TOC (%)	OM (%)
1	PRM	9.5	169.3	279.1	218.5	1.77	3.05
	M	8.9	106.6	125.6	152.3	0.71	1.22
	POM	9	138.0	189.5	172.5	0.49	0.85
2	PRM	9.4	155.6	275	212.5	2.40	4.13
	M	8.8	97.5	119.8	148.6	0.87	1.49
	POM	9	121.6	177.8	169.8	0.93	1.61
3	PRM	9.4	138.7	271.7	210.5	1.72	2.97
	M	8.8	84.6	112.6	146.5	0.64	2.02
	POM	9	110.4	173.7	165.4	1.17	1.11
4	PRM	9.2	164.6	255.2	199.9	1.72	2.97
	M	8.8	101.9	148.9	146.2	0.45	1.11
	POM	9	133.3	169.8	175.8	0.06	0.10
5	PRM	9	148.6	243.7	185.7	1.91	3.29
	M	8.4	98.7	136.8	144.5	0.39	0.66
	POM	9.1	121.4	159.8	170.8	0.08	0.14
6	PRM	9	135.6	240.9	182.5	1.55	2.69
	M	8.4	85.3	122.5	141.5	0.45	0.77
	POM	9.1	114.7	153.7	166.8	0.30	0.51
7	PRM	9.4	167.7	256.7	210.3	1.30	2.25
	M	8.9	103.5	171.3	147.7	0.29	0.5
	POM	9.1	134.8	186.3	168.4	0.57	0.98

Table 4.2 Continued.

8	PRM	9.3	152.6	252.3	206.5	0.63	1.08
	M	8.7	96.6	168.8	143.7	0.51	0.89
	POM	9	128.7	177.8	164.7	0.61	1.06
9	PRM	9.2	133.7	246.3	198.6	1.86	3.21
	M	8.7	80.5	161.7	138.7	0.32	0.55
	POM	9	121.4	168.8	162.6	1.08	1.86
10	PRM	9.5	175.6	255.7	174.7	1.77	3.05
	M	8.8	112.9	174.9	151.9	0.10	0.17
	POM	9.1	144.3	198.8	181.3	0.24	0.42
11	PRM	9.3	162.6	246.3	166.7	2.05	3.53
	M	8.6	98.5	168.9	147.6	0.32	0.55
	POM	9.1	138.5	191.2	177.7	1.08	0.50
12	PRM	9.3	152.3	235.8	164.3	2	3.45
	M	8.6	92.5	163.8	145.6	1.03	1.77
	POM	9	131.7	185.8	173.4	0.57	0.98
13	PRM	9.4	178.8	203.2	188.8	1.49	2.57
	M	8.5	116	161.4	150.2	0.06	0.11
	POM	9.2	147.4	184.5	172.3	0.08	0.13
14	PRM	9.4	156.3	193.3	179.7	1.72	2.97
	M	8.5	94.7	150.9	145	1.12	1.94
	POM	9.2	145.9	172.5	161.1	0.18	0.31
15	PRM	9.2	130.8	186.5	175.7	2	3.45
	M	8.4	88.7	138.9	139.7	1.03	1.33
	POM	9.2	139.8	164.6	153.2	0.57	1.22
16	PRM	9.3	181.9	206.5	219	1.63	2.81
	M	8.7	119.2	154.3	129.2	0.42	0.72
	POM	8.9	134.8	188.8	158.7	0.35	0.60
17	PRM	9.2	177.5	195.6	211.7	2.26	3.89
	M	8.7	94.6	148.9	146.8	0.39	0.66
	POM	8.8	127.8	175.7	160.1	0.2	0.34
18	PRM	9.2	163.6	189.8	209.7	1.60	2.77
	M	8.7	83.2	173.5	142.6	0.22	0.39
	POM	8.9	124.3	165.5	156.9	0.78	1.35
19	PRM	9.4	163.1	266.2	217.3	2.14	3.69
	M	9	100.4	154.6	163.3	0.83	1.44
	POM	9.2	131.7	197.3	195.2	0.74	1.27
20	PRM	9.4	156.8	257.8	208.6	2.35	4.05
	M	9.1	91.3	146.7	1598	0.67	1.16
	POM	9.2	126.5	185.5	186.8	0.59	1.01

Table 4.2 Continued.

21	PRM	9.3	150.4	253.2	203.9	2.14	3.69
	M	8.8	87.5	141.8	153.6	0.77	1.33
	POM	9.1	121.7	193.6	178.9	0.55	0.95
Minimum		8.4	80.5	112.6	129.2	0.06	0.1
Maximum		9.5	181.9	279.1	219	2.4	4.13
Average		9	128.4	189.2	171.5	0.95	1.64
Standard deviation		0.29	27.81	42.86	24.17	0.7	1.2

4.4 Heavy metal content of coastal sediments

Heavy metals accumulate in sediments rather than water because sediments tend to adsorb them (Clark *et al.*, 2023; Hou *et al.*, 2024; Sdiri *et al.*, 2012). The arithmetic mean, minimum, and maximum as well as other descriptive statistics for the parameters computed for coastal sediment samples are shown in Table 4.3 and the concentration of each heavy metal for pre-monsoon (PRM), monsoon (M), and post-monsoon (POM) can be seen in Table 4.4. The findings demonstrate that there are geographical and temporal variations in the amounts of heavy metals in coastal sediment samples from various sampling sites.

In coastal surface sediments, the concentrations of the studied heavy metals ranged from 1.3 to 14.7 mg/kg for nickel (Ni), 0.7 to 12.7 mg/kg for copper (Cu), 21.8 to 120.5 mg/kg for manganese (Mn), 10.6 to 98.4 mg/kg for chromium (Cr), 2.1 to 13.5 mg/kg for lead (Pb), 2.7 to 42.7 mg/kg for zinc (Zn), 1.3 to 8.4 mg/kg for cobalt (Co), 0.1 to 0.8 mg/kg for cadmium (Cd), and 364 – 696 mg/kg for iron (Fe). All research locations had average concentrations of these heavy metals in the following order: Fe > Mn > Cr > Zn > Pb > Ni > Cu > Co > Cd. When the content of heavy metals was compared to the Bureau of Indian Standards (BIS), it exceeded the allowable limits (BIS, 2012).

The spatial distribution of metals in coastal sediments helps identify regions with high metal concentrations in addition to providing an overall trend of potentially hazardous element distribution in sediments. In the PRM season, site 1 had the highest levels of contamination for both Cr (98.4 mg/kg) and Ni (14.7 mg/kg) in the coastal sediments. This location offers small ship servicing along with ferry service activities. Cu (12.7 mg/kg) and Pb (13.5 mg/kg) concentrations are high during PRM season at site 10. Shipbreaking is currently taking place at site 10 on a large scale. There are fishing and tourist activities at sites 3 and 19, and at site 3, the concentration of Mn was 120.5 mg/kg during the PRM season. Zn (42.7 mg/kg) and Fe (696 mg/kg) concentrations throughout the PRM season at site 19. It implies that large amounts of heavy metals from geogenic sources can be found at sites 3 and 19. Shipbreaking operations are located at Site 13, which also exhibits concentrations of Cd (0.8 mg/kg) during the PRM season and Co (8.4 mg/kg) during the M season. Therefore, it suggests that the concentration of heavy metals changes with space, with the concentration being highest in the wet season i.e., PRM. It implies that anthropogenic and geogenic sources contribute to the high concentrations of these elements.

Table 4.3 Concentrations of reported heavy metal (mg/kg) in coastal sediments of Bhavnagar coast, Gulf of Khambhat

	Ni	Cu	Mn	Cr	Pb	Zn	Co	Cd	Fe
Mean	7	5.2	58.9	42.0	8.2	12.5	2.7	0.3	561.4
Minimum	1.3	0.7	21.8	10.6	2.1	2.7	1.3	0.1	364.0
Maximum	14.7	12.7	120.5	98.4	13.5	42.7	8.4	0.8	696.0
Standard deviation	3.4	2.8	20.3	21.0	1.9	9.7	1.1	0.1	124.6
Crustal abundance[1]	75	55	950	100	12.5	70	25	0.2	56300
Shale abundance[2]	68	45	850	90	20	95	19	68	47200

[1] Taylor (1964), [2] Turekian and Wedepohl (1961).

Table 4.4 Seasonal measured concentrations of heavy metal (mg/kg)

Sampling site	Season	Ni	Cu	Mn	Cr	Pb	Zn	Co	Cd	Fe
1	PRM	14.7	12.4	112.4	98.4	8.8	17.3	4.5	0.2	696.0
	M	2.1	8.2	84.3	32.9	4.6	9.0	2.0	0.3	639.0
	POM	4.5	9.4	66.7	37.0	9.7	8.1	2.3	0.2	396.8
2	PRM	12.4	9.2	83.8	76.8	9.0	12.6	3.6	0.2	683.5
	M	1.6	7.9	67.0	29.4	3.8	8.3	1.4	0.3	635.5
	POM	4.3	4.3	32.8	30.0	8.1	3.5	1.5	0.1	381.7
3	PRM	9.5	12.7	120.5	72.9	11.5	20.6	3.5	0.3	677.5
	M	1.3	6.3	55.1	15.9	2.1	8.1	1.3	0.2	607.0
	POM	2.1	1.9	21.8	24.4	8.0	2.7	1.3	0.1	364.0
4	PRM	8.6	3.1	52.0	57.5	7.7	8.0	2.2	0.3	670.0
	M	5.0	4.6	89.1	24.3	8.2	33.8	3.9	0.3	625.9
	POM	5.2	4.1	71.3	33.1	8.7	5.4	2.8	0.2	400.0

Table 4.4 Continued.

5	PRM	8.0	1.7	59.3	49.2	8.3	7.1	2.3	0.2	658.5
	M	4.4	2.8	61.1	15.4	8.0	5.8	3.4	0.3	621.6
	POM	3.1	2.6	37.8	31.1	8.8	3.2	1.9	0.2	393.5
6	PRM	8.2	3.0	49.7	40.3	7.4	7.1	2.2	0.2	642.0
	M	4.0	2.4	47.3	14.4	7.9	5.0	2.7	0.2	600.5
	POM	3.1	2.0	38.5	24.8	7.7	2.8	1.6	0.2	375.0
7	PRM	12.7	8.9	86.2	76.2	8.8	12.3	3.4	0.2	683.5
	M	5.1	5.5	53.1	32.2	8.5	11.2	3.4	0.4	635.3
	POM	5.5	5.6	46.2	35.2	8.8	7.8	2.7	0.2	402.4
8	PRM	10.1	5.5	84.3	63.4	8.3	10.6	2.7	0.1	674.5
	M	4.6	5.2	50.8	23.7	8.3	6.3	2.9	0.3	623.8
	POM	4.7	4.7	46.0	32.5	8.8	7.2	2.5	0.2	398.4
9	PRM	8.7	3.4	76.2	56.0	7.8	9.6	2.1	0.1	662.5
	M	4.5	3.4	50.7	20.0	8.2	5.8	2.5	0.3	635.3
	POM	3.3	3.1	44.6	27.1	8.7	4.2	2.1	0.2	388.9
10	PRM	13.8	12.7	80.5	83.8	13.5	13.9	4.0	0.7	688.5
	M	7.1	9.9	73.3	44.2	9.6	33.7	4.0	0.4	652.9
	POM	7.3	6.4	58.5	46.9	9.8	7.0	2.2	0.2	391.1
11	PRM	12.2	10.1	61.5	78.8	9.0	20.4	3.2	0.4	685.5
	M	6.9	3.7	64.1	41.5	9.4	28.5	2.3	0.3	652.7
	POM	4.8	4.5	36.8	32.7	8.3	18.3	2.9	0.3	413.2
12	PRM	11.6	7.5	51.9	66.5	8.6	41.3	1.9	0.2	677.0
	M	6.6	2.5	42.3	30.9	8.8	25.6	1.9	0.3	631.4
	POM	3.7	3.6	25.4	27.2	8.2	8.7	1.3	0.2	381.8
13	PRM	12.3	7.0	58.4	72.2	8.4	15.7	2.9	0.8	680.0
	M	3.9	9.5	86.4	42.2	8.1	16.0	8.4	0.6	654.2
	POM	5.3	3.4	48.9	44.5	9.4	10.9	2.5	0.2	412.1
14	PRM	11.5	4.7	54.9	64.7	7.9	13.7	2.6	0.6	673.5
	M	3.4	5.3	73.3	32.9	7.7	11.7	3.9	0.3	636.3
	POM	4.3	4.7	34.9	30.3	8.3	6.3	1.9	0.2	386.7
15	PRM	10.2	3.6	65.8	52.7	7.7	6.9	2.8	0.3	656.0
	M	2.6	4.0	46.0	26.4	7.6	6.8	3.6	0.5	620.9
	POM	3.9	3.0	38.4	29.3	7.8	4.6	1.6	0.2	384.8
16	PRM	12.9	6.9	79.2	68.1	12.2	9.9	3.3	0.1	675.5
	M	7.1	4.4	72.1	29.9	7.7	7.2	4.2	0.6	628.1
	POM	7.6	4.5	78.9	40.3	8.7	22.9	3.5	0.3	405.2
17	PRM	10.1	4.6	42.6	50.8	8.8	7.1	1.8	0.1	656.0
	M	6.8	4.2	53.9	29.8	7.6	6.6	4.0	0.6	626.0
	POM	7.5	4.2	57.0	37.4	8.4	6.0	2.7	0.3	396.3

Table 4.4 Continued

18	PRM	8.4	3.4	70.1	36.5	6.9	4.6	2.1	0.1	633.0
	M	6.4	2.3	40.3	18.9	7.4	3.9	2.6	0.5	606.7
	POM	6.8	4.0	67.7	31.7	8.2	4.6	3.2	0.3	393.6
19	PRM	13.7	8.1	71.1	91.9	9.5	42.7	2.8	0.2	696.0
	M	6.5	6.8	67.4	38.9	12.5	28.8	3.1	0.6	642.8
	POM	7.4	4.6	55.0	38.0	8.3	7.3	2.9	0.3	395.7
20	PRM	14.5	7.6	92.5	91.1	10.6	33.7	4.2	0.1	692.0
	M	5.9	1.3	37.6	14.1	2.9	24.5	3.6	0.6	566.5
	POM	5.8	3.2	32.8	31.9	7.5	5.1	2.1	0.2	381.0
21	PRM	9.3	7.4	42.3	38.2	9.8	14.3	1.7	0.1	621.5
	M	5.6	0.7	33.7	10.6	2.4	22.6	2.3	0.6	521.3
	POM	4.9	2.7	29.3	28.6	7.5	5.1	1.9	0.2	381.0

Furthermore, the geographical distribution of heavy metals is influenced by the characteristics of the sediment. Sediment texture is a crucial component because finer sediment particles, in particular, have a higher ability to absorb heavy metals than do coarser sediment particles. The observed spatial disparities in metal concentrations throughout the research locations can be attributed to the larger surface area of small particles facilitating better adsorption and retention of heavy metals (Arienzo *et al.*, 2023; Naseem *et al.*, 2023; Singh *et al.*, 1999).

Seasonal fluctuations were the cause of the observed temporal change of the heavy metal in study. During the research time, it was easy to notice the change. Heavy metal concentrations in the sediment were found to be greater throughout the dry season i.e., pre-monsoon (PRM) and post-monsoon (PSM) than during the monsoon season (M). Anthropogenic activities are more prevalent during the dry season, which causes a greater buildup of heavy metals in sediments. However, the diluting impact of freshwater incursion during the wet season, or monsoon, leads to lower levels of heavy metal in the post-monsoon season, respectively (Debnath *et al.*, 2024; Li *et al.*, 2009; Salgado Bernal *et al.*, 2024; Zhang *et al.*, 2010).

Since background heavy metal concentration measurements distinct to the Bhavnagar coast were unavailable, the research was dependent on reference materials. This study establishes background values for metal concentrations using average shale values as a reference (Taylor, 1964). These reference materials used as standards for the comparison and quantification of the metal concentrations in contaminated sediment samples. Average shale values or average crustal abundance data have been used as reference baselines by many researchers, offering a standardized framework for assessing the level of metal contamination at their particular study locations (Ahmadov *et al.*, 2020; Islam *et al.*, 2021).

As was noted, there was significant variation in the concentrations of heavy metals in the sediments from the examined coastal locations; hence, given the geographical heterogeneity in the sediments (e.g., background levels of the heavy metals), these concentrations may not accurately reflect the real pollution levels. Consequently, it is impossible to evaluate the heavy metal contamination in the sediments using concentrations alone. To assess heavy metal pollution in sediments more precisely, background levels of sediments must be taken into account. Thus, the degree of heavy metal pollution in sediments has been evaluated using a few quantitative indices (C_f, E_f, I_{geo}, E_r, and RI).

4.4.1 Assessment of heavy metal contamination in coastal sediment

4.4.1.1 Contamination factor (C_f) of heavy metal in coastal sediment

The analysis of the study area mean C_f value is shown in Figure 4.4(A). The mean C_f values for Ni, Cu, Mn, Cr, Pb, Zn, Co, Cd, and Fe in the sediments along the Bhavnagar shore were 0.093, 0.96, 0.062, 0.425, 0.661, 0.18, 0.11, 1.308, and 0.0099 (Table 4.5). The determined contamination factor for the heavy metals under study varied from 0.01 to 1.95. According to Hakanson (1980) classification, the levels of contamination caused by the heavy metals varied, with Cd exhibiting moderate contamination ($Cf = 1 – 3$) at 17 sites (1, 4, 5, 7, 8, 10, 11 – 21). On the other hand, the surface sediments at all the studied sites showed low levels of contamination ($Cf < 1$) for Ni, Cu, Mn, Cr, Pb, Zn, Co, and Fe.

Table 4.5 Calculated C_f values of heavy metal in coastal sediments

Site	Ni	Cu	Mn	Cr	Pb	Zn	Co	Cd	Fe
1	0.095	0.182	0.092	0.561	0.613	0.163	0.115	1.000	0.010
2	0.081	0.129	0.064	0.454	0.555	0.116	0.085	0.917	0.010
3	0.057	0.126	0.069	0.377	0.575	0.149	0.080	0.917	0.010
4	0.083	0.071	0.075	0.383	0.653	0.224	0.117	1.259	0.010
5	0.069	0.043	0.055	0.319	0.667	0.077	0.100	1.056	0.010
6	0.067	0.045	0.048	0.265	0.612	0.071	0.086	0.981	0.010
7	0.103	0.121	0.065	0.478	0.693	0.149	0.126	1.278	0.010
8	0.086	0.093	0.064	0.398	0.675	0.114	0.107	1.056	0.010

Table 4.5 Continued.

9	0.073	0.059	0.060	0.344	0.656	0.093	0.089	0.963	0.010
10	0.125	0.176	0.074	0.583	0.875	0.260	0.135	1.389	0.010
11	0.106	0.111	0.057	0.510	0.709	0.320	0.112	1.130	0.010
12	0.097	0.082	0.042	0.415	0.680	0.360	0.067	1.000	0.010
13	0.095	0.121	0.068	0.529	0.689	0.203	0.184	1.889	0.010
14	0.085	0.089	0.057	0.426	0.635	0.150	0.111	1.694	0.010
15	0.074	0.064	0.053	0.361	0.615	0.087	0.105	1.556	0.010
16	0.122	0.096	0.081	0.461	0.760	0.190	0.146	1.556	0.010
17	0.108	0.078	0.054	0.393	0.662	0.094	0.113	1.472	0.010
18	0.108	0.078	0.054	0.393	0.662	0.094	0.113	1.472	0.010
19	0.122	0.118	0.068	0.562	0.809	0.375	0.116	1.954	0.010
20	0.116	0.073	0.057	0.457	0.557	0.301	0.132	1.481	0.010
21	0.087	0.066	0.037	0.258	0.523	0.199	0.078	1.454	0.009

4.4.1.2 Enrichment factor (E_f) of heavy metal in coastal sediment

A common technique to assess human impact on sediments is to compute a normalized enrichment factor (E_f) for metal concentrations over uncontaminated background values (Salomons & Förstner, 2012). The mean E_f value of the study location shown in Figure 4.4(B) was determined. The determined enrichment factor for the heavy metals under study ranges from 4.1 to 190.2. According to Grant and Middleton (1990) classification, the mean E_f of heavy metal was Cd (130.9), Pb (65.8), Cr (41.9), Zn (17.9), Co (11), Cu (9.5), Ni (9.3), and Mn (6.2) (Table 4.6). The E_f for each studied heavy metal ranged for Cd (91 – 190.2), Pb (55.1 – 85.3), Cr (27.7 – 56.8), Zn (6.4 – 36.5), Co (6.7 – 17.8), Cu (4.3 – 17.7), Ni (5.9 – 12.2) and Mn (4.1 – 9). For Ni E_f was found to be moderately severe enrichment (E_f = 5 – 25) at all the study sites; Cu had minor enrichment (E_f = 3–5) at two sites, namely site 5 and site 6, whereas the rest sites showed moderately severe enrichment for Cu; Ni was found to have moderately severe enrichment (E_f = 5–25) for all study sites; for Site 12 Mn exhibited minor enrichment, whereas other sites had relatively moderately severe enrichment; Pb had extremely severe enrichment (E_f > 50) at all studied sites; Zn had very severe enrichment for five sites (10, 11, 12, 20, 21) while other sites had moderately severe enrichment; Co had moderately severe enrichment at all studied sites; and Cr had extremely severe enrichment (E_f > 50) for four sites (1, 10, 13, 19) and other sites had very severe enrichment (E_f = 25 – 50); Cd had extremely severe enrichment at all the studied sites respectively. Elevated E_f values are thought to point to a human source of trace heavy metal contamination, primarily from activities that take place on land.

Table 4.6 Calculated E_f values of heavy metal in coastal sediments

Sites	Ni	Cu	Mn	Cr	Pb	Zn	Co	Cd
1	9.2	17.7	9.0	54.7	59.8	15.9	11.2	97.5
2	8.0	12.9	6.4	45.1	55.1	11.5	8.5	91.0
3	5.9	12.9	7.1	38.6	58.9	15.3	8.2	93.9
4	8.3	7.1	7.4	38.1	65.1	22.3	11.7	125.4
5	6.9	4.3	5.6	32.2	67.3	7.7	10.1	106.5
6	7.0	4.7	5.0	27.7	63.9	7.4	9.0	102.5
7	10.1	11.9	6.4	46.9	68.0	14.6	12.3	125.4
8	8.6	9.2	6.3	39.7	67.2	11.4	10.7	105.1
9	7.3	5.9	6.0	34.4	65.7	9.3	8.9	96.4
10	12.2	17.1	7.3	56.8	85.3	25.3	13.2	135.4
11	10.2	10.7	5.5	49.1	68.4	30.8	10.8	108.9
12	9.7	8.2	4.2	41.5	67.9	35.9	6.7	99.9
13	9.2	11.7	6.6	51.2	66.7	19.6	17.8	182.7
14	8.5	8.8	5.7	42.4	63.2	15.0	11.1	168.7
15	7.5	6.5	5.4	36.7	62.5	8.8	10.6	158.1
16	12.1	9.5	8.0	45.6	75.1	18.8	14.5	153.8
17	10.9	7.8	5.4	39.5	66.6	9.5	11.4	148.2
18	9.9	6.1	6.5	30.0	62.0	6.4	10.7	144.6
19	11.9	11.5	6.6	54.8	78.7	36.5	11.3	190.2
20	12.0	7.5	5.9	47.1	57.4	31.0	13.6	152.6
21	9.7	7.3	4.1	28.6	58.0	22.1	8.7	161.1

4.4.1.3 Geo-accumulation index (I_{geo}) of heavy metal in coastal sediment

The geo-accumulation index (I_{geo}) is a quantitative measure used to assess the level of pollution in aquatic sediments. It has a six-grade system that goes from clean conditions to different degrees of contamination. I_{geo} is a significant ecological measure that can determine the degree of pollution in coastal sediment and distinguish between geogenic and anthropogenic causes. The I_{geo}, and the results are displayed in Figure 4.4 (A). According to the Muller (1969) classification, all the heavy metals under study showed that the Igeo was unpolluted to moderately polluted. Cd (0.184 – 0.392), Pd (0.105 – 0.176), Cr (0.011 – 0.025), Cu (0.009 – 0.036), Mn (0.007 – 0.019), Zn (0.012 – 0.075), and Co (0.014 – 0.037) were the I_{geo} values recorded for the Bhavnagar coastal sediments. The mean I_{geo} value of investigated heavy metals was in the following order: Cd (0.262) > Pb (0.132) > Cr (0.084) > Zn (0.036) > Co (0.022) > Cu (0.019) > Ni (0.018) > Mn (0.012). In consideration of its apparent natural abundance in the earth's crust and the consequent lack of contamination concerns, iron (Fe) was chosen in the current study to compute the E_f; the I_{geo} value is not given here. All of the heavy metals under investigation were found to be either unpolluted or moderately polluted at all sites, based on predicted I_{geo} values (Table 4.7). This suggests that anthropogenic activity had minimal effect on the concentration levels of heavy metals in coastal sediments of the Bhavnagar coast, Gulf of Khambhat.

Table 4.7 Calculated I_{geo} values of heavy metal in coastal sediments

Sites	Ni	Cu	Mn	Cr	Pb	Zn	Co	Cd
1	0.019	0.036	0.019	0.113	0.123	0.033	0.023	0.201
2	0.016	0.026	0.013	0.091	0.111	0.023	0.017	0.184
3	0.011	0.025	0.014	0.076	0.115	0.030	0.016	0.184
4	0.017	0.014	0.015	0.077	0.131	0.045	0.024	0.253
5	0.014	0.009	0.011	0.064	0.134	0.015	0.020	0.212
6	0.014	0.009	0.010	0.053	0.123	0.014	0.017	0.197
7	0.021	0.024	0.013	0.096	0.139	0.030	0.025	0.256
8	0.017	0.019	0.013	0.080	0.135	0.023	0.021	0.212
9	0.015	0.012	0.012	0.069	0.132	0.019	0.018	0.193
10	0.025	0.035	0.015	0.117	0.176	0.052	0.027	0.279
11	0.021	0.022	0.011	0.102	0.142	0.064	0.022	0.227
12	0.019	0.017	0.008	0.083	0.136	0.072	0.014	0.201
13	0.019	0.024	0.014	0.106	0.138	0.041	0.037	0.379
14	0.017	0.018	0.011	0.086	0.127	0.030	0.022	0.340
15	0.015	0.013	0.011	0.072	0.123	0.017	0.021	0.312
16	0.025	0.019	0.016	0.092	0.153	0.038	0.029	0.312
17	0.022	0.016	0.011	0.079	0.133	0.019	0.023	0.295
18	0.019	0.012	0.013	0.058	0.120	0.012	0.021	0.281
19	0.025	0.024	0.014	0.113	0.162	0.075	0.023	0.392
20	0.023	0.015	0.011	0.092	0.112	0.060	0.026	0.297
21	0.018	0.013	0.007	0.052	0.105	0.040	0.016	0.292

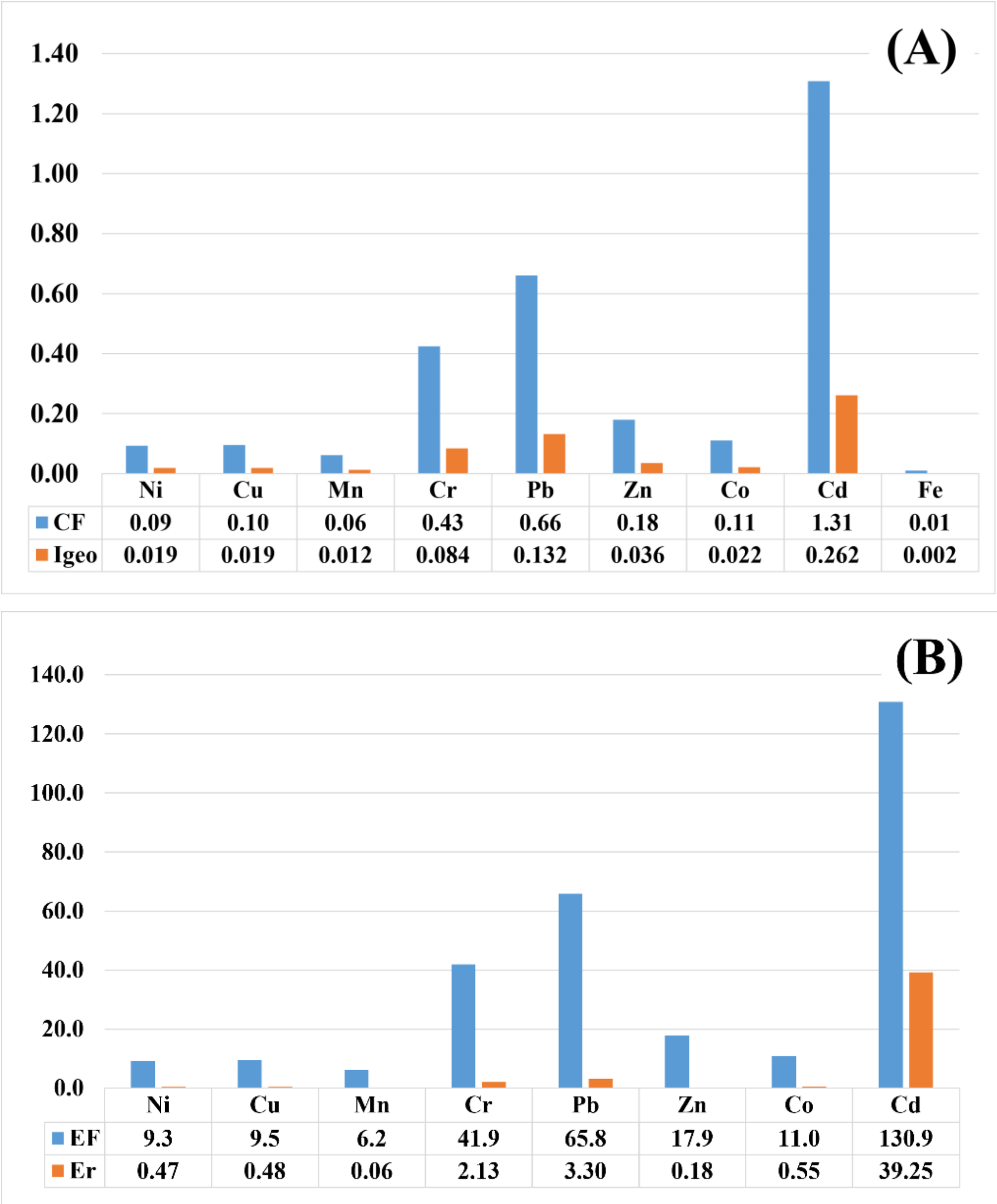

Figure 4.4. Means values of studied heavy metal of (A) C_f and I_{geo} values; (B) E_f and E_r values

4.4.1.4 Ecological risk factor (Er) and Ecological risk index (RI) of heavy metal

Filter-feeding species are directly threatened when heavy metal pollution enters the sediments. In addition, further ecological risks are produced when metals are released into water bodies. Thus, measuring the E_r can aid in our understanding of and ability to control pollution (Hossain *et al.*, 2021). Based on the classification given by Hakanson (1980), the E_r study shows the following trend Cd > Pb > Cr > Co > Cu > Ni > Zn > Mn (Figure 4.4 B). Except for Cd, which exhibited a moderate ecological risk (Er = ≤ 40 – < 80), the heavy metals (Pb, Cr, Co, Cu, Ni, Zn, and Mn) with values of Er < 40 imply minimal ecological risk in the current research.

For Cd, the E_r value at site 10 (E_r = 41.67), site 13 (E_r = 56.67), site 14 (E_r = 50.83), site 15 (E_r = 46.67), site 16 (E_r = 46.67), site 17 (E_r = 44.17), site 18 (E_r = 44.17), site 19 (E_r = 58.61), site 20 (E_r = 44.44), and site 21 (E_r = 43.61). E_r = 40–80 indicates that there was a moderate ecological risk associated with Cd at all locations. The estimated values of the ecological risk index (RI) and ecological risk (E_r) for the research region are displayed in Table 4.8. In the research region, minimal ecological risk is indicated by all sites having RI values less than 95. For all of the metals under investigation, the sediments in the research region therefore present a negligible ecological risk. Anthropogenic influence, natural geochemistry, and soil deposition all contribute to the variations in heavy metal pollution levels and geochemical speciation in the sediment samples examined (Böke Özkoç & Arıman, 2023). In addition to harming the environment, heavy metal exposure can lead to undesirable physiological reactions in humans, including cancer, heart issues, aberrant growth patterns, and hearing impairments (Sundar *et al.*, 2022).

Table 4.8 Calculated E_r and RI of heavy metal in coastal sediments

Sites	E_r								RI
	Ni	Cu	Mn	Cr	Pb	Zn	Co	Cd	
1	0.47	0.91	0.09	2.80	3.07	0.16	0.58	30.00	38.08
2	0.40	0.65	0.06	2.27	2.77	0.12	0.43	27.50	34.20
3	0.29	0.63	0.07	1.89	2.87	0.15	0.40	27.50	33.79
4	0.42	0.36	0.07	1.91	3.27	0.22	0.59	37.78	44.62
5	0.34	0.22	0.06	1.59	3.33	0.08	0.50	31.67	37.78
6	0.34	0.23	0.05	1.33	3.06	0.07	0.43	29.44	34.94
7	0.52	0.61	0.07	2.39	3.47	0.15	0.63	38.33	46.15
8	0.43	0.46	0.06	1.99	3.37	0.11	0.54	31.67	38.64
9	0.36	0.30	0.06	1.72	3.28	0.09	0.45	28.89	35.15
10	0.62	0.88	0.07	2.91	4.37	0.26	0.67	41.67	51.47
11	0.53	0.55	0.06	2.55	3.55	0.32	0.56	33.89	42
12	0.48	0.41	0.04	2.08	3.40	0.36	0.34	30.00	37.11
13	0.48	0.60	0.07	2.65	3.45	0.20	0.92	56.67	65.03
14	0.43	0.44	0.06	2.13	3.17	0.15	0.56	50.83	57.77
15	0.37	0.32	0.05	1.81	3.07	0.09	0.52	46.67	52.90
16	0.61	0.48	0.08	2.30	3.80	0.19	0.73	46.67	54.86
17	0.54	0.39	0.05	1.96	3.31	0.09	0.57	44.17	51.08
18	0.54	0.39	0.05	1.96	3.31	0.09	0.57	44.17	51.08
19	0.61	0.59	0.07	2.81	4.04	0.38	0.58	58.61	67.69
20	0.58	0.37	0.06	2.28	2.79	0.30	0.66	44.44	51.58
21	0.44	0.33	0.04	1.29	2.61	0.20	0.39	43.61	48.91

4.5 Microbial diversity of coastal surface sediment

On the assessment of microbial isolates data across all sites and zones, the total values for each season indicate that the pre-monsoon (PRM) season recorded the highest number of total microbial isolates (2163), followed by the post-monsoon (POM) (1798), with the Monsoon (M) season having the lowest total (1225) (Table 4.9). This suggests a general trend where the PRM period might be associated with higher biological activity or influence environmental factors that lead to increased measurements across all intertidal zones. The average values of isolates calculated for each season provide further insight, showing that the PRM season had the highest average (103), while the M season had the lowest (58). This average trend aligns with the total values, reinforcing the observation that seasonal dynamics play a crucial role in the variability of the data. The minimum and maximum values recorded across the dataset reflect the extreme variability within the observations. The minimum values are relatively low (e.g., 14 during PRM season in the lower intertidal zone of Site 2), while the maximum values are significantly higher (e.g., 354 during PRM season in the lower intertidal zone of Site 5). The values highlight the variation in the data, suggesting that different sites and zones respond differently to seasonal and environmental factors. Out of these, 49 colonies were selected for the biochemical characterisation based on visual morphological characteristics. After performing a biochemical characterization test out of 49 isolated colonies, 15 isolated colonies were selected for further polymerase chain reaction (PCR) and Sanger sequencing.

4.5.1 Morphological characteristics of isolates

The isolate's morphological characteristics are essential for their first identification and offer important clues about the possible identities of the microbes. Size, shape, pigmentation, margin, elevation, surface, and optical appearance are morphological features that are usually the first visible characters that might help to identify the taxonomic group or species that an isolate may belong to. Consequently, morphological traits are thoroughly analysed as the first stage in the identification process, directing further testing for the confirmation of microorganism. Microbial isolates were examined in depth for morphology, and the results show notable variations in colony height, surface roughness, and colour. The isolates showed different pigmentation patterns; some colonies had a white appearance, while others had yellowish to orange tones. This variance in colour indicates variations in pigment synthesis, which may be related to the metabolic processes or environmental adaptations of the isolates (Figure 4.5).

Table 4.9 Total number growth of colonies observed on the petri dish

Site	Intertidal zone	Pre-monsoon	Monsoon	Post-monsoon
1	Higher	171	87	102
	Middle	30	18	19
	Lower	168	109	204
2	Higher	68	25	38
	Middle	40	33	29
	Lower	14	24	32
3	Higher	128	98	288
	Middle	35	43	27
	Lower	31	74	106
4	Higher	63	42	74
	Middle	85	25	31
	Lower	57	36	28
5	Higher	56	41	25
	Middle	21	48	56
	Lower	354	54	128
6	Higher	268	110	136
	Middle	112	97	175
	Lower	63	56	40
7	Higher	155	63	110
	Middle	101	55	48
	Lower	143	87	102
Total		2163	1225	1798
Average		103	58	86
Minimum		14	18	19
Maximum		354	110	288
Std. Deviation		14	18	19

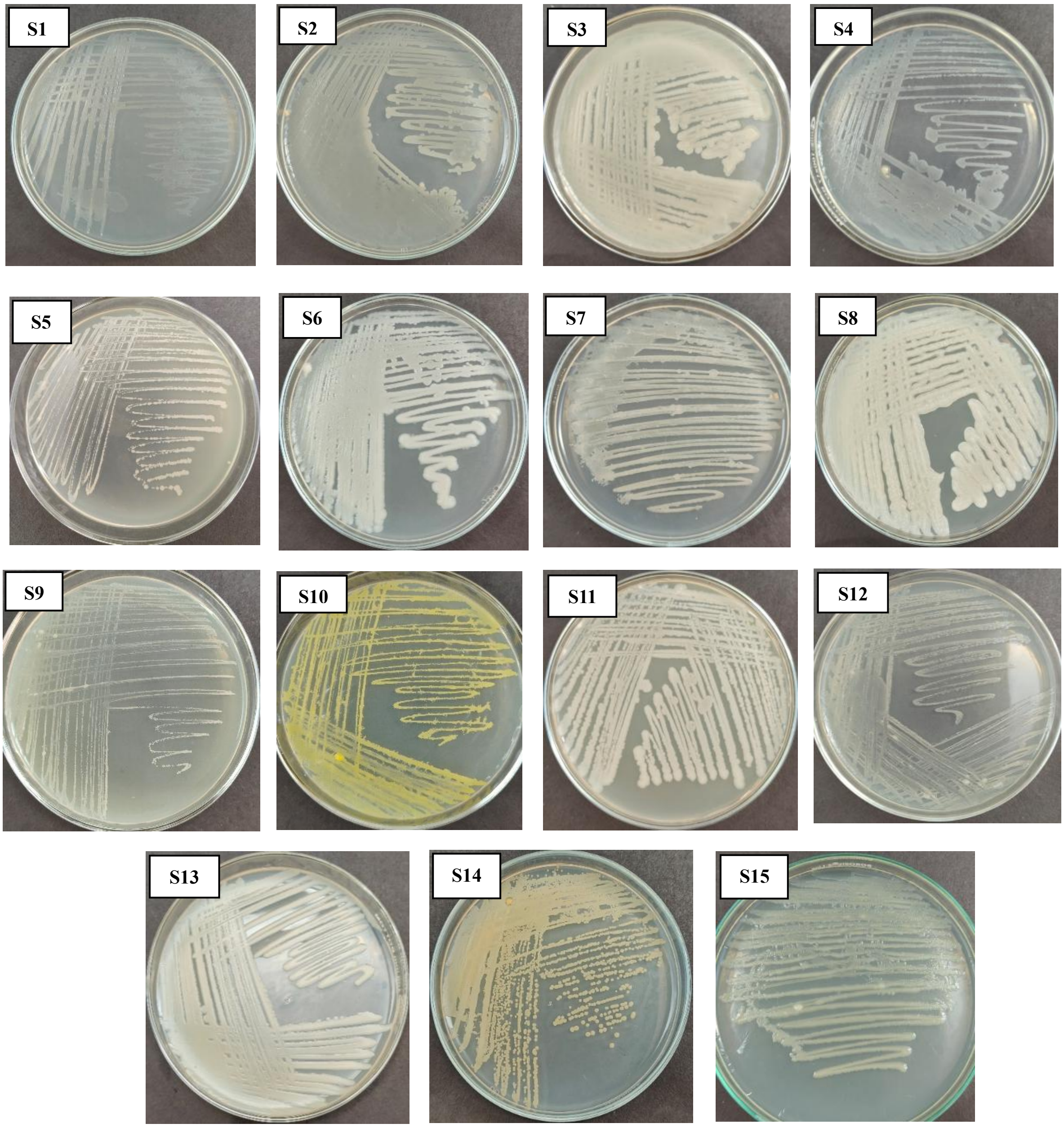

Figure 4.5 Growth of isolates on Zobell Marine Agar plates

Table 4.10 Morphological characteristics of bacterial isolates

Bacterial Isolates	Size	Shape	Pigmentation	Margin	Elevation	Surface	Optical appearance
S1	Small	Round	White	Entire	Flat	Smooth	Opaque
S2	Small	Round	White	Entire	Convex	Smooth	Opaque
S3	Medium	Round	Creamy-white	Entire	Convex	Smooth	Opaque
S4	Small	Round	White	Entire	Flat	Smooth	Opaque
S5	Small	Round	Creamy-white	Entire	Flat	Rough	Opaque
S6	Medium	Round	Creamy-white	Undulate	Convex	Mucoid	Opaque
S7	Small	Irregular	Creamy-white	Undulate	Raised	Rough	Opaque
S8	Medium	Round	Creamy-white	Entire	Convex	Smooth	Opaque
S9	Medium	Round	Creamy-white	Entire	Flat	Smooth	Opaque
S10	Small	Round	Yellowish	Entire	Convex	Smooth	Opaque
S11	Medium	Round	Creamy-white	Undulate	Convex	Smooth	Opaque
S12	Small	Round	White	Entire	Flat	Rough	Opaque
S13	Medium	Round	Creamy-white	Entire	Flat	Smooth	Opaque
S14	Small	Round	Yellowish	Entire	Flat	Rough	Opaque
S15	Small	Round	White	Enitre	Convex	Mucoid	Opaque

In terms of surface texture, the isolates displayed a range of phenotypes, from mucoid and smooth to rough surfaces. The mucoid appearance is often associated with the production of extracellular polysaccharides (EPS), which can be indicative of biofilm formation or a response to environmental stress. The presence of both smooth and rough textures among the isolates further underscores the phenotypic diversity within the isolates. Additionally, the isolates exhibited variability in colony elevation, with both flat and convex profiles observed. Flat colonies may indicate a more spreading growth pattern, while convex colonies suggest a more restricted, dome-shaped growth. This diversity in morphological traits, including pigmentation, surface texture, and elevation, points to the potential presence of multiple strains or species within the isolates, each with distinct phenotypic characteristics that may reflect underlying genetic differences.

4.5.2 Biochemical characterisation of microbial isolates

Out of the total isolates observed, 49 colonies were selected for biochemical characterization based on their distinct visual morphological characteristics, such as size, shape, pigmentation, margin, elevation, surface, and optical appearance. Subsequently, a series of biochemical characterization tests were performed on these 49 colonies to further refine their identification. These tests provided critical insights into the functional properties of the isolates, helping to differentiate between closely related species or strains to remove the repetition of the same microbial isolates.

Following the biochemical characterization, a subset of 15 colonies was selected for further molecular analysis through polymerase chain reaction (PCR) and Sanger sequencing. This selection was based on the results of the biochemical tests, with the aim of including colonies that showed unique or representative biochemical profiles. PCR and Sanger sequencing were employed to amplify and sequence-specific genetic markers, enabling precise identification of the colonies at the species or strain level. The integration of morphological, biochemical, and molecular data provided a comprehensive approach to the characterization and identification of the isolates, ensuring robust and accurate results.

The biochemical characterization provided in the Table 4.11 highlights the diversity among the 15 bacterial isolates, with each showing a unique combination of metabolic capabilities. These results are crucial for guiding the selection of isolates for further molecular analysis. The indole production was positive only for bacterial isolate S6, while the other isolates did not produce indole, indicating a specific pathway presence in bacterial isolate S6 that is absent in the others. S5, S7, S9, and S13 isolates were positive for the Methyl Red (MR) test, suggesting they utilize the mixed acid fermentation pathway. Voges-Proskauer (VP) test results were positive for bacterial isolates S2, S5, S7, S8, S9, S10, S11, S13, and S14, indicating the presence of the butanediol fermentation pathway.

Bacterial isolates S3, S4, S6, S7, S9, S10, S11, S13, S14, and S15 showed positive citrate utilization, indicating that these isolates can use citrate as their sole carbon source. S3, S6, and S11 were positive in the Triple sugar iron (TSI) test, which suggests that they can ferment glucose and possibly other sugars, with varying H_2S production and gas formation. Most isolates (S1, S2, S3, S5, S7, S11, S12, S13, and S15) were capable of fermenting multiple carbohydrates, including glucose, mannose, fructose, maltose, and sucrose, indicating a broad metabolic capability. The catalase test was positive in most isolates (except S8 and S12), indicating the ability to break down hydrogen peroxide into water and oxygen, which is common in aerobic and facultatively anaerobic organisms. Starch hydrolysis was positive for a majority of the isolates, such as S1, S3, S4, S6, S7, S9, S11, S13, and S14, indicating amylase production. Positive gelatin hydrolysis was observed in S2, S4, S9, and S13, suggesting these isolates produce gelatinase, an enzyme that hydrolyzes gelatin. Urease activity was positive in S6, S7, S11, and S15, indicating their ability to hydrolyze urea into ammonia and carbon dioxide. Only S15 produced H_2S, which could be important for distinguishing this isolate from others, particularly in identifying potential sulfate-reducing bacteria. Motility was observed in several isolates, including S3, S4, S5, S6, S7, S8, S9, S11, S13, and S14, indicating flagellar movement, which can aid in further classification. All isolates were Gram-positive suggesting these isolates have similar cell wall structures.

Table 4.11 Biochemical characteristics of isolates

Tests	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
Indole	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
Methyl Red	-	-	-	-	+	-	+	-	+	-	-	-	-	-	-
Voges-Proskauer	-	+	-	-	+	-	+	+	+	-	+	+	-	+	-
Citrate utilization	-	-	+	+	-	+	+	-	+	+	+	-	+	+	+
Triple sugar iron (TSI)	-	-	+	-	-	+	-	-	-	-	+	-	-	-	-
Carbohydrate															
Glucose	-	+	+	+	+	-	+	-	+	-	+	+	+	+	+
Mannose	-	+	+	-	+	-	+	-	-	-	+	+	+	-	+
Fructose	-	+	+	-	+	-	+	-	-	-	+	+	+	-	+
Maltose	-	+	+	-	+	-	+	-	-	+	+	+	+	-	+
Sucrose	-	+	+	+	+	-	+	-	+	+	+	+	+	-	+
Catalase	+	+	-	+	+	+	+	-	+	+	+	-	+	+	+
Starch agar	+	-	+	+	-	+	+	-	+	-	+	-	+	+	-
Gelatine	-	+	-	+	-	-	-	-	+	-	-	-	+	-	-
Ureas hydrolysis	-	-	-	-	-	+	+	-	-	-	+	-	-	-	+
H_2S production	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
Motility	-	-	+	+	+	+	+	+	+	-	+	-	+	+	-
Gram's staining	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

4.5.4 Overview of identified bacterial isolates

(A) S1 - *Fredinandcohnia humi*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Ferdinandcohnia*

Fredinandcohnia humi also referred to as *Bacillus humi*. These bacteria are Gram-positive, aerobic to facultative aerobic, motile, spore-forming, rod-shaped, halotolerant bacteria Many alkaliphilic and alkali-tolerant *Bacillus* species have been isolated from a wide range of alkaline habitats. At least 19 alkaliphilic and alkali-tolerant *Bacillus* species have been identified to date (Lee *et al.*, 2008). Phylogenetic analyses based on 16S rRNA gene sequences showed that strain BA288^T belonged to the genus *Bacillus* and that *Bacillus humi* LMG 22167^T isolated from sandy soil (Lee *et al.*, 2008). Similarly, the study conducted by Kang *et al.* (2020) from solar salt, Strains HMF5848^T showed the highest 16S rRNA gene sequence similarities to *Bacillus humi* LMG 22167^T (96.1%). The presence of *Fredinandcohnia humi* in coastal sediment from the Bhavnagar coast could be due to the presence salt producing activity as Bhavnagar is one of the salt-producing district in Gujarat and the salinity of the coastal water the responsible for the growth.

(B) S2 - *Bacillus safensis*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

Species: *B. safensis*

Bacillus safensis is a Gram-positive, spore-forming rod bacterium. The strain of *B. safensis* is a salt-tolerant in nature. Study conducted by Yousuf *et al.* (2017) from adjacent coastal areas observed that heterotrophic *Bacillus* sp. i.e., *Bacillus safensis* have the potential ability to fix nitrogen. *Bacillus safensis* was also reported from the mangrove area's soil (Dewiyanti *et al.*, 2022). It can live and thrive in a wide variety of habitats, such as salt deserts, industrial waste, oil-contaminated sites, plants, animal waste, and soil. *Bacillus safensis* is a bacterium with good physiological adaptations, which allows it to survive even in diverse and extreme environments and may have a severe impact on other bacteria (Dewiyanti *et al.*, 2022). Regarding fisheries, *Bacillus safensis* improves fish digestion, leading to increased growth, weight gain, and feed efficiency (Wu *et al.*, 2021). Additionally, the probiotic action of *Bacillus* sp. can support the immune system, promote growth, and preserve the density of beneficial bacteria in aquatic biota (Soltani *et al.*, 2019). The presence of *Bacillus safensis* could be linked to the mangrove presence toward the Bhavnagar coast i.e., Ghogha and Gopnath area. It could be helpful to mudskipper diversity that is reported along the coast.

(C) S3- *Bacillus thuringiensis*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

Species: *Bacillus thuringiensis*

Gram-positive, soil-dwelling *Bacillus thuringiensis*, also known as Bt, is the most widely used biological pesticide in the world. Additionally, *Bacillus thuringiensis* is found naturally on leaf surfaces, in aquatic settings, in animal excrement, insect-rich areas, flour mills, and grain storage facilities (Madigan & Martinko, 2005). A novel bacterium that breaks down pesticides and poly-aromatic hydrocarbons (PAHs) was discovered in contaminated coastal soil. Following physical and genetic analysis, the unique strain most closely resembled *Bacillus thuringiensis*. *Bacillus thuringiensis* has significant potential for mineralizing a broad range of newly discovered contaminants, including pesticides and PAHs (Ferreira *et al.*, 2016). The presence of *Bacillus thuringiensis* linked to agricultural runoff toward the coastal area. Although pesticides are essential for crop protection, they can be transported off-site from cropping systems into surface waterways via spray drift from adjacent fields, runoff from irrigation, or rain events endanger aquatic life and coastal waterways (Gress *et al.*, 2024).

(D) S4 - *Bacillus horikoshii*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

Species: *Bacillus horikoshii*

The bacteria *Bacillus horikoshii* is a facultative anaerobe. It is an aerobic endospore-forming, gram-positive, alkali-tolerant bacterium. It is renowned for its adaptability to a variety of conditions, particularly salty and coastal ones, and is less frequently seen than other Bacillus species. As is common for isolates from coastal areas, *Bacillus horikoshii* is halotolerant, meaning it can thrive in conditions with different salt concentrations. In Gujarat, India, *Bacillus horikoshii* was isolated from coastal saline soils (Yadav et al., 2015). According to Yang *et al.* (2021), manganese redox (Mn) cycling is fueled by *Bacillus horikoshii*, which can alter its redox ability under various oxygen concentration situations. The saline nature of coastal sediment, presence of manganese in coastal water, coastal sediment and the presence of the saltern pan toward the Bhavnagar coast could be the reason behind the presence of *Bacillus horikoshii*. Due to its capacity to build biofilms, this species can survive in the unstable and dynamic circumstances of coastal environments. *Bacillus horikoshii* contributes to the breakdown of organic matter and nutrient cycling in coastal environments. Additionally, as it breaks down contaminants, it could aid in bioremediation or the promotion of the health of coastal plant life.

(E) S5 - *Bacillus pumilus*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

Species: *Bacillus pumilus*

Bacillus pumilus is a Gram-positive, aerobic, spore-forming bacillus commonly found in soil. In accordance with its isolation from coastal habitats, *Bacillus pumilus* is slightly halotolerant, meaning it can survive and thrive in situations with increased salt concentrations. *Bacillus pumilus* may exhibit adaptations in coastal conditions, including as increased salt tolerance, surface biofilm formation, and secondary metabolite synthesis, which aid in the organism's survival in competitive microbial communities. *Bacillus pumilus* is marine bacteria is source for potential biosurfactant production (Nayak *et al.*, 2020; Parvathi *et al.*, 2009). *Bacillus pumilus* is involved in the cycling of nutrients, specifically in the breakdown of organic materials.

(E) S6 - *Bacillus cohnii*

Scientific classification

Domain: Bacteria

Phylum: Firmicutes

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

Species: *Bacillus cohnii*

Coastal *Bacillus cohnii* may have a higher resistance to salt, which is an adaptation that enables it to flourish in salinity. Its capacity to generate enzymes that break down different kinds of substrates implies that it might be engaged in the breakdown of contaminants or other man-made substances in coastal and marine environments. *Bacillus cohnii* also reported from the northeastern Arabian Sea (Basu *et al.*, 2013).

(F) S7 - *Bacillus licheniformis*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: Bacillus

Species: *Bacillus licheniformis*

Bacillus licheniformis is a Gram positive, spore-forming, facultative anaerobic, rod-shaped bacterium commonly found in the soil. Because of the shifting salinity, moisture, and nutrient levels seen in coastal regions, B. licheniformis is ideally suited to these circumstances. It contributes to the nutrient cycles in these habitats and aids in the breakdown of organic waste. The potential of *Bacillus licheniformis* in bioremediation is often investigated, particularly in coastal locations where organic contaminants or hydrocarbons have contaminated the environment. *Bacillus licheniformis* also isolated from mangroves soil region (Behera *et al.*, 2016). *Bacillus licheniformis* reported to be having nitrogen fixing potential (Yousuf *et al.*, 2017). According to the study Swaathy *et al.* (2014), *Bacillus licheniformis* showed biosurfactant gene expression.

(G) S8 - *Peribacillus huizhouensis*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Peribacillus*

It is a Gram-positive, spore-forming bacterium, like other members of the Bacillaceae family. *Peribacillus huizhouensis* colonies are typically spherical, smooth, and may have a hint of sheen. Usually, the hue is off-white or white. Its ability to form spores and survive in fluctuating environmental conditions makes it a resilient member of the coastal microbial community. *Peribacillus huizhouensis* showed phosphate-solubilizing potential (Zhong *et al.*, 2021).

(H) S9 - *Bacillus sonorensis*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

Species: *Bacillus sonorensis*

The spore-forming, Gram-positive bacteria *Bacillus sonorensis* was first isolated from desert conditions, notably the Sonoran Desert, thus the name. It has, nonetheless, also been discovered in a wide range of different settings, such as coastal regions. *Bacillus sonorensis* EPS producing bacteria isolated from the coastal habitat (Saber Kelany *et al.*, 2019; Spanò *et al.*, 2013).

(I) S10 - *Bacillus haynesii*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Caryophanales

Family: Bacillaceae

Genus: *Bacillus*

Species: *Bacillus haynesii*

Bacillus haynesii is Gram-positive, rod-shaped frequently found in a variety of settings, including as soil and water systems. Strains that are isolated from coastal regions have salinity adaptations. It is able to endure and flourish in conditions with high salinity, such as marine or coastal areas. *Bacillus haynessi* halotolerant EPS producing bacteria found in the marine habitat (Rajitha *et al.*, 2020). *Bacillus haynessi* also identified from agricultural soil of Saurashtra coastal area of Gujarat (Reang *et al.*, 2022).

(J) S11 - *Bacillus cereus*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

Species: *Bacillus cereus*

It is Gram-positive, endospore-forming, could be aerobic or facultative anaerobic in nature. Jung *et al.* (2011), reported *Bacillus cereus* species from foreshore tidal flat sediment. According to Liu *et al.* (2017), the genetic diversity of bacteria belonging to the *Bacillus cereus* group was discovered to be very varied and widely distributed in marine habitats. Compared to sea water samples, sediment samples have a much greater bacterial abundance. *Bacillus cereus* also reported from mangrove area from coastal zone (Zhang *et al.*, 2015).

(K) S12 - *Bacillus fengqiuensis*

Scientific classification

Domain: Bacteria

Phylum: Firmicutes

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Bacillus*

It is a Gram-positive, endospore-forming, moderately alkaliphilic bacterium. There are only two researches that found *Bacillus fengqiuensis*. Zhao *et al.* (2014) reported *Bacillus fengqiuensis* from sandy soil and Verma *et al.* (2024) reported *Bacillus fengqiuensis* from the Bay of Bengal coastal sediments.

(L) S13 - *Priestia flexa*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

A rod-shaped, gram-positive, halophytic bacterium belonging to the Bacillaceae family of the Bacillales order is called *Priestia flexa*. *Priestia flexa* isolated mangrove coastal area found to be helpful for biodegradation of poly(3-hydroxybutyrate) (Chathalingath *et al.*, 2023).

(M) S14 - *Fictibacillus phosphorivorans*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Bacillaceae

Genus: *Fictibacillus*

Species: *Fictibacillus phosphorivorans*

Fictibacillus phosphorivorans is a Gram-positive, aerobic and spore-forming bacteria. *Fictibacillus* isolated from the coastal mangrove sediment which is promising cellulolytic bacteria (Pramono *et al.*, 2021). *Fictobacillus* found in highly alkaline environment (Kalwasińska *et al.*, 2017).

(N) S15 - *Staphylococcus hominis*

Scientific classification

Domain: Bacteria

Phylum: Bacillota

Class: Bacilli

Order: Bacillales

Family: Staphylococcaceae

Genus: *Staphylococcus*

Species: *Staphylococcus hominis*

It is Gram-positive *staphylococcus hominis* that may also be isolated from a variety of settings, including coastal locations. *Staphylococcus* sp. found in marine and estuarine waters (Gunn *et al.*, 1982). *Staphylococcus* sp. isolated from marine waters was reported to be antibiotic-resistant (Skórczewski *et al.*, 2014). Al-Garni *et al.* (2024) also reported *Staphylococcus hominis* from coastal water in their study.

In the present study, total of 15 isolates from coastal sediments were identified as *Fredinandcohnia humi*, *Bacillus safensis*, *Bacillus thuringiensis*, *Bacillus horikoshii*, *Bacillus pumilus*, *Bacillus cohnii*, *Bacillus licheniformis*, *Peribacillus huizhouensis*, *Bacillus sonorensis*, *Bacillus haynesii*, *Bacillus cereus*, *Bacillus fengqiuensis*, *Priestia flexa*, *Fictibacillus phosphorivorans*, and *Staphylococcus hominis* from the Bhavnagar coast, Gulf of Khambhat, Gujarat, India. Similar efforts were also made by different researchers to check the microbial diversity from the Gujarat coast of India. According to Dholakiya *et al.* (2017), a study conducted on the Alang coast of the Gulf of Khambhat revealed the isolation of novel marine *Actinobacteria* that are Gram-positive and were found in sea sediment. These bacteria were found to have 84% similarity in 16S rRNA gene sequence (KT588655) with *Streptomyces variabilis* (EU841661), and were therefore named *Streptomyces variabilis* RD-5. One potentially useful source of bioactive secondary metabolites is the species *Streptomyces*. The study by Nathani *et al.* (2019) from the pelagic sediment of the Gulf of Khambhat found that there are 2354 distinct resistance gene types, and the region where human activities were being conducted on land had the most varied and prolific gene profile. Among the most common phyla are *Actinobacteria*, *Firmicutes*, *Proteobacteria*, and *Bacteroidetes*. *Pelobacter*, *Thermotaga*, and *Desulfovibrio* have been proposed as possible antibiotic biomarkers.

Marine salterns are artificial extremely thalassohaline environments consisting of discontinuous salinity gradients. Effort made by Dave and Desai (2006) to check the diversity of marine saltern areas near Bhavnagar Gujarat. Analysis of the 16s rRNA was revelaed the bacteria to be *Natrinema thermotolerant*, a member of the *Halobacteriaceae* family, and it was proven to be haloarchaea. This culture could endure temperatures up to 60°C and flourished up to 50°C. While phosphatidic acid was present in the remaining isolates, their characteristics were more halotolerant than halophilic. According to the study conducted by Mootapally *et al.* (2019) from the Pelagic Sediments of the Gulf of Kutch and Gulf of Khambhat showed most diverse in resistance gene profile. *Proteobacteria* species in the Arabian Sea and Gulf of Kutch have resistance genes, whereas *Aquificae*, *Acidobacteria*, and *Firmicutes* species in the Gulf of Khambhat. Water bodies become a reservoir for newly resistant bacteria because they absorb antibiotic toxins from the surrounding habitat (Chen *et al.*, 2019).

In the Arabian Sea, Gujarat, India, the community composition and dispersion at three distinct localities (Diu, Alang, and Sikka) were investigated using a culture-dependent and next-generation sequencing (NGS) technique. Using the NGS method, the *Proteobacteria* were the most prevalent phylum found at the sample locations. The class *Gammaproteobacteria* dominated both site surfaces, accounting for 46.7% to 89.2% of the overall abundance. *Proteobacteria* and *Firmicutes* were shown to be the two most prevalent phyla on the surfaces of the sample sites, according to the culture-dependent analysis (Kumar *et al.*, 2022). Diverse microbial diversity seen in marine ecosystems is adaptable to a range of stressors and environmental situations. Gujarat has two Gulfs and a broad coastline, each having its own distinct and varied speciality. Since they are xenobiotics, polyaromatic hydrocarbons (PAHs) pose harm to the ecosystem and are introduced into marine habitats through a variety of anthropogenic wastes. *Penicillium ilerdanum* NPDF1239-K3-F21 and *Aspergillus versicolor* NPDF190-C1-26 showed an ability to degrade the PAHs isolated from coastal sediments (Mahajan *et al.*, 2021).

Multiple polycyclic aromatic hydrocarbons (PAHs) degrading bacteria were isolated and screened from historically polluted coastal locations, namely the Alang-Sosiya Ship Breaking and Recycling Yard (ASSBRY) and Navlakhi Port (NAV), Gujarat, on India's north-west coast. *Bacillus oceanisediminis* (BS1), *Bacillus circulans* (BS7), *Lelliottia amnigena* (BS8), *Bacillus campisalis* (GH1), *Achromobacter mucicolens* (GH4), and *Stenotrophomonas maltophilia* were found (Sachaniya *et al.*, 2021). The composition and organization of coastal marine bacterial communities from Gujarat's coastal region, which is situated along the Indian western coast (the Arabian Sea), were examined by Kumar *et al.* (2019). *Firmicutes* have been demonstrated to be the dominant group after Proteobacteria, according to molecular phylogeny. The majority of the sequences belonged to the *Gammaproteobacteria* class within the *Proteobacteria* phylum. Raiyani and Singh (2023) made an effort to check the microbial diversity of marine sediment from Kachchigadh (Shivrajpur), Dwarka and Alang-Sosiya shipbreaking yard, Bhavnagar of the Coastal Gujarat, India. *Proteobacteria* dominated all research locations. Other phyla included *Actinobacteria*, *Bacteroidetes*, *Planctomycetes*, *Acidobacteria*, *Chlorofexi*, *Nitrospirae*, *Cyanobacteria*, *Verrucomicrobia*, *Tenericutes*, and *Chlorobi*. Surprisingly, almost 50% of genera fall into unclassifiable groups. The major genera identified were *Acinetobacter*, *Bacillus*, *Pseudomona*, *Idiomarina*, *Thalassospira*, *Marinobacter*, *Halomonas*, *Planctomyces*, *Psychrobacter*, and *Vogesella*.