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Sediment Carbon Stock in Natural and Transplanted Mangroves in Bahrain, Arabian Gulf

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Abstract: Mangroves in the Arabian Gulf provide several biological, ecological, and environmental services. They are also considered among the largest carbon sinks. However, mangroves along the coastlines of the Arabian Gulf have degraded in recent decades, mainly due to urbanization and coastal development. Therefore, restoration and afforestation programs have been initiated to enhance the services and functions of mangrove ecosystems and as part of national targets to mitigate climate change. Increasing carbon sinks by quadrupling the current areas covered by mangroves through afforestation programs by 2035 is one of the strategies to mitigate climate change in Bahrain. The aim of the present study was to estimate the organic carbon stocks in the sediments of natural and transplanted mangroves in Bahrain. Within the protected areas of Tubli and Arad Bays, sediment samples were taken down to a depth of 70 cm from natural and transplanted mangroves as well as a bare mudflat. The findings of the present study indicated that the total sediment organic carbon concentrations at three sampling sites of natural and transplanted mangroves and the mudflat were 200.54 ± 24.52, 112.36 ± 55.51, and 81.56 ± 8.92 Mg C/ha, respectively. The natural mangroves in Tubli Bay differed considerably from those in Arad Bay ($p \leq 0.001$), based on the concentrations of organic carbon in sediments. However, there was a noticeable similarity seen in the organic carbon of the mangroves in Arad Bay that were transplanted 25 years prior and the natural mangroves in Tubli Bay, indicating the importance of a long-term mangrove afforestation strategy to mitigate climate change in the Arabian Gulf.

Keywords: afforestation; rehabilitation; blue carbon; coastal sediment; arid environment; climate change mitigation

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Citation: Naser, H.A. Sediment Carbon Stock in Natural and Transplanted Mangroves in Bahrain, Arabian Gulf. *Land* **2023**, *12*, 2055. https://doi.org/10.3390/land12112055

Academic Editors: Pavel Krasilnikov, Lúcia Helena Cunha dos Anjos and Ligang Xu

Received: 21 September 2023
Revised: 8 November 2023
Accepted: 9 November 2023
Published: 12 November 2023

1. Introduction

Mangroves are woody plants found in tropical and sub-tropical regions that develop at the interface of land and water [1]. These plants have vast biological, ecological, and socio-economic values and functions [2,3]. Mangrove habitats support a rich diversity of terrestrial, marine and avifauna species [4]. They are considered as important fishery resources for coastal communities by maintaining nursery grounds for several commercially important species, including fish and crustaceans [5]. Mangroves are crucial for protecting the shoreline from sedimentation and flooding [6]. They also provide several ecotourism and recreational services [7]. Mangroves are considered one of the most productive ecosystems in the world [8]. Because of the high rates of sedimentation and the anaerobic conditions found in soils, they have a tremendous ability to store carbon in their soil system for an extended length of time [9]. Consequently, mangroves are important carbon sinks worldwide that support efforts to mitigate climate change by capturing and storing organic carbon, especially in their soils [10–12].

Mangroves occupy around 165 km^2 in the Arabian Gulf [13]. Only two mangrove species, namely *Avicennia marina* and *Rhizophora mucronate*, exist in the Arabian Gulf due to extreme environmental conditions represented by seasonal temperature fluctuations (16–36 °C) and high levels of salinity exceeding 42 psu [14]. The latter species is found only in restricted areas along the Iranian coast [15], occupying around 0.2 km^2 [16]. Due to its adaptability to fluctuating seasonal temperature and salinity extremes, *A. marina* is the predominant species along the Arabian Gulf's beaches [17,18].

According to Almahasheer [13], the United Arab Emirates has the largest overall mangrove coverage in the Arabian Gulf (78.76 km^2), followed by Iran (65.24 km^2), Saudi Arabia (10.36 km^2), Qatar (9.97 km^2), Bahrain (0.58 km^2) and Kuwait (0.58 km^2). Mangroves are the only evergreen plant species in the desert of the Arabian Gulf, providing food for livestock and other wild animals [19]. Mangrove ecosystems in the Arabian Gulf are highly productive, supporting a variety of terrestrial and marine species, including fish, shrimps, turtles, birds, and other invertebrates [20,21]. Mangroves in the Arabian Gulf contribute to the protection of coastlines against erosion [22], promotion of ecotourism [23], and climate change-related impacts, such as sea level rise [24]. Additionally, mangroves in the Arabian Gulf are considered a major carbon sink that contribute to absorption and storage of atmospheric CO_2 [25,26].

The Arabian Gulf has witnessed a rapid growth in human population and an increased economic development associated with intensive coastal urbanization [27]. Several mangrove habitats along the coastlines of the Arabian Gulf have been degraded by the intensive dredging and reclamation activities and oil pollution [28,29]. There have been reports of significant mangrove habitat losses in various Arabian Gulf locales. Almahasheer et al. [28] reported that Tarut Bay in Saudi Arabia had lost around 55% of mangrove coverage between 1972 and 2011. Similarly, more than 95% of the spatial coverage of mangroves in Tubli Bay in Bahrain were lost between 1967 and 2020 [30]. Decline and degradation of blue carbon habitats in the Arabian Gulf, including mangroves, have been considered as a prime cause of potential biological diversity loss and associated ecosystem services [31]. Additionally, degradation of these habitats can affect an important climate mitigation service, and potentially release additional CO_2 to the atmosphere [32].

Mangrove restoration and rehabilitation are regarded as natural ways to mitigate the effects of climate, while also preserving fisheries, and coastal habitats [12,33,34]. Therefore, national programs for mangrove conservation and afforestation have been initiated in the Arabian Gulf countries [19,35]. Successful establishment of planted mangroves has resulted in several ecological benefits, including increasing local growth of mangrove stands [36], enhancing biodiversity [35], facilitating habitat complexity [37], and protecting shorelines against erosion [22].

The protection of the mangrove ecosystem and its associated ecological services is a conservational priority in Bahrain. Mangroves aggregating in Ras Sand area in Tubli Bay were declared as a national nature reserve in 1986. Additionally, Tubli Bay was designated as a wetland site of international importance for birds (Ramsar Convention) in 1997 [38]. The Fisheries Department started an initiative for afforestation of mangroves in 1998 by transplanting mature seedlings in the mudflats of Arad Bay. Additionally, Bahrain launched a nationwide program for mangrove restoration and planting in 2013 with the support of the Supreme Council for Environment and other partners. This effort involves planting mangroves in Tubli and Arad Bays, and other appropriate coastal locations. This program aimed to rehabilitate coastal areas, increase carbon sequestration, and contribute to coastal protection. For instance, around 1009, 680, 1077, and 1763 seedlings of mangrove were transplanted in 2013, 2015, 2017, and 2018, respectively [39].

Bahrain has established a national objective of becoming carbon neutral by 2060 at the 2021 United Nations Climate Change Conference (COP 26), with an intermediate goal of reducing CO_2 emissions by 30% by 2035. Bahrain announced its intention to quadruple the present mangrove lands by 2035 as part of its strategy to fulfill the national interim target of a 30% reduction in CO_2 emissions [40]. Bahrain recognized mangrove plantation as a realistic approach to meeting national climate goals. It is important to examine the efficacy of mangrove transplanting initiatives in accomplishing their carbon sequestration goals in order to meet national climate targets and promote conservation. [41]. Estimation of carbon stocks in sediment can provide insight into the management and effectiveness of mangrove afforestation programs in achieving their objectives. Therefore, there was a need to estimate the carbon stock in the sediment of both the natural and transplanted mangroves in Bahrain. The aim of the present study was to compare the organic carbon in the sediments between natural mangroves in the protected area of Tubli Bay, transplanted mangroves in the protected area of Arad Bay, and a bare mudflat in Arad Bay. This study might contribute to providing quantitative data related to the carbon stock in natural and transplanted mangroves in the Arabian Gulf.

2. Material and Methods

2.1. Study Areas

The study was conducted in two protected areas, namely Tubli and Arad Bays (Figure 1). Tubli is a sheltered bay located in the northeast of Bahrain. This bay supports a variety of habitats, including mudflats, algal mats, and mangrove swamps. Due to its importance as a feeding ground for a substantial population of waders, the bay has been declared as a Ramsar site in 1997. Tubli Bay hosts the remaining natural mangrove stands in Bahrain, with the main aggregation in the Ras Sand area. The muddy nature of the sediment, and the input of low salinity water from nearby farms and underground springs, which used to be abundant, in the Ras Sand area provide favorable conditions for the growth and development of mangrove plants [38]. Mangrove plants were historically dominant on the coastlines of Tubli Bay [42]. However, coastal development associated with reclamation activities along the bay have substantially reduced the mangrove stands. A recent study by Aljenaid et al. [30] indicated that mangrove cover in Tubli Bay has declined from 328 ha in 1967 to 48 ha in 2020. The first regional Red List evaluation of specific species in the Kingdom of Bahrain rated mangroves as ‘Critically Endangered’ [43].

Arad Bay is a sheltered mudflat located in the northeast of Bahrain. The area of the bay is around 0.5 km^2, which exposes a large intertidal area with rich benthic organisms [44]. The bay was designated as a natural marine protected area in 2003 due to its importance as a feeding and roosting ground for important shorebird populations [45]. In addition to its ecological importance, Arad Bay is a national park with several recreational and amenity values. Mangrove plants have been transplanted in the bay since 1998, with potential contribution to the coastal productivity, represented by high levels of abundance and diversity in macrobenthos and birds [44,45]. The transplanted mangroves display variable tree heights and canopy covers in the bay. When compared with the younger mangroves that were transplanted in 2013, the older mangroves (about 25 years) in the bay’s south-east corner have the tallest trees and thickest canopy.

2.2. Sediment Sampling

Sediment sampling was conducted during December 2022 and February 2023. Three sampling sites were specified, including one site in the natural mangroves in Tubli Bay, and two sites in Arad Bay (transplanted mangroves and a bare mudflat) (Figure 2). Samples were taken from three plots (10 × 10 m) in each site. In each plot, three undisturbed sediment samples were taken with a PVC corer (inner diameter = 3.56 cm) down to a depth of 70 cm. Mangroves in the Ras Sand area are densely grown, with the presence of a network of large roots and extensive pneumatophores. Priorities were set throughout the sampling design and the pilot sampling to minimize disturbance of the protected mangroves and avoid destructive sampling. As a result, samples were taken from the borders of the internal channels of the Ras Sand natural mangroves, which represent three zones of the mangroves’ primary aggregate.

In Arad Bay, samples were collected during low tide from the transplanted mangroves located in the south-east area of the bay. To minimize the disturbance and reduce hazards associated with deep mud, the three plots were established within around 8 m from the edge of the transplanted mangroves. Additionally, three plots were sampled from bare mudflats in Arad Bay.

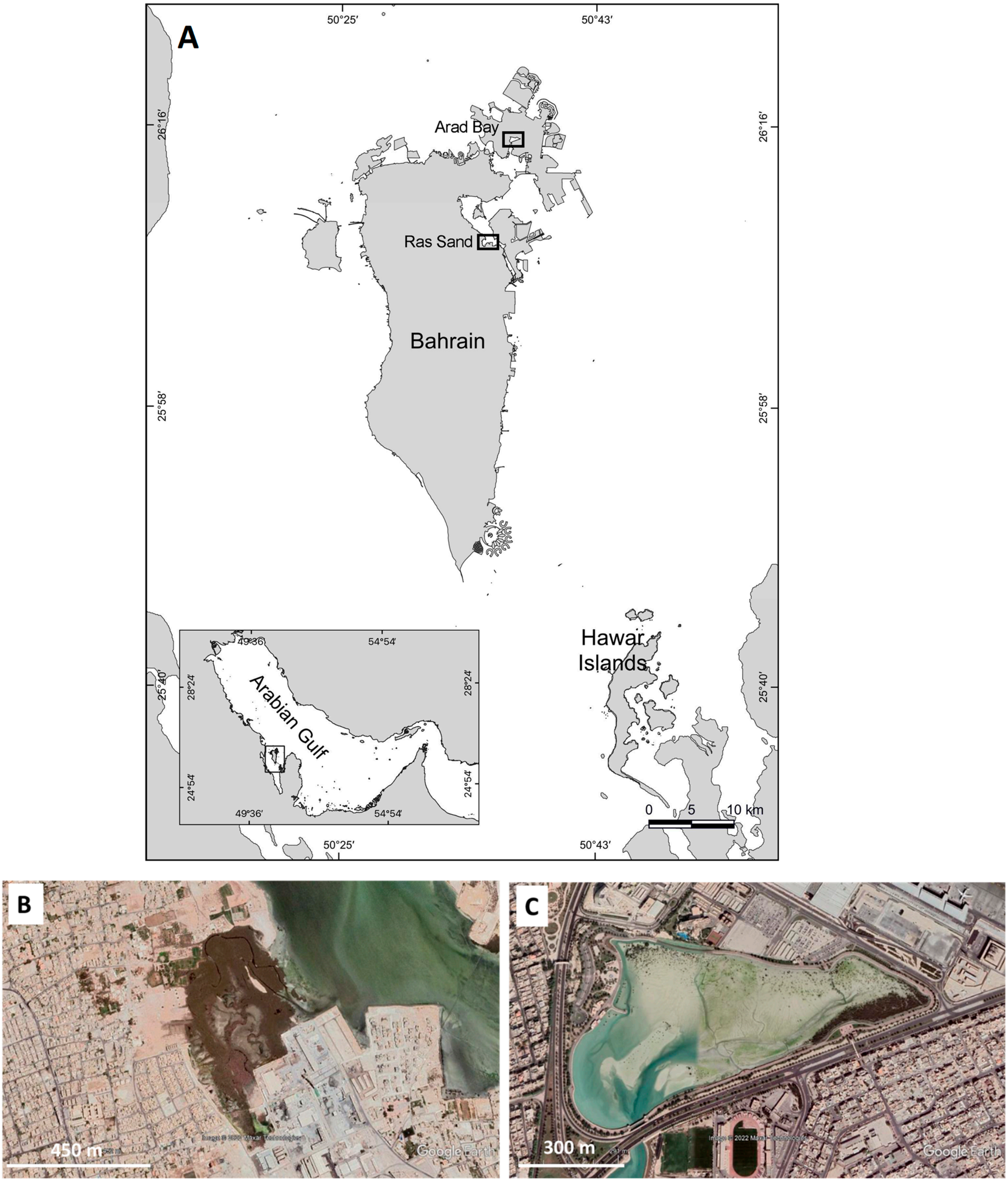

Figure 1. A map of Bahrain showing the locations of the Ras Sand area and Arad Bay (**A**), Ras Sand area in Tubli Bay, hosting the remaining natural mangroves in Bahrain (**B**), Arad Bay, a mudflat with transplanted mangroves (**C**).

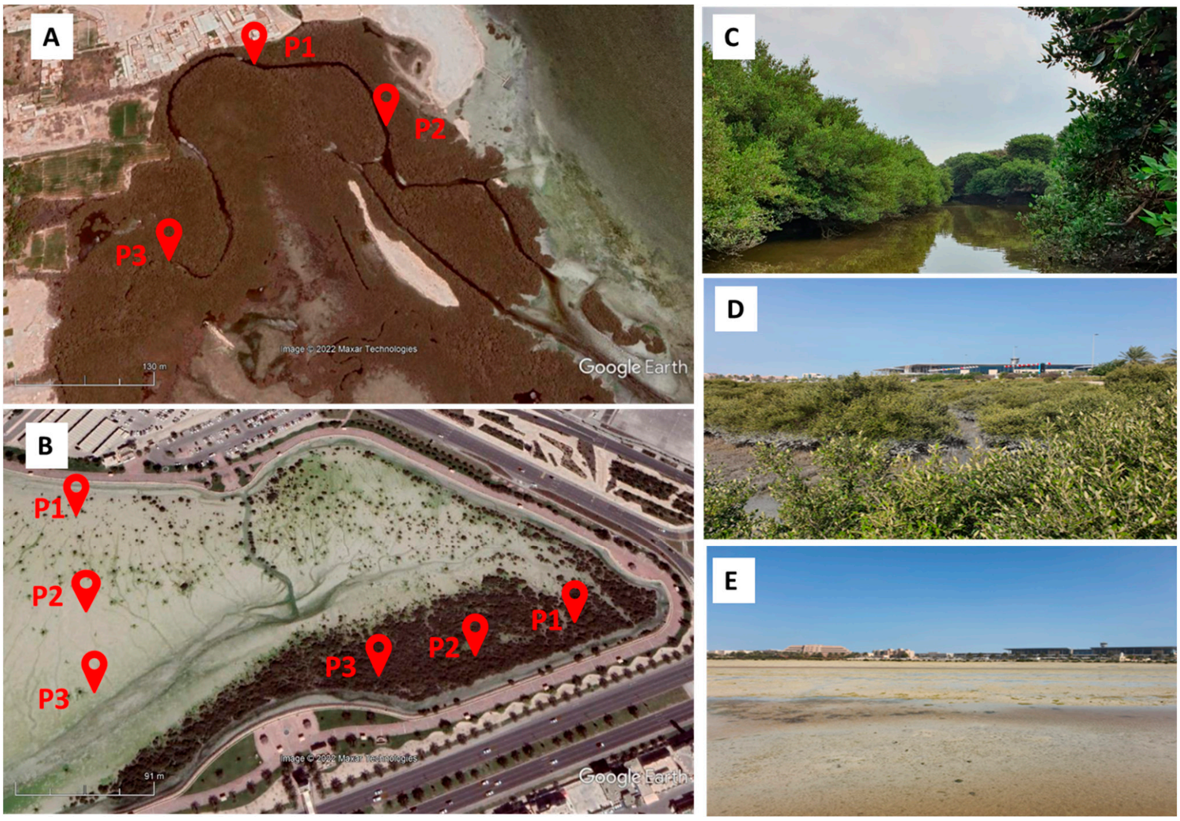

Figure 2. Sampling locations in Ras Sand natural mangroves (**A**), Arad transplanted mangroves and Arad mudflat (**B**), Ras Sand mangroves (**C**), Arad mangroves (**D**), and Arad mudflat (**E**).

The geographical coordinates of all sampling plots are presented in Table 1. Sediment core samples were divided into 7 depth intervals: 0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70 cm. A relatively uniform and representative section (5 cm) of sediment was collected from the 7 intervals. Sediment samples were then placed in labelled polyethylene bags and transferred in an icebox and stored at 4 °C at the laboratory to minimize decomposition of organic matter and microbial growth. In total, 189 sediment samples were collected from the three study areas (3 sites × 3 plots × 3 replicates × 7 depth intervals).

Table 1. Geographical coordinates of the sampling plots in Tubli and Arad Bays.

Area	Plot	Latitude N	Longitude E
Tubli Mangrove	1	26°09′16.79″ N	50°35′29.70″ E
Tubli Mangrove	2	26°09′08.89″ N	50°35′27.78″ E
Tubli Mangrove	3	26°09′13.89″ N	50°35′26.09″ E
Arad Mangrove	1	26°15′42.71″ N	50°38′00.34″ E
Arad Mangrove	2	26°15′41.80″ N	50°37′57.49″ E
Arad Mangrove	3	26°15′41.00″ N	50°37′53.83″ E
Arad Mudflat	1	26°15′45.18″ N	50°37′44.35″ E
Arad Mudflat	2	26°15′42.81″ N	50°37′44.51″ E
Arad Mudflat	3	26°15′40.36″ N	50°37′44.64″ E

2.3. *Sediment Treatment*

Dry Bulk Density (DBD) for each sediment interval was obtained by drying a known volume of the wet sample in an oven (LTE OP150). Oven-dried sediment samples were cooled down to room temperature in a desiccator and weighed. The sediment was then re-dried to reach a constant weight (60 °C for 48 h) [46].

Dry sediment samples were cleared from roots, shells, and gravels before organic content analyses. Sediment samples were homogenized using a pestle and mortar and sieved using 1 mm mesh size. The Loss on Ignition (LOI) method was used to estimate the soil organic content. The LOI method estimates the organic content of soil by oxidizing organic matter to CO_2 at an elevated temperature in a muffle furnace and measuring the weight loss [47]. Low temperature ignition (375 °C) was selected to avoid the overestimate of organic carbon resulting from calcium carbonate decomposition associated with ignition in high temperatures [48,49]. Known weights of sediment samples were placed in pre-weighted crucibles and ashed in a muffle furnace (Carbolite AAF 1100) at 375 °C for 17 h [47].

2.4. Estimation of Soil Carbon Stock

According to Howard et al. [50], the total soil carbon in mangroves is determined by the amount of organic carbon within a defined area and soil depth, which requires specifying soil depth, depth interval, dry bulk density, and percentage of organic carbon. The Dry Bulk Density (DBD) was obtained based on the following equation:

$$\text{DBD (g/cm}^3\text{)} = \text{Mass of dry soil (g)/Original volume sampled (cm}^3\text{)} \tag{1}$$

Percentage of sediment organic matter (SOM) for the samples was estimated using the following equation:

$$\text{SOM (\%)} = \text{(Initial dry mass} - \text{Mass after ashing)} \times 100 \tag{2}$$

Further conversion of sediment organic matter to percentage organic carbon content (SOC) was conducted based on the following equation:

$$\text{SOC (\%)} = \text{SOM\%}/1.92 \tag{3}$$

where 1.92 is the conversion factor of SOM to SOC. This conversion factor was recently used to estimate organic carbon in arid mangroves, including the Arabian Gulf countries of United Arab Emirates [51] and Qatar [26].

The soil organic carbon density (C_{di}) for each depth interval was calculated based on the following equation:

$$C_{di}\ \text{(g/cm}^3\text{)} = \text{DBDi (g/cm}^3\text{)} \times \text{(\% SOCi/100)} \tag{4}$$

where Cdi is soil organic carbon density of interval i, DBDi is soil dry bulk density of interval i, and SOCi is soil organic carbon for interval i.

The amount of organic carbon in each depth interval was calculated based on the following equation:

$$\text{Soil organic carbon interval i (g/cm}^2\text{)} = \text{Soil carbon density i (g/cm}^3\text{)} \times \text{Interval (10 cm)} \tag{5}$$

The organic carbon (g/cm^2) was converted to the most commonly unit used in carbon stock assessment (M g C/hectare), by multiplying the carbon in the intervals (g/cm^2) by 100.

The sum of the amount of carbon in core intervals over the total sampling depth (70 cm) was calculated by summing the organic carbon (Mg C/ha) in the 7 intervals. The above calculations were conducted for each core sample. The average amount of carbon in each sampling site for the given depth (70 cm) was calculated by summing the carbon (Mg C/ha) in the cores divided by number of cores in each sampling area (n = 9). All the above calculations are provided as Supplementary File S1.

2.5. Statistical Analyses

Statistical analyses were conducted using IBM SPSS Statistics 25 and PRIMER v7 [52]. Descriptively, results were expressed as mean ± standard deviation. Data were initially tested for normality using the Shapiro–Wilk test utilizing the SPPS statistical package. All the tested variables in the depth intervals, namely dry bulk density, percentage of organic matter, percentage of organic carbon and organic carbon (Mg C/ah), were found to be statistically significant ($p \leq 0.001$). Therefore, the non-parametric test of Kruskal–Wallis was utilized to assess differences in carbon stock variables among the sampling areas, followed by multiple pairwise comparisons between the groups. In order to investigate the relationship between depth and DBD, percentage of carbon and organic carbon organic (Mg C/ha), non-parametric Spearman correlation was used at the three sample locations. The PRIMER statistical package was employed to gain further spatial insights into the similarities between mangroves in Tubli and Arad Bays based on organic carbon. The organic carbon data were square-root-transformed, and a similarity matrix was constructed based on Euclidean distance, which is a coefficient widely used in environmental data analysis. Typically, a stress value <0.05 gives an excellent representation with no prospect of misinterpretation of the data [53]. A non-metric multi-dimensional scaling ordination (MDS) was generated, which showed the relative similarity of organic carbon variables among the two areas of mangroves.

3. Results

Total soil organic carbon (depth 70 cm) in the three sampling sites of natural mangroves in Tubli Bay, transplanted mangroves in Arad Bay, and the mudflat in Arad Bay were 200.54 ± 24.52, 112.36 ± 55.51, and 81.56 ± 8.92 Mg C/ha, respectively (File S1). Mean variations of DBD (g/cm^3), percentage of organic carbon and organic carbon (Mg C/ha) with soil depth (70 cm) are presented in Table 2.

Table 2. Mean variations of DBD (g/cm^3), % of organic carbon and organic carbon (Mg C/ha) with soil depth (70 cm) (cores n = 9).

	Tubli Mangroves			Arad Mangroves			Arad Mudflat		
Depth cm	**DBD g/cm^3**	**Org. Carbon %**	**Org. Carbon M g/ha**	**DBD g/cm^3**	**Org. Carbon %**	**Org. Carbon M g/ha**	**DBD g/cm^3**	**Org. Carbon %**	**Org. Carbon M g/ha**
10	0.49 ± 0.07	6.65 ± 1.47	31.97 ± 3.21	0.65 ± 0.25	2.77 ± 1.36	19.07 ± 12.45	0.68 ± 0.10	2.02 ± 0.17	13.59 ± 0.90
20	0.47 ± 0.06	6.49 ± 1.20	30.30 ± 3.31	0.72 ± 0.17	2.43 ± 1.55	17.64 ± 11.51	0.78 ± 0.12	1.58 ± 0.25	12.18 ± 2.17
30	0.48 ± 0.09	6.33 ± 1.02	29.61 ± 3.30	0.76 ± 0.14	2.41 ± 1.58	16.45 ± 8.85	0.86 ± 0.08	1.27 ± 0.27	10.87 ± 1.88
40	0.46 ± 0.08	6.51 ± 1.21	29.04 ± 3.54	0.78 ± 0.15	2.31 ± 1.34	15.01 ± 6.35	0.86 ± 0.13	1.20 ± 0.11	10.40 ± 1.79
50	0.49 ± 0.07	6.00 ± 1.12	29.19 ± 4.28	0.79 ± 0.20	2.44 ± 1.26	14.23 ± 5.70	0.85 ± 0.15	1.44 ± 0.17	12.16 ± 1.32
60	0.49 ± 0.14	5.63 ± 1.75	25.93 ± 6.65	0.81 ± 0.15	2.38 ± 1.17	15.22 ± 6.31	0.77 ± 0.21	1.50 ± 0.23	11.23 ± 1.90
70	0.44 ± 0.07	5.56 ± 1.37	24.52 ± 6.75	0.77 ± 0.13	2.56 ± 1.10	14.76 ± 6.40	0.77 ± 0.22	1.49 ± 0.20	11.12 ± 2.25

Statistical analysis revealed significantly differences in organic carbon between the sampling sites, H (2) = 99.32, $p \leq 0.001$. However, pairwise comparisons between groups indicated that mangroves in Tubli Bay differed significantly from mangroves in Arad Bay ($p \leq 0.001$) and the mudflat in Arad Bay ($p \leq 0.001$), while no significant difference was detected between the mangroves and the mudflat in Arad Bay ($p = 0.194$). Similar patterns were observed for soil organic percentage and dry bulk density between the sampling sites, H (2) = 122.06, $p \leq 0.001$ and H (2) = 95.71, $p \leq 0.001$, respectively. Likewise, there were no significant differences in soil organic percentage and dry bulk density between mangroves and the mudflat in Arad Bay ($p = 0.843$ and $p = 0.947$, respectively) (Figure 3).

The mean soil DBD values were 0.47 ± 0.81, 0.75 ± 0.17 and 0.80 ± 0.16 g/cm^3 for Tubli mangroves, Arad mangroves, and Arad mudflat, respectively. DBD in the sediment of Tubli mangroves ranged between 0.31 and 0.83 g/cm^3, while it varied from 0.19 to 1.02 g/cm^3 in the sediment of Arad mangroves and 0.43 to 1.09 g/cm^3 in the Arad mudflat.

The mean soil organic carbon percentage values were 6.16 ± 1.32, 2.30 ± 1.33, and 1.50 ± 0.32 for Tubli mangroves, Arad mangroves, and Arad mudflat, respectively. The largest variation was detected in Tubli mangroves (2.15–8.53%), followed by Arad mangroves (1.01–5.06%), and Arad mudflat (0.96–2.36%).

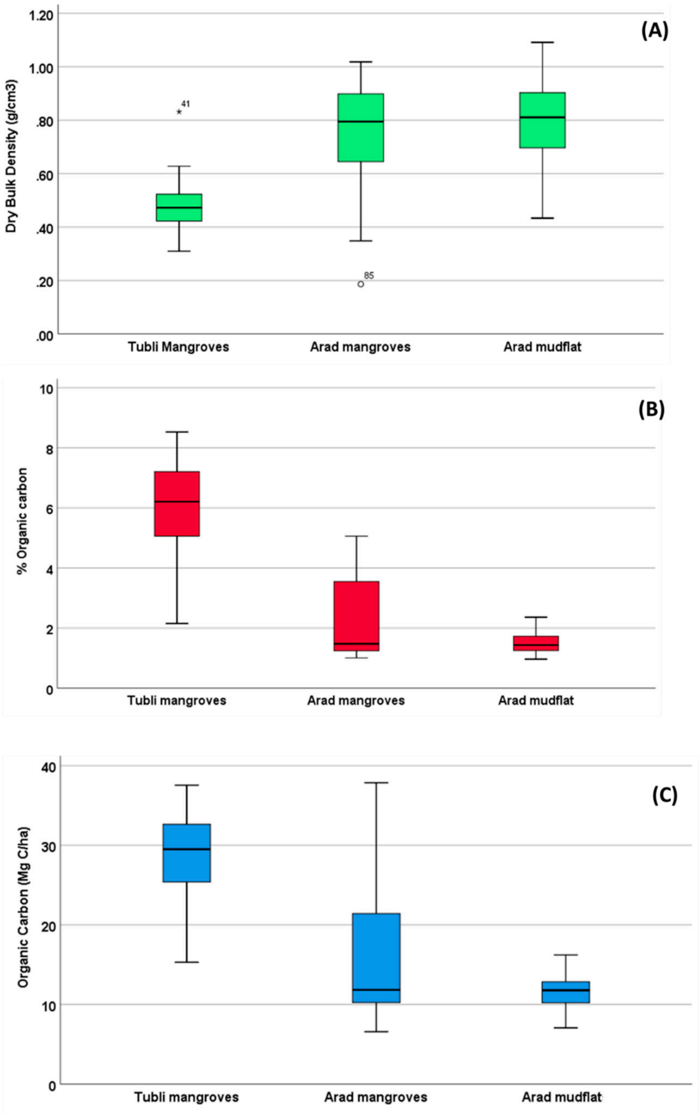

Figure 3. Boxplot charts of the DBD (g/cm^3) (**A**), percentage of organic carbon (**B**), and organic carbon (Mg C/ha) (**C**), presented as the median and interquartile range.

The mean organic carbon values were 28.65 ± 5.04, 16.05 ± 8.35, and 11.65 ± 1.98 Mg C/ha for Tubli mangroves, Arad mangroves, and Arad mudflat, respectively. The largest variation was detected in Arad mangroves (6.58–37.87 Mg C/ha), followed by Tubli Bay mangroves (15.31–37.56 Mg C/ha), and Arad mudflat (7.06–16.23 Mg C/ha). Almost similar maximum values of organic carbon (Mg C/ha) were recorded in Tubli and Arad mangroves (37.56 and 37.87 Mg C/ha, respectively).

Non-parametric Spearman correlation revealed weak negative correlation R_s (61) = −0.386, P = 0.002 between depth and organic carbon (Mg C/ha) in Tubli Bay. Similarly, a weak negative correlation R_s (61) = −0.282, P = 0.025 was observed between depth and organic carbon in the Arad mudflat. However, no significant association of depth and organic carbon was detected in Arad mangroves. Further, no significant correlations were observed between depth and dry bulk density in the three sampling sites. A weak negative correlation between depth and organic carbon percentage in sediment was found in Tubli Bay R_s (61) = −0.254 (P = 0.045) and Arad mudflat R_s (61) = −0.270 (P = 0.003).

The sediment's DBD mean values changed with depth, showing a progressive rise from the upper to the deeper layers and a slight drop in the Arad mudflat at a depth of 60 cm. Generally, the highest levels of organic percentage and organic carbon were recorded in the top 30 cm in the three sampling sites (Figure 4).

The multidimensional scaling (MDS) analysis based on similarities in organic carbon in the sediment of mangroves in Tubli and Arad Bays revealed two main groups (Figure 5). Mangroves in Tubli Bay distinctly differed from those in Arad Bay (stress value = 0.01). However, relative resemblance was detected between organic carbon in plot one of Arad Bay and those in Tubli Bay (Figure 5), indicating that sediment of mangroves transplanted 25 years ago shows relatively similar levels of organic carbon compared to those in the natural mangroves.

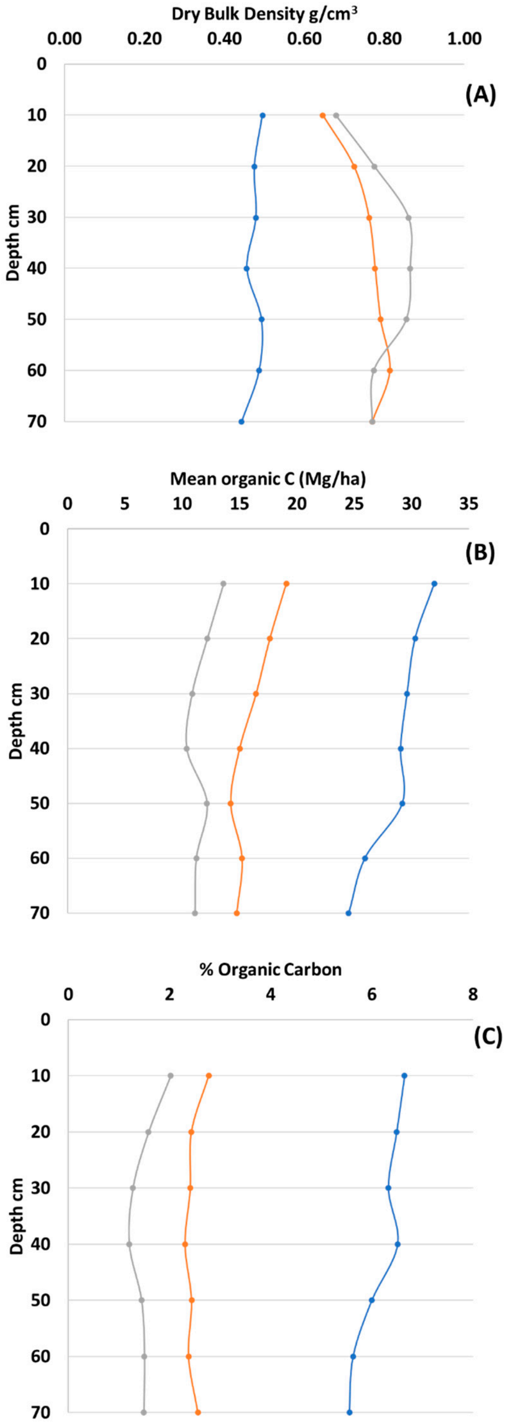

Figure 4. Changes in mean depth values for DBD (**A**), organic carbon (Mg C/ha) (**B**), and percentage of organic carbon (**C**) in the sampling sites (blue color =Tubli mangroves, orange color =Arad mangroves, and grey color = Arad mudflat).

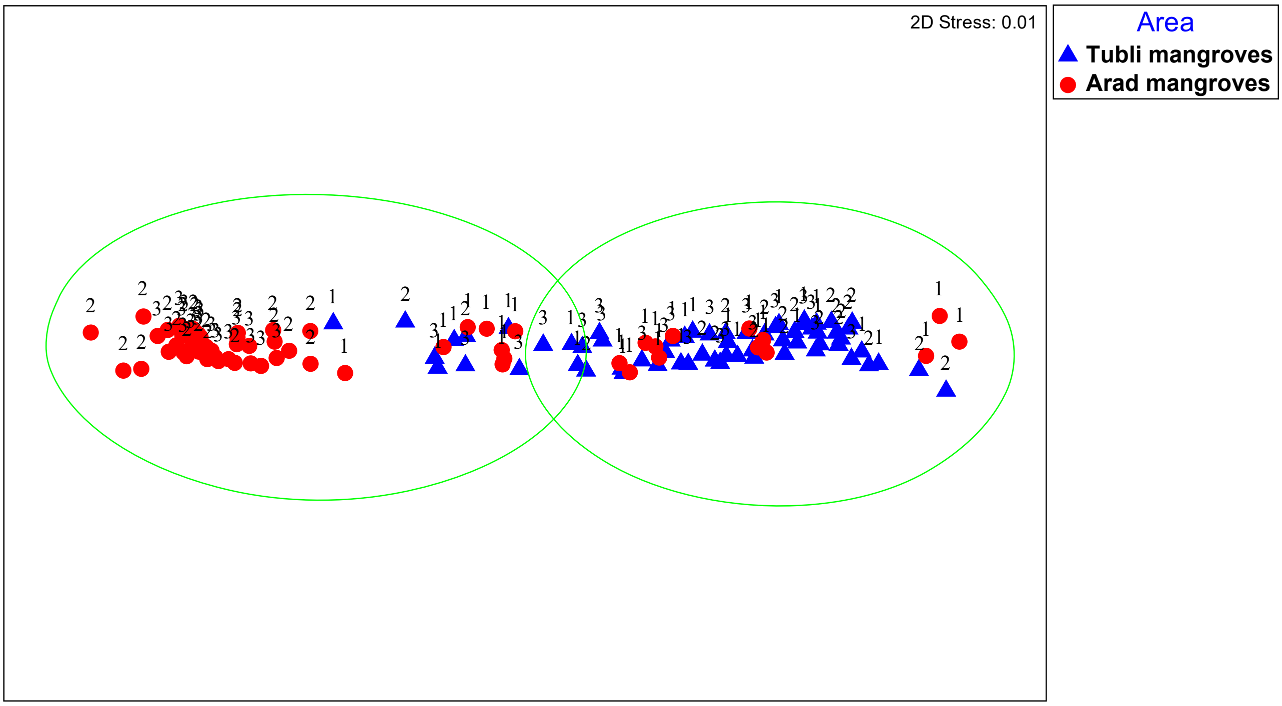

Figure 5. A non-parametric MDS of organic carbon releveled two distinct groups in the mangrove areas in Tubli and Arad Bays, with mangroves in plot one of Arad showing relative similarity with those in Tubli Bay (numbers indicate plots).

4. Discussion

4.1. Carbon Stock in Sediments

Globally, carbon stocks at a range of 455–856 Mg/ha are stored in mangrove forests [9]. Belowground carbon stored in roots and sediments contains around 82–91% of the total mangrove ecosystem carbon stock [54], indicating the major role of soil carbon stock in climate change mitigation strategies. The present study investigated the carbon stocks in the sediment of natural and transplanted mangroves and a bare mudflat. The findings of the present study indicated that natural mangroves stored the highest amount of carbon in the sediment (200.54 Mg C/ha) compared with the transplanted mangroves (112.36 Mg C/ha) and the mudflat (81.56 Mg C/ha). The ranges of carbon stocks found in the present study are generally in line with the reported ranges from different parts of the Arabian Gulf (Table 3), reflecting the lower carbon stock in arid mangroves compared to global ranges [26,55]. According to Boone & Bhomia [54], mangrove forests in the Arabian Gulf and Gulf of Oman hold around 217 Mg C/ha. Similarly, Sanderman et al. [56] estimated soil organic carbon in the Arabian Gulf to be around 278.4 Mg C/ha. The combination of hot and dry conditions in the Arabian Gulf may affect the ability of blue carbon habitat, including mangroves, to store carbon within their sediments in comparison with other regions [31]. Additionally, the high proportion of carbonates due to the dominance of marine sediment inputs in arid regions can affect the carbon budget and the role of mangrove areas as carbon sink [55]. In the Arabian Gulf, carbonates range between 20% and 60% of the soil carbon [24]. Aljenaid et al. [30] reported that the mean carbon stock in mangrove sediment (depth 35 cm) in Tubli Bay in Bahrain was 55.2 Mg C/ha. Savari et al. [57] indicated that the mean sediment carbon stock in the Gulf of Oman during both pre- and post-monsoon was around 227 Mg C/ha. The mean carbon stock in 1 m deep sediment was 76 Mg C/ha in mangrove habitats along the western coastline of the Arabian Gulf [32]. Additionally, the mean sediment carbon stock to 1 m depth along Qatar coastline was around 50.17 Mg C/ha [26]. Further, a mean of 108 Mg C/ha in the top 1 m of the sediment was reported in a mangrove wetland along the Strait of Hormoz in the Arabian Gulf [58].

Conversely, high levels of carbon stock were reported in the Arabian Gulf. For instance, Mahmoudi et al. [59] compared carbon stock in the sediment of three mangrove forests within a gradient of human activities along the Iranian coast of the Arabian Gulf. The mentioned study revealed higher levels of carbon stock in the sediment (867.4, 728.4, and 612.6 t/ha) that were equal or higher than carbon stock of other mangroves in many parts of the world [59].

Soil dry bulk density (DBD) plays some important roles in the porosity and aeration of the soil [60]. Although no significant association was detected between depth and DBD in the present study, generally, in most of the sampling plots the deepest soil layers were relatively higher in DBD than the uppermost ones. Similarly, no geographical difference or significant changes with depth were observed in DBD across vegetated coastal habitats in the Arabian Gulf [32]. The present study also showed that DBD was high in the mudflat, followed by the transplanted mangroves and the natural mangroves. Likewise, the average soil bulk density was relatively higher in rehabilitation areas (0.96 g/cm^3) in comparison with natural mangrove areas (0.85 g/cm^3) along the riverside of Mahakam in Indonesia [61].

The present study revealed that the mangrove area in Tubli Bay exhibited the highest percentage of organic carbon (Mean = 6.16%). Ras Sand in Tubli Bay is considered the most sheltered coastal area in Bahrain [62], which increases the deposition of organic carbon. Additionally, Arad Bay is a semi-enclosed coastal area with relatively high levels of sediment deposition. These conditions can increase the levels of sediment and associated organic matter. Studies conducted in Tubli and Arad Bays reported high levels of organic matter [44,63,64]. Therefore, it is argued that mangrove areas and intertidal mudflats in Bahrain are productive habitats and should be given priority for conservation. Additionally, coastal mudflats and sabkhas in the Arabian Gulf store substantial carbon as demonstrated in two sabkha sites in Qatar with carbon stocks of 109.11 and 67.77 Mg C/ha [65]. Similarly, a range of 51.0–120.5 Mg C/ha was reported in coastal sabkha in the UAE [31].

4.2. Natural vs. Transplanted Mangroves

The findings of the present study indicated that there was a decrease of around 40% in sediment carbon stock between the natural mangroves in Tubli Bay and transplanted mangroves in Arad Bay. Similar patterns of carbon stock in natural and transplanted mangroves were reported in the Arabian Gulf. For instance, Cusack et al. [32] reported a decrease of 38% in sediment carbon stock between natural (91 Mg C/ha) and transplanted 56 Mg C/ha) in the UAE mangroves. Likewise, a difference of 35% in carbon stock in the sediment was found between natural (156 Mg C/ha) and planted (102 Mg C/ha) mangroves in the UAE [25]. Further, in an estuary along the Bay of Bengal in India, the total carbon was reported to be 98.2% higher in natural mangroves and 41.8% in planted mangroves than that in non-mangrove soil [66].

According to Lovelock et al. [67], restored mangrove forests may require around 20–25 years to reach similar levels of carbon stock in sediment to those of undisturbed mangroves. Additionally, the organic carbon storage in the sediment tended to increase with the age of restored mangroves [68]. The present study reported a high level of similarities in carbon stock between the natural mangroves in Tubli Bay and the oldest mangroves that were transplanted around 25 years ago in Arad Bay (Figure 5). Although no significant difference was detected between the two areas, the mean of carbon of the three sediment cores of plot one in Arad Bay was 185.56 Mg C/ha, which is relatively comparable to the overall mean of the natural mangroves in Tubli Bay (200.54 Mg C/ha).

4.3. Roles of Transplanted Mangroves

Several studies have indicated that mangrove restoration enhanced sediment organic carbon. For instance, Pham et al. [68] reported that restored mangroves in Vietnam predominantly contributed organic carbon to the sediments with the mean of below ground carbon stock ranging between 103. 8 to 412.4 Mg C/ha. Similarly, DelVecchia et al. [69] indicated the long-term carbon storage of planted mangroves in the Ecuador. The sediment from natural mangroves in three sites in Ecuador stored organic carbon of 397, 356, and 374 Mg C/ha, compared with 304 Mg C/ha in a site of afforested mangroves [69]. Amelia et al. [70] indicated that planting propagules and seedlings of mangroves in abandoned sites in Indonesia was a successful approach in enhancing the carbon stocks in the sediments and reported values of 506.89 and 461.85 Mg C/ha, respectively. Additionally, Aye et al. [71] showed that mangrove plantations in Myanmar played an important role in mitigating climate change and reported an estimated average carbon storage of 135.11 Mg C/ha in planted mangrove forests.

Table 3. Comparison of sediment carbon stocks (Mg C/ha) in natural and transplanted mangroves, and mudflats with selected studies from different regions.

Country	Natural Mangroves	Planted Mangroves	Mudflats/ Sabkhas	References
Bahrain	200.54 (70 cm)	112.36 (70 cm)	81.56 (70 cm)	The Present study
Bahrain	55.2 (35 cm)			[30]
Qatar			109. 11 and 67.77	[65]
UAE	156	102		[25]
KSA-Arabian Gulf	91	56		[32]
Iran-Gulf of Oman	227			[57]
Arabian Gulf	217			[54]
Arabian Gulf	278.4			[56]
Egypt-Red Sea	284.35 and 428.02	189.14	98.04	[60]
Indonesia	477.82	363.54		[72]
Indonesia		136.8		[73]
Indonesia		506.89 and 461.85		[70]
Ecuador	397	304		[69]
Globally	445–856			[9]

Planting and restoring mangroves contributed to enhancing the carbon stock in the sediments [68,74]. Kusumaningtyas et al. [74] reported that rehabilitated mangroves stored higher carbon in the sediment (364 Mg C/ha) than in natural sites of mangroves in Indonesia (126 Mg C/ha). Additionally, protected and rehabilitated mangroves in the industrial city of Yanbu in Saudi Arabia along the Red Sea showed higher levels of carbon stocks both in plants and sediments in comparison with natural unprotected mangroves [75]. Likewise, planted and rehabilitated mangroves increased the levels of carbon stock in the sediments in the Arabian Gulf [25,32]. The present study also revealed higher amounts of carbon stock in transplanted mangrove plantation sediment when compared to bare mudflat, suggesting that mangrove plantations may be able to slow down the effects of climate change in the Arabian Gulf.

4.4. Mangrove Afforestation and Management

Multiple biological and ecological benefits of mangrove plantation and restoration have been reported in the Arabian Gulf. For instance, planted mangroves provided an important habitat for a variety of marine organisms and increased ecological complexity on artificial islands in Kuwait [37]. Planted mangroves along a shoreline in Abu Dhabi, UAE, created a habitat for birds and macrobenthos, enhanced coastal biodiversity and strengthened the coastal protection and minimized erosion [22]. Similarly, Farshid et al. [76] indicted that planting of mangroves along the northern coasts of the Arabian Gulf can improve the ecosystems of the tidal area and increase fishery productivity. Additionally, as a country composed of a group of small islands, plantation of mangroves along the coastline of Bahrain may contribute to protection against sea level rise and floods.

Globally, the destruction of mangroves and the increasing impacts of climate change make restoring mangroves a priority [77]. Increasing vulnerability and degradation of Arabian mangroves due to natural and anthropogenic pressures have increased regional initiatives for the management, conservation, and restoration of mangrove ecosystems [29]. There are immense ecological and environmental benefits associated with mangrove restoration and afforestation programs. However, effective management requires considering the change in ecosystem and habitat functions that may induced by these programs. Erftemeijer and Lewis [78] argued that intertidal mudflats are important areas for conservation, and environmental assessment should be made of the potential social and environmental impacts associated with afforestation programs. Arad Bay is designated as a protected area primarily due to its importance as a feeding ground for wader populations. Additionally, this bay has amenity and recreational values for the public. Therefore, intensive afforestation may alter the ecological function of the bay as feeding ground for waders and affect the amenity and recreational benefits provided by the bay.

Finding appropriate locations for mangrove restoration and plantation is seen to be a top priority. Several factors should be integrated into the assessment of suitable habitats for mangrove afforestation. These can include physical, environmental, soil, water characteristics, climatic conditions, sources of disturbance, and anthropogenic stressors [79]. Additionally, adequate monitoring and reporting of the afforestation programs [77] and adaptive management approaches that integrate environmental, social and economic aspects and coordinate the efforts of different stakeholders [3] can contribute to both the protection and restoration of mangrove ecosystems.

5. Conclusions

Bahrain has recently accelerated mangrove afforestation programs as a measure to meet its national targets related to the mitigation of climate change. The present study estimated the sediment carbon stocks of natural and transplanted mangroves and a mudflat in two protected areas in Bahrain. The findings indicated that organic carbons stored in the sediments in the three sampling sites were comparable to those in arid regions. Natural mangroves stored the highest levels of carbon, indicating the priority to protect the remaining natural mangrove stands in Bahrain. However, afforestation programs in the long-term are providing promising results in terms of carbon stock and other ecological and environmental functions. Therefore, mangrove plantation and restoration programs are considered an important potential solution for increasing sediment organic carbon storage and as a critical component of coastal management and climate change mitigation strategies in the Arabian Gulf.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12112055/s1, File S1: Calculations of sediment carbon stocks in the natural and transplanted mangroves and the mudflat in Bahrain.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data of this study are provided in the Supplementary Materials.

Acknowledgments: The logistical support provided by the Department of Biology, College of Science, University of Bahrain, and the Supreme Council for Environment in Bahrain is greatly appreciated. Special thanks are extended to Nouf Al-Wasmi, Ali Isa and Mohamed Marafi from the Supreme Council for Environment for facilitating the sampling from the protected areas of Tubli and Arad Bays. Appreciation goes to Ahmed Khamis for generating the map of Bahrain, and Qaisar Mahmood for critically editing the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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