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Seasonal Evaluation of Physicochemical Parameters of Marine Sediments on the Coasts of Al-Mukalla and Broom Districts, Hadhramout, Yemen

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Abstract

Human activities are the primary sources of pollution, the severity of which has increased significantly in recent decades, placing immense pressure on both human societies and coastal ecosystems. Seasonal conditions play a crucial role in determining the spread, dilution, or accumulation of pollutants in marine environments. Consequently, assessing seasonal variations in marine sediments subjected to sewage pollution is essential for understanding the extent of this dynamic impact, which is of paramount importance for evaluating and developing effective management and protection strategies. This study investigates seasonal variations in some of the physicochemical parameters of marine sediments along the coasts of the Al-Mukalla and Burum districts in the Hadhramaut Governorate, Yemen. A range of statistical methods were employed to analyze a comprehensive dataset on marine sediment quality over two seasons. This research aims to provide some necessary insights into the extent of pollution in coastal sediments near sewage outlets and to assess the quality of sediments that serve as habitats for a diverse array of marine organisms. The results indicated temporal and spatial variations in coastal sediment pollution in both regions during both seasons, exceeding Yemeni and international permissible limits. The concentrations of environmental parameters, such as temperature, pH, Ca^{2+}, Mg^{2+}, Cl^{-}, HCO_3^{-}, and SO_4^{2-} decreased during the first season compared to those during the second. This was accompanied by an increase in both EC and TDS . Overall, this variation may be attributed to its association with varying discharge rates, biological processes, and natural factors affecting the seasons. This also underscores the role of sewage as a primary cause of coastal degradation in marine ecosystems. Such pollution is expected to have significant environmental and health consequences by destroying essential habitat structures (such as coral reefs or seagrass meadows), causing toxicity, impaired growth, and disrupting reproductive processes. In turn, this negatively impacts biodiversity and ecosystem resilience.

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1. INTRODUCTION

The Hadhramout Governorate overlooks the Arabian Sea to the south, with a coastline stretching approximately 303.9 km [1]. The coastline is mainly characterized by long sandy beaches interspersed with prominent rocky outcrops that frequently extend into shallow coastal waters [2]. The coastline is predominantly a high-energy environment with soft substrates [3, 4].

The coastal habitats of the Hadhramout Governorate are among the most ecologically significant and unique along Yemen's southern shoreline. Nesting beaches in this region are recognized as some of the best remaining nesting grounds for marine turtles globally [5]. In addition to turtle nesting sites, the Hadhramout coast supports a variety of other important habitats, including coral reefs, seagrass meadows, salt marshes, and mangrove stands, which sustain diverse marine life [6, 7]. The coastal region of Yemen, including the Hadhramout Governorate, is affected by two distinct monsoon seasons: the southwest (SW) monsoon from the Indian Ocean, which occurs between May and September, and the northeast (NE) monsoon, which dominates from October to April [8, 9]. The climate along Yemen's coast and adjacent waters is characterized by hot and extremely arid conditions. Occasionally, the coastal area of Hadhramout is exposed to frequent storms and heavy rainfall events, resulting in flooding and coastal inundation [10]. The seasonal monsoon plays a critical role in shaping coastal hydrodynamic sediment transport and resuspension processes along the Gulf of Aden and Arabian Sea regions. Such processes directly influence sediment grain size distribution, redox conditions, and the accumulation or dispersion of dissolved and particulate constituents within nearshore sediments [11].

In addition to these climatic drivers, the coastal environment is also affected by anthropogenic pollution sources, primarily associated with wastewater treatment plants linked to an older infrastructure project that serves approximately 50% of the city. The daily wastewater discharge from these facilities has more than doubled in recent years, reaching approximately 3000 L per day [12]. Untreated or partially treated wastewater discharge introduces nutrients, organic matter, and other chemical constituents into the coastal waters, which can alter sediment physicochemical properties and degrade benthic habitat quality.

This study evaluated the physicochemical properties of seawater and marine sediments along the coastal areas of the Hadhramout Governorate, particularly along the coasts of the Al-Mukalla and Broom districts. Based on the strong seasonal variability imposed by the SW and NE monsoon systems, as well as increasing anthropogenic pressure along the Hadhramout coastline, we hypothesized that sediment physicochemical properties show clear seasonal variation driven by monsoon hydrodynamics, with stations near wastewater discharge exhibiting altered characteristics compared to less impacted areas.

Assessing physicochemical parameters is crucial for determining the current environmental status and detecting potential sources of marine pollution, particularly those associated with wastewater discharge, as most wastewater treatment plants are currently out of service due to the ongoing national conflict. By measuring key factors, such as temperature, salinity, and pH, this study aims to generate baseline environmental data for this understudied region.

Although several studies have examined the physicochemical characteristics of marine sediments worldwide [13–16] and at the regional scale [17], comparable investigations along the southern Yemeni coast remain scarce, with only one previous study addressing these parameters in the study area [18]. The present study differs from earlier work by providing a seasonally resolved assessment under monsoon-dominated conditions in a region experiencing prolonged disruption of environmental monitoring due to socio-political instability and increasing amounts of untreated wastewater input. This study contributes region-specific baseline data that are largely absent from the existing literature and are essential for future environmental assessments, restoration efforts, and evidence-based coastal zone management. The results are intended to support conservation planning and facilitate the monitoring of both natural and human-induced impacts on marine ecosystems.

2. MATERIALS AND METHODS

2.1. The Study Area

The Hadhramout Governorate is one of the largest governorates in southern Yemen. It is located in the eastern part of Yemen between 14° 30´ and 14° 56´ N latitude and 49° 07´ and 50° 21´ E longitude [11, 19]. It is bordered by the Shabwa Governorate to the west and the Al-Mahra Governorate to the east and overlooks the Gulf of Aden and the Arabian Sea to the south (Figure 1). The coastal area of the governorate is characterized by persistently hot and arid conditions; however, episodic storm events and intense rainfall occasionally affect the coastal area of Hadhramout, resulting in flooding and coastal inundation [10].

2.2. Methodology

Fourteen sampling locations were selected along the coastal zones of two districts in the Hadhramout Governorate, namely, the Al-Mukalla and Broom districts, to represent areas subjected to anthropogenic effects. Sampling stations were intentionally located in proximity to known or suspected wastewater discharge points, as well as at comparatively less-impacted sites, to assess spatial variability in sediment and water physicochemical characteristics. The spatial distribution of sampling stations relative to discharge sources is illustrated in Figure 1.

The study covered two main seasonal periods during 2024, from February to November, and encompassing pre-monsoon and post-monsoon conditions. This temporal framework was designed to capture the influence of the NE and SW monsoon systems on nearshore environmental conditions.

The research methodology employed an integrated

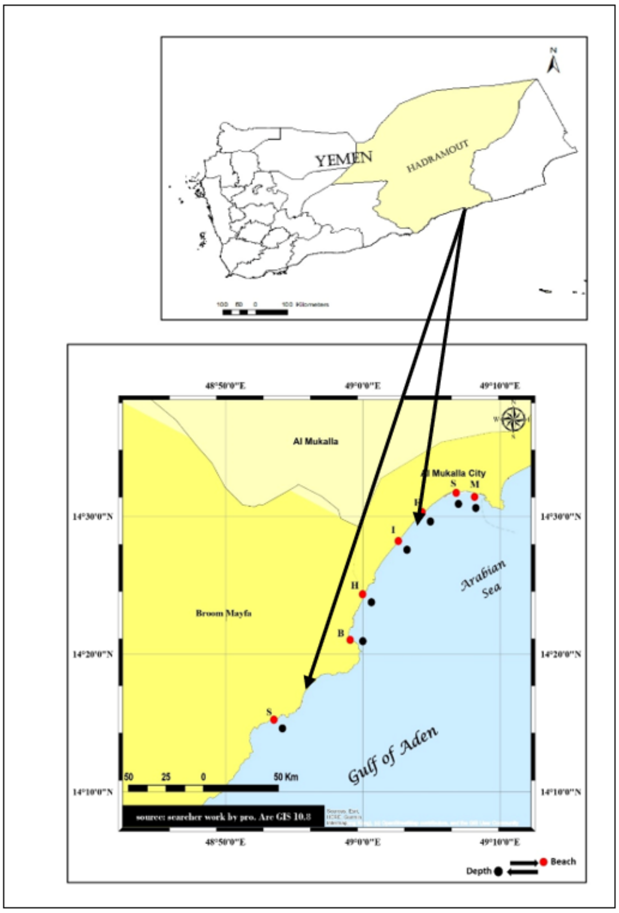

Figure 1. Map of Hadhramout Governorate showing the sampling locations.

approach that combined field surveys and laboratory analyses. All analyses were conducted using standardized procedures appropriate for each specific water quality parameter, as outlined by the American Public Health Association (APHA) [20, 21]. Modern analytical techniques and specialized software tools were employed to enhance data acquisition, processing, and interpretation, ensuring accuracy and reliability in the assessment. All measurements were conducted in accordance with internationally recognized quality assurance and quality control (QA/QC) protocols.

Marine sediment samples were collected to assess physicochemical properties within the ecologically active nearshore zone. Approximately 1–2 kg of surface sediment was collected at water depths of 4–5 m, corresponding to the shallow subtidal zone that is directly influenced by coastal hydrodynamics, wastewater inputs, and sediment resuspension processes.

Sampling was conducted between the low-tide mark and distances ranging from 50 to 150 m offshore, where fine sediments are more likely to accumulate and retain physicochemical signals of both natural and anthropogenic origin. The selected sampling depth (4–5 m) was chosen to minimize the effects of direct wave breaking while still capturing zones of active sediment–water interaction, making it suitable for assessing seasonal and spatial variability in sediment quality.

After collection, samples requiring laboratory analysis were immediately transported to the laboratory in an icebox. The sediment samples were divided into two subsamples: the first was used to determine grain size distribution, organic matter (OM), and total organic carbon (TOC), while the second was used to determine the concentrations of selected major ions and chemical constituents, including calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), chloride (Cl^{-}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^{-}), and sulfate (SO_4^{2-}). All investigated parameters were measured following standardized and widely accepted analytical procedures [21–23].

3. RESULTS AND DISCUSSION

3.1. Hydro-Climatic Factors

The results indicate that hydroclimatic factors exert strong control over seasonal environmental variability along the Hadhramout coast. The coastal zones of Al-Mukalla and the Broom Districts experience climatic conditions ranging from mild to severe, reflecting broader regional climatic variability and global warming trends [19, 24]. Both areas are characterized by a hot desert climate, with high summer temperatures averaging 35.7 and 35.1 °C, and relatively mild winter temperatures decreasing to averages of 25.1 and 25.2 °C, respectively [25].

Seawater temperature is a key regulator of dissolved oxygen solubility and directly influences the metabolic activity of fish and other aquatic organisms, microbial processes, and biogeochemical cycling within sediments [26]. Elevated thermal conditions during the study period likely enhanced microbial degradation rates and nutrient fluxes at the sediment–water interface. Global warming also contributes to sea-level rise, intensifying tidal amplitudes [27], which ranged from 41.25 to 69.67 cm during low tide to 102–109 cm during high tide during the study period [3, 4].

In addition, the location of the investigated areas is influenced by two distinct monsoons, *i.e.* the southwest monsoon winds and dry northeast winds, with wind speeds ranging between 15.3 and 17.2 km/h, as indicated by [8, 28]. This is often associated with heavy rainfall ranging between 13 and 14 mm under high temperatures and relative humidity of 63–65% (Figure 2) [3, 29–31]. Together, these hydroclimatic drivers govern sediment resuspension, mixing intensity, and the redistribution of dissolved and particulate constituents, thereby providing a dynamic framework for interpreting seasonal changes in sediment physicochemical properties.

3.2. Physicochemical Parameters in Marine Sediments

Grain Size Distribution

Grain size analysis revealed spatial variability in sediment texture across the study sites, primarily controlled by hydrodynamic energy conditions. Shallow coastal sediments were dominated by sandy fractions, reflecting the high-energy nature of the Hadhramout coastline. Grain size distribution is widely recognized as an indicator of current strength, wave action, and depositional environment [3, 25, 32].

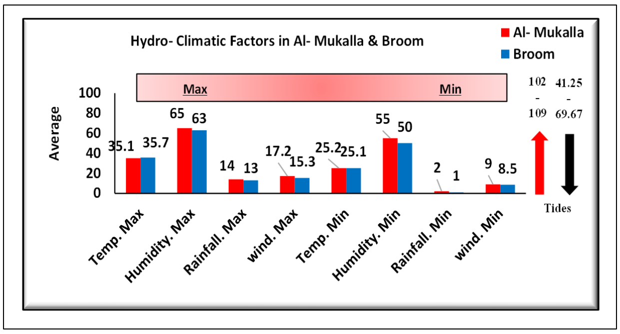

Figure 2. Seasonal Average of Temp (℃), Humidity (%), Rainfall (mm), Wind (km/h) for Al-Mukalla & Broom districts during the study period.

The surface sediments consisted predominantly of sand (85%–98%), with minor proportions of silt (1%–9%) and clay (0.2%–4%) (Table 1). Sand dominance extended along the coast from Al-Mukalla in the east to the Broom District in the west, whereas the silt and clay fractions remained consistently low. These findings are consistent with previous regional and international studies conducted in high-energy coastal settings [33–35].

The degree of coarseness and softness of the sediments varied across all sites. **Spatial** variations in sediment texture were evident, with coarser sediments at Is2, Hs1, Bs1, and Sts1, and finer sandy sediments occurring in limited quantities at sites such as Sts2, Ms1, Ms2, Ss1, Ss2, Fs1, Fs2, Is1, Hs2, and Bs2 (Table 1). In general, the gravel and sand fractions decreased slightly with increasing depth and distance from the shore, whereas silt and clay increased marginally. Localized enrichment of finer sediments at certain coastal sites may reflect anthropogenic disturbances, such as shoreline modification, landfilling, and construction activities, which alter sediment supply and nearshore hydrodynamics. This observation is consistent with previous findings by [34, 36, 37].

Temperature

The results showed that the average sediment temperature ranged from 28 to 30 ± 2 ℃ during the pre-monsoon period and increased to 30–32 ± 2 ℃ during the post-monsoon period at the study sites. The mean temperatures recorded in both seasons were higher than the permissible limits recommended by the World Health Organization [38]. Elevated sediment temperatures can intensify microbial activity, accelerate organic matter decomposition, and alter nutrient regeneration processes [39].

The observed post-monsoon increase in sediment temperature likely reflects enhanced solar radiation, reduced cloud cover, and limited sediment mixing following monsoonal circulation. Sustained thermal elevations above guideline values suggest cumulative thermal stress on benthic habitats, potentially reducing ecosystem resilience to additional pressures, such as organic enrichment or chemical contamination. Under ongoing climatic warming, such conditions may amplify sediment–water feedbacks and disrupt benthic community structure [40].

Hydrogen Ion pH

Sediment pH values varied between 6.7 and 7.74 at Hs_1, reaching a maximum of 8.76 at Is_1 (Figure 3, Table 2). **Statistically** significant seasonal differences were recorded ($P > 0.02$– 0.000), with a strong correlation (R = 0.6–0.9) (Table 3). Although pH values did not exceed the World Health Organization (WHO) limits, elevated levels were observed at Is1, Ms2, Ss2, Ss1, and Sts1.

Lower pH values at several coastal sites during the first period likely reflect enhanced organic matter decomposition and CO_2 production, which increases acidity under conditions of reduced wind and wave mixing. Minimum pH values occurred near wastewater treatment plant (WWTP) outlets (Hs1, Hs2, Ss1, Is1, Fs1, Bs1), indicating localized anthropogenic effects. Such acidification can modify metal solubility, nutrient availability, and benthic organism tolerance thresholds, consistent with previous studies [34, 41].

Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

Electrical conductivity (EC) and total dissolved solids (TDS) values exhibited clear spatial and seasonal variations. The lowest values were recorded at Bs2 (2036.6 $\mu s/cm$ – 1305.2 mg/l during the pre-monsoon; and 1521.9 $\mu s/cm$ – 975.8 mg/l during the post-monsoon), while the highest values occurred at Fs1 (4179.6 $\mu s/cm$ – 2676.7 mg/l; and 2718.4 $\mu s/cm$ – 1741.6 mg/l) (Figure 3; Table 2). Seasonal differences were statistically significant (P < 0.002), and EC was strongly positive correlated with TDS (R = 0.7) (Table 3).

EC values exceeded WHO limits during the pre-monsoon period at several coastal sites, while TDS exceeded permissible limits at nearly all sites. Elevated values near wastewater treatment plant (WWTP) outlets indicate anthropogenic inputs, which are compounded by reduced wind-driven mixing and elevated temperatures. In contrast, higher EC values offshore at the Sts sites likely reflect natural mineral inputs from sediment weathering and salt-bearing geological formations [35, 42].

Lower EC and TDS values during the post-monsoon period indicate dilution effects driven by intensified hydrodynamic mixing associated with seasonal winds, facilitating the dispersion of dissolved constituents [43]. These patterns highlight the combined influence of natural seasonal forcing and localized wastewater inputs on sediment ionic composition.

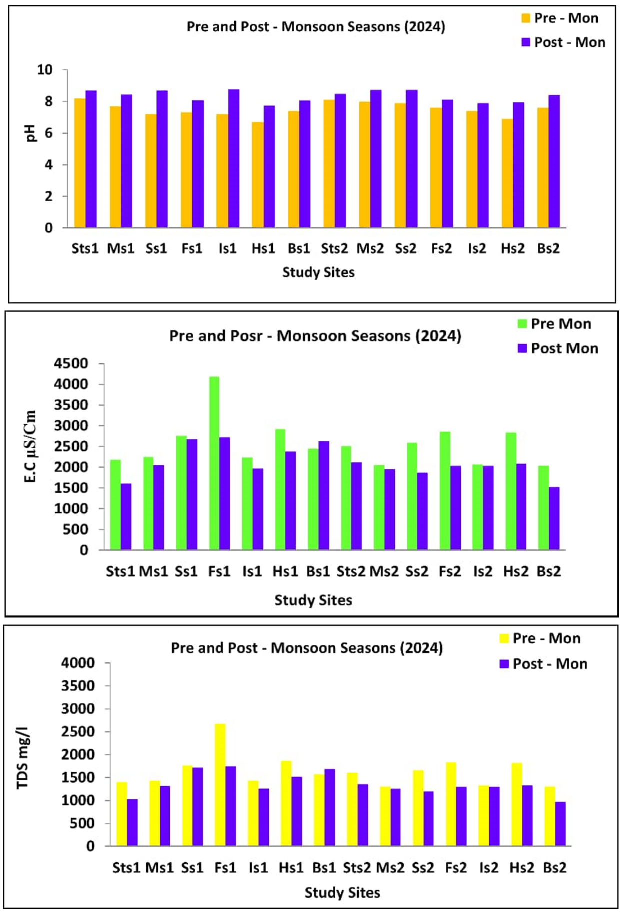

Figure 3. Seasonal Variations of pH, E.C ($\mu S/cm$), and TDS (mg/l) of Marine Sediment during the study period.

Organic Matter (OM) and Total Organic Carbon (TOC)

The concentrations of OM and TOC showed clear temporal and spatial variations between the two monsoon periods. During the pre-monsoon, TOC and OM values ranged from 0.07% to 0.04% to 0.28% to 0.16% at sites Ms1, Ms2, and Fs1, while during the post-monsoon, they increased to 0.25% to 0.15% and 0.74% to 0.43% at sites Sts1 and Hs2, respectively (Figure 4, Table 2). Differences between the two periods were statistically significant (P = 0.003–0.004; 0.000), with strong positive correlations (R = 0.7–0.9) (Table 3).

Despite localized enrichment, overall OM and TOC levels remained relatively low, likely due to rapid microbial degradation and active sediment–water exchange. During the post-monsoon period, deeper sediments exhibited higher OM accumulation, driven by seasonal hydrodynamics and reduced resuspension, consistent with previous studies [44–46]. These findings suggest that organic enrichment is spatially constrained but may intensify under prolonged reductions in hydrodynamic energy.

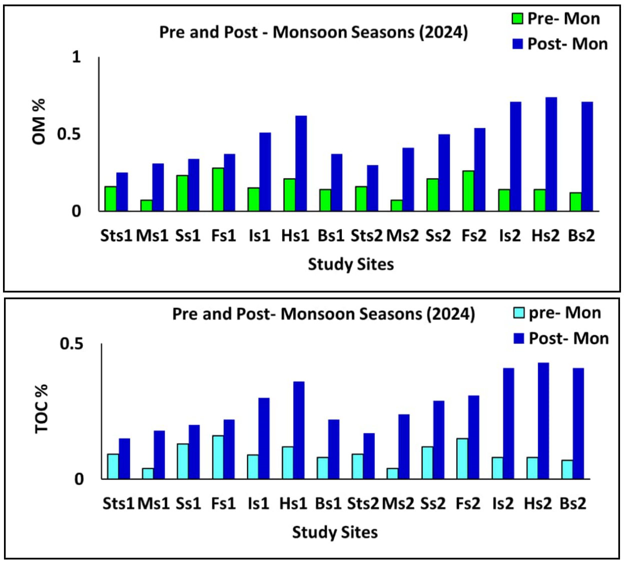

Figure 4. Seasonal Variations of OM & TOC% of Marine Sediment during the study period.

Cations in Marine Sediments (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+})

Understanding the distribution of cations in marine sediments is ecologically important. Some cations are essential for regulating sediment geochemistry, mineral formation, and nutrient availability [47]. They play important roles in carbonate precipitation and dissolution processes, carbon storage, and biogeochemical processes [48]. Therefore, studying their concentrations in marine sediments offers valuable information about ecosystem processes and the condition of benthic habitats. Investigating these ions in sediment environments supports the detection of environmental changes, improves forecasts of ecological dynamics, and strengthens the scientific basis for coastal protection and management.

Concentrations of Ca^{2+} markedly increased during the second post-monsoon period at Bs1, Hs1, Sts1, Ms1, and Fs1, reaching 300, 252, 170, 162, and 162 mg/l, respectively (Figure 5). This enrichment is likely driven by intensified wave action, stronger water-column mixing, and elevated CO_2 uptake, which collectively enhance $CaCO_3$ precipitation. The lower Ca^{2+} levels observed during the first period were likely associated with biological uptake for shell and skeletal formation [43]. Although Ca^{2+} remained below typical seawater values ($\tilde{4}00\ mg/l$) [49], spatial variability highlights localized geochemical controls.

During the first period, Mg^{2+} concentrations exceeded WHO guideline limits at most stations, except Bs1, Is1, and Sts1, where the values were 98, 140, and 143 mg/l, respectively (Figure 5). The subsequent reduction in Mg^{2+} during the second period may reflect biogenic utilization by shell-forming organisms, many of which incorporate both $CaCO_3$ and $MgCO_3$ into their skeletal structures. It is important to note that Mg^{2+} is a naturally occurring and essential element for marine organisms, playing key roles in enzyme activity, physiological regulation, and salt balance. Elevated Mg^{2+} levels at Hs1 and Bs1 following rainfall reflect mineralogical controls and terrestrial inputs [45].

In contrast, both Na^+ and K^+ concentrations exceeded the permissible WHO limits at most sites during both seasons, except at Fs2 and Is2 during the pre-monsoon period and at Is1 during the second post-monsoon period (Figure 5). Elevated levels, particularly at stations located near WWTP outlets, are likely influenced by wastewater discharges containing high concentrations of sodium and potassium salts. Such inputs can contribute to the formation of toxic compounds, including $NaNO_3$, KNO_3, and KCl, along with increases in NaCl levels, all of which may pose ecological risks to marine organisms [50]. The distribution of Na^+ and K^+ in marine sediments may also be interdependent, reflecting shared sources, similar geochemical behavior, and comparable transport pathways [51]. Increased concentrations of Na^+ and K^+ due to sustained anthropogenic influence may alter sediment ionic balance and impose chronic osmotic stress on benthic organisms [52].

Anions in Marine Sediments (Cl^-, HCO_3^-, SO_4^{2-})

Anion concentrations increased during the second period, with Cl^-, HCO_3^-, and SO_4^{2-} averaging 1870, 220, and 280 mg/l, respectively, particularly at Bs2, Fs1, and Sts sites (Figure 6, Table 2). Statistically significant differences were detected for most anions between the two seasons (P = 0.004–0.001), except for Cl^- during the first period. Strong correlations were observed, including R = 0.8 for SO_4^{2-} and R values ranging from 0.6 to –0.5 for Cl^- (Table 3). Elevated alkalinity corresponded with higher HCO_3^- concentrations, especially at Sts2 (200 mg/l), while the lowest values occurred at Is1 (34–35.7 mg/l). Seasonal comparison also showed significant variation in HCO_3^- ($P < 0.001$; R = 1) (Table 3).

Lower Cl^- levels during the first period may be related to decreased pH (toward acidity) at coastal sites compared with deeper stations, as well as lower tidal heights (41.25–69.67 cm), which reduce saltwater intrusion. In contrast, the pronounced increase in Cl^- during the second period reflects enhanced seawater mixing and salt transport under the influence of higher tidal conditions (102–109 cm), stronger wind-driven circulation, and the movement of colder water masses. Additional contributions from evaporation, increased drainage, and the input of terrestrially transported sediments during rainfall events (Figure 2) also support Cl^- enrichment, consistent with observations reported by [43]. The data further showed higher mean HCO_3^- concentrations at

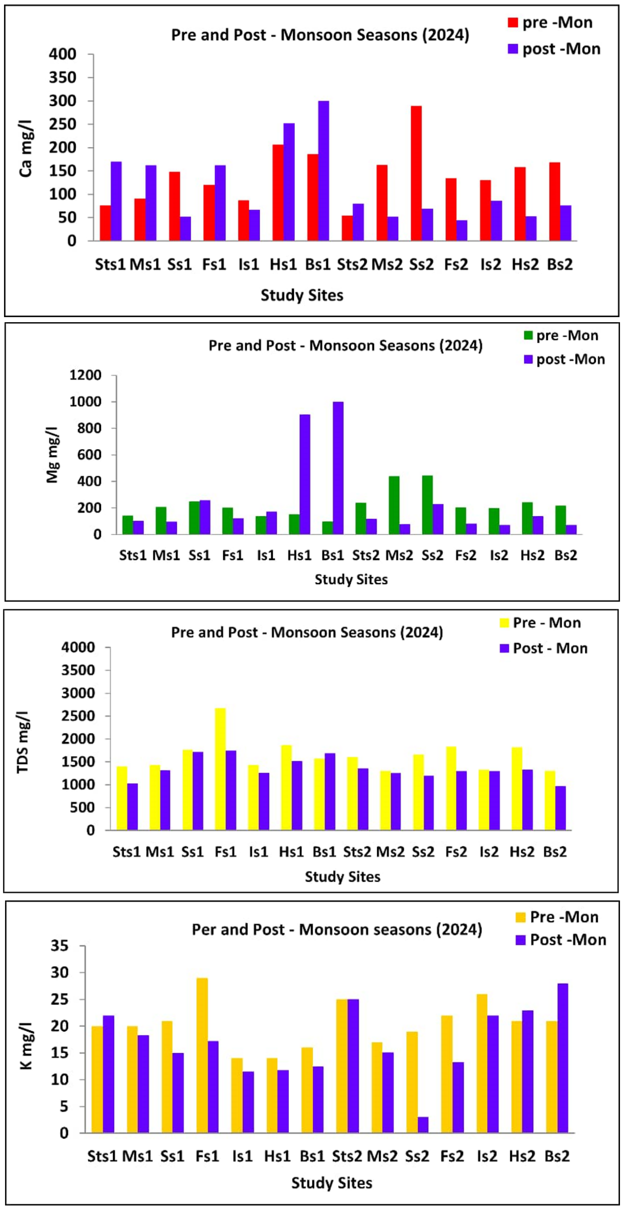

Figure 5. Seasonal Variations of Ca^{2+}, Mg^{2+}, Na^+, K^+ (mg/l) of Marine Sediment during the study period.

deep-water sites relative to coastal areas, except at Fs1. The slight coastal decline in HCO_3^- during the second period likely resulted from increased organic matter inputs from sewage, where microbial decomposition releases CO_2 that combines with water to form HCO_3^-. Alkaline substances in sewage also elevate the water's acid-neutralizing capacity. This pattern aligns with the upwelling of cold, low-saturation waters driven by monsoon winds, which helps redistribute HCO_3^- between the surface and deeper layers [53]. SO_4^{2-} concentrations remained below the WHO and USEPA limits during the first period, except at Sts1, where levels reached 190 mg/l. During the second period, SO_4^{2-} increased significantly at Sts1, Sts2, Is2, and Bs2. This increase is attributed to both natural and anthropogenic sources: sulfate derived from the oxidation of reduced minerals, such as pyrite (FeS_2), as well as inputs from detergents

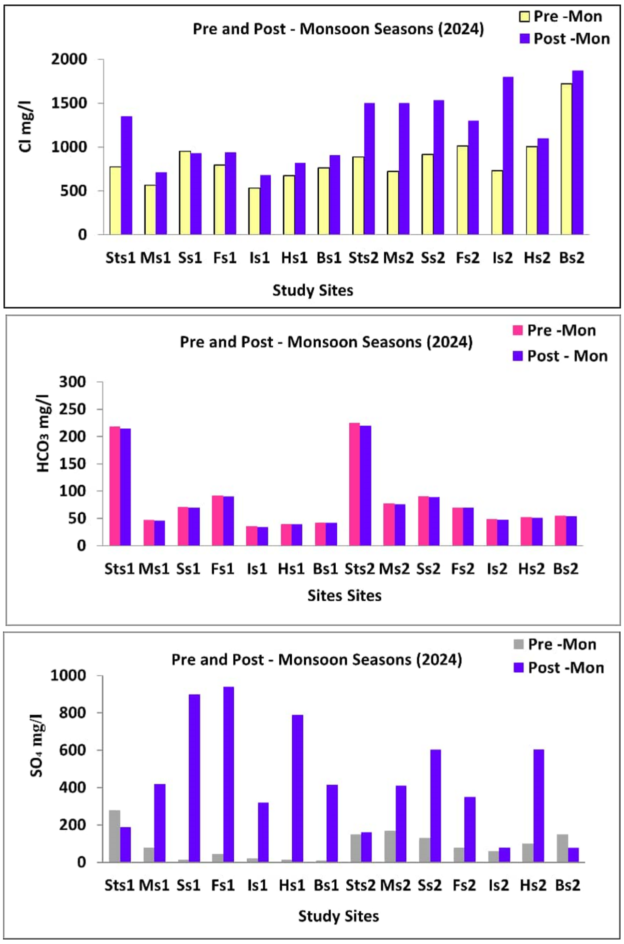

Figure 6. Seasonal Variations of Cl^-, HCO_3^- SO_4^{2-} (mg/l) of Marine Sediment during the study period.

and organic waste. Seasonal declines in SO_4^{2-} are consistent with bacterial sulfate reduction under anaerobic conditions, where sulfate is converted to hydrogen sulfide (H_2S) during microbial respiration. H_2S produced in sediments provides an energy source for chemo-symbiotic organisms inhabiting benthic fauna. This explains the first-period decrease in SO_4^{2-} associated with reduced organic carbon, especially at coastal sites compared to deeper waters, or through reactions with sodium ions forming compounds such as Na_2SO_4 [54].

Overall, the results demonstrate that sediment physicochemical properties along the Hadhramout coast are governed by the interaction between monsoon-driven hydrodynamics and localized wastewater inputs. Seasonal mixing regulates dilution and redistribution processes, whereas untreated sewage acts as a persistent source of ionic and organic enrichment at nearshore sites. These findings highlight the need for targeted monitoring near discharge zones and reinforce the importance of restoring wastewater treatment capacity to mitigate cumulative impacts on benthic habitats.

4. CONCLUSION

This study demonstrates that seasonal variability in the physicochemical properties of coastal marine sediments along the Hadhramout coast is primarily governed by the interaction between monsoon-driven hydrodynamics and localized anthropogenic pressures. Seasonal changes in Ca^{2+} and Mg^{2+} reflect carbonate system dynamics and sediment–water exchange processes, whereas consistently elevated Na^+ and K^+ concentrations at nearshore

Table 1. The Percentage of Grain Size Distribution During Fields (for 14 Sites).

Area	Sites	Sand %	Silt %	Clay %	Textural Triangle	Size 600g	R-Yemen		R-USA	
							C.S (2-0.2)	F.S (0.2-0.02)	C.S (2-0.5)	F.S (0.25-0.1)
						%	mm			
1	**Sts$_1$**	90	9	0	*Sand*	0	✓	0	✓	0
	Sts$_2$	86	9	3	*Sand*	1.2%	✓	0.1	✓	0.1
2	**Ms$_1$**	95	1	2	*Sand*	2.4%	✓	0.2	✓	0.2
	Ms$_2$	96	2	2	*Sand*	0.6%	✓	0.05	✓	0.05
3	**Ss$_1$**	96	2	1	*Sand*	0.6%	✓	0.05	✓	0.05
	Ss$_2$	95	2	4	*Sand*	2.4%	✓	0.2	✓	0.2
4	**Fs$_1$**	92	4	3	*Sand*	1.2%	✓	0.1	✓	0.1
	Fs$_2$	85	9	4	*Loamy Sand*	2.4%	✓	0.2	✓	0.2
5	**Is$_1$**	95	4	0	*Sand*	1.2%	✓	0.1	✓	0.1
	Is$_2$	89	8	2	*Sand*	0	✓	0	✓	0
6	**Hs$_1$**	98	1	0	*Sand*	0	✓	0	✓	0
	Hs$_2$	93	5	0.2	*Sand*	0.3%	✓	0.025	✓	0.025
7	**Bs$_1$**	90	9	0	*Sand*	0	✓	0	✓	0
	Bs$_2$	96	3	0.2	*Sand*	0.3%	✓	0.025	✓	0.025
1 Zaluma, 2 Al-Mukalla, 3 Al-Sharg, 4 Bajrash, 5 Ibn Sina, 6 Al-Shageen, 7 Broom										

Table 2. Seasonal Average of Organic matter; Total Organic Carbon and Physicochemical Parameters in Marine Sediment at the Study Area During Pre- Monsoon, Post-Monsoon.

Seasons		Per- Monsoon												Post- Monsoon											
Area	**Site**	**pH**	**E.C µS/cm**	**T.D.S mg/l**	**O.M %**	**T.O.C %**	**Ca^{2+} mg/l**	**Mg^{2+} mg/l**	**Na^{+} mg/l**	**K^{+} mg/l**	**Cl^{-} mg/l**	**HCO_3^{-} mg/l**	**SO_4^{2-}mg/l**	**pH**	**E.C µS/cm**	**T.D.S mg/l**	**O.M %**	**T.O.C %**	**Ca^{2+} mg/l**	**Mg^{2+} mg/l**	**Na^{+} mg/l**	**K^{+} mg/l**	**Cl^{-} mg/l**	**HCO_3^{-} mg/l**	**SO_4^{2-} mg/l**
Zaluma	**Sts_1**	8.2	2179.4	1396.6	0.16	0.093	76	143	516	20	773	219	280	8.70	1604.7	1027	0.25	0.15	170	105	550	22	1350	215	190
	Sts_2	8.1	2506.1	1605.7	0.07	0.04	54	240	436	25	887	225	150	8.47	2121.9	1358	0.30	0.17	80	120	650	25	1500	220	160
Al-Mukalla	**Ms_1**	7.7	2242.5	1437	0.07	0.04	91	208	397	20	563	47	80 bb	8.44	2056.9	1318.2	0.31	0.18	162	96	230	18.33	710	46	420
	Ms_2	8	2058.67	1307	0.23	0.13	163	440	233	17	722	78	170	8.73	1959.2	1255.7	0.41	0.24	52	78	190	15.1	1500	76	410
Al-Sharg	**Ss_1**	7.2	2753.6	1764	0.21	0.12	148	250	340	21	952	71	15	8.7	2684	1719.6	0.34	0.20	52	258	220	15	928	70	900
	Ss_2	7.9	2586.7	1657.3	0.28	0.16	289	444	236	19	916	90.8	130	8.72	1866.4	1194.5	0.50	0.29	69	230	180	3	1534	89	603
Bajrash	**Fs_1**	7.3	4179.6	2676.7	0.26	0.15	120	202	491	29	793	92	45	8.07	2718.4	1741.6	0.37	0.22	162	122	251	17.2	940	90	940
	Fs_2	7.6	2856.3	1829.8	0.15	0.09	134	206	195	22	1011	70	80	8.11	2030.3	1299.4	0.54	0.31	44	82	130	13.3	1300	70	350
Ibn-Sina	**Is_1**	7.2	2240.8	1435.9	0.14	0.08	87	140	233	14	533	35.7	20	8.76	1970.27	1263	0.51	0.30	67	172	191	11.5	680	34	320
	Is_2	7.4	2065.5	1323.7	0.21	0.12	130	200	189	26	731.3	49	60	7.9	2028.1	1299.8	0.71	0.41	86	72	185	22	1800	48	80
Al-Shageen	**Hs_1**	6.7	2914.5	1867	0.14	0.08	206	153	545	14	673	39.8	15	7.74	2373.3	1520.7	0.62	0.36	252	905	320	11.8	820	39	790
	Hs_2	6.9	2833.5	1815.3	0.14	0.08	158	243	230	21	1003	52	100	7.95	2085.7	1336.7	0.74	0.43	53	140	120	23	1100	51	605
Broom	**Bs_1**	7.4	2448	1568.5	0.12	0.07	186	98	593	16	763	42.84	10	8.05	2632.2	1686.7	0.37	0.22	300	1000	365	12.5	910	42	415
	Bs_2	7.6	2036.6	1305.2	0.16	0.093	168	218	244	21	1721	55.08	150	8.41	1521.9	975.8	0.71	0.41	76	71	183	28	1870	54	78
Min		6.7	2036.6	1305.2	**0.07**	**0.04**	**54**	**98**	**189**	**14**	**533**	**35.7**	**10**	7.63	1521.9	975.8	**0.25**	**0.15**	**44**	**71**	**120**	**3**	**680**	**34**	**78**
Max		8.2	4179.6	2676.7	**0.28**	**0.16**	**289**	**444**	**593**	**29**	**1721**	**225**	**280**	8.61	2718.4	1741.6	**0.74**	**0.43**	**300**	**1000**	**650**	**28**	**1870**	**220**	**940**
WHO		6.5 – 8.5	1500	1000	**N**	**N**	**200**	**150**	**200**	**8**	**250**	**N**	**250**	6.5 -8.5	1500	1000	**N**	**N**	**200**	**150**	**200**	**8**	**250**	**N**	**250**
National Guidelines		6.5 - 9	2500	1500	**N**	**N**	**200**	**150**	**400**	**12**	**N**	**N**	**400**	6.5-9	2500	1500	**N**	**N**	**200**	**150**	**400**	**12**	**N**	**N**	**400**

Table 3. Seasonal Analysis to Std, L.S.D, and Corr. R of Ecological Parameters in Marine Sediment at the Study Area Pre-Monsoon, Post-Monsoon.

Seasons	**Per- Monsoon**			**Post- Monsoon**			**Per & Post- Monsoon**		
Analysis Variation	**Std. Deviation**	**L.S.D $_{0.05}$**	**Corr. (R)**	**Std. Deviation**	**L.S.D $_{0.05}$**	**Corr. (R)**	**Std. Deviation**	**L.S.D $_{0.05}$**	**Corr. (R)**
pH	0.237	0.02	0.9 $_{SR+}$	0.418	0.9	0.4 $_{WR+}$	0.357	000	0.6 $_{SR+}$
E.C µS/cm	507.61	0.18	0.7 $_{SR+}$	562.26	0.15	-0.5 $_{SR-}$	420.62	0.002	0.7 $_{SR+}$
TDS mg/l	324.49	0.18	0.7 $_{SR+}$	360.27	0.15	-0.5 $_{SR-}$	270.24	0.002	0.7 $_{SR+}$
O.M %	0.023	0.06	0.9 $_{SR+}$	0.093	0.003	0.8 $_{SR+}$	0.180	000	- 0.03 $_{WR-}$
T.O.C %	0.014	0.06	0.9 $_{SR+}$	0.526	0.004	0.9 $_{SR+}$	0.103	000	- 0.03 $_{WR-}$
Ca^{2+} mg/l	65.179	0.33	0.5 $_{SR+}$	94.470	0.03	-0.2 $_{WR-}$	96.358	0.3	0.1 $_{WR+}$
Mg^{2+} mg/l	77.718	0.008	0.8 $_{SR+}$	400.90	0.12	-0.01 $_{WR-}$	356.34	0.8	-0.4 $_{WR-}$
Na^{+} mg/l	124.874	0.006	0.4 $_{WR+}$	105.55	0.13	0.8 $_{SR+}$	120.18	0.02	0.7 $_{SR+}$
K^{+} mg/l	6.630	0.37	-0.2 $_{WR-}$	9.93	0.45	-0.1 $_{WR-}$	5.884	0.05	0.5 $_{SR+}$
Cl^{-} mg/l	320.08	0.06	0.3 $_{WR+}$	364.70	0.004	-0.1 $_{WR-}$	321.80	0.001	0.6 $_{SR+}$
HCO_3^{-} mg/l	16.314	0.14	1 $_{SR+}$	14.435	0.12	1 $_{SR+}$	1.334	000	1 $_{SR+}$
SO_4^{2-} mg/l	89.24	0.16	0.4 $_{WR+}$	197.98	0.01	0.8 $_{SR+}$	330.86	0.002	-0.5 $_{SR-}$

stations clearly indicate the effects of untreated wastewater discharge. Variations in Cl^{-}, HCO_3^{-}, and SO_4^{2-} further highlight the role of tidal mixing, upwelling, and organic matter decomposition in controlling sediment geochemistry.

The key environmental issue identified is the persistent discharge of untreated or partially treated sewage, which alters sediment chemical composition and poses a long-term risk to benthic habitat quality and ecosystem functioning. These impacts are intensified during periods of reduced hydrodynamic mixing, underscoring the vulnerability of nearshore sediments to cumulative anthropogenic stress.

To address these risks, local environmental and coastal management authorities should prioritize (i) the rehabilitation and upgrading of wastewater treatment facilities, (ii) enforcement of effluent discharge standards, and (iii) the implementation of routine, seasonally resolved monitoring programs. Monitoring efforts should focus on sediments and overlying waters near wastewater outlets and include key indicators such as major ions, organic matter content, and sulfate reduction processes, which provide an early warning of sewage-derived impacts. The baseline data generated by this study provide a critical foundation for evidence-based coastal management and future environmental assessments along Yemen's southern coast.

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