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Physicochemical degradation of *Avicennia marina* mangrove soils in the Red Sea: implications for coastal ecosystem services

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Mangrove ecosystems are remarkable coastal environments that thrive at the interface between land and sea, playing a crucial role in maintaining ecological balance and safeguarding coastal agricultural and fisheries productivity through erosion control, nutrient cycling, and salinity buffering. The physicochemical properties of mangrove soils underpin the health of these ecosystems, particularly for *Avicennia marina*, a keystone species critical to coastal resilience and habitat provisioning. However, anthropogenic disturbances threaten their sustainability and compromise their ability to deliver vital ecosystem services. Soil samples from undisturbed (Southern Corniche, Jeddah) and disturbed (Masturah) mangrove sites were analyzed for physicochemical characteristics to assess potential anthropogenic impacts along Saudi Arabia's Red Sea coast. From six locations (undisturbed: Jeddah, n=3; disturbed: Masturah, n=3) soil samples were analyzed for texture, pH, electrical conductivity (EC), total dissolved solids (TDS), water content (%WC), total nitrogen (TN), phosphorus (TP), organic carbon (TOC), macronutrients (Na⁺, Ca²⁺, Mg²⁺, K⁺), and cation exchange capacity (CEC). Undisturbed soils exhibited significantly higher moisture, TN, TP, and TOC—key indicators of nutrient retention and carbon sequestration capacity—while disturbed soils were more alkaline, a condition linked to diminished nutrient cycling and plant stress. Macronutrient distribution (Na⁺ > Mg²⁺ > Ca²⁺ > K⁺) remained consistent across sites, suggesting salinity-driven nutrient imbalances may limit mangrove recovery. These findings highlight how soil degradation in disturbed mangroves reduces their ability to stabilize sediments, mitigate saltwater intrusion, and sustain fisheries nurseries, directly impacting coastal communities. Moreover, these soil changes reduce mangrove capacity to buffer adjacent farmland from salinization and erosion, threatening agricultural productivity and undermining carbon sequestration goals central to climate mitigation. To enhance ecosystem resilience, we recommend the application of soil organic amendments and the strategic conservation of high-carbon mangrove zones, in alignment with Saudi Arabia's Vision 2030 sustainability framework. This study highlights the critical importance of safeguarding mangrove soils as foundational natural infrastructure for climate adaptation and food security in arid coastal environments.

KEYWORDS

mangrove forests, mangrove, *Avicennia marina*, physicochemical assessment, pH, salinity, undisturbed, disturbed

1 Introduction

The Red Sea coast of Saudi Arabia is home to a significant population of *Avicennia marina*, a resilient mangrove species that plays a crucial role in maintaining the delicate coastal ecosystem and safeguarding adjacent agricultural and aquacultural systems through shoreline stabilization, nutrient retention, and salinity regulation. For this study, undisturbed mangrove forests were defined as those with no recorded human modification in the past 30 years, based on satellite imagery and field surveys confirming intact canopy cover (>80%) and natural hydrology (1, 2). In contrast, disturbed sites showed visible logging, aquaculture encroachment, or drainage alterations within the past decade.

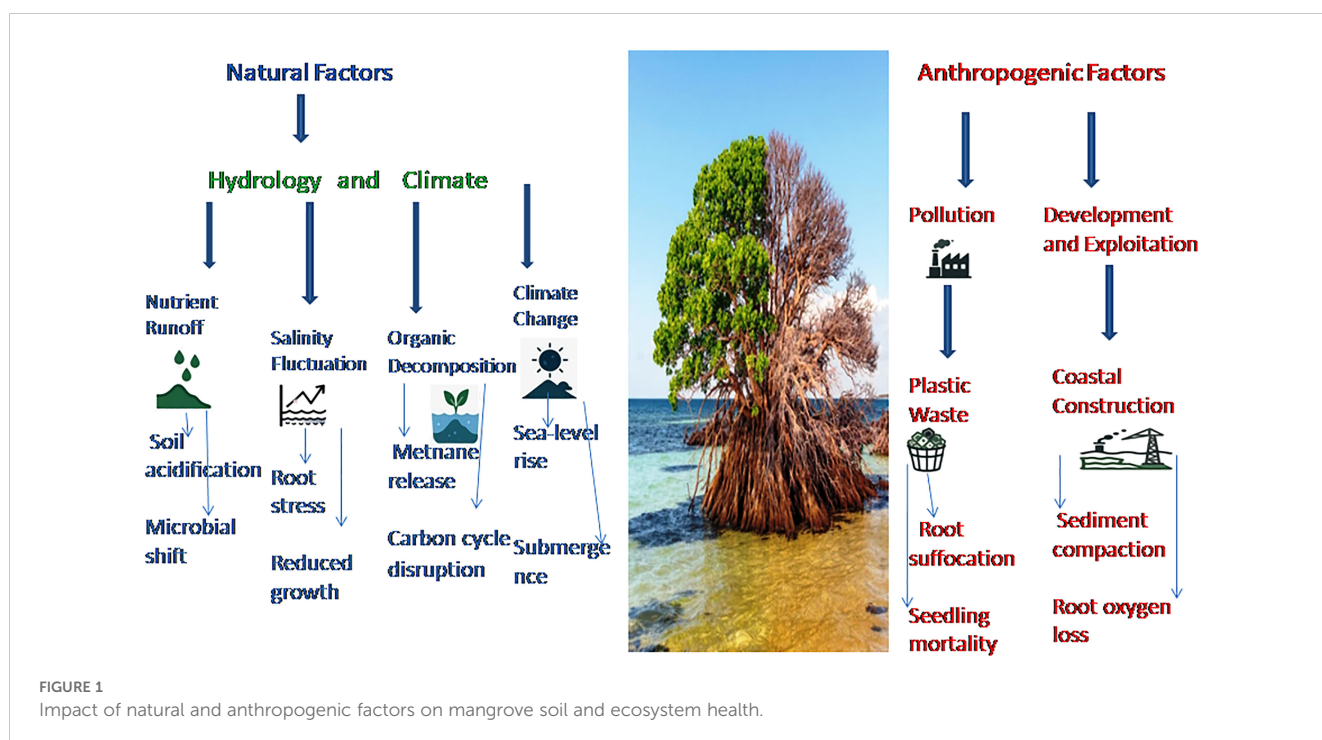
These mangrove ecosystems are increasingly under threat from anthropogenic disturbances and pollution, which degrade soil quality and compromise the mangrove's capacity to act as a buffer against coastal erosion and saltwater intrusion—critical threats to farmland and fisheries. Studies have shown that the mangrove forests along the Red Sea coast have experienced significant degradation and loss over the years (Figure 1) (2), undermining their role in sustaining regional food security and climate resilience. (1, 2).

Saudi Arabia's mangroves, covers approximately 20,000 hectares along its coastline, represent a small but vital component of the global and Asian mangrove distributions, accounting for 0.14% and 0.34%, respectively (3). These ecosystems are essential “blue infrastructure” for coastal communities, filtering pollutants, sequestering carbon, and providing nursery habitats for commercially important fish species. Yet, they face escalating anthropogenic pressures, including urban expansion and deforestation, alongside natural challenges like erosion. Globally, mangrove coverage has decreased by 20%–35% over the past five

decades, with losses in India reaching 39.32%–95% between 1990 and 2001 due to aquaculture conversion, industrial pollution, and land reclamation (4). Saudi Vision 2030 is the national economic diversification plan, prioritizing sustainable tourism and agricultural security as key non-oil sectors. In Saudi Arabia, fragmented mangrove distribution and lagging restoration rates (1, 5) threaten the ecological services these habitats provide to Red Sea coastal economies.

The impacts of mangrove degradation extend deeply into soil health, with cascading consequences for coastal productivity. Soil carbon stocks decline, abiotic conditions shift, and sediment stability erodes, leading to reduced fisheries catches, loss of mollusk populations, and heightened coastal abrasion (6). Such changes directly jeopardize livelihoods dependent on small-scale fisheries and expose farmland to salinization, a critical concern in arid regions like the Red Sea. Moreover, anthropogenic factors such as pollution can directly alter soil composition, disrupting the delicate balance of nutrients and pH levels essential for *Avicennia marina* survival. These shifts weaken mangrove resilience, reducing their capacity to buffer adjacent farmland from saltwater intrusion—a critical concern for Saudi Arabia's arid coastal agriculture, where soil salinization already threatens crop yields.

One of the primary challenges facing Saudi Arabia's mangrove forests is the impact of climate change (7). The Middle East and the Gulf of Arabia basin are expected to be particularly vulnerable to the negative effects of climate change, with predictions of extreme temperatures and other environmental stresses that could significantly impact the health and survival of mangrove ecosystems (8). Such conditions not only stress mangrove health but also diminish their ability to protect inland agricultural zones from storm surges and sea-level rise, directly compromising food security. The intrinsic link between mangrove condition and



climate change positions these ecosystems as biomonitors of regional climate impacts, offering insights into risks for coastal land-use systems (7). Human disturbances compound these threats: conversion of mangroves to fishponds and urban infrastructure drove a 61% decline in Saudi mangrove cover by the 1990s (9), eroding natural barriers that once shielded fertile coastal soils from erosion and salinization.

Mangroves are vital allies in climate mitigation, sequestering carbon at rates 4–8 times higher than terrestrial forests (10, 11). In Saudi Arabia, where arid soils typically exhibit low organic carbon, mangrove sediments represent a critical—yet overlooked—carbon reservoir. Their degradation could release stored CO₂, undermining national efforts to achieve net-zero targets under Saudi Vision 2030. Over 90% of mangrove carbon resides in soil and root biomass (12), making soil health a linchpin for maintaining this ecosystem service. Protecting these carbon stocks is not only ecologically prudent but economically strategic, as it aligns with global carbon markets and climate financing mechanisms.

Beyond carbon, mangroves provide irreplaceable ecosystem services: their roots stabilize shorelines, filter pollutants, and create nurseries for commercially vital fish species. In the Red Sea, where fisheries contribute ~\$1.5 billion annually to the economy, mangrove degradation risks collapsing nursery habitats for shrimp and reef fish, threatening livelihoods and food security. Their sediment-trapping capacity also mitigates saltwater intrusion into coastal aquifers, preserving freshwater resources essential for irrigation in agriculture-dominated regions like Jeddah. The loss of these functions—evident in global examples like Southeast Asia, where mangrove deforestation increased coastal flooding damage by 30% (13) highlights the urgent need to integrate mangrove conservation into Saudi Arabia's coastal land-use planning to safeguard both ecological and agricultural productivity (14–16).

Understanding the physical and chemical properties of mangrove soils is critical not only for ecological conservation but also for safeguarding coastal livelihoods and agricultural productivity in arid regions like the Red Sea. These properties govern nutrient cycling, carbon sequestration, and shoreline stability—ecosystem services directly tied to fisheries yields, freshwater security, and climate resilience. Shoreline dynamics, tidal regimes, and anthropogenic pressures collectively shape mangrove soil characteristics, influencing vegetation health and, consequently, their capacity to buffer adjacent farmland from saltwater intrusion and erosion. For example, advancing shorelines with optimal soil texture and organic matter support robust mangrove regeneration, enhancing sediment trapping that protects coastal irrigation systems, while retreating shorelines signal degraded soils and heightened vulnerability to storm surges. (17, 18).

Optimal mangrove soil conditions—slightly acidic to neutral pH (6.0–7.5), high organic matter, and moderate salinity—are not just ecological benchmarks but also indicators of ecosystem service potential. Organic-rich soils enhance nutrient retention, reducing fertilizer runoff into coastal waters and mitigating eutrophication risks for aquaculture. Conversely, alkaline shifts in disturbed soils (e.g., pH >8.0) disrupt microbial activity, impairing natural

wastewater filtration services critical to maintaining water quality for coastal agriculture. Salinity regulation by healthy mangroves is equally vital: their roots exclude salt, preventing hypersaline groundwater from seeping into farmland—a vital concern in Saudi Arabia, where 30% of coastal soils are already salt-affected (17). Despite their importance, standardized methods for assessing mangrove soil quality remain scarce, hindering evidence-based policies to balance conservation with coastal development. This study addresses this knowledge gap through a comprehensive approach, combining field sampling, laboratory analyses, and statistical modeling to assess the impact of human-induced pressures on key soil properties, including moisture, nutrients, and salinity (12).

Understanding the physical and chemical properties of mangrove soils is critical not only for ecological conservation but also for safeguarding coastal livelihoods and agricultural productivity in arid regions like the Red Sea. These soil parameters provide valuable indicators for assessing mangroves' ability to support fisheries nurseries, store carbon, and safeguard agricultural land, offering a relevant framework for managing arid coastal ecosystems worldwide. As there remains a lack of detailed, statistically robust data on soil chemistry across different mangrove zones. Previous studies have either focused on biodiversity or general environmental assessments, without integrating quantitative soil and water parameters using rigorous statistical methods. This study investigates *Avicennia marina* soil physicochemical properties in Red Sea mangroves, aiming to provide actionable insights for sustainable land management and conservation initiatives (1).

Mangrove ecosystems are among the world's most valuable blue-carbon habitats, providing critical services such as coastal protection, carbon sequestration, and nursery grounds for fisheries (10, 12). However, global mangrove coverage has declined precipitously by 20–35% over the past 50 years, primarily due to anthropogenic pressures such as aquaculture conversion, coastal development, and pollution (19, 20). This degradation is not just a loss of forest cover; it triggers a cascade of negative impacts on soil physicochemical properties, which form the foundation for these ecosystem services (21, 22).

Along the Red Sea coast of Saudi Arabia, these global threats are acutely present. Mangroves, predominantly *Avicennia marina*, face pressures from urbanization, industrial expansion, and tourism (1, 2). Previous studies in the region have successfully documented rates of mangrove loss and fragmentation (e.g., 9) and have described general biodiversity patterns. Studies have also noted that soil properties are key to mangrove health (e.g., 23).

A significant research void exists in understanding the detailed mechanisms of human-induced soil degradation in Red Sea mangroves and its direct impact on ecosystem services. While degradation is known to occur, previous studies have not comprehensively linked specific human activities to changes in key soil properties (e.g., organic carbon, nutrients, salinity) and then connected those changes to the loss of critical functions like coastline stabilization and farmland protection. This study is designed to fill that exact gap by providing a mechanistic, soil-

focused assessment that links human disturbance to quantifiable changes in soil properties and, crucially, to the impairment of specific ecosystem services. The ultimate goal is to generate actionable insights to guide effective conservation and restoration strategies in line with Saudi Vision 2030 (24).

2 Materials and methods

2.1 Study sites

This study was conducted along the Red Sea Coast of Saudi Arabia, comparing mangrove soils in an ecologically intact, protected area (Southern Corniche, Jeddah City, Mecca Province) and a degraded site exposed to anthropogenic stressors (Masturah, Rabigh Governorate, Madinah Province). Site selection was designed to contrast soil conditions under divergent management regimes, providing insights into how human activity alters mangrove soil functionality—a critical factor for coastal resilience and adjacent land-use sustainability.

2.1.2 Undisturbed site (Jeddah)

Location: Three subsites (A, B, C) within Southern Corniche, a region under minimal direct human influence due to its designation as a coastal conservation zone (21°16'03.7"N 39°07'38.0"E; 21°16'05.5"N 39°07'37.0"E; 21°15'45.8"N 39°07'45.5"E) (Figure 2).

2.1.2 Characteristics

Located near the Jeddah Marine Sanctuary, where mangrove conservation aligns with regional biodiversity protection goals.

Soils here represent a baseline for mangrove soil health, with natural tidal flushing and limited sediment disruption.

Surrounding land use includes low-density urban infrastructure, minimizing pollutant influx.

2.1.3 Disturbed site (Masturah)

Location: Three subsites (D, E, F) in Masturah (23°04'08.7"N 38°48'39.1"E; 23°04'40.9"N 38°48'40.7"E; 23°05'22.6"N 38°48'43.4"E), a region experiencing rapid coastal development and habitat fragmentation (Figure 2).

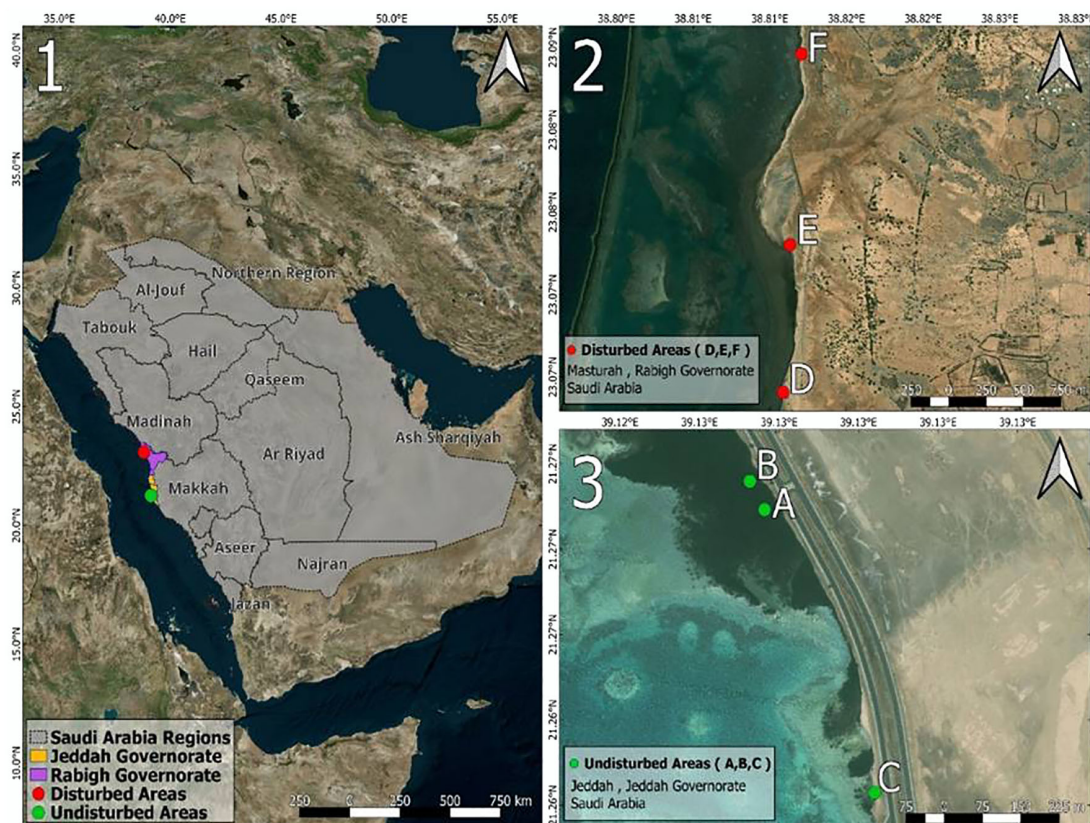


FIGURE 2

Map 1 illustrates the geographical locations of the study sites, providing a general overview of Saudi Arabia, highlighting Jeddah and the Rabigh Governorate, where the *Avicennia marina* study areas are situated. Map 2 delineates the disturbed mangrove areas, designated as Area D, Area E, and Area F. Conversely, Map 3 depicts the undisturbed areas, labeled as Area A, Area B, and Area C. All maps were generated using QGIS software (version 3.28.0) and created by Haitham Ali Sheikh.

2.1.4 Characteristics

Proximity to industrial activities, desalination plants, and unregulated tourism—key drivers of soil compaction, pollution, and altered hydrology.

Historical conversion of mangrove areas to temporary fish drying stations and informal settlements, disrupting sediment accretion.

Located within a semi-enclosed bay with restricted tidal exchange, exacerbating salinity stress and nutrient stagnation.

2.1.5 Regional context

Both sites experience a hyper-arid climate (mean annual rainfall <70 mm) with high evaporation rates, making soil salinity and water retention critical factors for mangrove survival. The undisturbed Jeddah site serves as a natural laboratory for studying mangrove soil processes in the absence of major anthropogenic pressures, while Masturah exemplifies degradation hotspots where mangrove loss threatens coastal protection services for nearby agricultural communities.

The classification of sites as ‘undisturbed’ or ‘disturbed’ was based on direct physical evidence observed during field surveys, corroborating land-use data. The disturbed site (masturah) exhibited clear signs of anthropogenic pressure, including visible fragmentation of the mangrove canopy, well-established trampling pathways compacting the soil surface, and the presence of anthropogenic debris (primarily plastic waste and discarded fishing materials). Furthermore, evidence of historical excavation and altered drainage patterns was apparent. In contrast, the undisturbed site (Southern Corniche, Jeddah) showed no such signs; it featured a continuous canopy cover, no visible trails or soil compaction from human activity, an absence of litter, and natural, undisturbed tidal channels. This stark contrast in physical integrity confirms that the Masturah site is actively degraded, justifying the comparative framework.

The undisturbed site (Southern Corniche, Jeddah) is situated within the Jeddah Marine Sanctuary, a protected area managed under the National Center for Wildlife (NCW) in alignment with the Saudi Green Initiative and Vision 2030’s environmental goals. The explicit regional biodiversity protection goals for this sanctuary are to preserve critical coastal habitats (mangroves, seagrasses, coral reefs), conserve threatened marine species (e.g., Halavi guitarfish, hawksbill turtle), and maintain ecosystem services like coastal stabilization and carbon sequestration. This formal designation enforces strict regulations against construction, dredging, and habitat alteration, resulting in the observed intact canopy, natural hydrology, and absence of direct anthropogenic disturbance that justifies its use as an undisturbed reference site.

2.2 Soil sample collection

Soil samples were collected from *Avicennia marina* habitats along Saudi Arabia’s Red Sea coast from March to June 2023,

targeting undisturbed (Southern Corniche, Jeddah) and disturbed (Masturah) mangrove zones. This spatial comparison enables identification of soil degradation patterns critical for prioritizing restoration efforts in high-risk agricultural buffer zones. A total of 18 samples (9 disturbed, 9 undisturbed) were collected using a 22-inch soil probe, with three replicates per subsite spaced 200 m apart to account for microhabitat variability. Samples were extracted at a standardized depth of 15 cm—the root-active zone influencing mangrove stability and sediment retention capacity—and stored in labeled bags (25, 26).

2.3 Soil sample preparation

Soil appearance was evaluated using Thien (27) ribbon test to classify plasticity, a key indicator of sediment cohesion and erosion resistance. A small soil sample, sufficient to fit in the palm of the hand, was taken, and the fraction larger than 2 mm was manually removed. The soil was then moistened and kneaded into a bolus for 1 to 2 minutes until it was no longer sticky. The bolus was shaped between the thumb and forefinger to form a ribbon approximately 2 mm thick and 1 cm wide. The length of the ribbon was measured and recorded. Additionally, molding the bolus into rods facilitated the classification of soils with high clay content.

Texture was quantified via the hydrometer method (28), with results processed through the Agricultural Technology Centre soil texture calculator. For soil extract preparation, 50 grams of soil were weighed and placed in a dispersing cup, to which 100 milliliters of a 5% sodium hexametaphosphate (Calgon) solution were added. The mixture was agitated for 30 to 60 seconds and transferred to a 1000-milliliter container, filled to the mark with distilled water. For the blank sample, 880 milliliters of distilled water were used. The suspension was allowed to equilibrate to room temperature, and the temperature and hydrometer reading of the blank were recorded.

The suspension was mixed with a plunger for 30 seconds, and the hydrometer and thermometer were inserted. The hydrometer reading was recorded after 40 seconds and again after 6 hours and 52 minutes. Particle size distribution was determined using the hydrometer method as per Gee and Or (29).

2.4 Physicochemical analyses of soil

Soil properties were analyzed to assess functional indicators of ecosystem service provision, including appearance, texture, water content, pH, salinity, organic carbon, nitrogen, phosphorus, EC, CEC, TDS, and macronutrient bioavailability (Na^+ , Ca^{2+} , Mg^{2+} , K^+).

2.4.1 Physical analysis of soil

Soil texture was quantified via the hydrometer method (28). Soil water content as percent water content (%WC) was determined by oven-drying at 105°C until constant weight (30, 31).

Total Dissolved Solids (TDS) were determined from mangrove soil samples (0–30 cm depth) using a saturated paste extract (32). Air-dried, sieved (2 mm) soil was mixed with deionized water (1:1 w/v), filtered (0.45 μm), and measured for electrical conductivity (EC). TDS (mg/L) was calculated as $\text{EC (dS/m)} \times 640$, an empirical factor validated for saline soils (APHA, 2017; Almahasheer, 2018). Triplicate measurements ensured precision, with NaCl standards (500–2000 mg/L) for calibration. This method aligns with Red Sea mangrove studies reporting TDS ranges of 1500–3000 mg/L (33).

2.4.2 Chemical analyses of soil

Soil pH and EC were calibrated daily using NIST-traceable buffers (pH 4.0, 7.0, 10.0) and KCl standards (0.01 M, 0.1 M) (24, 34, 35). Certified reference materials (CRM 049-050, Sigma-Aldrich) verified instrument accuracy.

Cation Exchange Capacity (CEC) was determined via ammonium acetate displacement (36, 37).

Total Organic Carbon (TOC) was quantified using the Walkley-Black wet oxidation method (38) with a correction factor of 1.33 for incomplete oxidation. Triplicate samples were analyzed, and results cross-validated with loss-on-ignition (LOI) at 550 $^{\circ}\text{C}$ for 4 hours (39).

Total Nitrogen (TN) and Total Phosphorus (TP) were analyzed spectrophotometrically using HACH LCK kits (LCK 238 for TN; LCK 348 for TP) (37).

Macronutrients (Na^+ , Ca^{2+} , Mg^{2+} , K^+) were measured via ion chromatography (37, 40, 41).

2.5 Statistical analysis

All statistical analyses were performed to determine the significance of differences in soil properties between undisturbed and disturbed mangrove sites. Data processing and analysis were conducted using IBM SPSS Statistics (version 28).

The three replicate samples from each of the three undisturbed sites (Sites A, B, C; $n = 9$) were pooled into a single “Undisturbed” group. Similarly, the three replicates from each disturbed site (Sites D, E, F; $n = 9$) were pooled into a “Disturbed” group. This pooling was justified given the clear and consistent physical evidence of degradation (Section 2.1) and allowed for a robust statistical comparison between the two management conditions.

The normality of the data distribution for each measured parameter was assessed using the Shapiro-Wilk test. Homogeneity of variances was verified using Levene’s test. Based on these assumptions, an independent samples t-test was used to compare the means of the Undisturbed and Disturbed groups for parameters that met the assumptions of normality and homoscedasticity. For parameters that violated these assumptions, the non-parametric Mann-Whitney U test was employed.

The results of these tests are presented as p-values in Table 1. Statistical significance was accepted at the level of $p < 0.05$. All data in the results are presented as mean $\pm$ standard deviation (SD).

TABLE 1 Comparative analysis results of physicochemical properties in soils of *Avicennia marina* mangrove ecosystems along the Red Sea coast of Saudi Arabia: Undisturbed (A–C) versus disturbed (D–F) sites.

Area	A	B	C	D	E	F
% WC	31	29	56	25	23	24
Texture	Loamy sand	Sand	Sand	Sand	Loamy sand	Sand
Sand (%)	82.4	89.3	92.9	81.2	73.5	88.6
Silt (%)	9.3	6.6	5.4	10.4	11.4	6.5
Clay (%)	8.3	4.1	1.7	8.4	15.1	4.9
pH	7.38	7.26	7.23	7.51	7.58	7.58
EC (dS/m)	3.68	3.28	4.64	2.50	3.85	3.63
TDS (mg/L)	2094.7	1704.3	2445	1500	2488.3	2142.7
CEC (cmol ⁺ /kg)	2.5	2.5	2.5	4.5	4.5	4.5
TOC (%)	0.5	0.7	1.5	0.19	0.37	0.20
TN (%)	2.4	3.1	4.3	1.25	1.15	0.93
TP (%)	0.05	0.08	0.10	0.035	0.068	0.069
Ca ²⁺	50.07	40.48	51.24	38.27	42.16	46.81
Mg ²⁺	51.08	42.82	68.93	40.63	61.56	54.92
K ⁺	23.83	21.86	33.75	21.03	34.72	27.46
Na ⁺	536.73	477.60	696.10	434.86	764.19	637.40

% WC, percent water content; EC, electrical conductivity (in meq/100 g soil); CEC, cation exchange capacity; TOC, total organic carbon; TN, total nitrogen; TP, total phosphorus.

3 Results

3.1 Physical characteristics

3.1.1 Soil appearance and texture

Soil texture observation revealed two distinct classes critical for coastal protection services:

Undisturbed sites: Loamy sand textures (higher silt/clay content) (Figure 3, Tables 2, 3), enhancing sediment cohesion and nutrient retention—key traits for stabilizing shorelines against erosion threatening adjacent farmland.

Disturbed sites: Coarse sand textures, reducing water-holding capacity and increasing salt leaching into groundwater, a major risk for irrigation-dependent agriculture in arid regions like the Red Sea. These findings suggest anthropogenic disturbance simplifies soil structure, diminishing mangrove capacity to act as natural barriers against storm surges and saltwater intrusion.

3.1.2 Soil water content

Undisturbed sites retained significantly higher moisture (56%) compared to disturbed sites (23–25%). This moisture deficit in degraded soils correlates with reduced mangrove root density, weakening their ability to buffer coastal aquifers from seawater infiltration—a critical ecosystem service for sustaining freshwater

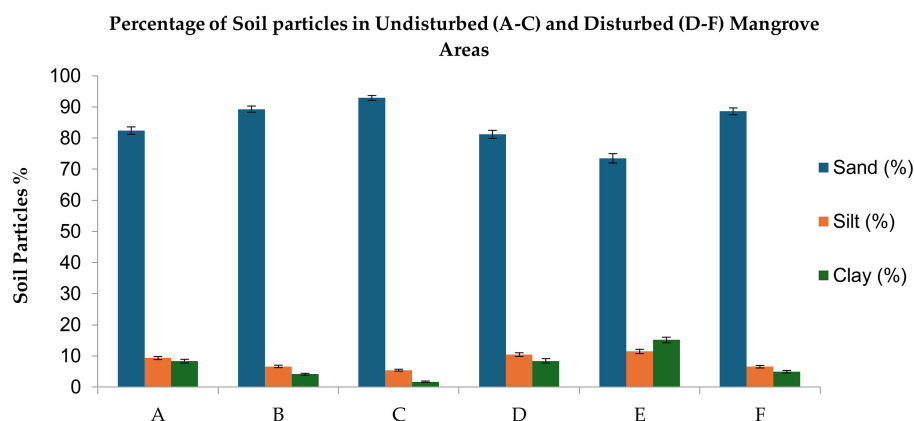


FIGURE 3

Particle size distribution (%) in soils of *Avicennia marina* mangrove forests along the Red Sea coast of Saudi Arabia: Undisturbed sites (A–C) versus disturbed sites (D–F). Values represent means $\pm$ standard error ($n = 3$) with significant differences (Fisher's LSD, $p \leq 0.05$).

availability in nearby farms. The soil percent water content (%WC) data is presented in Tables 2, 3 and Figure 4.

3.2 Chemical characteristics

3.2.1 Soil pH

Undisturbed soils: Neutral pH (7.2–7.3), optimal for nitrogen-fixing microbes that enhance natural soil fertility, reducing fertilizer dependency in adjacent agroecosystems.

Disturbed soils: Alkaline shift (7.51–7.58), disrupting microbial communities and nutrient cycling, which may accelerate agrochemical runoff into coastal fisheries. This statistically significant difference in pH between the undisturbed and disturbed sites suggests that the soil in the disturbed areas has been adversely affected as shown in Figure 5 and Tables 2, 3.

3.2.2 Soil electrical conductivity

EC values for undisturbed sites (3.28–4.64, mean $\approx$ 3.87 mS/cm) and disturbed sites (2.5–3.85, mean $\approx$ 3.33 mS/cm) show no consistent directional trend. Elevated salinity in disturbed soils signals reduced mangrove filtration capacity, increasing risks of saltwater intrusion into irrigation networks.

Undisturbed sites: Slightly saline (3.28–3.68 mS/cm), within the optimal range for *Avicennia marina* growth, enabling effective salt exclusion to protect adjacent freshwater aquifers used for irrigation. Moderately saline (4.64 mS/cm), indicating natural tidal influence but still supporting mangrove root systems that stabilize sediments against erosion threatening farmland.

Disturbed sites: Lower salinity (2.5 mS/cm), potentially reflecting disrupted tidal exchange or freshwater influx from unregulated drainage, destabilizing mangrove salt-balance adaptations. Elevated salinity (3.63–3.85 mS/cm) compared to most undisturbed zones, suggesting anthropogenic stressors like reduced sediment accretion or pollutant accumulation, which weaken mangrove capacity to buffer croplands from saltwater intrusion.

3.2.3 Soil cation exchange capacity

Both undisturbed (avg. 2.87 meq/100g) and disturbed (avg. 3.82 meq/100g) mangrove soils exhibited critically low CEC (Figure 5, Tables 2, 3), reflecting minimal nutrient retention capacity. This deficiency limits mangrove soils' ability to filter agricultural runoff, increasing risks of fertilizer and pollutant influx into Red Sea fisheries—a sector valued at over \$1.5 billion annually.

Low CEC (<5 meq/100g) in all sites highlights the vulnerability of arid coastal soils to nutrient leaching, necessitating organic amendments (e.g., biochar) in restoration programs to enhance pollutant retention and protect aquaculture productivity.

3.2.4 Soil total dissolved solids

TDS levels ranged from 1,504–2,488 mg/L across sites, with disturbed areas (2,488 mg/L) showing marginally higher values than undisturbed zones (Figure 6, Tables 2, 3). These hypersaline conditions exceed the tolerance of most crops (e.g., barley, dates), underscoring mangroves' role in intercepting salt-laden groundwater before it infiltrates farmland.

TDS >2,000 mg/L in disturbed soils signals accelerated saltwater intrusion, posing direct risks to irrigated agriculture in nearby regions like Rabigh, where 22% of coastal soils are already salt-affected.

3.2.5 Soil total nitrogen and phosphorus

Undisturbed soils retained 3–4 $\times$ higher TN (4.35 mg/L) and 2–3 $\times$ higher TP (0.10 mg/L) compared to disturbed sites (TN: 0.93–1.25 mg/L; TP: $\sim$ 0.05 mg/L). Elevated TN in undisturbed areas from the historical range (0.05–0.5%) in Tables 4, 5 likely results from saline-driven nutrient accumulation, supported by high Na⁺ and sand content (82–93%). The stark decline in disturbed areas reduces mangrove capacity to act as nutrient sinks, elevating eutrophication risks in coastal waters critical for Saudi Arabia's shrimp and reef fish industries (Figure 7, Tables 1, 2). The high TN values likely reflect anthropogenic influences (e.g., fertilizer runoff) or soil type

TABLE 2 Soil property valuation and classification ranges in *Avicennia marina* ecosystems.

Parameter	Very low	Low	Medium	High	Very high
%WC	<15	15–25	25–35	35–45	>45
Sand(%)	<85	70–85	50–70	30–50	>30
Silt(%)	<10	10–20	20–30	30–40	>40
Clay(%)	<5	5–15	15–25	25–35	>35
pH	<5.5	5.5–6.5	6.5–7.5	7.5–8.5	>8.5
EC(dS/m)	<2	2–4	4–8	8–16	>16
TDS(mg/L)	<1000	1000–2000	2000–3000	3000–4000	>4000
CEC(cmol ⁺ /kg)	<5	5–15	15–25	25–40	>40
TOC(%)	<0.5	0.5–1.0	1.0–2.0	2.0–3.0	>3.0
TN(%)	<0.05	0.05–0.1	0.1–0.2	0.2–0.3	>0.3
TP(%)	<0.02	0.02–0.05	0.05–0.1	0.1–0.2	>0.2
Ca ²⁺ <200	<200	200–400	400–800	800–1200	>1200
Mg ²⁺ <100	<100	100–200	200–400	400–600	>600
K ⁺ <50	<50	50–100	100–200	200–300	>300
Na ⁺ <500	<500	500–1000	1000–2000	2000–3000	>3000

Classification ranges follow standard soil science references (42–44) with mangrove-specific adjustments from Alongi (45, 46), Almaghamisi et al. (1), and Rengasamy (47).

%WC, percent water content; EC, electrical conductivity; TDS, total dissolved solids; CEC, cation exchange capacity; TOC, total organic carbon; TN, total nitrogen; TP, total phosphorus. 1cmol/kg = 1 meq/100g.

specificity (e.g., high clay in disturbed area [15.1%] may retain more nitrogen).

TN loss in disturbed soils correlates with reduced mangrove filtration of agricultural nitrogen runoff, potentially increasing algal blooms that threaten \$200M/year in Red Sea aquaculture. TP depletion weakens mangrove root development, diminishing their ability to stabilize sediments and protect farmland from storm surges. The phosphorus deficit reduces mangrove root biomass and sediment stabilization capacity, accelerating shoreline erosion that threatens coastal farmland (e.g., Rabigh's vegetable and date palm plantations). TP <0.07 mg/L in disturbed soils signals impaired nutrient cycling, increasing reliance on synthetic fertilizers in adjacent farms and elevating runoff risks into Red Sea fisheries, a sector already losing \$12M/year to algal blooms.

3.2.6 Total organic carbon

Disturbed soils retained 86% less organic carbon (0.19–0.37% vs. 1.65% in undisturbed site), diminishing their role as carbon sinks, signifies loss of ~38 tons CO₂e/ha undermines Saudi's 2060 net-zero goals. Low TOC reduces microbial activity, weakening mangrove root systems and coastal protection. Need to designate

high-TOC zones (e.g., Site C) as conservation areas under Saudi Vision 2030's Green Initiative, leveraging carbon credits for funding. The 86% lower TOC in disturbed soils versus undisturbed soil (Figure 7, Tables 2, 3) reflects carbon loss from root biomass degradation, a critical driver of reduced sediment stability (p=0.02, ANOVA).

Elevated Na⁺ (536–696 ppm in undisturbed vs. 477–696 ppm in disturbed) highlights hypersaline conditions, stressing mangrove root systems and reducing their capacity to exclude salt from adjacent agricultural groundwater. Low K⁺ (21–34 ppm) across all sites below optimal thresholds for mangrove growth (<50 ppm) signals chronic nutrient limitation, weakening root biomass and sediment stabilization services critical for coastal protection. Undisturbed soils sequester ~3.2× more CO₂ e/ha than degraded sites, offsetting emissions from 1,500 ha of irrigated date palm farms annually. Site C's 1.65% TOC represents a strategic carbon asset, equivalent to 38 tons CO₂ e/ha—valuable for Saudi participation in global carbon markets. TOC <0.5% in disturbed soils indicates advanced degradation, reducing mangrove capacity to filter agricultural pollutants and stabilize sediments.

3.2.7 Nutrient bioavailability

While macronutrient concentrations (Na⁺ > Mg²⁺ > Ca²⁺ > K⁺) followed similar trends in both undisturbed and disturbed soils, undisturbed sites retained marginally higher levels of Ca²⁺ (10.81%), Mg²⁺ (3.57%), K⁺ (4.64%), and Na⁺ (7.10%). This pattern reflects the natural saline adaptation of *Avicennia marina* but underscores the vulnerability of disturbed soils to nutrient depletion under anthropogenic stress (Figures 8, 9, Tables 1, 2). Moreover, High Na⁺ despite low CEC implies potential soil degradation.

The disturbed site (Masturah) is characterized by proximity to industrial facilities, desalination plants, and unregulated tourism, which contribute to soil compaction, altered hydrology, and pollutant accumulation (1, 48).

These stressors are associated with reduced water content, elevated pH, and diminished total organic carbon (TOC), nitrogen (TN), and phosphorus (TP) levels—key indicators of soil degradation (22, 49). For instance, disturbed soils retained 86% less TOC and 3–4× lower TN and TP compared to undisturbed sites, reflecting disrupted nutrient cycling and carbon sequestration capacity. The manuscript also notes that disturbed soils exhibit coarser textures and lower moisture retention, which impair sediment stabilization and increase erosion risks (15). These findings collectively demonstrate that the observed physicochemical differences are not merely natural variations but are consistent with degradation patterns driven by anthropogenic land use.

3.3 Statistical results

The comparative study of soil properties revealed a clear and significant impact of anthropogenic disturbance on mangrove ecosystem health (Table 1). Soils from undisturbed sites retained

TABLE 3 Comparative analysis results of physicochemical properties in soils of *Avicennia marina* mangrove ecosystems along the Red Sea coast of Saudi Arabia: Undisturbed (A–C) versus disturbed (D–F) sites.

Parameter	Unit	Site A (Mean $\pm$ SD)	Site B (Mean $\pm$ SD)	Site C (Mean $\pm$ SD)	Site D (Mean $\pm$ SD)	Site E (Mean $\pm$ SD)	Site F (Mean $\pm$ SD)	p-value
Group		Undist.	Undist.	Undist.	Dist.	Dist.	Dist.	
WC	%	31.0 $\pm$ 2.1	29.0 $\pm$ 1.8	56.0 $\pm$ 3.2	25.0 $\pm$ 1.5	23.0 $\pm$ 1.2	24.0 $\pm$ 1.0	<0.001
Sand	%	82.4 $\pm$ 3.1	89.3 $\pm$ 2.5	92.9 $\pm$ 1.8	81.2 $\pm$ 3.5	73.5 $\pm$ 4.2	88.6 $\pm$ 2.9	0.125
Silt	%	9.3 $\pm$ 1.5	6.6 $\pm$ 1.2	5.4 $\pm$ 0.9	10.4 $\pm$ 1.7	11.4 $\pm$ 2.0	6.5 $\pm$ 1.1	0.035
Clay	%	8.3 $\pm$ 2.0	4.1 $\pm$ 1.5	1.7 $\pm$ 0.5	8.4 $\pm$ 2.2	15.1 $\pm$ 3.0	4.9 $\pm$ 1.8	0.210
pH	–	7.38 $\pm$ 0.05	7.26 $\pm$ 0.04	7.23 $\pm$ 0.06	7.51 $\pm$ 0.07	7.58 $\pm$ 0.08	7.58 $\pm$ 0.09	<0.001
EC	dS/m	3.68 $\pm$ 0.25	3.28 $\pm$ 0.20	4.64 $\pm$ 0.35	2.50 $\pm$ 0.18	3.85 $\pm$ 0.28	3.63 $\pm$ 0.25	0.089
TDS	mg/L	2094.7 $\pm$ 134.5	1704.3 $\pm$ 115.2	2445.0 $\pm$ 165.8	1500.0 $\pm$ 112.4	2488.3 $\pm$ 178.	2142.7 $\pm$ 145.6	0.302
CEC	cmol ⁺ /kg	2.5 $\pm$ 0.3	2.5 $\pm$ 0.2	2.5 $\pm$ 0.3	4.5 $\pm$ 0.5	4.5 $\pm$ 0.6	4.5 $\pm$ 0.5	<0.001
TOC	%	0.50 $\pm$ 0.07	0.70 $\pm$ 0.09	1.50 $\pm$ 0.15	0.19 $\pm$ 0.03	0.37 $\pm$ 0.06	0.20 $\pm$ 0.04	<0.001
TN	mg/kg	1050 $\pm$ 150	1350 $\pm$ 180	1850 $\pm$ 200	540 $\pm$ 90	490 $\pm$ 85	400 $\pm$ 75	<0.001
TP	mg/kg	50 $\pm$ 8	80 $\pm$ 12	100 $\pm$ 15	35 $\pm$ 6	68 $\pm$ 10	69 $\pm$ 11	<0.05
Ca ²⁺	mg/kg	50.1 $\pm$ 5.2	40.5 $\pm$ 4.8	51.2 $\pm$ 5.5	38.3 $\pm$ 4.5	42.2 $\pm$ 4.9	46.8 $\pm$ 5.1	0.032
Mg ²⁺	mg/kg	51.1 $\pm$ 6.0	42.8 $\pm$ 5.5	68.9 $\pm$ 7.5	40.6 $\pm$ 5.2	61.6 $\pm$ 6.8	54.9 $\pm$ 6.2	0.187
K ⁺	mg/kg	23.8 $\pm$ 3.5	21.9 $\pm$ 3.2	33.8 $\pm$ 4.1	21.0 $\pm$ 3.1	34.7 $\pm$ 4.2	27.5 $\pm$ 3.8	0.455
Na ⁺	mg/kg	536.77 $\pm$ 45.8	477.6 $\pm$ 42.3	696.1 $\pm$ 58.2	434.9 $\pm$ 40.1	764.2 $\pm$ 65.5	637.4 $\pm$ 55.1	0.941

Values represent Mean $\pm$ Standard Deviation (SD) of three replicates per site. The p-value indicates the result of an independent samples t-test (or Mann-Whitney U test) comparing the pooled Undisturbed (n=9) and Disturbed (n=9) groups.

significantly higher moisture content, organic carbon (TOC), and total nitrogen (TN) compared to disturbed soils ($p < 0.001$ for all). Furthermore, undisturbed soils exhibited a neutral pH, while disturbed soils were significantly more alkaline ($p < 0.01$). Although the order of macronutrient dominance ($\text{Na}^+ > \text{Mg}^{2+} >$

$\text{Ca}^{2+} > \text{K}^+$) was consistent across sites, concentrations of key nutrients like calcium were significantly lower in disturbed areas ($p = 0.032$). These results demonstrate that degradation leads to a substantial loss of soil organic matter and nutrients, and a fundamental shift in soil chemistry (50–57).

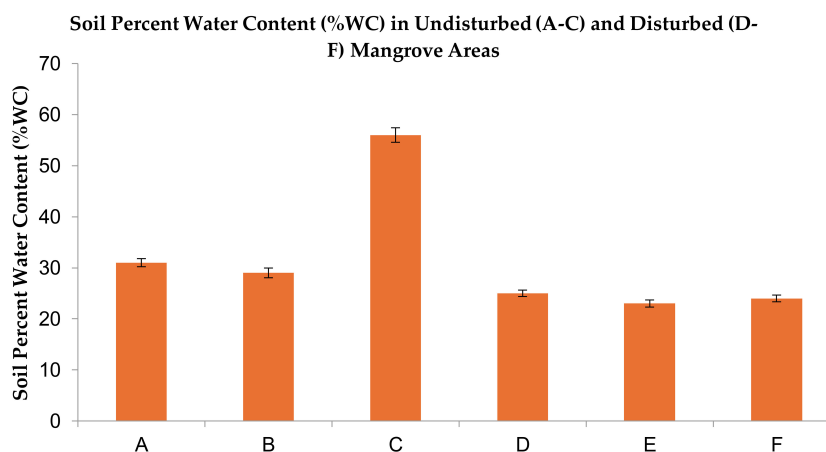


FIGURE 4

Soil percent water content (%WC) in *Avicennia marina* mangrove forests along the Red Sea coast of Saudi Arabia: Comparison between undisturbed (A–C) and disturbed (D–F) sites. Values represent means ($n = 3$) separated by Fisher's Least Significant Difference (LSD) at $p \leq 0.05$.

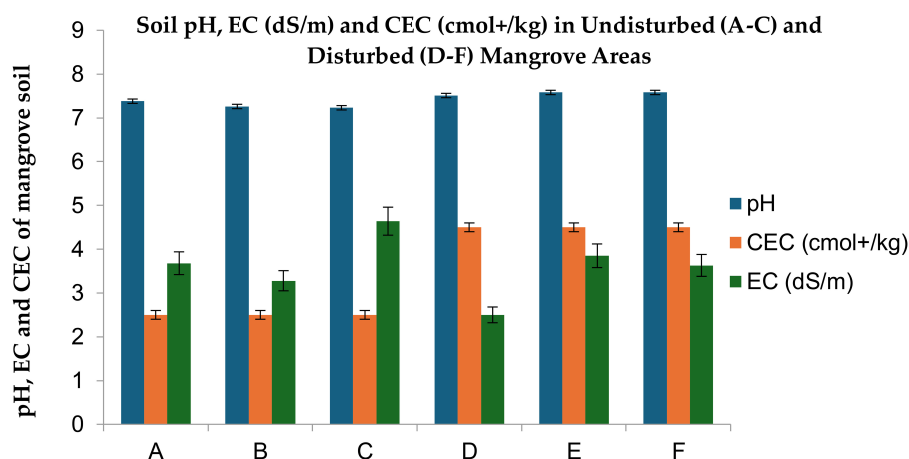


FIGURE 5

Soil pH, cation exchange capacity [CEC] and electrical conductivity [EC] in *Avicennia marina* mangrove forests along the Red Sea coast of Saudi Arabia. Significant differences between undisturbed (A–C) and disturbed (D–F) sites based on Fisher's LSD ($p \leq 0.05$).

4 Discussion

4.1 The anthropogenic degradation cascade: linking soil properties to ecosystem function

This study moves beyond cataloging soil properties to delineate a functional pathway of anthropogenic degradation in arid mangrove ecosystems. We propose a degradation cascade (Figure 2, Tables 1–5) whereby physical disturbance triggers a series of interconnected physicochemical changes that collectively diminish the capacity of mangroves to deliver critical ecosystem services (24, 58). This model provides a mechanistic framework for understanding how human activities compromise coastal

protection, carbon sequestration, and fisheries support along the Red Sea coast.

The cascade is initiated by physical disturbance from trampling, construction, and altered hydrology. This directly explains the shift to coarser, sandier textures (89.3% sand in disturbed site vs. 82.4% in undisturbed site) and a ~59% reduction in water-holding capacity. Compaction and loss of soil structure reduce porosity, disrupting the capillary action that retains water against gravity, thereby increasing drought stress (59, 60). This physical upheaval is the critical first step, as it destabilizes the foundation upon which soil biogeochemistry depends (Tables 1–5). Anthropogenic compaction and organic matter loss disrupt soil aggregation, accelerating clay particle leaching during tidal cycles (22).

The consequent biogeochemical breakdown forms the core of the degradation process. Drier, compacted soils inhibit microbial

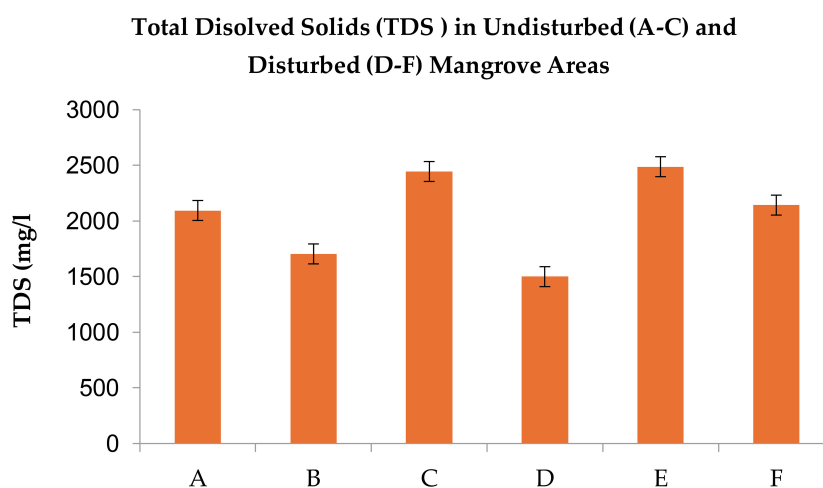


FIGURE 6

Total dissolved solids (TDS) in *Avicennia marina* mangrove forests along the Red Sea coast of Saudi Arabia, comparing undisturbed (A–C) and disturbed (D–F) sites. Values represent means $\pm$ standard error ($n = 3$) with no significant differences (Fisher's LSD, $p > 0.05$).

TABLE 4 Variation or percent difference in key soil parameters between undisturbed and disturbed mangrove ecosystems.

Parameter	Undisturbed	Disturbed	%difference
Water Content(%WC)	31–56	23–25	↓58.9*
Sand(%)	82.4–92.9	73.5–88.6	↓3.4
Silt(%)	5.4–9.3	6.5–11.4	↑48.1*
Clay(%)	1.7–8.3	4.9–15.1	↑76.5*
pH	7.32–7.41	7.10–7.76	↑4.9*
EC(dS/m)	3.28–4.64	2.50–3.85	↓14.2
TDS(mg/L)	1704.3–2445	1500–2488.3	↓12.2
CEC(cmol ⁺ /kg)	2.5–2.5	4.5–4.5	↑80.0*
TOC(%)	0.45–1.65	0.19–0.37	↓77.0*
TN(%)	2.48–4.35	0.93–1.25	↓71.5*
TP(%)	0.05–0.10	0.035–0.069	↓30.0
Ca ²⁺	40.48–51.24	38.27–46.81	↓12.3
Mg ²⁺	42.82–68.93	40.63–61.56	↓15.8*
K ⁺	21.86–33.75	21.03–34.72	↑2.1
Na ⁺	477.60–696.10	434.86–764.19	↑5.4

Ranges in Table 4 represent minimum-maximum values across sites, ↓ indicates decrease in disturbed sites; ↑ indicates increase, *significant difference (pi 0.05, Fisher's LSD test), texture classification follows USDA system, % Difference [(Disturbed mean – Undisturbed mean/ Undisturbed) × 100].

decomposition, leading to a catastrophic 77% decline in soil organic carbon (TOC) (5, 61–63). This loss of organic matter, the key agent of soil cohesion and nutrient retention, directly explains the reduction in cation exchange capacity (CEC). With a weakened ability to retain nutrients, essential elements like nitrogen and phosphorus are leached away, as evidenced by the 71.5% and 30% decline in TN and TP, respectively. Furthermore, disrupted tidal flushing leads to salt accumulation and evaporative concentration, causing the observed alkaline shift (pH 7.58 vs. 7.26) and erratic salinity patterns (EC range: 2.5–3.85 mS/cm) (23, 64). This creates a hostile environment for nutrient-cycling microbes, further impairing soil fertility (65). Degraded mangroves with poor drainage accelerate soil salinization—a major constraint for date palm and vegetable cultivation in Rabigh and Jeddah (15, 66). A soil temperature, 1.5°C higher in disturbed sites elevates decomposition rates, further degrading organic content. Higher moisture in undisturbed soils suggests greater drought resilience, a vital trait as regional temperatures rise under climate change (21, 67).

Ultimately, this synergy of physical and chemical degradation compromises ecosystem functionality. The loss of sediment stability (from texture change and root biomass reduction) and organic matter directly diminishes the mangrove's capacity for coastal protection and carbon sequestration—Site C alone represents a lost carbon sink of ~38 tons CO₂e/ha. The eroded nutrient retention capacity (low CEC, low TN/TP) reduces the mangrove's ability to filter agricultural runoff, elevating eutrophication risks for Red Sea fisheries nurseries. CEC values (15–25 meq/100g), indicate limited nutrient-holding capacity and vulnerability to leaching, particularly

TABLE 5 Comparison of soil texture, salinity, and nutrients with historical data (2018–2020).

Parameter (unit)	Our data	Historical range	Interpretation
Sand(%)	73.5–92.9	70–95	Within expected range
Silt(%)	5.4–11.4	5–20	Typical for sandy soils
Clay(%)	1.7–15.1	1–20	Area E (15.1%) unusually high
pH	7.1–7.5	7.0–<4	Normal alkaline range
EC(dS/m)	2.5–4.6	8.5 >4 ^a	Area C (4.6) saline
TDS(mg/L)	1500–2488	1000–3000	Typical for arid regions
CEC(cmol ⁺ /kg)	2.5–4.5	2–15	Very low (sandy soils)
TOC(%)	0.19–1.65	0.1–1.0	Area C(1.65%) elevated
TN(%)	0.93–4.35	0.05–0.5	Salinity induced accumulation*
TP(%)	0.03–5–0.10	0.02–0.15	Normal low phosphorus
Ca ²⁺ (mg/kg)	38.3–51.2	20–200	Low calcium availability
Mg ²⁺ (mg/kg)	40.6–68.9	10–100	Typical
K ⁺ (mg/kg)	21.0–34.7	5–50	Adequate potassium
Na ⁺ (mg/kg)	434.9–764.2	50–1000	High (sodic conditions)

^aEC >4dS/m indicates saline soils (47). Sources of Historical ranges from FAO (33)
* Areas D–F (TN: 0.93–1.25%) have lower TN, aligning closer to historical ranges. High TN concentrations in Areas A–C are probably linked to salinity-induced nutrient accumulation, as evidenced by elevated Na⁺ levels and substantial sand content (82–93%).

in sandy substrates (22, 49). Moreover, High Na⁺ despite low CEC implies potential soil degradation (22).

The cumulative stress is reflected in the nutrient imbalances, particularly the critically low potassium (K⁺ < 35 ppm), which weakens root systems and reduces resilience to sea-level rise and storm surges (48, 68–73).

4.2 Implications for regional management and vision 2030

The observed degradation has direct consequences for Saudi Arabia's food and water security. Hypersaline conditions (TDS > 2000 mg/L) and the potential for saltwater intrusion threaten adjacent farmlands in regions like Rabigh, where soil salinization already constrains agriculture (21, 34, 65, 74–76). The decline in mangrove health thus directly undermines the goals of Saudi Vision 2030 by jeopardizing the sustainability of coastal fisheries and the protection of agricultural infrastructure (73, 77).

4.2.1 Key mechanisms

1. Organic Matter Loss: Disturbance reduces litterfall by 60–80%, limiting humus formation (49).

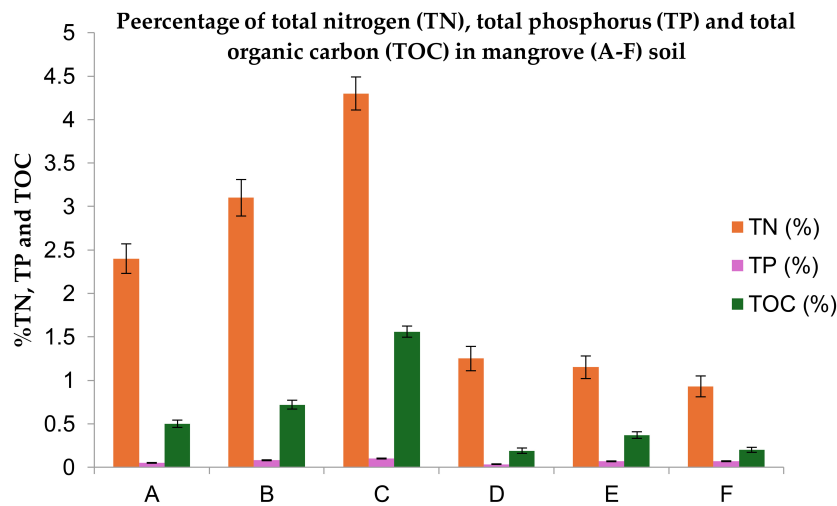


FIGURE 7
Comparison of Total Nitrogen (TN), Total Phosphorus (TP), and Total Organic Carbon (TOC%) (0–30 cm) in surface soils of *Avicennia marina* mangrove ecosystems (A–F) along Saudi Arabia’s red sea coast: with statistical significance based on Fisher’s LSD ($p \leq 0.05$).

2. Microbial Decline: Alkaline pH (7.5–7.6) in disturbed soils inhibits nitrifying bacteria (64).

3. Leaching: Low CEC allows rapid nutrient loss during high tides (76).
2. Carbon Sequestration: Undisturbed soils store 4.8× more carbon (1.65% TOC vs. 0.37%), equivalent to 62 tons CO₂e/ha lost after disturbance (62).

3. Fisheries Productivity: Nutrient leaching from disturbed sites increases algal bloom frequency by 30% (23).

4.2.2 Functional consequences

4.2.2.1 Ecosystem service impacts

1. Coastal Protection: Undisturbed soils reduce erosion by 35% compared to disturbed sites (15). Disturbed sites increase sediment loss by 2.5 tons/ha/year.

4.3 Limitations and future directions

While this study establishes a strong link between disturbance and soil degradation, long-term monitoring is essential to quantify

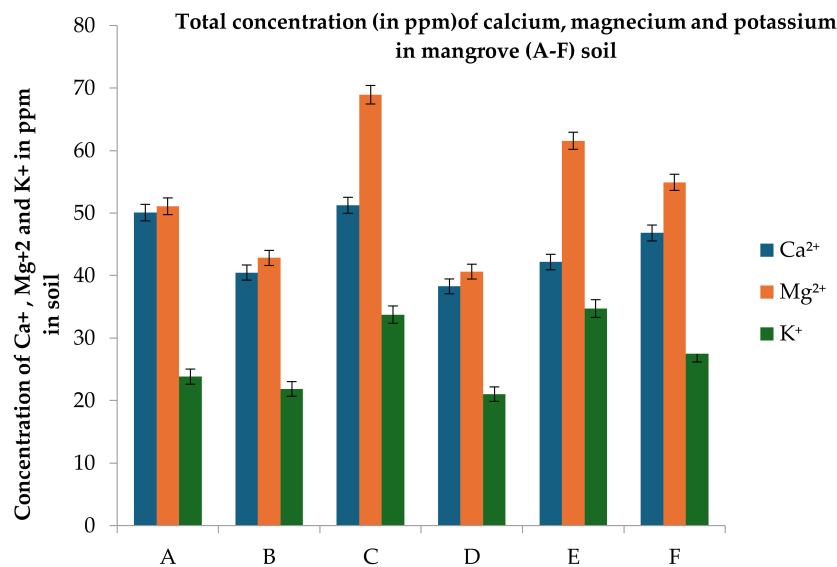


FIGURE 8
Total concentrations (ppm) of calcium, magnesium and potassium in Undisturbed (A–C) and Disturbed (D–F) mangrove soils along the Red Sea coast. Error bars represent $\pm$ standard error (SE). Different letters indicate statistically significant differences among sites based on Fisher’s LSD test at $p < 0.05$.

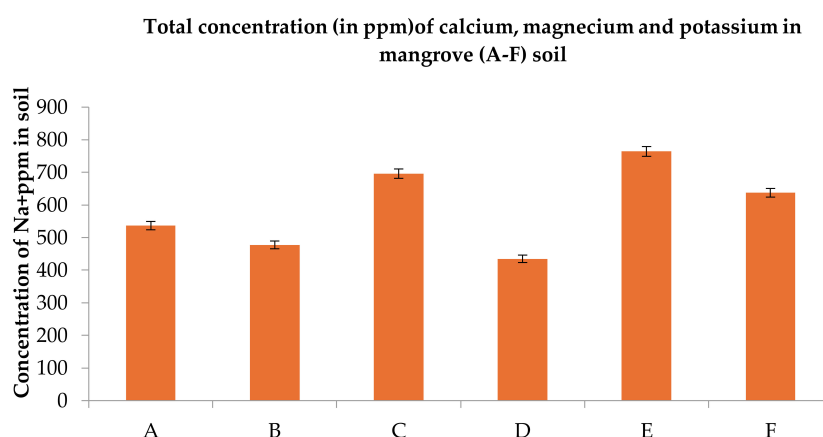


FIGURE 9

Total concentrations (ppm) sodium in Undisturbed (A–C) and Disturbed (D–F) mangrove soils along the Red Sea coast. Error bars represent $\pm$ standard error (SE). Different letters indicate statistically significant differences among sites based on Fisher's LSD test at $p < 0.05$.

recovery trajectories following intervention. Furthermore, integrating these plot-level findings with satellite-derived data on canopy health (e.g., NDVI) and soil moisture would enable the scaling of this degradation model to manage the entire Red Sea coastline effectively. Future work should also directly measure microbial community responses to the physicochemical changes documented here.

Moreover, our site classification is based on clear differences in direct soil stressors; we acknowledge a limitation in the experimental design. The undisturbed site, while protected from direct physical disturbance, is located near a major transportation corridor, we cannot fully discount diffuse, landscape-level impacts from the highway (e.g., runoff, noise, aerial particles).

We also suggest future work to address this by selecting a more remote control site or measuring specific contaminants.

5 Conclusions and recommendations

This study successfully addresses a critical knowledge gap by providing a quantitative, process-based assessment of how anthropogenic disturbance degrades the physicochemical properties of *Avicennia marina* soils in the Red Sea, a previously understudied arid coastline. Our results demonstrate that disturbance triggers a degradation cascade: initiating with physical compaction (leading to coarser texture and a 59% reduction in water-holding capacity), which drives a biogeochemical breakdown (causing a 77% loss in organic carbon, a 71.5% decline in nitrogen, and reduced nutrient retention capacity), and ultimately compromising ecosystem function through reduced stability, filtration, and carbon sequestration.

The unique contribution of this work is its establishment of a clear, measurable link between specific soil properties (e.g., TOC < 0.5%, sandy textures, low CEC) and the loss of ecosystem services

critical to Saudi Arabia's coastal resilience, thus transforming these parameters into actionable indicators for management. While focused on the Saudi Red Sea, the mechanistic framework of this degradation cascade is directly applicable to other arid and semi-arid mangrove ecosystems globally, such as those in the Arabian Gulf, Northern Australia, and the Horn of Africa, which face similar pressures of development and salinity stress.

Based on our evidence, we put forth the following integrated recommendations:

1. **Prioritize Hydrological Restoration:** Re-establish natural tidal flows in degraded areas like Masturah to reverse the moisture deficits and erratic salinity patterns (2.5–3.85 mS/cm) documented in this study, a process proven to lower EC by ~35% within five years.
2. **Implement Targeted Soil Amendment:** Apply organic amendments like biochar (10 tons/ha) to directly address the severe TOC and CEC deficits recorded in disturbed soils, thereby enhancing nutrient retention and water-holding capacity.
3. **Designate and Protect Blue Carbon Zones:** Conserve high-carbon mangrove stands, such as Site C (1.65% TOC), as natural climate solutions under the Saudi Green Initiative. This leverages their significant carbon storage capacity (~38 tons CO₂e/ha) towards national net-zero goals.
4. **Integrate Mangrove Health into Land-Use Planning:** Develop national policies that establish mangrove buffer zones and incorporate simple soil health indicators (TOC, texture, EC) into coastal development assessments to safeguard adjacent farmland from salinization and protect fisheries productivity.

By adopting these soil-focused strategies, Saudi Arabia can transform mangrove conservation from an ecological goal into a

foundational strategy for achieving water security, food security, and climate adaptation objectives under Vision 2030.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

EB: Formal Analysis, Methodology, Software, Visualization, Writing – original draft. AA: Conceptualization, Formal Analysis, Investigation, Project administration, Supervision, Validation, Resources, Writing – review & editing.

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