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# Blue carbon storage variability in a hyper-arid evaporitic environment: A comparative study of inland and coastal sabkhas ecosystems

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ABSTRACT

*Sabkhas*, or salt marshes, are important wetland habitats that play a vital role in capturing and storing carbon. This research examines the capacity of six salt marshes to sequester carbon, with a focus on comparing inland and coastal salt marshes. Six *Sabkhas* sites were sampled for soil and plants, three of which were inland (Aushazia, Ghuwaymid, Al Qasab) and three of which were coastal (Asfar Lake, Al Uqayr, Al Dnan). Four stands were selected at each *Sabkha* site, and three plots of soil cores were collected at each sampling stand. The depth of the corer's penetration was 25 cm. After extraction, each core was divided into five layers spaced five centimeters apart, spanning the 0–25 cm depth range, i.e., 6 sites × 4 stands × 3 soil plots × 5 sections = 360 soil samples. Across these sites, measurements were made of the soil bulk density (SBD), soil organic carbon (SOC) concentration, SOC stock, and plant organic carbon (POC) stock. The results revealed significant spatial variability in SBD and SOC across the marshes ($P \leq 0.001$). Inland Aushazia presented the highest SOC concentration (43.62 ± 2.09 g C/kg) and SOC stock (0.97 ± 0.06 t C/ha), as well as the highest POC stock (8.53 ± 0.97 t C/ha), indicating superior carbon sequestration capacity. Conversely, coastal Al Dnan presented the lowest SOC concentration (5.15 ± 1.34 g C/kg) and SOC stock (0.15 ± 0.05 t C/ha). Between 0.6 and 1.5 g/cm$^3$ was the range of the (SBD), with inland-Al Qasab and coastal-Al Dnan exhibiting the highest values (1.22 ± 0.02 g/cm$^3$ and 1.24 ± 0.28 g/cm$^3$, respectively). Application of the principal component analysis (PCA) biplot on the data reveals distinct spatial separation between coastal and inland localities based on environmental and/or biological variables. Moreover, in the most studied sites, the association between SBD and the SOC concentration was explored through nonlinear regression analysis. Compared with coastal sabkhas, inland *sabkhas* have a greater capacity for carbon sequestration in both sediments and plants. The results offer valuable insights for conservation and restoration strategies aimed at enhancing the carbon sequestration capabilities of salt marshes in Saudi Arabia, underscoring the necessity for site-specific management practices.

## 1. Introduction

Salt marshes are among the most productive coastal habitats and serve as significant blue carbon sinks by capturing atmospheric $CO_2$ in biomass and sediments (Kang *et al.* 2024; Maxwell *et al.* 2024; Sarika and Zikos 2021; McLeod *et al.* 2011). Their high primary productivity and slow organic matter decomposition of carbon sequestration rates that surpass those of most terrestrial forests. In coastal *sabkhas*, elevated carbon accumulation and low methane emissions further enhance their storage capacity (Al Disi *et al.* 2023; Neubauer and Megonigal 2021; Drake *et al.* 2015).

McLeod *et al.* (2011) outlined a detailed framework for understanding how coastal ecosystems, particularly salt marshes, mangroves, and seagrasses, contribute to global carbon storage, emphasizing the urgent need to conserve these habitats for climate regulation. Morris *et al.* (2012) assessed the amount of carbon sequestered in various coastal wetlands, concluding that significant amounts of carbon can be sequestered over long-time scales. Kelleway *et al.* (2016) investigated the sediment characteristics that influence carbon retention in southeastern Australian salt marshes, finding that grain size was a key determinant, while vegetation cover showed no significant effect. Chmura (2013) emphasized the necessity of comprehensive assessments to ascertain the stability of carbon stores over time in tidal marshes. Similarly, Osland *et al.* (2013) compared the effects of winter climate shifts on marshes and mangroves in the southeastern coast of the United States, revealing the resilience of marshes in colder climates and their notable carbon storage potential in areas with dense vegetation.

Quantifying carbon stored in tidal and non-tidal marsh soils and vegetation is essential both for effective ecosystem management and for assessing their role in climate change mitigation (Maxwell *et al.* 2024; Hengl *et al.* 2017; Granek *et al.* 2010; Chmura *et al.* 2003). While localized studies have documented SOC in tidal marshes and mangrove soils, such as in Saudi Arabia (Eid *et al.* 2019; Cusack *et al.* 2018) and Egypt (Youssef *et al.* 2024; Shaltout *et al.* 2020), there remains a lack of large-scale analyses that integrate extensive field data, especially for arid inland marshes like those in Saudi Arabia (El-Sheikh *et al.* 2018).

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Without such data, researchers and practitioners must rely on resource-intensive field sampling or on generalized global estimates that may not reflect the specific conditions of these ecosystems.

In Saudi Arabia, particularly in the inland and eastern coastal regions, salt marshes are common features of the landscape. These environments experience extreme climatic stress, which strongly shapes their ecological processes, yet studies on their carbon storage remain limited. For example, salt marshes along the western Arabian Gulf have been found to store an average of 81 Mg C/ha (Cusack *et al.* 2018). However, much of the carbon research in Saudi Arabia has concentrated on mangroves. In one study, carbon sequestration was compared between rehabilitated mangroves in Yanbu and those grown without intervention, with significant storage observed in all sites (Al-Guwaiz *et al.* 2021). Mangrove biomass carbon stocks along the coast of the Red Sea vary between 87.6 to 412.5 Mg C/ha (Shaltout *et al.* 2021), with soil carbon levels varying by species (Eid *et al.* 2020), indicating the influence of plant species and vegetative cover on storage potential.

In salt marshes, vegetation predominantly comprising halophytic plants plays a crucial role in stabilizing sediments, minimizing erosion, and promoting organic matter build-up. Although numerous studies have addressed the role of vegetation in enhancing the carbon storage capacity of *sabkhas*, few have investigated the sequestration potential of coastal salt marshes, and no work has compared inland and coastal marshes directly. Such a comparative study can illuminate the environmental drivers, ecological adaptations, and biogeochemical processes that shape these habitats, as well as their unique biodiversity and hydrological dynamics. Insights gained are valuable for environmental monitoring, sustainable resource management, and climate change impact assessments.

This study addresses this gap by assessing soil and plant carbon stocks in hyper-arid inland and coastal sabkhas of Saudi Arabia, investigating biogeochemical drivers of spatial variability, and identifying the main factors influencing blue carbon storage in these unique ecosystems.

## 2. Materials and Methods

### 2.1 Study site

The study area included different salt marshes (sabkhas) in the inland and coastal eastern regions of Saudi Arabia. The first study sites are situated in the central region's inland *sabkhas* of Saudi Arabia, which are in the northern part of the central Arabian Peninsula. Three inland *sabkhas* were selected in the central region. Aushazia *sabkha* is the first site that is situated east of Unayzah, approximately 20 km away (26° 07' 55" N, 44° 16' 34" E). The area of the *sabkha* is approximately 18 km$^2$. In general, it extends in a longitudinal direction from northwest to southeast (Fig. 1a). Ghuwaymid *sabkha* is the second site, located at 26° 17' 52" N and 44° 17' 27" E. The sabkha is situated 30 km before it reaches the city of Buraidah on the Riyadh-Qassim main road (Fig. 1b). Al Qasab salt marsh (25° 18' 47" N, 45° 39' 01" E) in Shaqra Governorate (Fig. 1c) is located 150 km northwest of Riyadh city. It extends in a northerly direction toward Al-Nafud Al-Gharbi (Ariq Al-Buldan) and reaches eastward to the road. Al Qasab *sabkha* is characterized by the presence of salt-tolerant flowering plants.

The second area is situated along the eastern coast of Saudi Arabia, bound by Dhahran to the north, the Arabian Gulf to the east, Al-Ghuwaybah village to the south, and the Riyadh region to the west (Fig. 1). The first coastal *Sabkha* site is Asfar Lake, which is approximately 20.8 km$^2$ in area and is situated in the Javora Sands area (Fig. 1d). The second coastal *Sabkha* site, Al Uqayr Sabkha (Fig. 1e), is situated near the Arabian Gulf and occupies an area of 10 km$^2$. Al Dnan *Sabkha* is the third coastal site, located at 25° 50' 30.1\" N and 50° 05' 30\" E (Fig. 1f). It is in the Dammam region and stretches along the Arabian Gulf coast between the governorates of Dammam and Abqaiq.

There are six study sites, '*Sabkhas*,' in all. At each studied site, four stands were selected to collect soil and plant samples (Figs. 1a-f). From each of the four selected stands in one region, one stand without any vegetative cover was selected as a control to examine the differences in the levels of carbon sequestration in the presence or absence of vegetative cover, i.e., the total number of stands was 6 sites × 4 stands = 24 stands, with each stand area measuring 50 m × 50 m. The coordinates of the sampling stands were recorded (Table 1) and drawn on a geographical map.

### 2.2 Climate

The inland *Sabkhas* sites are largely influenced by a similar climate, with heat and rain occurring at the same period, with a mean annual temperature of around 26°C and precipitation averaging 101.3 mm. The average yearly temperature in the coastal *Sabkhas* sites is 26.4°C, and the average yearly precipitation is roughly 88 mm. As is typical of a hyper-arid desert climate, both locations experience long, hot summers and short, mild winters.

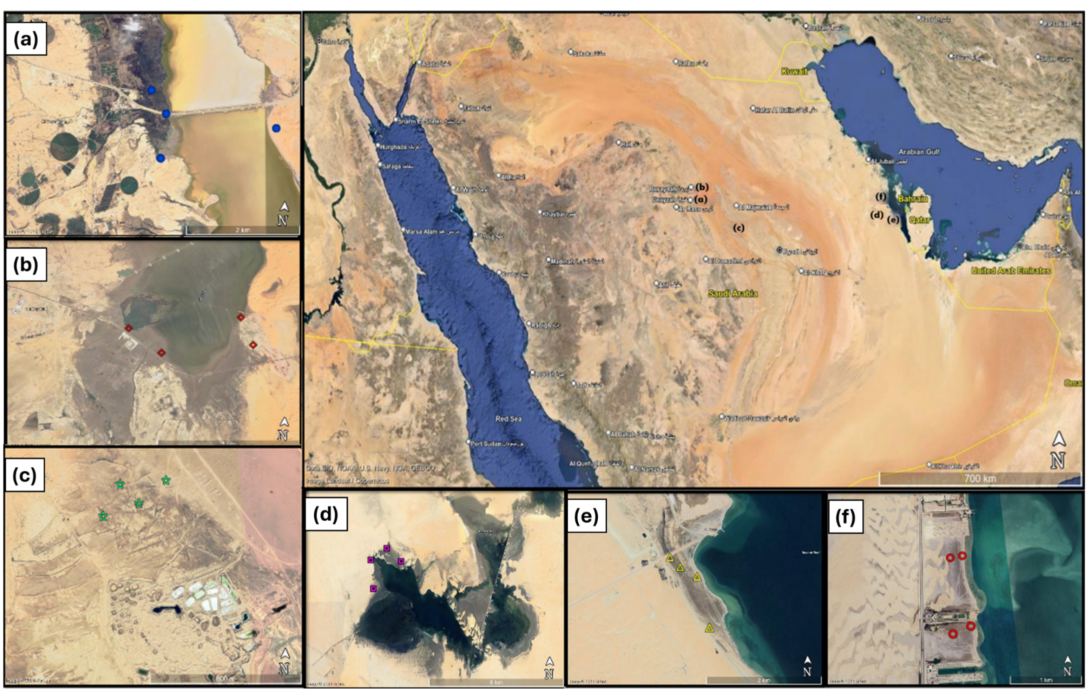


**Fig. 1.** Map illustrating the study locations and sampled stands. Insets show the six sabkha sites: (a) Aushazia, (b) Ghuwaymid, (c) Al Qasab, (d) Asfar Lake, (e) Al Uqayr, and (f) Al Dnan. Colored dots mark sampling stands in each area.

**Table 1.**
The geographical coordinates of the 24 stands (50×50 m) that were sampled across the six studied salt marshes, with notes on the characteristics of each stand.

| Stand no. | Salt marsh | Latitude | Longitude |
|---|---|---|---|
| Inland *Sabkhas* of the Central region | | | |
| 1 | Aushazia | 26° 03' 44.6" N | 44° 08' 28.1" E |
| 2 | Aushazia | 26° 03' 16.8" N | 44° 08' 26.2" E |
| 3 | Aushazia | 26° 03' 59.2" N | 44° 08' 16.9" E |
| 4 | Aushazia | 26° 03' 39.6" N | 44° 09' 42.9" E |
| 5 | Ghuwaymid | 26° 08' 45.2" N | 44° 12' 10.2" E |
| 6 | Ghuwaymid | 26° 08' 29.1" N | 44° 12' 39.2" E |
| 7 | Ghuwaymid | 26° 08' 59.2" N | 44° 13' 45.6" E |
| 8 | Ghuwaymid | 26° 08' 36.2" N | 44° 13' 55.2" E |
| 9 | Al Qasab | 25° 16'31.0" N | 45° 31' 27.7" E |
| 10 | Al Qasab | 25° 16' 35.5" N | 45° 31' 32.4" E |
| 11 | Al Qasab | 25° 16' 34.5" N | 45° 31' 24.1" E |
| 12 | Al Qasab | 25° 16' 28.5" N | 45° 31' 21.6" E |
| Coastal *sabkhas* of the Eastern region | | | |
| 13 | Asfar Lake | 25° 32'19.1" N | 49° 46' 32.3" E |
| 14 | Asfar Lake | 25° 33' 07.8" N | 49° 46' 25.1" E |
| 15 | Asfar Lake | 25° 33' 28.4" N | 49° 46' 53.5" E |
| 16 | Asfar Lake | 25° 33' 04.7" N | 49° 47' 20.5" E |
| 17 | Al Uqayr | 25° 38' 03.8" N | 50° 12' 41.2" E |
| 18 | Al Uqayr | 25° 37' 30.3" N | 50° 12' 48.3" E |
| 19 | Al Uqayr | 25° 38' 10.9" N | 50° 12' 29.3" E |
| 20 | Al Uqayr | 25° 38' 18.1" N | 50° 12' 22.0" E |
| 21 | Al Dnan | 26° 02' 15.1" N | 49° 59' 59.0" E |
| 22 | Al Dnan | 26° 02' 11.4" N | 49° 59' 49.2" E |
| 23 | Al Dnan | 26° 02' 54.2" N | 49° 59' 48.7" E |
| 24 | Al Dnan | 26° 58' 55.3" N | 50° 00' 08.4" E |

*2.3 Soil sample collection*

Three soil cores were taken from each stand, spaced 15 m apart in a triangle. A handheld corer with a 5-cm diameter was used for sampling to reduce compaction and structural disturbance (Eid *et al*., 2016; Tan, 2005). Cores were taken to a depth of 25 cm and sectioned into five 5-cm intervals. This resulted in a total of 360 soil samples (6 sites × 4 stands × 3 cores × 5 sections). Before being analyzed in the laboratory, samples were placed in sealed plastic containers and kept on ice (Bernal and Mitsch, 2008).

*2.4 Biomass sampling*

To estimate standing crop biomass in vegetated stands, above-ground plant material was clipped from three randomly chosen quadrats 0.5 $m^2$ within each stand. After recording the fresh weight, samples were oven-dried at 75°C until the dry weight remained constant (Kent, 2011).

*2.5 Soil carbon measurements*

Soil bulk density (SBD) g $cm^{-3}$ was determined by dividing the oven-dried mass of each soil sample (dried at 105°C for 72 h) by its corresponding core volume (Wilke, 2005):

Contents of soil organic matter (SOM) were assessed using the loss-on-ignition, where samples were combusted at 450°C for 3 h (Jones, 2001). Soil organic carbon (SOC) was then derived from SOM using a conversion factor specific to salt marsh soils (Ouyang and Lee, 2020).

The SOC stock, expressed as tons of carbon per hectare, was calculated by integrating SBD, SOC concentration, and layer thickness across the sampled depth profile, standardized to a reference depth (Meersmans *et al.* 2008).

*2.6 Determination of plant organic carbon*

The estimation of plant organic carbon (POC) stock was based on dry biomass per unit area. After extrapolating biomass values to the hectare level (Mokany *et al.* 2006), carbon stock was derived by multiplying dry biomass by a carbon fraction of 0.47, following Goslee *et al.* (2016).

*2.7 Statistical analysis*

Data were tested for normality and homogeneity before analysis. Two-way ANOVA was applied to evaluate the effects of site and depth on SBD and SOC. One-way ANOVA was used to test for variation among sites, with Duncan's multiple range test applied for post-hoc comparisons at a significance level of $P \leq 0.05$. Student's t-test was used to compare inland and coastal sabkhas. Pearson's correlation was applied to examine relationships between SBD and SOC, and principal component analysis (PCA) was performed in R to explore multivariate variation associated with site, locality (inland vs. coastal), soil depth, and vegetation cover.

## 3. Results

*3.1 SBD analysis*

SBD varied notably across the six salt marshes of inland central and coastal eastern Saudi Arabia. Values ranged between 0.6 and 1.5 g $cm^{-3}$ depending on depth and location (Fig. 2). Two-way ANOVA indicated that both site ($P \leq 0.001$) and depth ($P \leq 0.05$) significantly influenced SBD, while their interaction was not significant. Among the sites, Aushazia exhibited the lowest average density (0.89 g $cm^{-3}$), followed by Al Uqayr, whereas Al Dnan and Al Qasab recorded the highest values (1.24 and 1.22 g/$cm^3$, respectively). Comparisons between inland and coastal *sabkhas* showed no significant differences in SBD ($t = -0.72$, $P = 0.47$).

*3.2 SOC concentration*

SOC concentrations also differed significantly among sites ($P \leq 0.001$; Fig. 3), ranging from 0 to 60 g C/kg. In contrast to SBD, neither depth nor the site × depth interaction influenced SOC. Aushazia had the highest mean SOC (43.62 g C/kg), while Al Dnan recorded the lowest (5.15 g C/kg). Inland *sabkhas* (58.51 g C/kg) contained significantly higher SOC levels than coastal sites (26.41 g C/kg; $t = -8.22$, $P \leq 0.001$).

*3.3 SBD and SOC relationship*

Nonlinear regression was used to assess the relation between SBD and SOC (Fig. 4, Table 2). Overall, the associations were weak in most

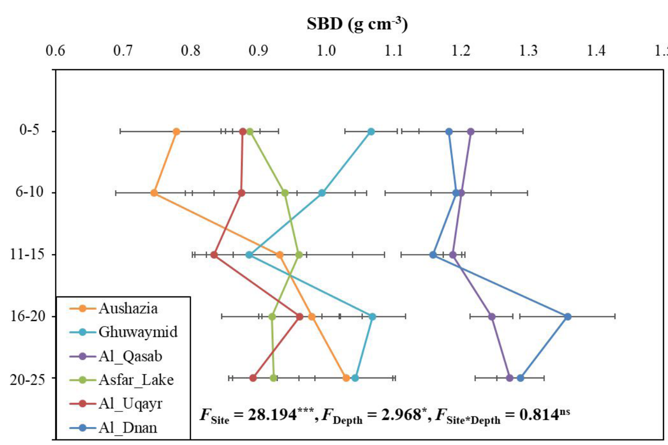


**Fig. 2.** Mean of SBD across depth profiles in six *sabkhas*. Error bars = SE (N = 4). ANOVA significance: *** $P \leq 0.001$; * $P \leq 0.05$; ns = not significant.

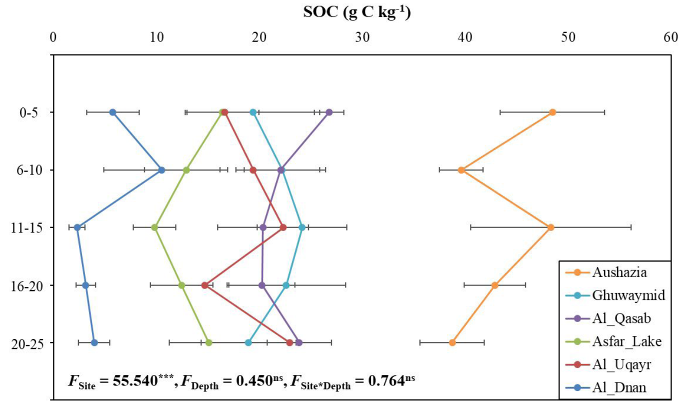


**Fig. 3.** Depth-dependent distribution of mean SOC across study areas. Error bars = SE (N = 4). Significance codes as in Fig. 2.

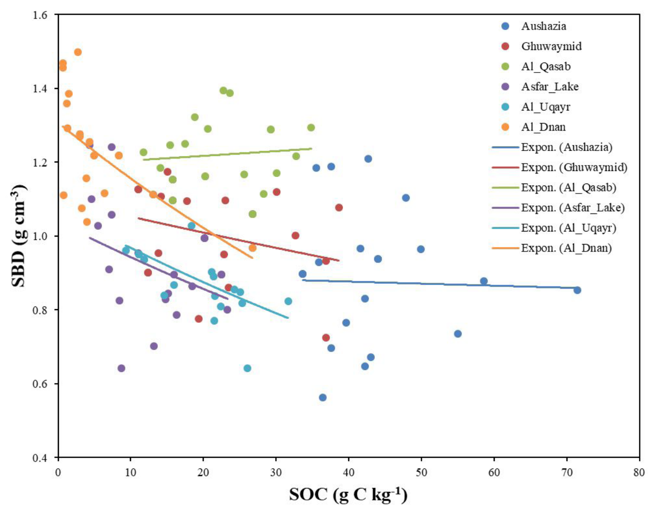


**Fig. 4.** Nonlinear relationship between SBD (Y-axis) and SOC (X-axis) concentration from 120 soil samples collected from 24 stands (four per *Sabkha*).

**Table 2.**
Nonlinear SBD-SOC relationships across the six *sabkha* sites.

| Salt marsh | Equation | $R^2$ | Significance [1] |
|---|---|---|---|
| Aushazia | $y = 0.8994e^{-6E-04x}$ | 0.0008 | ns |
| Ghuwaymid | $y = 1.0978e^{-0.004x}$ | 0.0805 | ns |
| Al Qasab | $y = 1.192e^{0.001x}$ | 0.0088 | ns |
| Asfar Lake | $y = 1.0376e^{-0.01x}$ | 0.1334 | ns |
| Al Uqayr | $y = 1.071e^{-0.01x}$ | 0.3148 | ** |
| Al Dnan | $y = 1.3079e^{-0.012x}$ | 0.3868 | ** |

[1] ns: not significant, **: $P \leq 0.01$.

*sabkhas*, with significant correlations observed only at Al Uqayr ($R^2$ = 0.315, P ≤ 0.01) and Al Dnan ($R^2$ = 0.387, P ≤ 0.01), both coastal sites. The regression results highlight site-specific variability in this relationship.

### 3.4 Overall carbon stocks

Considerable differences were observed in SBD, SOC concentration, SOC stock, and POC stock across sites (Table 3). The highest SBD occurred at inland Al Qasab (1.22 g/cm$^3$) and coastal Al Dnan (1.24 g/cm$^3$), while Aushazia and Al Uqayr displayed the lowest values. SOC concentration and stocks were greatest at Aushazia (43.62 g C/kg; 0.97 t C/ha) and lowest at Al Dnan (5.15 g C/kg; 0.15 t C/ha). Significant differences were also evident in stocks of POC (P ≤ 0.001), with inland Aushazia showing the highest values (8.53 t C/ha). In contrast, Al Qasab, Al Uqayr, and Al Dnan recorded the lowest and did not differ significantly.

**Table 3.**
Summary of SBD, SOC concentration, and carbon stocks (soil and plant) in the studied *sabkhas*.

| Salt marsh | SBD (g/cm³) | SOC (g C/kg) | SOC Stock (t C/ha) | POC Stock (t C/ha) |
|---|---|---|---|---|
| Inland *Sabkhas* | | | | |
| Aushazia | 0.89 ± 0.04 c | 43.62 ± 2.09 a | 0.97 ± 0.06 a | 8.53 ± 0.97 a |
| Ghuwaymid | 1.01 ± 0.03 b | 21.47 ± 2.07 b | 0.54 ± 0.08 bc | 4.15 ± 0.68 b |
| Al Qasab | 1.22 ± 0.02 a | 22.67 ± 1.49 b | 0.70 ± 0.07 b | 2.52 ± 0.22 c |
| Coastal *Sabkhas* | | | | |
| Asfar Lake | 0.93 ± 0.04 bc | 13.33 ± 1.44 c | 0.30 ± 0.04 de | 2.88 ± 0.38 bc |
| Al Uqayr | 0.89 ± 0.02 c | 19.21 ± 1.44 b | 0.42 ± 0.02 cd | 2.47 ± 0.13 c |
| Al Dnan | 1.24 ± 0.28 a | 5.15 ± 1.34 d | 0.15 ± 0.05 e | 2.20 ± 0.13 c |
| *F*-value [1] | 27.20 *** | 59.13 *** | 28.57 *** | 21.85 *** |

[1] F-values from one-way ANOVA (site as source of variation). Values are means ± SE (n = 4). Different letters indicate significant differences (Duncan's test, P ≤ 0.05). Significance: ***P ≤ 0.001.

**Table 4.**
Comparison of soil and plant carbon stocks between inland and coastal *sabkhas*.

| Location | Inland *sabkhas* | Coastal *sabkhas* | t [1] | P value |
|---|---|---|---|---|
| Stock of SOC (t C/ha) | 0.73 ± 0.07 a | 0.29 ± 0.04 b | -2.98 | 0.041 |
| Stock of POC (t C/ha) | 5.07 ± 0.85 a | 2.52 ± 0.15 b | -2.97 | 0.007 |

[1] t-values are from two-sample Student's t-tests, with marsh location (inland vs. coastal) as the factor. Values represent means of 12 replicates ± standard error. Different letters within the same row denote significant differences at P ≤ 0.05.

### 3.5 Comparison of carbon sequestration between inland and coastal sabkhas

Comparison of inland and coastal sabkhas showed higher carbon sequestration in inland sites for both SOC and POC (Table 4). Inland sabkhas stored 5.80 t C/ha in total, compared with 2.81 t C/ha in coastal ones. In both ecosystems, vegetation cover stored more carbon than the soil.

PCA (Fig. 5) further distinguished inland from coastal marshes based on environmental and/or biological variables. The first principal component (PC1), which explains 69.8% of the total variance, largely separates the inland (cyan) and coastal (red) groups, indicating substantial carbon sequestration capacity differences between these localities. The second principal component (PC2) accounts for 28.3% of the variance, adding additional separation within each locality type. The key environmental variables affecting this separation are SOC, SOM, and density, which are comparatively elevated in coastal regions, as seen by the direction and length of their respective vectors. The aggregation of inland regions, including Aushazia and Ghuwaymid, adjacent to the vector for SOC and SOM, indicates that organic matter content is crucial in these ecosystems. In contrast, coastal regions (i.e., Asfar Lake, Al Uqayr, and Al Dnan) are more significantly affected by various soil or habitat attributes. The convergence of specific locations, such as Al Qasab, on PC1 and PC2 indicates transitional zones or variability in environmental conditions within these areas.

## 4. Discussion

The results of this study highlight the notable spatial variability in SBD and SOC levels across salt marshes of central and eastern Saudi Arabia. The significant influence of site-specific factors on both SBD and SOC concentration underscores the heterogeneity of these ecosystems. These results suggest that differences in soil texture, hydrological regimes, and plant communities strongly influence soil properties and their capacity to store carbon, as has also been observed in other studies

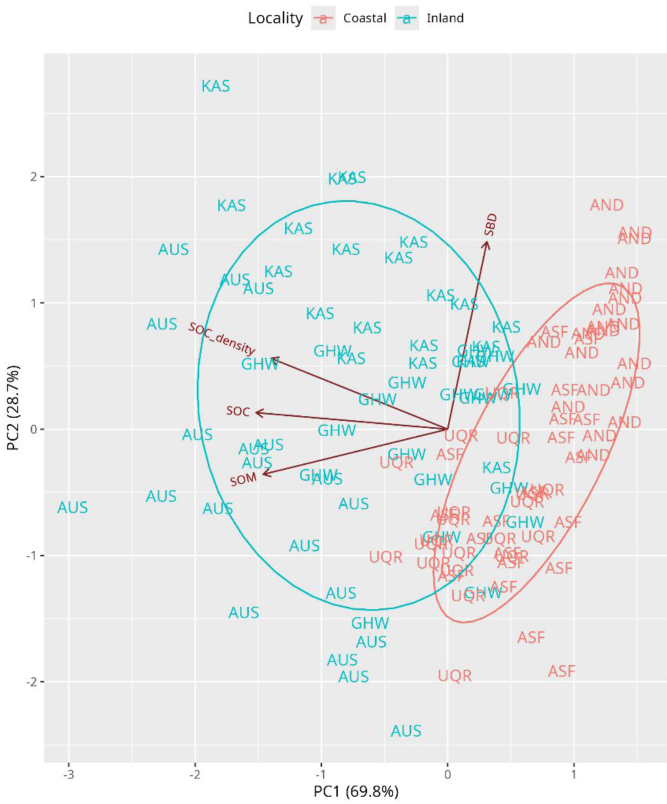


**Fig. 5.** PCA biplot separating inland and coastal *sabkhas*. AUS = Aushazia, GHW = Ghuwaymid, KAS = Al Qasab, ASF = Asfar Lake, UQR = Al Uqayr, AND = Al Dnan.

of coastal wetlands (Duarte *et al.* 2005; Ouyang and Lee 2014; Ouyang and Lee 2020).

Interestingly, inland *sabkhas* have shown a greater capacity for carbon sequestration in sediments and plants than coastal *sabkhas*. The inland *sabkhas* excel in carbon sequestration mainly because of their high plant productivity, slow rate of decomposition, and minimal physical disturbance, allowing carbon to accumulate more when compared to coastal *sabkhas*. This agrees with studies showing that vegetation traits such as plant species diversity, biomass production, and species composition can strongly regulate soil carbon cycling (Chmura *et al.* 2003; McLeod *et al.* 2011). Conversely, the relatively young vegetation in coastal *sabkhas* may explain their lower carbon storage, as immature plant stands may not yet have significantly altered soil properties (cf. Al-Guwaiz *et al.*, 2021). On the other hand, the observed depth-related variations in the SBD indicate that soil compaction and density increase with depth, which is a common pattern in many wetland ecosystems (Craft *et al.* 1991). However, the lack of a significant depth effect on SOC suggests that the organic carbon distribution is more influenced by surface inputs and microbial activity than by soil compaction.

The nonlinear correlation analysis between the SBD and SOC concentration revealed weak relationships at most sites, except for coastal Al Uqayr and Al Dnan. These significant correlations suggest that under certain conditions, denser soils might be associated with higher carbon concentrations, potentially due to the compaction of organic material and reduced decomposition rates. However, the low R-squared values imply that additional, unmeasured environmental factors likely influence SOC concentration. Comparable findings have been reported in mangroves and similar semi-aquatic ecosystems (Al-Guwaiz *et al.* 2021; Eid *et al.* 2016; Eid *et al.* 2020; Shaltout *et al.* 2021)

PCA biplot highlights the ecological differentiation between coastal and inland localities, driven primarily by soil- and habitat-related factors. Coastal localities are characterized by relatively high organic matter contents (SOC and SOM), which likely reflects the influence of proximity to marine systems, increased vegetative productivity, or deposition processes. These factors may promote nutrient-rich soils conducive to supporting diverse or specialized biological communities. The clear segregation along PC1 suggests strong environmental gradients that influence the carbon sequestration potential at the study sites. The clustering of sites within locality types also points to consistency in environmental conditions within these regions. However, the partial overlap of some sites suggests the presence of ecotones or zones of transition, which may be of particular interest for further ecological studies. Understanding the drivers of such transitional zones could provide insights into ecosystem connectivity and resilience under changing environmental conditions. Future studies should concentrate on measuring the specific contributions of these variables to biological diversity and investigating how these patterns are maintained or altered under anthropogenic pressures or climate change scenarios.

The overall higher carbon stocks in marshes such as inland Aushazia highlight the importance of site-specific characteristics in determining carbon sequestration potential. Factors such as soil type, water salinity, and tidal influence could all contribute to the observed differences. Such site-specific variability is widely acknowledged in salt marshes globally (Chmura 2013; Chmura *et al.* 2003; McLeod *et al.* 2011).

This study was limited by a restricted number of sampling locations (six sites-three from inland and three from coastal *sabkhas*). Nonetheless, the chosen sites were representative of the key characteristics of both inland and coastal sabkhas in the region, ensuring that essential biogeochemical processes were documented despite the small sample size. Another constraint is the lack of direct comparisons with other *sabkhas* in arid regions, which is due to the lack of published data on carbon sequestration in similar environments. Despite these limitations, the present study provides significant data on carbon sequestration in under-researched arid *sabkhas*, emphasizing their potential contribution to regional carbon budgets.

Future studies should emphasize long-term monitoring of plant cover and community dynamics to capture temporal trends in C-sequestration. More detailed assessments of plant diversity, hydrological patterns, and soil chemistry are also needed to clarify the mechanisms controlling carbon storage. Such work is essential for developing management strategies that enhance the C-sequestration potential of Saudi salt marshes and other arid-region wetlands.

Overall, these results highlight the urgent need for conservation strategies tailored to hyper-arid salt marshes. Since soil carbon storage is shaped by a combination of soil characteristics, vegetation, climate, and land use, integrated management that prioritizes high-performing sites could significantly strengthen regional carbon budgets and contribute to climate mitigation.

## 5. Conclusion

This study highlights the significant role of salt marshes in inland central and coastal eastern Saudi Arabia in terms of carbon sequestration. It also reveals considerable spatial variability in the SBD, SOC concentration, SOC stock, and POC stock across different sites. Inland Aushazia has emerged as the most effective carbon sink, with the highest SOC concentration, SOC stock, and POC stock, whereas coastal Al Dnan has the lowest values. These findings indicate that local environmental conditions and site-specific factors predominantly influence carbon sequestration potential. The complex interplay between soil properties and site characteristics necessitates tailored conservation and management strategies to optimize carbon storage in these ecosystems. Future research should prioritize long-term monitoring and a more comprehensive investigation of the interactions between vegetative cover, soil properties, and hydrological conditions. This information will facilitate a deeper understanding of and enhance the carbon storage potential of *Sabkhas* in these arid regions. These insights are crucial for informing effective conservation practices aimed at mitigating climate change through improved carbon management in salt marshes.

## CRediT authorship contribution statement

**Hala K. AL Rabiah, Mohamed A. El-Sheikh:** Designed the experiments, collected and analyzed the data, and drafted the manuscript. **Abdurahman A. Alatar:** Contributed to the experimental design, supervised the work, finalized the manuscript. **Waleed A. Alsakkaf:** Assisted with data collection and analysis, contributed to manuscript writing. **Paulo A. Pereira:** Contributed substantially to data analysis, visualization, and manuscript preparation.

## Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work presented in this paper

## Declaration of Generative AI and AI-assisted technologies in the writing process

The authors confirm that there was no use of Artificial Intelligence (AI)-Assisted Technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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