Scientific Journal for Damietta Faculty of Science **14**(1) 2024, 41-54
doi: 10.21608/sjdfs.2024.251195.1147
ISSN Print 2314-8594
ISSN Online 2314-8616

https://sjdfs.journals.ekb.eg/

Biomass Carbon Stock and Carbon Sequestration Potentiality in Mangrove Ecosystem along the Egyptian Red Sea Coast

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Received: 25 November 2023 /Accepted: 04 March 2024

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Abstract

Mangrove forests are the most carbon-dense ecosystems on the planet, with most of the carbon retained in the soil around the shore environment. This work was done by evaluating the rate of carbon sequestration (CSR) and carbon sequestration potential (CSP) of mangrove forests at three locations (Hurghada, Al-Quseir and Wadi Hamata) that extended along 600 km of Egyptian Red Sea coast. The results revealed that the mean ecosystem carbon stock in Hurghada (202.87 Mg C yr^{-1}) was in high value comparing with that in Al-Qusier (164.33 Mg C yr^{-1}) and Wadi Hamata (96.53 Mg C yr^{-1}). In addition, *Avicennia marina* stand grown at Al-Qusier have lower potential carbon sequestration (0.43 Mg C yr^{-1}) than that of Hurghada Island and Hamata (3.65 Mg C yr^{-1} at 3.82 Mg C yr^{-1}, respectively). The obtained findings authorize the stability between deceased mangrove and afforestation through the last decades and give the upper boundaries of CSP in mangrove swamp along the Egyptian Red Sea coast.

Keywords: Biomass Carbon Stock; Carbon Sequestration; Mangrove; Red Sea, Egypt.

Introduction

Carbon occurs as a key component of biological matter and sedimentary rocks in atmospheric gases, dissolved ions in the hydrosphere, and solids (FAO, 1997). However, photosynthesis and respiration are the primary sources of carbon mobility, with additional exchange occurring between the biosphere, atmosphere, and hydrosphere. Because of their low-cost efficiency and related environmental and social advantages, mangrove forests have a tremendous potential to store a large quantity of atmospheric CO_2 (Al-Nadabi and Sulaiman, 2021). Carbon sequestration occurs in a variety of environments, including marshes, swamps, forests, biomass, and geologic formations and soils (Page, 2019). Biomass, wetlands, and soils are important carbon sources and sinks in mangrove ecosystems. Carbon pools are made up of these (Berhe et al., 2013; Shahid and Joshi, 2015). Mangrove forests are among the most carbon-dense ecosystems on the planet, with most of the carbon deposited in the soil around the shore (Hengl et al., 2018; Gajula et al., 2020; Blanco-Sacristán et al., 2022). Mangroves' importance in global carbon cycles has been underappreciated, possibly because to their tiny overall area and frequently smaller physical stature than many surrounding tropical wet forests. In fact, they may be rather significant (Spalding 2010; Gajula, et al. 2020). Because of their higher amount of below-ground biomass, their biomass is equivalent to that of higher-canopy terrestrial forests. They may also play a larger role in the sequestration of fresh CO_2 from the atmosphere than other forests due to higher rates of productivity and higher rates of long-term carbon deposition in soils and perhaps offshore (Afefe, et al., 2021). Avoiding deforestation of mangroves may not only reduce CO_2 emissions, but also play a larger role in extra CO_2 sequestration than other forest types. The resulting international legal and policy papers, which may even include ongoing cash compensation for averted deforestation, may be essential for both mangrove protection and CO_2 emissions reduction (Spalding, 2010). At the same time, mangrove soils are often anaerobic with a slow decomposition rate, creating optimal circumstances for the retention of organic carbon (Shaltout et al., 2020). Thus, the carbon sequestration rate (CSR) of mangrove stands throughout the Egyptian Red Sea coast was more than three times that of mud flat stands (Eid and Shaltout, 2016). The average CSR of mangrove stands (6.1 g C m^{-2} yr^{-1}) was greater than that of mud flat stands (2.0 g C m^{-2} yr^{-1}) along the Egyptian Red Sea coast (Eid and Shaltout, 2016). The total carbon sequestration potential of mangrove forests in Egypt was 3.17 ± 0.05 Gg C yr^{-1} based on the area of mangrove stands and CSR (Eid and Shaltout, 2016). The CSP of mangrove forests in Egypt provides a significant motivation to prioritize mangrove ecosystem protection. As a result, protecting and restoring these ecosystems is critical for carbon sequestration as well as other ecosystem services (Alongi 2002; Richards and Friess, 2016). With the rising understanding that effective climate change action would include a mix of emissions reductions and carbon sequestration, natural carbon sinks have become political objectives. The primary causes of loss include aquaculture conversion, particularly shrimp farming, agriculture, and urban growth (Valiela et al., 2001; Spalding, 2010). However, loss due to extreme weather events is becoming increasingly likely (Duke, 2017). Importantly, (Kauffman et al., 2014) discovered that converting these mangrove forests to shrimp ponds resulted in the loss of 90% of the carbon in the top 3 m of soil (612-1036 Mg C ha^{-1}).

There was an increase in sediment bulk density while a reduction in concentration and density of sediment organic carbon (SOC) with sediment depth in both polluted and non-polluted mangrove areas (Sahu et al., 2016; Arshad et al., 2018). Furthermore, the SOC pool of non-contaminated areas is larger than that of polluted sites caused by human activity. Similarly, the average CSR in non-contaminated areas (5.1 g C m^{-2} yr^{-1}) was substantially ($P < 0.01$) quicker than in polluted areas (4.4 g C m^{-2}). The goal of this study was to first quantify carbon storage (above- and below-ground carbon) in biomass and soil sediment of mangrove forests (*A. marina* and *R. mucronata*) throughout the Egyptian African Red Sea Coastline from Hurghada in the north to Wadi Hamata in the south. In addition, allometric equations were used to calculate above- and below-ground biomass. Finally, the total carbon store in the mangrove ecosystem along the research region was calculated.

Methodological Tools: -

Description of study Site: -

The Egyptian Red Sea coast characterized with an arid climate, with annual rainfall increasing southerly from 4 mm in Al-Quseir to 20 mm in Ras Benas (Eladawy et al. 2017). The yearly average temperature is high and ranged between 21.8 and 46.0 °C in the summer and in the winter from 15 and 22 °C. On the other hand, daily evaporation is greater (13.7-21.5 mm day^{-1} in summer) than (5.2 -10.4 mm day^{-1} in the winter), humidity reduced from 43% to 65% during the summer (Eladawy et al., 2017).
The Egyptian Red Sea coast, which includes the

mangrove forests, is categorized as a warm coastal desert. This study area extending both offshore mangroves located at northern location (Hurghada) and the coastal mangrove at the middle location (Al- Qeusir stands) and the southern location (Hamata stands) at the Egyptian Red Sea Coast. As shown in Table 1 and Fig. 1, each stand's coordinates were recorded using the Global Positioning System (GPS; Garmin Etrex 10).

Mangrove trees *(Avicenna marina)* (Forssk.) Vierh. is the most main species at the current study which introduced to numerous threats, i.e., high temperature, lack of rainfall and nutrients, and urban activities (e.g., shrimp farms and camel grazing), as well as severe ecological conditions surrounding which reduces growing rates of mangrove swamps.

Table 1 Coordinates of studied mangrove stands along the Egyptian Red Sea Coastline during this study

Locations	Longitude	Latitudes	Description
Hurghada	33º 52' 60″ E	27 º13' 75″ N	It is one of the Red Sea offshore islands and located 5 km west of Hurghada coast and inhabited with a huge *Avicennia marina* stands that occurred in the center of the island and along a shallow channel, covering an area of approximately 72 hectares.
Al-Quseir	34 º 00' 65″ E	26º 37' 00″ N	It is characterized by a small *Avicennia marina* stands occupy a sheltered area interspersed with mud flats that spinning an area of about 4 hectares. These stands also characterized with accumulated plastic wastes
Wadi Hamata	35 º 30' 97″ E	24º 23' 37″ N	It is classified to four massive mangrove stands which growing at the mouths of Wadi Hamata, where silt and sand loads are deposited in the coastal zone by occasional flooding of wadi Hamata stands have a mean height of approximately 2.8 m and a total area accounting 4 ha, with a maximum tallness of up to 5.5 m and covering of 66 hectares. On the landward side, the trees are short and over grazing are occurred.

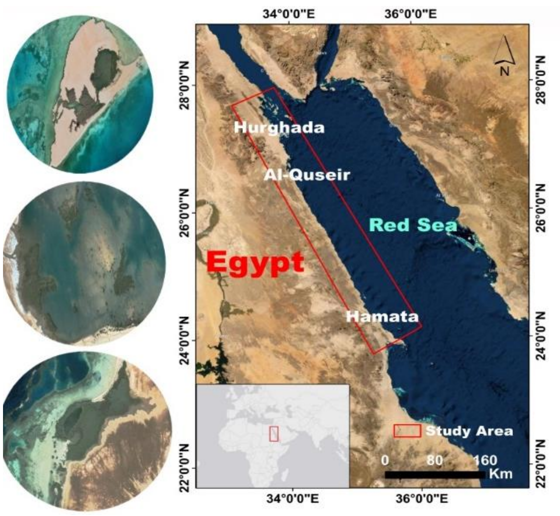


Figure 1. Location of study locations along the Egyptian Red Sea coast

Sediment sampling and characterization: -

From June to December 2019, nine sample stands were conducted to measure sediment organic carbon (SOC) and carbon sequestration rate (CSR) by rotating three places, including Hurghada, Al-Quseir, and Hamata stands to represent the mangrove forests along the Egyptian Red Sea coast of the Red Sea.

Using a polyvinyl chloride (PVC) core (60 cm long and 5 cm in diameter), triplicate representative sediment samples were collected from each sampling site at 3 graded depths (0 - 15, 15 - 30, and 30 - 45 cm) and mixed manually to get composite samples. The sediment core was gently separated and was directly segmented into samples 15 cm thick by using a blade and packed in clean polythene bags and stored until further analyses (Bernal and Mitsch, 2008).

To eliminate debris and gravels, air-dried sediment samples were sieved using 2-mm sieve and then homogenized in a mortar to determine the physical and chemical characteristics of selected sediments according to the following standard methods; the standardized pipette method was utilized to estimate the particle size distribution was analyzed according to (Sparks et al., 2020). Electrical conductivity (EC) was determined at~27°C in sediment/deionized water extract (1:2.5) using HANNA (HI9835 Meter). Also, sediment reaction (pH) was recorded in (1:2.5 suspension) using a Beckman glass electrode according to (Jackson, 2005). Furthermore, using a dry combustion procedure, concentrations of total organic C and N were estimated via Thermo Scientific Flash 2000 elemental analyzer (Thermo Fisher Scientific™, USA) (Sparks et al., 2020).

To estimate sediment bulk density in the samples, each sample was dried in an oven for 72 hrs. at 105°C, put in a desiccator to cool under room temperature, and then weighed. The calculation is following the equation (Sahu et al. 2016).

$$Psj = \frac{mj}{vj} \quad (2)$$

Where ρ_{sj}; the SBD of the j^{th} horizon, m_j; the dried sediment sample mass (g) of j^{th} horizon, and v_j:; the sediment sample volume (cm^3) of the j^{th} horizon.

- Sediment organic carbon (SOC) of selected samples was analyzed in each layer in the laboratory following the addition of sulfuric acid (H_2SO_4; 98%w/w) solution and 1N potassium dichromate ($K_2Cr_2O_7$) using wet digestion method **(**Walkley and Black 1934**):**

$$\text{SOC}\ (\text{g C kg}^{-1}) = 0.58 \times \text{SOM}\ (\text{g C kg}^{-1}) \quad (3)$$

Also, the following equation was used to compute the SOC density (kg Cm^{-3}) (Han et al., 2010):

$$SOC_{dj} = \rho_{sj} \times SOC_j \quad (4)$$

Where, SOC_{dj} represents the SOC density of the j^{th} horizon, ρ_{sj} is the SBD of the j^{th} horizon, SOC_j is the SOC content of the j^{th} horizon.

To determine the SOC of a profile, the following formula was used to estimate the SOC pool (kg C m^{-2}) (Meersmans et al., 2008):

$$SOC_p = \frac{\sum_{j=1}^{k} SOC_{dj} \times T_j}{\sum_{j=1}^{k} T_j} \times D_r \quad (5)$$

where SOC_p is the SOC pool, *Dr* represents the initial depth (= 0.45 m), T_j is the thickness (m) of the j^{th} horizon, and k is the layer numbers (=3).

The carbon sequestration rate (CSR) of the i_{th} horizon was calculated using soil bulk density (SBD), sedimentation rate (R), and soil organic carbon (%) (Xiaonan et al., 2008):

$$CSR_i\ (\text{g C m}^{-2}\ \text{year}^{-1}) = \rho_{si} \times SOC_i \times R \quad \textbf{(6)}$$

Where, ρ_{si} represents SBD of the i_{th} horizon, SOC_i is the SOC content (%) and R: sedimentation rate in the mangroves (the global mean equal 2.8 mm $year^{-1}$)

Carbon sequestration potential (CSP) was calculated as the following equation (Xiaonan, et al., 2008) :

$$\text{CSP}\ (\text{Mg C year}^{-1}) = \text{CSR} \times \text{A}\ (\text{m}^2) \quad (7)$$

Where, A is an area dominated by mangrove vegetation.

According to (Sahu et al., 2016) suggestion, the sediment carbon (Mg ha^{-1}) per sampled depth interval was calculated as follows:

Sediment Carbon (Mg ha^{-1}) = bulk density (g·cm^{-3}) × sediment depth interval (cm) ×%SOC (8)

Above and below-ground biomass characteristics

By using allometric equations, above-ground biomass (AGB) and below-ground biomass (BGB) were determined to get best biomass estimations based on Kauffman and Cole (2010).

To calculate the biomass of trees, allometric equations were used to calculate the breast height diameter (DBH) of tree trunks at 1.3 m above the ground (Romero et al., 2020)**.** The density of vegetation, trunk diameter and tree height of mangrove trees were determined for each sampling stand, inside the three randomly distributed quadrates (100 m^2).

As illustrated in Table 2, the strong allometric relationships between the tree height, DBH, and biomass were utilized to derive AGB and to calculate carbon stocks (Dharmawan and Siregar**,** 2008). Additionally, the standing dead wood biomass was determined with the Kauffman & Donato, (2012) given formula.

Table 2 Allometric equations for calculating above-ground biomass (ABG) and below-ground biomass (BGB), DBH refers to diameter at breast height (cm) and ρ refers wood density.

Variables		Allometric equation	Wood density (*ρ*)	References
Above ground biomass (AGB)		$0.1848\times dbh^{2.3524}$	0.661	Dharmawan & Siregar, 2008
Below ground biomass (BGB)		$0.199 \times 0.661^{0.899} \times dbh^{2.22}$	0.62	Komiyama *et al*. 2005
Dead tree	Decay Status 1	0.975 x AGB		Kauffman & Donato, 2012
	Decay Status 2	0.8 x AGB		

Total ecosystem carbon storage capacity

Ultimately, the mangroves ecosystem's total carbon stock was assessed as follows:

Total carbon stock (Mg ha^{-1}) = C tree AGB + C tree BGB + C soil (9)

Statistical data analysis

First, the obtained data were estimated for normal distribution and homogeneity of variance. Then ANOVA was utilized to recognize significant differences for all variables. One-way ANOVA of variance (ANOVA-1) was utilized to identify statistically significant variations in the SOC pool, CSR, tree density, individual height, and crown diameter of *A. marina* populations for the various research locations. In addition, two-way ANOVA (ANOVA-2) was used to find statistically significant changes in SBD, SOC concentrations, SOC density, and sediment depths. The Statistical Package for the Social Sciences (SPSS) (version 23.0) was used to statistically assess all the gathered data.

Results:

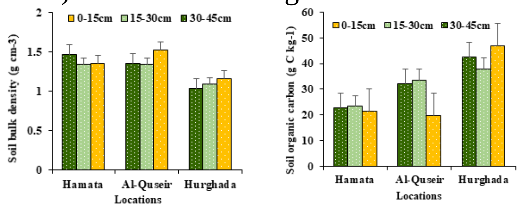
Table 3 exhibits the descriptive statistics and the range of variations in pysico-chemical properties for the studied sediments i.e., sand, mud, conductivity, acidity, and C/N ratio. In this study, the sediments were primarily composed of sand that ranged from 63.80% to 95.00% with mean of 82.24 ± 1.79% at Al-Quseir and Wadi Hamata locations, respectively. Meanwhile, the mud fraction varied from 5.00% at the surface layer of Al-Quseir to 36.20% at the surface layer of Hamata location, with a mean value of 18.86 ± 1.69%. This soil can be categorized as *siliceous, hyperthermic,* and *aquic torripsamments*.

Table 3. Physico-chemical properties of sediments along the Egyptian coast of the Red Sea.

Characters	Range	Mean	Std. Error	Std. Deviation	Variance	Skewness	Kurtosis
Sand (%)	63.80 - 95.00	82.24	1.79	9.29	86.35	-0.154	-1.30
Mud (%)	5.00 - 36.20	18.86	1.69	7.12	82.79	0.154	-1.29
pH (1:2.5 H_2O)	7.00 - 8.52	7.73	0.09	0.46	0.21	0.22	-0.98
EC (dSm^{-1})	7.50 - 31.59	18.63	1.76	8.61	74.07	0.20	-1.56
$CaCO_3$ (%)	12.0 -22.00	18.23	0.89	2.99	10.92	0.77	1.23
C/N ratio	6.03 - 21.11	11.84	0.80	4.18	17.48	0.50	- 0.65

Significant: Skewness is significant if skewness divided by standard error of skewness > 2.
Kurtosis is significant if kurtosis divided by standard error of kurtosis < 2.

All over the world, many researchers revealed that mangrove environments can increase the amount of accumulated suspension solids by depressing the hydraulic pathways and then providing extreme time for fine-grained sediments (Spencer et al. 2003; Mosa et al., 2022). Under the current study, the sediment pH values had a tight range from 7.0 at the bottom sediment layer of Al-Quseir to 8.52 at the surface layer of Wadi Hamata location, with a mean of 7.73 ± 0.09. In Wadi Hamata location, EC recorded the maximum value of 31.59 dSm^{-1} with the mean of 18.63 ± 1.76 dSm^{-1}). The highest values of EC in Wadi Hamata area can be attributed to a barrier road that involved mangrove trees from the open seawater. The present study found that the concentrations of $CaCO_3$ in the sediments had its lowest value of 12.0% at Wadi Hamata and the highest of 22.00% at Al-Qusier with the mean of 18.32%. This is because the carbonate content was primarily derived from biogenic and terrigenous sources on land. Furthermore, mangroves' ability to contribute to the carbon sequestration process was constrained because the sediments were primarily made of biogenic coarse carbonates at the Red Sea coastline of Saudi Arabia (Almahasheer et al., 2017). Finally, C/N ratio recorded the highest value (21.11) in the bottom sediments of Wadi Hamata area and the lowest value (6.03) in the bottom sediments of Al-Quseir location. The distribution of bottom SBD and SOC contents for the different depths (0 -15, 15 - 30, and 30 - 45 cm) is illustrated in Figs. 2 and 3.



$F_{Locations}$=10.9**; F_{Depths}= 0.7; $F_{Locations\ x\ Depths}$=1.1*

$F_{Locations}$=10.6**; F_{Depths}= 0.3; $F_{Locations\ x\ Depths}$=2.2*

Figure 2 Distribution of sediment bulk density (g cm^{-3}) and sediment organic carbon relation to depth (cm) of *Avicennia marina* swamps along the Egyptian Red Sea coast. F-values represent the two-way ANOVAs. Locations; Hurghada, Al-Quseir, Hamata; Depth: 0-15, 15-30, 30-45cm. ***P < 0.01*.

In the present study, sediment bulk density values (g cm^{-3}) of the selected locations were in the following order: Al-Quseir (1.40) >

Wadi Hamata (1.33) > Hurghada (1.09) (Fig. 2).

Meanwhile, SOC values (g C kg^{-1}) followed the order Hurghada (42.34) > Al-Quseir (28.48) > Wadi Hamata (22.56).

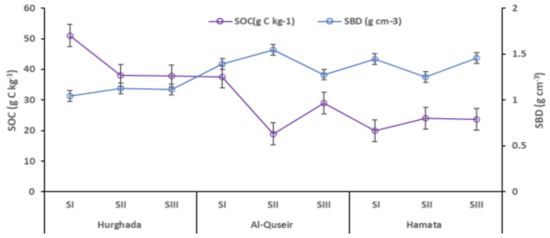


Figure 3 Averages of SOC (g C kg^{-1}) and SBD (g cm^{-3}) at the different locations and their regressions.

As presented in Table 4, the height of tree (m $Ind.^{-1}$), DBH (cm $Ind.^{-1}$), and tree density per hectare exhibited marked differences among the three studied locations. For the tree height, the values fluctuated from 2.60 to 6.70 m, with the mean of 4.50 ± 0.50 m. It was obvious that Al-Qusier showed the highest average of tree height (4.88m), while Hamata exhibited the lowest (4.08 m) Meanwhile, the DBH had values that ranged between 12.6 and 32.6 cm, with the mean of 22.30 ± 2.20 cm.

Table 4: Analysis of variance for vegetative and biomass components of *Avicennia marina* in the studied areas

Studied areas		Tree Height (m $Ind.^{-1}$)	Tree density (ha^{-1})	DBH (cm $Ind.^{-1}$)	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	Biomass (Mg ha^{-1})
Average		4.5^{b}	1200^{c}	22.30^{c}	189.9^{c}	14.9^{c}	204.8^{c}
Min.		2.8	400.0	12.55	32.75	3.77	41.1
Max.		6.7	1800.0	32.55	331.90	31.27	344.38
Std. Error		0.5	168.3	2.20	31.0	3.10	30.90
Hurghada	Mean	4.57^{ab}	1000^{d}	17.50^{d}	276.20^{a}	8.36^{d}	284.58^{a}
	Min.	3.55	500	12.55	214.49	3.77	218.26
	Max.	6.50	1400	21.50	331.93	12.45	344.38
	Std. Error	0.97	265	2.63	34.03	2.52	36.55
Al-Qusier	Mean	4.88^{a}	1367^{a}	24.20^{b}	206.00^{b}	17.67^{b}	223.67^{b}
	Min.	3.60	1000	17.45	170.03	7.83	183.94
	Max.	6.65	1800	32.55	247.49	31.27	278.75
	Std. Error	0.91	233	4.43	22.53	7.02	28.43
Hamata	Mean	4.08^{c}	1233b	25.10^{a}	87.46^{d}	18.60^{a}	106.06^{d}
	Min.	2.80	400	18.00	32.75	8.39	41.14
	Max.	5.55	1800	30.60	115.54	27.26	141.36
	Std. Error	0.80	426	3.72	27.36	5.50	27.50
F-Value		0.202*	0.338	1.280	11.308**	1.119	7.719**

F-values exhibited One-way ANOVA, *$P < 0.05$; **$P < 0.01$*. According to Tukey's HSD test, averages in the same columns tracked by varied letters are significantly different at $P < 0.05$.

For the tree density per hectare, the values ranged from 400 to 1800, with the mean of 1200 ± 168.3 trees per hectare. In Hamata, DBH of the mangrove trees was found to be comparable with those in Al-Qusier (24.20 -25.10 cm).

According to the overall tree height, density of tree, and DBH, the vegetation of *A. marina* in Al-Qusier (the middle patches of study locations) exhibited the greatest tree height (4.08 ± 0.91 m $Ind.^{-1}$) and tree density (1367 ± 233 trees per hectare). Meanwhile, the mangrove vegetation in the southern location (Hamata) recorded the highest DBH (25.10 ± 3.72 cm $Ind.^{-1}$) followed by the middle location (Al-Qusier). From the overall height, DBH, and tree density from all studied locations, the present study might conclude that the mangrove stands of the middle location (Al-Qusier) seem to be fully grown trees of *A. marina* compared with those in the southern location (Hamata) and the northern location (Hurghada). This might had been attributed to the enriched sediments in the landward region, where stronger roots have adapted and are able to provide more mechanical support for their above-ground weight.

Statistically, AGB that involved dead roots and litters of mangrove components in the studied locations varied from 32.88 to 331.9 Mg ha^{-1}, with the mean of 189.90 ± 31.0 Mg ha^{-1}. Hurghada (the northern patches) recorded the highest value of mangrove AGB (276.20 ± 34.03 Mg ha^{-1}). Meanwhile, BGB increased from 3.80 to 31.30 Mg ha^{-1}, with the mean of 14.90 ± 3.1 Mg ha^{-1}. Hamata (the southern patches) registered the highest value of BGB (18.60 ± 5.50 Mg ha^{-1}). These results of AGB values are comparable with that recorded from east Sumatra and Sri Lanka (Kusmana et al. 1992). In this study, there were considerable alterations in the mangrove trees' biomass at different locations that were increasing from

41.1 to 344.4 Mg ha^{-1}. The mean biomass of *A. marina* in Hurghada (the northern location), Al-Qusier (the middle location) and Hamata (the southern location) was found to be 204.8 ± 30.9 Mg ha^{-1}. Among the different locations, the highest biomass of *A. marina* was 284.58 ± 36.55 Mg ha^{-1}, recorded in Hurghada (the northern location), whereas the lowest biomass was 106.06 ± 27.50 Mg ha^{-1} in Hamata (the southern location).

Discussion:

It is documented that sediment bulk density varied with the physical features of the mangrove–sediment system (Chaudhari et al., 2013). It provides the porosity and water retention of soil (Huang, 2015) and supplies the distribution of sediment organic contents (Johnston et al. 2004). As presented in Table 5, the result had been detected by numerous studies in different locations, including Red Sea coastline in Egypt (Afefe et al., 2020) and coastline of the Red Sea in Saudi Arabian (Saderne et al., 2020; Shaltout et al., 2020; Al-Guwaiz et al., 2021) exhibited some variations. This alteration in SBD was associated with the decomposition of mangrove plants, that is, dead litters, endemic matters, and gathered in different bottom sediments (Schiff et al., 1998). However, the dissimilarity in SOC contents of different layers may be attributed to intraspecific processes such as the decay of plants, biotic pathways, wet/dry sediment regimes, climatic deposition, anthropogenic aspects, and weathering of various ions in mangrove-sediment systems (Alongi, 1998; Sanderman et al., 2018).

Globally, SOC content in mangrove forests increased from 2 to above 300 g C kg^{-1}, and this is mainly related to the vegetation range, biomass, soil texture, ecological features, tidal flux, and human activities in mangrove sediment systems (Gao et al., 2019). In this study, Table 4 shows the mean SOC content of 31.13 g C kg^{-1} was above local value of 15.5 g C kg^{-1} presented by Eid and Shaltout (2016) in the Egyptian Red Sea coast, and those recorded in the mangrove forests of many other countries, including the southern and central portions of Saudi Arabia's coastline, Mozambique, Batticaloa Lagoon of Sri Lanka, Vietnam, China, and India.

Table 5: SOC content (g C kg^{-1}), SOC stock (kg C m^{-2}) and carbon sequestration ratio (CSR, g C m^{-2} year^{-1}) in the *Avicennia marina* forests in the study area as compared with coastal areas from Egypt and around the world.

Locations	**Depth (cm)**	**SBD (g cm^{-3})**	**SOC (g C kg^{-1})**	**SOC stock (kg C m^{-2})**	**CSR (g C m^{-2} y^{1})**	**References**
Average	15-45	1.29	31.13	5.77	10.77	Current study
Minimum	0	0.94	15.08	3.52	6.59	
Maximum	45	1.68	58.46	8.80	16.43	
Std. Error	-	0.04	2.33	0.32	0.59	
The Coastal areas of Red Sea						
Red Sea coast, Egypt	40	1.4	15.5	8.50	6.10	Eid and Shaltout (2016)
Farasan Island, Saudi Arabia	50	1.55	16.30	12.30	5.40	Eid et al., (2020)
Central Saudi, Saudi Arabia	100	-	2.0 -15.0	2.5 -7.6	1.5 - 5.5	Almahasheer et al. (2017)
Southern Saudi, Saudi Arabia	100	1.66	17.7	29.20	-	Eid et al. (2019)
Southern Saudi, Saudi Arabia	50	1.5-1.9	14.4-18.1	6.70 -10.5	5.0 - 6.0	Shaltout et al. (2019)
Southern Saudi, Saudi Arabia	-	1.53-1.66	12.6-15.7	9.9-11.5	4.4-5.10	Arshad et al. (2018)
Around the world						
Arabian Gulf, United Arab Emirates	100		NA	10.2-15.6		Schile et al. (2017)
Zambezi River Delta, Mozambique	200	0.72-0.95	14.5 -23.6	27.5-31.40		Stringer et al. (2015)
Africa’ Sahel, Senegal	40		NA	7.4-10.7		Woomer et al. (2004)
Pohnpei Island, Micronesia	365	0.10-0.43	114.6-364.9	177.1-211.6	53.0 - 93.0	Fujimoto et al. (1999)
Lagoons and estuaries, Sri Lanka	45	0.97-1.37	53.0 - 97.0	31.6-58.1		Perera and Amarasinghe (2019)
Batticaloa Lagoon, Sri Lanka	80	0.40-1.60	3.0-51.0	100.9-784.6		Jonsson and Hedman (2019)
Honda Bay, Philippines	300	0.48-0.62	64.3 - 87.3	85.2		Castillo et al. (2017)
Mekong Delta, Vietnam	250	0.52-0.86	17.9 -52.0	66.7		Dung et al. (2016)
Pulau Ubin Island, Singapore	100	0.73	45.0	30.7		Phang et al. (2015)
Zhangjiang Estuary, China	100	0.94	12.7	9.60		Gao et al. (2019)
Leizhou Peninsula, China	90	0.93-1.12	7.1-16.4	7.1-14.0	37.0 - 205.0	Yang et al. (2014)
Bay of Bengal, India	-	0.56	9.2	2.8		Sahu and Kathiresan (2019)
La Paz Bay, Mexico	45	0.90	NA	10.0-23.9		Ochoa-Gómez et al. (2019)
Caribbean coast, Venezuela	20	0.26-0.39	100 -120	3.1-3.8		Barreto et al. (2016)

Tampa Bay, USA	50	0.44-0.90	63.0-110.0	10.1		Radabaugh et al. (2018)
New Caledonia	100	0.24-0.45	51.0-115.3	25.6		Jacotot et al. (2018)
Coastal wetlands, Dominican Republic	195	0.30	175.0	75.3	-	Kauffman et al. (2014)

However, the observed values were lower than those estimated in Micronesia and the lagoons and estuaries of Sri Lanka, Philippines, Singapore, Venezuela, USA, and New Caledonia. Moreover, SOC stock in different mangrove forests ranged between 3.52 and 8.80 kg C m^{-2}, with the mean of 5.77 kg C m^{-2} (Donato et al., 2011; Sanders et al., 2016). The SOC stock had 5.77 kg C m^{-2} only over India's Bay of Bengal (Sahu and Kathiresan 2019) and the Caribbean coastline, Venezuela (Barreto et al., 2016). Meanwhile, the mean of this parameter was lower than those recorded on the Egyptian Red Sea coast, Mozambique, Sri Lanka, Philippines, Singapore, Venezuela, and New Caledonia, as shown in Table 5. Finally, the mean CSR was 10.77 g C m^{-2} yr^{-1}, which is greater than those recorded in the coastal areas of the Red Sea (Arshad et al., 2018;Shaltout et al., 2020).

In addition, the huge difference in mangrove productivity and population is mainly affected by tree age, weathering, nutrient supply in the sediment column, human activities, and the distance between the sea and the mangrove stands (Fatoyinbo et al., 2008; Komiyama et al., 2008). Previously, Vinod et al., (2018) discovered around 236.7 ha^{-1} of biomass in the Kadalundi mangroves in Northern Kerala. AGB and BGB contributed 92.73% and 7.27% of the plant mangrove biomass, respectively, which were almost comparable to those in the mangrove systems of oligohaline zones in Sundarbans, Bangladesh (Kamruzzaman et al., 2017). Consequently, AGB values were higher than BGB, as agree with by Borah et al., (2015), who recorded that AGB was higher than BGB in Perancak Estuary.

As shown in Table 6, vegetation carbon stock parameters varied between significant and no significant difference (P < 0.05) among the three mangrove areas. In this study, the mean biomass carbon stock of the mangrove forests fluctuated from 19.3 to 161.9 Mg ha^{-1}, with the mean value of 96.2 ± 14.5 Mg ha^{-1}.

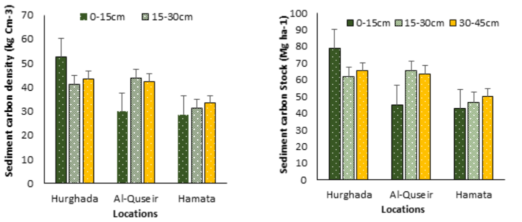
Table 6: Mean ± standard error of biomass C-stock (Mg C ha^{-1}), SOC-stock (Mg C ha^{-1}), carbon sequestration rate-CSR (g $Cm^{-2}yr^{-1}$), and carbon sequestration potential -CSP (Mg C yr^{-1}) of *Avicennia marina* locations along the Egyptian Red Sea Coast.

Studied locations		**Biomass C-stock**	**Sediment C-stock**	**Ecosystem C-stock**	**CO_2 equivalent**	**CSR**	**CSP**
Average		204.8	5770	173.09	567.3	10.77	2.64
Min.		41.1	35.29	128.77	260.9	6.59	0.26
Max.		344.4	88.02	235.89	886.7	16.43	5.05
Std. Error		30.90	3.10	13.66	64.0	0.59	0.32
Hurghada	Mean	133.75	69.12	202.87	744.53	12.80	3.65
	Min.	102.58	63.26	166.95	612.70	10.30	2.94
	Max.	161.86	79.74	241.60	886.66	15.87	4.53
	Std. Error	17.18	5.32	21.59	79.25	0.70	0.201
Al-Qusier	Mean	105.12	59.20	164.33	603.08	10.83	0.43
	Min.	86.45	43.91	141.91	520.82	6.58	0.26
	Max.	131.01	78.24	176.15	646.46	16.43	0.66
	Std. Error	13.36	10.09	11.21	41.15	1.30	0.052
Hamata	Mean	49.85	46.68	96.53	354.26	8.68	3.82
	Min.	19.34	43.20	71.08	260.88	7.07	3.11
	Max.	66.44	51.75	111.53	409.33	11.47	5.05
	Std. Error	15.28	2.59	12.79	46.94	0.42	0.189
F Value		7.780*	2.775	11.508**	11.510**	2.08**	1.38**

F-values exhibited One-way ANOVA, * $P < 0.05$; ** $P < 0.01$. According to Tukey's HSD test, averages in the same columns tracked by varied letters are significantly different at P < 0.05.

The biomass carbon stock of *A. marina* in Hurghada exhibited the greatest mean values (133.75 ± 17.18 Mg ha^{-1}) followed by that in Al-Qusier estimated at 105.12 ± 13.36 Mg ha^{-1} and that in Hamata recorded at 49.85 ± 15.28 Mg ha^{-1}, respectively. This is mainly due to the great above-ground weight involved, including dead trees, litter, and wood remains of mangrove compartments. The variations in the biomass carbon stock of mangrove pitches along the different locations may be attributed to human activities, grazing of camels, and less freshwater flow into the mangrove ecosystems. Moreover, the study areas reflected saline and hyperiid areas (EEAA, 2018). In contrast, Syam'ani et al., (2012) reported that photosynthetic activities in both vertical and horizontal growth were the primary cause of upsurge of vegetative biomass.

However, the mean SOC stock of the northern location (69.12 Mg C ha^{-1}) was significantly higher than those of the middle location (59.20 Mg C ha^{-1}) and the southern locations (46.68 Mg C ha^{-1}). As presented in Fig. 4, in Hurghada (northern), the SOC density decreased significantly from 52.74 kg C m^{-3} at upper layer to a minimum of 41.21 kg C m^{-3} at 15 -30 cm depth, and ultimately elevated to 43.51 kg C m^{-3} at 30–45 cm depth. On the other hand, SOC density in Al-Quseir (middle) markedly increased from 29.95 kg C m^{-3} at upper layer to a maximum of 43.62 kg C m^{-3} at depth of 15 -30 cm and then eventually diminished to 42.45 kg C m^{-3} at depth of 30 - 45 cm, respectively. Meanwhile, in Wadi Hamata (southern), SOC density was crucially enhanced from 28.54 kg C m^{-3} at upper layer to a maximum of 31.14 kg C m^{-3} at depth of 15-30 cm and then improved to 33.34 kg C m^{-3} at 30 - 45 cm depth, respectively.



$F_{Locations}$=4.97**; F_{Depths}= 0.85; $F_{Locations\ x\ Depths}$= 2.43*

$F_{Locations}$=6.07**; F_{Depths}= 1.15; $F_{Locations\ x\ Depths}$= 7.03*

Figure 4 Sediment carbon density (kg cm^{-3}) and sediment carbon stock to sediment depth (cm) of *Avicennia marina* forests along the Egyptian Red Sea coast. F-values represent the two-way ANOVAs. Locations; Hurghada, Al-Quseir, Hamata; Depth: 0-15, 15-30, 30-45cm. **: *P < 0.001*.

For the sediment carbon stock, in Hurghada (the northern location), it markedly decreased from 78.67 Mg C ha^{-1} at 0 - 15 cm depth to a minimum of 61.82 Mg C ha^{-1} at 15 - 30 cm depth and then finally increased to 65.27 Mg C ha^{-1} at 30 - 45 cm depth. In contrast, SOC density in Al-Quseir (the middle location) markedly increased from 44.92 kg C m^{-3} at 0 - 15 cm depth to a maximum of 65.43 Mg C ha^{-1} at 15 - 30 cm depth and then finally decreased to 63.67 Mg C ha^{-1} at 30 - 45 cm depth, respectively. In Hamata (the southern location), SOC density significantly increased from 42.80 Mg C ha^{-1} at 0 - 15 cm depth to 46.71 Mg C ha^{-1} at 15 - 30 cm depth and then further increased to 50.01 Mg C ha^{-1} at 30 - 45 cm depth, respectively.

According to Donato et al., (2011), the total carbon storage in mangrove sediments could amount to 1023 Mg ha^{-1} on average. The enormous growth of old mangrove trees and organic elements in sediments may have contributed to the formation of these carbon stocks (Donato et al., 2009; Kusumaningtyas et al., 2019).

At the global level, Schile et al., (2017) reported that mangroves in West-Central Africa have a carbon stock (soil and biomass) of approximately 800 Mg C ha^{-1}, which is somewhat lesser than that of mangroves in Latin America (939 Mg C ha^{-1}) or Asia-Pacific (1.095 Mg C ha^{-1}). These results were much higher than that recorded for the Arabian Gulf/Oman mangroves (217 Mg C ha^{-1}), because of the region's exceptionally dry climate and coarse-textured soils. This highlights the significance of considering the soil carbon stock in attempts to mitigate climate change, and we agree with those results for Egypt's case.

Overall, Table 6 represents the mean ecosystem carbon stock of *A. marina* which was evaluated to be 173.10 ± 13.66 Mg C ha^{-1}. The mean ecosystem carbon stock in the northern location (202.87 Mg C yr^{-1}) was higher than those in the middle location (164.33 Mg C yr^{-1}) and the southern location (96.53 Mg C yr^{-1}). Whereas it was shown that the values of ecosystem carbon were below the mean of 332–2205 Mg C ha^{-1} reported by Alongi (2012) for replanted and natural mangrove trees in Southeast Asian and demonstrated the mean carbon stocks in mangrove forests was (885 Mg C ha^{-1}) globally. This result agrees with the view of Kauffman and Bhomia (2017) which reported that salinity, soil texture, and depths affect ecosystem carbon stocks.

In addition, the obtained results revealed that an estimated CO_2 equivalent in the northern location (744.53 Mg CO_2 ha^{-1}) was better than those in the middle location (603.08 Mg CO_2 ha^{-1}) and southern location (354.26 Mg CO_2 ha^{-1}) as shown in Table 6. The obtained results found that CSR fluctuated between 6.59 and

16.43 g C m^{-2} yr^{-1}, with the mean value in the sediments was10.77 g C m^{-2} yr^{-1}. A long the coastline of the Red Sea, the CSR value is greater than that of the obtained value at 5.60 g C m^{-2} yr^{-1} at southern Saudi Arabian, which was assessed by (Shaltout et al., 2020) and of the central Red Sea value which was estimated by (Almahasheer et al., 2017) at 3.5 g C m^{-2} yr^{-1}. For worldwide comparisons, the mean CSR values ranged from 37.0 to 205.0 g C m^{-2} yr^{-1} as described by (Yang et al., 2014) in Leizhou Peninsula, China, and 53.0 to 93.0 g C m^{-2} yr^{-1} as estimated by (Fujimoto et al.,1999) in Pohnpei Island, Micronesia. The relatively low CSR in this study may be associated with anthropogenic, oligotrophic, and hard environmental features such as low rainfall and extreme temperature, which restrict the vegetation of mangroves the Red Sea's coastline (Eid et al., 2020). Moreover, (Feller et al., 2003; Suárez-Abelenda, et al., 2014) estimated the release of N and P can supply the breakdown of organic materials in a mangrove ecosystem and thus diminish the SOC stock, as reported.

Furthermore, Table 6 revealed that CSP values of mangrove ecosystem prevalent along the Red Sea's coastline in Egypt ranged from 0.264 to 5.06, with the mean CSP of 2.64 ± 0.32 Gg C yr^{-1}. The obtained results elucidated that *A. marina* trees in Al-Qusier (middle location) can potentially sequestrate carbon (0.43 Mg C yr^{-1}) less than those in Hurghada (northern location) at 3.65 Mg C yr^{-1} and Hamata (southern location) at 3.82 Mg C yr^{-1}, verifying that anthropogenic features resulting from overgrazing and human activities in the middle location in recent years are serious issues affecting SOC value. Moreover, in the present study the mean (2.64 Mg C yr^{-1}) was found to be greater than the mean (0.27 Mg C yr^{-1}) reported by Eid, Arshad et al. (2019) along the Red Sea's coastline in the Saudi Arabian. In contrast, the mean CSP (2.64 Mg C yr^{-1}) was lower than the mean CSP values of 10.3 and 11.8 Mg C yr^{-1} for *R. mucronata* and *A. marina* trees, respectively, along the Farasan Islands coast, Saudi Arabia (Eid et al., 2020). This low value of CSP may have been due to the river's scarcity, the tremendously arid conditions affecting the primary production of mangrove, and sewage depositions that may inversely impact the production of mangrove vegetation (Bouillon et al., 2008).

Under the current study, varimax rotated principal component analysis (PCA) and estimated eigenvalues had a considerable task to assess the potentially carbon sequestration associated with alteration of mangrove-sediment formations. Subsequently, loadings more than 0.60 are significantly and are marked in bold as illustrated in Table 7. The outlying of varimax rotated principal component analysis involved four factors that accounted 97.33 % of total data in the mangrove-sediment ecosystem.

The first major factor approximately 58.70 % of the total variance with an eigenvalue of 5.87. This factor gave significant load to only the vegetative growth of mangrove trees then carbon-rich above ground biomass [Mg ha^{-1}] and ecosystem C stock.

These findings, which accord with those of Kauffman et al., (2011), suggest that mangrove forests have higher carbon stores than other dry zones due to their relatively large above-ground biomass and carbon-rich soils. The second factor (22.10 % of the total variance with Eigenvalue = 2.21) showed substantial loading on the sediment organic carbon and sediment C stock [Mg ha $^{-1}$]. These results could be attributed to the higher potential of mangrove sediments to play as a greater carbon capture compared to the upland environment in the same area (Saha et al., 2010; Kauffman et al., 2011).

Table 7. Varimax rotated principal component analysis (PCA) of measured biomass parameters and sediment samples.

Investigated Variables	PCA1	PCA2	PCA3	PCA4
Sediment bulk density [g cm^{-3}]	-0.294	-0.698	0.598*	
Sediment organic carbon [%]	0.508	0.820*	-0.205	
Tree Height [m]	0.217		-0.149	0.964*
Tree density per ha	-0.277	0.174	0.915	-0.163
Biomass [Mg ha^{-1}]	0.957*	0.132	-0.203	0.141
Above ground biomass-C [Mg ha^{-1}]	0.946*	0.226	-0.173	0.126
Below ground biomass-C GB-C [Mg ha^{-1}]		-0.926	-0.285	0.138
Biomass C-Stock [Mg ha^{-1}]	0.957*	0.132	-0.203	0.141
Sediment C stock [Mg ha^{-1}]	0.480	0.813*		
Ecosystem C stock [Mg ha^{-1}]	0.925*	0.328	-0.146	0.124
Eigenvalue	5.87	2.21	0.93	0.72
Variance %	58.70	22.10	9.31	7.22
Cumulative %	58.70	80.80	90.12	97.33

bold loadings are statistically significant

On the other direction, the third component accounted 9.31% of the total variance with an eigenvalue = 0.93. This factor gave significant load to only tree density. Finally, the fourth factor amounted for only 7.22 % of total variance, with an eigenvalue of 0.72 and gave load to tree height [m].

Conclusion:

Mangrove forests play as a protective factor to mitigate the global warming in arid zones. The obtained results revealed that the biomass carbon stock of *A. marina* in Hurghada stands presented the greater values followed by Al-Qusier and Hamata, respectively. Further, *A. marina* trees that grown on Hamata potentially sequestrate carbon greater than that grown on Hurghada and Al-Qusier. In the future, the CSP of the mangrove forests in Egypt should contribute to making reliable and knowledgeable decisions to sustainably protect this valuable ecosystem from all challenging and environmental threats. Thus, monitoring the current extent of mangrove swamps provide the decision makers to protect and develop mangrove ecosystem along the Egypt's Red Sea coastline.

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الملخص العربي

عنوان البحث: مخزون الكربون بالكتلة الحيوية وإمكانية عزل الكربون ببيئة المانجروف على طول ساحل البحر الأحمر المصري

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تعتبر غابات المانجروف من أكثر النظم البيئية كثافة بالكربون في العالم، حيث يتم تخزين معظم الكربون في التربة على طول المناطق الساحلية .
أجريت هذه الدراسة لتقييم معدل احتجاز الكربون (CSR) وإمكانات عزله (CSP) في غابات المانجروف وذلك في ثلاثة مواقع على طول الساحل المصري للبحر الأحمر وهي كالتالي: الغردقة (الموقع الشمالي)، والقصير (الموقع الأوسط)، ووادي حماطة (الموقع الجنوبي) والتي تمتد على طول ٦٠٠ كم من منطقة الدراسة. أوضحت النتائج أن متوسط مخزون الكربون في النظام البيئي بالغردقة (٢٠٢,٨٧ ملجم كربون / سنة) كان ذا قيمة عالية مقارنة مع المخزون من الكربون في موقع القصير (١٦٤,٣٣ ملجم كربون/ سنة) ووادي حماطة (٩٦,٥٣ ملجم كربون/ سنة) .
وفي النهاية، تتمتع أشجار المانجروف المنزرعة في موقع القصير باحتمالية احتجاز للكربون (٠,٤٣ ملجم كربون سنويًا) أقل من تلك الموجودة في الأشجار الموجودة في الغردقة بمتوسط ٣,٦٥ ملجم كربون سنويًا، وفي وادي حماطة بمتوسط ٣,٨٢ ملجم كربون سنويًا .
وتشير النتائج التي تم الحصول عليها مدى التوازن بين أشجار المانجروف الميتة والأشجار الحية خلال السنوات الماضية والتي تظهر إسقاط إشعاعي في مستنقعات المانجروف على طول ساحل البحر الأحمر المصري.