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Growth Performance of *Sonneratia alba* Plantations and Their Role in Coastal Environmental Protection and Storm Mitigation in Thua Thien Hue, Vietnam

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ABSTRACT

Mangrove forests play a crucial role in protecting the central coast of Vietnam, an area devastated by 5–12 typhoons annually. The main objective of this study is planting and protecting these forests is to provide scientific information for selecting adaptable tree species and developing environmental protection measures along estuaries and coastlines. This study has selected the adaptable species *Sonneria alba*, with specific objectives: (1) *Sonneria alba* forest growth of ages 1–4 on 3 basic sites, (2) Determining soil and water characteristics on planted forest land, (3) Determining the relationship between soil and water environment with forest growth and vice versa, (4) Building a scientific basis for the restoration of coastal estuarine forests in central Vietnam. New findings show that *Sonneratia alba* plantations with tidal flooding of 5–6 h/day, flooding depth of 80 cm, and sediment thickness less than 20 cm above the compact substrate layer improve water quality such as pH, humus, nitrogen, phosphorus, potassium, and clay content in the surface layer (0–50 cm), reducing Al^{3+}, Fe^{2+}, and SO_4^{2-} in soil and water. The growth of *Sonneratia alba* plantations in the 0–50 cm soil layer, along with the increase in salt content, Al^{3+}, Fe^{2+}, and SO_4^{2-} in water, improves

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the soil environment of *Sonneratia alba* plantations. Based on the results of this study, a theoretical framework for afforestation on mangrove forests in estuarine and coastal areas with similar conditions is developed.

Keywords: Mangrove Plantation; *Sonneratia alba*; Coastal Ecosystem; Soil-Water Interaction; Mangrove Restoration

1. Introduction

Mangrove ecosystems in Thua Thien Hue Province are mainly distributed in estuarine and lagoonal environments, particularly the Tam Giang–Cau Hai Lagoon. The coastal terrain is low-lying and flat, comprising tidal flats, river mouths, and sandy barriers. Soils are predominantly alluvial, consisting of sand, silt, and clay with high organic matter, and are typically saline and waterlogged. The region has a tropical monsoon climate, characterised by a mean annual temperature of 24–26 °C and annual rainfall of 2,500–3,500 mm, concentrated primarily from September to November. Hydrological conditions are governed by semi-diurnal tides with amplitudes of 0.5–2.0 m, controlling inundation regimes. Wave action and frequent storms (3–5 events per year) influence sediment dynamics. Salinity varies seasonally from 15–30‰ in the dry season to lower levels during the rainy season, shaping mangrove structure and distribution.

During forest growth, trees return organic matter, minerals, and water to the soil. At the same time, forests are shaped by environmental factors, such as climate, topography, soil conditions, and human activities. This reflects a close interaction between forests and the environment [1]. Mangrove forests play an important ecological role and have received attention from researchers in ecology, forestry, water management, and environmental protection. Understanding these relationships provides a scientific basis for forest management strategies, environmental restoration, and the development of measures to control flooding and reduce erosion in coastal and estuarine areas.

Previous studies on mangrove forests have mainly addressed silviculture and coastal reforestation [2–5]. Research has also examined seedling growth and age determination [6,7], dispersal and establishment patterns [8], and forest structure and litter dynamics [9]. In addition, spatial distribution and zonation have been analyzed using remote sensing approaches [10,11]. Other studies have focused on allelopathic effects of invasive species [12], the influence of abiotic factors on seedling survival [13], and the biological and chemical characteristics of the genus *Sonneratia* [14].

Recent studies have further examined mangrove ecology from multiple perspectives. These include seed dormancy and restoration potential [15], litterfall production and its contribution to carbon accumulation [16–18], and population structure, flowering traits, and genetic diversity of *Sonneratia* species [19,20]. Other work has evaluated the invasiveness of exotic species [21] and their effects on sediment microbial communities and nitrogen fixation processes [22,23].

Environmental studies on mangroves have focused on soil characteristics, biomass, and their relationships with forest growth and planting techniques [24,25]. Research has also examined litter production and its variation between native and exotic species [26], as well as the relationships between soil properties and mangrove diversity [27].

Mangrove responses to environmental change have been widely investigated, including the effects of climate variability [28] and historical sea-level fluctuations on population dynamics [29]. Other studies have explored phenology [30], sediment nutrient processes [31], and the interactions between soil nutrients, vegetation structure, and productivity under salinity stress [32].

In addition, research has addressed microbial community structure and functional diversity in mangrove sediments [33], nutrient content in litter [34], and ecosystem functions such as biomass accumulation, carbon storage, and oxygen production [35]. Molecular adaptations of *Sonneratia alba* to salinity fluctuations have also been reported [36].

Studies on carbon stocks in mangroves have mainly focused on changes following afforestation with *Sonneratia apetala* [37–39]. Research has also shown that the colonization of native species can enhance carbon storage in exotic monocultures [40]. In addition, comparisons of carbon reserves among mangrove species and assessments across different regions have been conducted to better understand spatial variation in carbon stocks [41,42].

Previous studies have not clearly addressed the relationships between soil and water characteristics and mangrove forest growth. Building on existing research, this study focuses on changes in soil and water properties under mangrove canopies and their relationships with the growth of newly planted *Sonneratia alba* in Thua Thien Hue Province, central Vietnam.

Mangrove studies in central Vietnam generally follow two main directions.

First, most research has examined distribution, species composition, structure, growth, site conditions, nursery techniques, planting, productivity, and material cycling. This study builds on these findings and establishes experimental plantations of *Sonneratia alba* in coastal areas to support forest development and enhance resilience to seasonal storms.

Second, Previous studies on mangrove forests have primarily focused on their distribution in coastal areas. Previous work has largely emphasized spatial distribution, with limited attention to the effects of soil and water changes under the canopy and their interactions with forest growth. This study addresses this gap by analyzing variations in soil and water characteristics and their influence on mangrove growth.

2. Materials and Methods

2.1. Experimental Design and Data Collection

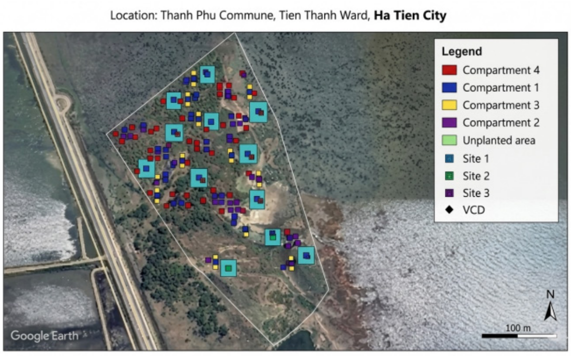
Suitable sites for planting *Sonneratia alba* were determined (**Tables 1–2** and **Figure 1**) following established criteria [43]. Plantations were established in 2023 across three site types (I, II, and III) based on mangrove classification [4]. Six-month-old seedlings grown in polyethylene bags (25 × 30 cm) were selected based on good health, straight stems, and absence of pests and diseases [44]. Seedlings had a minimum stem diameter (D_0) of 0.5 cm and height (H) of 50 cm. Design a fully randomized block design with 3 replications for a single-factor experiment.

Table 1. Coordinates of experimental plots across three terrain sites with three replications.

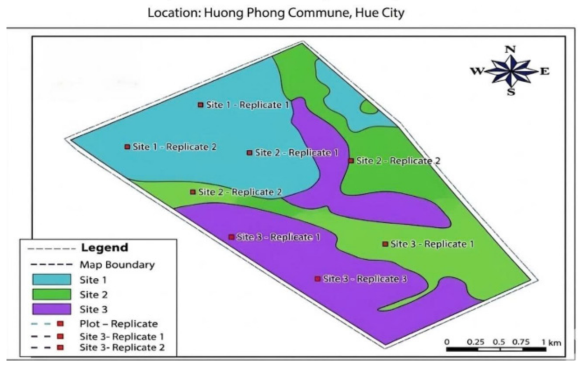
Site	Replication	X (m)	Y (m)
Site 1	Replicate 1	780,197	1,832,187
	Replicate 2	780,148	1,832,136
	Replicate 3	780,218	1,832,118
Site 2	Replicate 1	780,295	1,832,024
	Replicate 2	780,290	1,832,113
	Replicate 3	780,188	1,832,081
Site 3	Replicate 1	780,253	1,832,126
	Replicate 2	780,209	1,832,033
	Replicate 3	780,262	1,831,988

Table 2. Tidal inundation regime and surface elevation in experiment plots.

Site Characteristics	Site Type		
	I	II	III
Tidal Inundation Regime			
Ti dal inundation duration (h)	8–12	5–6	<5
Tidal inundation depth (m)	0.8–1.5	0.6–1.0	<0.6
Surface Elevation	≤0.2	≤0.2	>0.3
Soil type: Slightly to moderately saline soils (Molli Salic Fluvisols)	Sandy loam	Sandy clay loam	Sand
Degree of soil development	Poorly developed	Moderately developed	Well developed



(**a**) Experimental Plot Distribution Map.



(**b**) Experimental Plot Layout Map.

Figure 1. Experimental Plot Distribution and Layout Map.

Planting was conducted on March 15 during low tide. Seedlings were arranged in rows perpendicular to the coastline at a density of 3,300 trees ha^{-1} (1.5 × 2.0 m). Each seedling was supported by three bamboo stakes (2–3 cm diameter, 100–150 cm height), driven 40–60 cm into the soil and tied at two-thirds of the seedling height to reduce damage from wind and waves. Experimental plots (15 × 20 m; 300 m^2) were fenced with bamboo to limit wave action and algae intrusion. Each site type included three replicates.

Growth and soil data were collected after 6 months, 1 year, and 4 years. Soil samples were taken under the canopy to assess changes in site conditions. Forest growth was measured in 100 m^2 (10 × 10 m) subplots located at the center of each plot. Thirty trees were assessed per site type (10 trees per replicate). Site effects were evaluated based on survival rate (S), growth, and forest quality after 4 years. Measured variables included stand density (N), stem diameter (D_0), tree height (H), canopy diameter (Dc), biomass (B), and tree quality (good, average, poor).

Soil and water characteristics under plantation canopy (**Tables 1–2** and **Figure 1**):

Soil was assessed before planting and under plantations aged 1–4 years across site types. Three profiles (one per replicate) were located at plot centers (70 × 150 cm). Due to shallow roots, samples were taken at 0–20 cm and 20–50 cm (0.5–1.0 kg per layer). Ten indicators were analyzed: , pH_{KCl}, humus (%), total N (%), P_2O_5 (%), K_2O (%), Al^{3+}, Fe^{2+}, and SO_4^{2-} (me/100 g).

Water was analyzed in 1–4-year-old plantations at site type II. Three samples were collected per sampling. Parameters included , Dissolved Oxygen (DO, mg/L), salinity (‰), Al^{3+}, Fe^{2+}, and SO_4^{2-}. Analyses followed Vietnamese standards: SoVN 5979:2007 (pH), 7325:2016 (DO), 8727:2012 (salinity), 6177:1996 (Fe^{2+}), 6657:2000 (Al^{3+}), and 6656:2000 (SO_4^{2-}). pH was measured by a pH meter, DO by electrode, salinity by refractometer, and Al^{3+}, Fe^{2+}, SO_4^{2-} by colorimetry. Sampling was conducted monthly (15th), and annual means were calculated. Analyses were performed at the Soil and Water Environment Laboratory of the Southern Vietnam Forestry Science Institute.

2.2. Data Processing Methods

Growth Analysis of Planted Forests

The survival rate (SV, %) of *Sonneratia alba* plantations was calculated. Growth variables (D_0, H, Dc) were summarized by age (A = 6 months and 1–4 years) across three site types.

Stand volume at age A (MA, m^3/ha) was calculated as:

$$MA = NA \times V(av)A,$$

where V(av)A is the average tree volume at age A and NA is the stand density.

Biomass (Bi, t/ha) was calculated as:

$$Bi = NA \times Bi(av)A,$$

where Bi(av)A includes BTo, BT, BC and BL at the average tree level.

Biomass components at the individual tree level were estimated using:

$$Bi = a + b \times D_0^2 + c \times D_0^3 + d \times (D_0^3/H),$$

where Bi includes B_{To}, BT, BC, BL, and B_{CL}; D_0 is trunk diameter; H is tree height; and a, b, c and d are model parameters.

Above-ground carbon stock (MC, t/ha) was calculated from biomass using a carbon fraction of 0.47. CO_2 sequestration (MCO_2, t/ha) was estimated as:

$$MCO_2 = C \times 3.67.$$

The SCI index was calculated as:

$$SCI = (N \times D \times H)/10^5,$$

where N is tree density, D is mean diameter, and H is mean height.

Tree competition was assessed using:

$$CCIi = STi/Z,$$

where Sci (m^2) is the total canopy area, calculated as:

$$ST = \Sigma\,(0.0000785 \times Dci^2), \text{ and } Z = 300\ m^2 \text{ (plot area)}.$$

Stand stability was analyzed across site types to determine suitable planting sites. Site suitability was selected based on maximum values of SV, D_0, H, M, and Bi.

Relationship between SCI and Environmental Factors

The relationship between SCI and soil characteristics was described as:

$$SCI = f\,(N, P, K, Al, Fe, SO_4).$$

The relationship between SCI and water characteristics was described as:

$$SCI = f\,(Salinity, Al, Fe, SO_4).$$

The contribution of each factor was evaluated using standardized regression coefficients. Variables were ranked based on the absolute values of these coefficients.

Descriptive statistics, hypothesis testing, and graphing were performed using Excel and STATGRAPHICS Centurion XV.I 15.1.02.

3. Results

3.1. The Research Aims to Plant *Sonneratia alba* Forests for National Disaster Prevention

Figures 2 and **3** present the study's strategic objective: establishing a coastal estuarine plantation forest using *Sonneratia alba* to improve environmental conditions (soil and water) and mitigate storm-related disasters in central Vietnam.

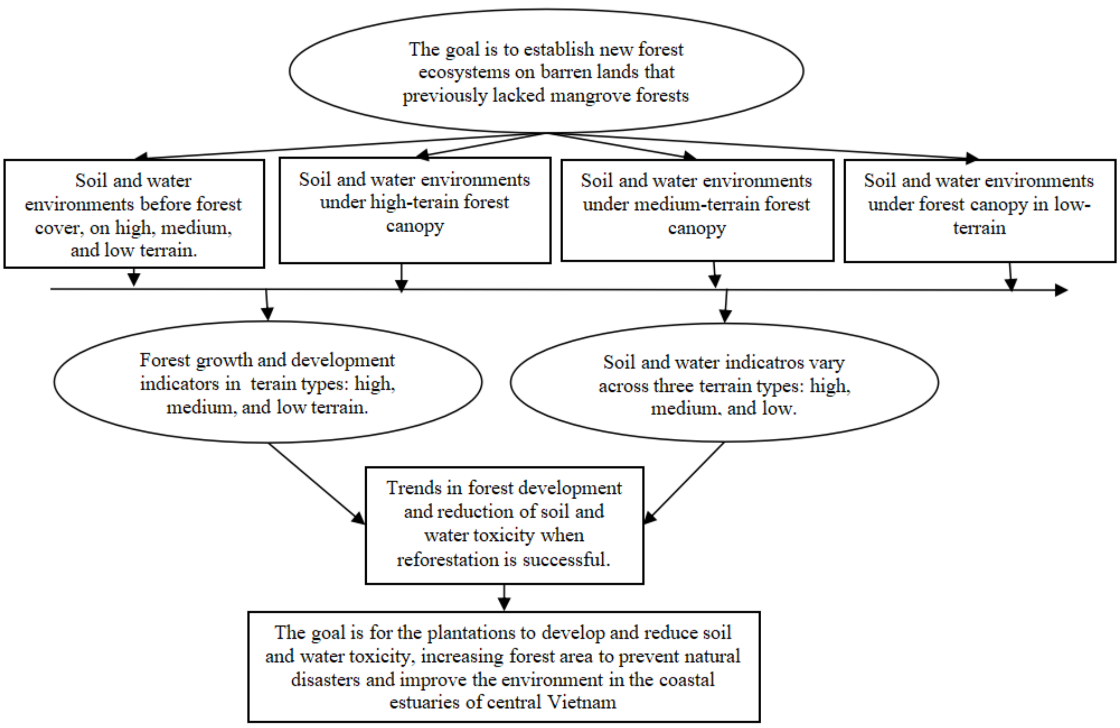


Figure 2. The research aims to establish *Sonneratia alba* forests for disaster prevention and environmental improvement.

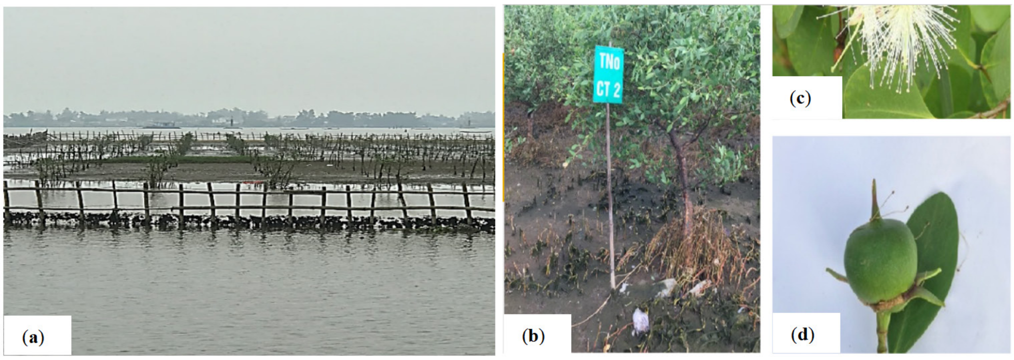


Figure 3. (**a**) Protective fences and the experimental plots; morphological characteristics of *Sonneratia alba* in the experimental plot: (**b**) Trees; (**c**) Flowers; (**d**) Fruit and leaf.

Key activities include reforestation research; monitoring growth indicators ($D_{1.3}$ and height) from age 1 to 4 until canopy closure; collecting and comparing soil and water samples across three site types (high, medium, low) and unplanted areas; and analyzing relationships between forest growth and environmental factors.

The target outcomes are a survival rate >85%, over 75% of trees classified as: (a) good or (b) medium, improved soil and water quality through reduction of chemical toxins, and strong growth performance to support expanded planting and enhance typhoon disaster mitigation.

3.2. Growth of *Sonneratia alba* Plantations on Different Sites

3.2.1. Growth Diameter $D_{1.3}$ and Height H

Diameter $D_{1.3}$ and Height H

Statistical characteristics of the diameter and height of *Sonneratia alba* plantations on three site types are summarized in **Tables 3–6** and **Figure 4**. Results for 4-year-olds show that ZD_0 and ΔD_0 increased with age across all sites. Compared with site III (1.5 cm and 1.3 cm), these values were 15.4% and 19.5% higher on site I (1.7 cm and 1.5 cm), and 83.1% and 60.3% higher on site II (2.7 cm and 2.0 cm). Similarly, ZH and ΔH increased with age. Relative to site III (47.8 cm and 60.2 cm), site I (63.5 cm and 67.9 cm) showed increases of 32.7% and 12.9%, while site II (73.9 cm and 75.2 cm) showed increases of 54.5% and 25.0%, respectively. Overall, growth was highest on site II.

Canopy Diameter and Length Growth

Mean canopy diameter (Dc) at ages 1–4 was lowest on site III (0.51, 0.65, 0.78, 1.22 m) and highest on site II (0.70, 0.93, 1.13, 2.23 m). Mean canopy length (Lc) followed the same pattern, lowest on site III (0.60, 0.76, 0.91, 1.43 m) and highest on site II (0.80, 1.07, 1.41, 2.57 m). Differences among sites were significant (Dc: $F = 41.9$, $p < 0.01$; Lc: $F = 38.1$, $p < 0.01$) (**Table 5**).

Stand Complexity Index (SCI)

SCI increased with age and varied by site. On site I, SCI rose from 5.2 (age 1) to 56.4 (age 4); on site II, from 6.2 to 100.4; and on site III, from 3.2 to 26.5. At age 4, SCI on site II was 1.8 and 3.9 times higher than on sites I and III, respectively. Canopy coverage at age 4 reached 0.68, 1.12, and 0.23 times the ground area on sites I, II, and III, respectively (**Table 6**).

Table 3. Diameter growth of *Sonneratia alba* forest on three site types.

A (Year)	$D_{0(av)}$ (cm)	Min (cm)	Max (cm)	±SEE	CV%	N (Tree/ha)	Survival Rate N (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	
			Site Type I				
6 months	0.9	0.8	1.1	0.10	10.7	3,082	93.39
1	1.8	1.5	2.0	0.16	8.9	2,987	90.52
2	2.6	2.1	3.2	0.36	13.5	2,914	88.30
3	4.5	4.3	4.6	0.13	2.8	2,864	86.79
4	7.0	6.7	7.3	0.21	2.9	2,828	85.70

Table 3. *Cont.*

A (Year)	$D_{0(av)}$ (cm)	Min (cm)	Max (cm)	±SEE	CV%	N (Tree/ha)	Survival Rate N (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	
Site Type II							
6 months	1.0	0.8	1.1	0.10	10.5	3,145	95.30
1	2.0	1.7	2.2	0.16	8.0	3,059	92.70
2	2.9	2.3	3.4	0.31	10.9	2,987	90.52
3	7.2	6.7	7.6	0.36	5.0	2,914	88.30
4	10.7	10.2	11.1	0.32	3.0	2,871	87.00
Site Type III							
6 months	0.9	0.8	1.1	0.11	11.4	2,492	75.52
1	1.5	1.2	1.7	0.17	11.4	2,386	72.30
2	2.4	1.8	2.9	0.34	14.1	2,264	68.61
3	3.3	3.1	3.6	0.15	4.7	2,053	62.21
4	6.3	6.1	6.4	0.15	2.4	1,993	60.39

Notes: $D_{0(av)}$ (cm): tree stump diameter, N number of trees (trees/ha), Survival rate N (%), H (cm) tree height, SEE = standard deviation; CV% = coefficient of variation.

Table 4. Height growth of *Sonneratia alba* forest on three site types.

A (Year)	H (cm)	Min(cm)	Max(cm)	± SEE	CV%
(1)	(2)	(3)	(4)	(5)	(6)
Site Type I					
6 months	57.4	48	66	5.4	9.5
1	96.0	92	99	2.1	2.2
2	123.0	115	131	4.7	3.8
3	154.8	152	158	2.1	1.4
4	284.7	275	294	6.1	2.1
Site Type II					
6 months	59.3	56	63	2.1	3.5
1	102.1	62	106	5.2	5.1
2	136.8	129	145	4.7	3.5
3	179.7	177	183	2.0	1.1
4	326.8	317	336	5.9	1,8
Site Type III					
6 months	57.8	48	66	5,6	9.6
1	89.3	86	93	2,5	2.8
2	112.6	105	121	4,7	4.2
3	134.8	130	140	3.2	2.3
4	211.4	174	240	22.4	10.6

Note: H(cm) tree height, SEE = Standard deviation; CV% = Variation coefficient.

Table 5. Growth in diameter and height of *Sonneratia alba* plantations on 3 site types.

Growth in Diameter and Height of *Sonneratia alba* Plantations on Site Type I								
A (Year)	**Diameter Growth**				**Height Growth**			
	D_0 (cm)	ZD_0 (cm)	ΔD_0 (cm)	Pd (%)	H (cm)	ZH (cm)	ΔH (cm)	pH (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	1.3	1.3	1.3	100.0	74.0	74.0	74.0	100.0
2	3.0	1.7	1.5	55.5	137.1	63.1	68.5	46.0
3	4.8	1.8	1.6	37.8	196.6	59.5	65.5	30.3
4	6.7	1.9	1.7	28.6	253.9	57.3	63.5	22.6
Medium		1.7	1.5			63.5	67.9	

Table 5. *Cont.*

Growth in Diameter and Height of *Sonneratia alba* Plantations on Site Type II								
A (Year)	Diameter Growth				Height Growth			
	D_0 (cm)	ZD_0	ΔD_0	Pd(%)	H (cm)	ZH (cm)	ΔH (cm)	pH (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	1.3	1.3	1.3	100.0	77.0	77.0	77.0	100.0
2	3.8	2.4	1.9	64.7	150.9	73.9	75.4	49.0
3	6.9	3.2	2.3	45.6	223.6	72.7	74.5	32.5
4	10.7	3.7	2.7	35.1	295.6	72.0	73.9	24.4
Medium		2.7	2.0			73.9	75.2	
Growth in Diameter and Height of *Sonneratia alba* Plantations on Site Type III								
A (Year)	Diameter Growth				Diameter Growth			
	D_0 (cm)	ZD_0	Δc	Pd (%)	H (cm)	ZH (cm)	ΔH (cm)	pH (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	1.1	1.1	1.1	100.0	78.5	78.5	78.5	100.0
2	2.5	1.4	1.2	57.5	122.6	44.0	61.3	35.9
3	4.1	1.6	1.4	39.4	159.0	36.5	53.0	22.9
4	5.8	1.7	1.5	29.9	191.3	32.3	47.8	16.9
Medium		1.5	1.3			47.8	60.2	

Note: ZD_0 and ZH = Annual growth of D_0 and H; ΔD_0 and ΔH = Annual growth of D_0 and H; Pd (%) and pH (%) = Growth rate of D and H.

Table 6. Complexity index of the structure of *Sonneratia alba* plantations across three site types.

A (Year)	N (Trees/ha)	D_0 (m^2)	H (cm)	Index SCI
Site Type I				
1	2,987	1.8	96.0	5.2
2	2,914	2.6	123.0	9.3
3	2,864	4.5	154.8	20.0
4	2,828	7.0	284.7	56.4
Site Type II				
1	3,059	2.0	102.1	6.2
2	2,987	2.9	136.8	11.9
3	2,914	7.2	179.7	37.7
4	2,871	10.7	326.8	100.4
Site Type III				
1	2,386	1.5	89.3	3.2
2	2,264	2.4	112.6	6.1
3	2,053	3.3	134.8	9.1
4	1,993	6.3	211.4	26.5

Note: N: number of trees/ha, D_0: tree stump diameter, H (cm): tree height, SCI: Structure Complexity Index.

3.2.2. Timber Volume, Biomass, and Carbon Stock

Results in **Tables 7** and **8** show that timber volume varies with age and site. Taking site III (100%) as reference, timber volume at age 4 was 1.34 times higher on site I and 4.28 times higher on site II. Overall, timber volume was highest on site II and lowest on site III. Total biomass on site I increased from 0.42 t/ha (age 1) to 13.89 t/ha (age 4); on site II from 0.57 to 50.58 t/ha; and on site III from 0.18 to 9.89 t/ha. Carbon stock in biomass was highest on site II and lowest on site III; compared with site III at age 4, biomass carbon stock and CO_2 absorption on sites I and II were 1.4 and 5.1 times greater, respectively.

Table 7. Growth and Timber Volume Increase on 3 Site Types.

Growth and Timber Volume Development in *Sonneratia alba* Forest on Site Type I				
A (Year)	**M (m^3/ha)**	**ZM (m^3/ha/Year)**	**ΔM (m^3/ha/Year)**	**PM%**
(1)	**(2)**	**(3)**	**(4)**	**(5)**
1	0.01	0.01	0.01	100.0
2	0.61	0.60	0.31	98.6
3	4.09	3.48	1.36	85.0
4	12.72	8.63	3.18	67.8
Growth and Timber Volume Development in *Sonneratia alba* Forest on Site Type II				
A (Year)	**M (m^3/ha)**	**ZM (m^3/ha/Year)**	**ΔM (m^3/ha/Year)**	**PM%**
(1)	**(2)**	**(3)**	**(4)**	**(5)**
1	0.01	0.01	0.01	100.0
2	1.94	1.92	0.97	99.4
3	13.93	11.99	4.64	86.1
4	40.56	26.63	10.14	65.7
Growth and Timber Volume Development in *Sonneratia alba* Forest on Site Type III				
A (Year)	**M (m^3/ha)**	**ZM (m^3/ha/Year)**	**ΔM (m^3/ha/Year)**	**PM%**
(1)	**(2)**	**(3)**	**(4)**	**(5)**
1	0.01	0.01	0.01	100.0
2	0.10	0.09	0.05	89.5
3	1.79	1.70	0.60	94.7
4	9.48	7.69	2.37	81.1

Note: M = Average timber volume; ZM = Annual growth of timber volume; ΔM = Average annual growth of timber volume; PM (%) Growth rate of timber.

Growth in Canopy Diameter and Height of Planted Forests

Table 8. Biomass of *Sonneratia alba* forest on 3 Site Types.

Biomass of *Sonneratia alba* Forest on Site Type I					
A (Year)	**Biomass Components (t/ha)**				
	B_{To}	**B_{Tr}**	**B_{Br}**	**B_{L}**	**B_{BrL}**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
1	0.42	0.38	0.02	0.01	0.04
2	1.06	0.91	0.10	0.05	0.16
3	4.13	3.31	0.52	0.30	0.82
4	13.89	10.65	1.91	1.34	3.25
Biomass of *Sonneratia alba* Forest on Site Type II					
A (Year)	**Biomass Components (t/ha):**				
	B_{To}	**B_{Tr}**	**B_{Br}**	**B_{L}**	**B_{BrL}**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
1	0.57	0.51	0.04	0.02	0.06
2	1.41	1.19	0.15	0.08	0.22
3	15.44	11.80	2.13	1.51	3.64
4	50.58	37.43	7.22	5.94	13.15
Biomass of *Sonneratia alba* Forest on Site Type III					
A (year)	**Biomass Components (t/ha):**				
	B_{To}	**B_{Tr}**	**B_{Br}**	**B_{L}**	**B_{BrL}**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
1	0.18	0.17	0.00	0.00	0.01
2	0.71	0.59	0.08	0.04	0.12
3	1.67	1.36	0.21	0.11	0.32
4	9.89	7.60	1.38	0.92	2.30

Note: B_{To} = Total biomass; B_{Tr} = Trunk biomass; B_{br} = Branch biomass; B_{L} = Leaf biomass; B_{BrL} = total biomass of branches and leaves.

(**a**) *Sonneratia alba* after two years.

(**b**) *Sonneratia alba* after four years.

Figure 4. *Sonneratia alba* plantation.

Influence of Site on Forest Structure

Forest structure was assessed using the H/D ratio and tree quality (**Table 8**). Trunk form decreased with age across all sites, while H/D ratios remained <0.80 at all ages, indicating stable growth. Tree quality differed clearly among sites; at age 4, the proportion of good and medium trees was highest on site II (90.1%) and lowest on site III (70.9%).

3.3. Soil Characteristics under Plantation Canopy

Soil properties under 1–4-year-old *Sonneratia alba* plantations varied with age and site type (**Table 9** and **Figure 5**).

Table 9. Changes in soil parameters under 1–4 year old planted forests across.

Changes in Soil Indicators under the Canopy of 1–4 Year Old Planted Forests on Site Type I					
Soil Characteristics	**Forest Age (Years)**				
	Land No Forest	**1**	**2**	**3**	**4**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	5.9	6.1	6.3	6.5	6.5
pH_{KCL}	5.8	5.9	5.7	5.9	6.0
Humus (%)	1.20	1.79	2.05	2.18	2.44
Nitrogen (%)	0.056	0.099	0.113	0.110	0.122
Phosphorus (%)	0.050	0.082	0.081	0.073	0.091
Kalium (%)	0.129	0.181	0.221	0.215	0.262
Al^{3+} (me/100 g)	1.68	1.27	1.17	0.97	1.02
Fe^{2+} (me/100 g)	113.7	92.0	79.6	66.6	51.6
SO_4^{2-} (me/100 g)	0.099	0.081	0.070	0.061	0.067
Clay rate (%)	12.8	14.3	15.5	14.3	18.0
Alluvial rate (%)	8.0	9.7	10.0	7.0	8.1
Sand rate (%)	79.2	76.0	74.5	78.7	73.9

Table 9. *Cont.*

Changes in Soil Indicators under the Canopy of 1–4 Year Old Planted Forests on Site Type II					
Soil Characteristics	**Forest Age (Years)**				
	Land No Forest	**1**	**2**	**3**	**4**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	6.1	6.6	6.8	6.8	6.5
pH_{KCL}	5.9	6.0	5.9	6.0	5.9
Humus (%)	1.20	0.72	0.96	1.04	1.09
Nitrogen (%)	0.056	0.064	0.074	0.101	0.123
Phosphorus (%)	0.050	0.065	0.065	0.069	0.078
Kalium (%)	0.129	0.142	0.182	0.195	0.234
Al^{3+} (me/100 g)	1.681	0.539	0.749	0.775	0.562
Fe^{2+} (me/100 g)	113.7	65.3	65.5	60.6	45.5
SO_4^{2-} (me/100 g)	0.097	0.059	0.051	0.042	0.045
Clay rate (%)	12.8	12.7	12.0	12.5	12.5
Alluvial rate (%)	8.0	7.4	7.7	5.8	5.5
Sand rate (%)	79.3	79.9	80.4	81.7	82.0
Changes in Soil Indicators under the Canopy of 1–4 Year Old Planted Forests on Site Type III					
Soil Characteristics	**Forest Age (Years)**				
	Land No Forest	**1**	**2**	**3**	**4**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	6.1	6.3	6.5	6.5	6.8
pH_{KCL}	5.9	6.0	5.9	6.0	6.0
Humus (%)	1.20	1.43	1.69	1.94	2.28
Nitrogen (%)	0.056	0.083	0.094	0.088	0.178
Phosphorus (%)	0.051	0.080	0.079	0.083	0.092
Kalium (%)	0.129	0.182	0.220	0.233	0.256
Al^{3+} (me/100 g)	1.681	0.787	0.852	0.677	0.835
Fe^{2+} (me/100 g)	113.7	112.0	79.9	86.9	73.6
SO_4^{2-} (me/100 g)	0.099	0.084	0.070	0.074	0.062
Clay rate (%)	14.3	15.4	16.6	17.2	18.0
Alluvial rate (%)	6.4	6.9	7.1	5.3	5.5
Sand rate (%)	79.3	77.8	76.4	77.5	75.9

Note: Land no forest before plantation: year 1: after 1 year planted forest; year 2: after 2 years planted forest; year 3: after 3 years planted forest; and year 4: after 4 years planted forest.

On site I, six parameters (, humus, N, P, K, and clay) increased with age, while Al^{3+}, Fe^{2+}, SO_4^{2-}, loam, and sand decreased; pHKCl remained stable (5.8–6.0). At age 4, compared to unplanted soil, these six parameters increased by 10.2%, 103.3%, 117.9%, 82.0%, 103.1%, and 40.6%, respectively, whereas Al^{3+}, Fe^{2+}, SO_4^{2-}, and sand decreased by 39.3%, 54.6%, 32.3%, and 6.7%.

On site II, soil pH, humus, N, P, K, and clay increased markedly with age, while Al^{3+}, Fe^{2+}, SO_4^{2-}, and sand decreased; pH_{KCl} remained stable (5.9–6.0). At age 4, increases compared to unplanted soil were 6.6%, 119.6%, 56.0%, and 81.4%, while decreases were 66.6%, 60.0%, 53.6%, and 31.3%.

On site III, , humus, N, P, K, and clay increased significantly with age, whereas Al^{3+}, Fe^{2+}, SO_4^{2-}, and loam decreased; pH_{KCl} remained stable (5.9–6.0). At age 4, increases were 11.5%, 90.0%, 217.9%, 80.4%, 98.4%, and 25.9%, while decreases were 50.3%, 35.3%, 37.4%, and 14.1%.

Statistical analysis indicated that nine soil parameters (, pH_{KCl}, humus, P, Fe^{2+}, SO_4^{2-}, clay, loam, and sand) differed significantly among sites ($p < 0.05$), whereas N, K, and Al^{3+} showed no significant differences ($p > 0.05$).

(**a**) Collection of soil samples in plots.

(**b**) Plantation forest collected soil samples.

Figure 5. Collect soil samples.

3.4. Relationship between Soil Characteristics and Growth of *Sonneratia alba* Plantations

Relationship between Forest Growth and Soil Properties

Forest growth (SCI) significantly influenced soil indicators across sites. On site I, seven factors (, pH_{KCl}, humus, N, P, K, and clay) showed strong positive correlations ($p < 0.01$), while Fe^{2+}, SO_4^{2-}, and silt showed negative correlations ($p < 0.01$). On site II, N, P, K, and clay were positively correlated ($p < 0.01$), whereas Al^{3+}, Fe^{2+}, SO_4^{2-}, and silt were negatively correlated ($p < 0.01$). On site III, seven factors (, pH_{KCl}, humus, N, P, K, and clay) were positively correlated ($p < 0.01$), while Al^{3+}, Fe^{2+}, SO_4^{2-}, loam, and sand showed negative correlations ($p < 0.01$) (**Table 10**).

Table 10. The correlation between soil environmental factors of *Sonneratia alba* plantations across three site types.

The Correlation between Soil Environmental Factors of *Sonneratia alba* Plantations in Site Type I			
Soil Characteristics	**r**	**P_α**	**K(Samples)**
(1)	**(2)**	**(3)**	**(4)**
	0.483	0.007	30
pH_{KCL}	0.560	0.001	30
Humus (%)	0.829	0.000	30
Nitrogen (%)	0.676	0.000	30
Phosphorus (%)	0.546	0.002	30
Kalium (%)	0.808	0.000	30
Al^{3+} (me/100g)	−0.204	0.279	30
Fe^{2+} (me/100g)	−0.855	0.000	30
SO_4^{2-} (me/100g)	−0.638	0.000	30
Clay rate (%)	0.661	0.000	30
Alluvial rate (%)	−0.552	0.002	30
Sand rate (%)	−0.355	0.054	30

Table 10. *Cont.*

The Correlation between Soil Environmental Factors of *Sonneratia alba* Plantations in Site Type II			
Soil Characteristics	**r**	**P_α**	**K (Samples)**
(1)	**(2)**	**(3)**	**(4)**
	0.277	0.138	30
pH_{KCL}	−0.006	0.976	30
Humus (%)	0.046	0.808	30
Nitrogen (%)	0.688	0.000	30
Phosphorus (%)	0.649	0.000	30
Kalium (%)	0.796	0.000	30
Al^{3+} (me/100g)	−0.406	0.026	30
Fe^{2+} (me/100g)	−0.752	0.000	30
SO_4^{2-} (me/100g)	−0.686	0.000	30
Clay rate (%)	−0.042	0.825	30
Alluvial rate (%)	−0.665	0.000	30
Sand rate (%)	0.418	0.021	30
The Correlation between Soil Environmental Factors of *Sonneratia alba* Plantations in Site Type III			
Soil Characteristics	**r**	**P_α**	**K (Samples)**
(1)	**(2)**	**(3)**	**(4)**
	0.501	0.005	30
pH_{KCL}	0.145	0.444	30
Humus (%)	0.760	0,000	30
Nirogen (%)	0.515	0.004	30
Phosphorus (%)	0.620	0.000	30
Kalium (%)	0.767	0.000	30
Al^{3+} (me/100g)	−0.240	0.202	30
Fe^{2+} (me/100g)	−0.754	0.000	30
SO_4^{2-} (me/100g)	−0.676	0.000	30
Clay rate (%)	0.714	0.000	30
Alluvial rate (%)	−0.370	0.044	30
Sand rate (%)	−0.266	0.156	30

Notes: r = correlation coefficient; P_α = Statistical significance level; K = Number of samples.

Regression Analysis of Soil Factors

Regression models relating soil properties to plantation age were highly significant ($p < 0.01$), with R^2 ranging from 74–99%. On site I, six factors (humus, N, P, K, Fe^{2+}, SO_4^{2-}) were estimated using Functions 1–6; on site II, six factors (N, P, K, Al^{3+}, Fe^{2+}, SO_4^{2-}) using Functions 7–12; and on site III, six factors (humus, N, P, K, Fe^{2+}, SO_4^{2-}) using Functions 13–18 (**Table 11**).

Table 11. Estimates of soil factors based on the age of planted forests across three site types.

No.	**Function**	**R^2 (%)**
1	$\text{Humus} = (1.10024 + 0.228186 \times \sqrt{A})^2$	99.54
2	$N = \sqrt{0.00359117 + 0.00565127 \times \sqrt{A}}$	95.63
3	$P = 1/(18.7432 - 3.98414 \times \sqrt{A})$	76.04
4	$K = \exp(-2.04343 + 0.337414 \times \sqrt{A})$	96.46
5	$Fe^{2+} = (10.5822 - 0.839019 \times A)^2$	99.42
6	$SO_4^{2-} = \sqrt{0.00957254 - 0.00299218 \times \sqrt{A}}\ )$	93.56
7	$N = \sqrt{0.00306812 + 0.00075658 \times A^2}$	99.43
8	$P = 1/(19.6885 - 3.31256 \times \sqrt{A})$	94.44
9	$K = \exp(-2.0598 + 0.150819 \times A)$	97.55

Table 11. *Cont.*

No.	Function	R^2 (%)
10	$Al^{3+} = \sqrt{2.37241 - 1.18256 \times \sqrt{A}}$	73.93
11	$Fe^{2+} = (10.4608 - 1.77942 \times \sqrt{A})^2$	92.66
12	$SO_4^{2-} = \exp(-2.37032 - 0.416317 \times \sqrt{A})$	95.46
13	$Humus = (1.0936 + 0.102606 \times A)^2$	99.89
14	$N = \sqrt{0.00358122 + 0.00288369 \times \sqrt{A}}$	88.81
15	$P = \sqrt{0.00286209 + 0.00264951 \times \sqrt{A}}$	92.45
16	$K = (0.358129 + 0.0736772 \times \sqrt{A})^2$	99.38
17	$Fe^{2+} = (10.7029 - 0.542894 \times A)^2$	80.71
18	$SO_4^{2-} = \sqrt{0.0097568 - 0.002881 \times \sqrt{A}}$	94.54

3.5. Relationship between Water and Other Factors of the Plantation

Water Characteristics under Plantation Canopy

Water properties showed limited variation with plantation age. On site II, ranged from 6.3–6.4 (CV < 2.5%), and DO ranged from 5.4 (unplanted) to 5.5 under canopy (mean 5.4; CV = 2.6%). Compared to unplanted land (100%), water under 1–4-year-old plantations showed reduced salinity by 6.6%, 12.6%, 14.9%, and 17.7%; Al^{3+} by 5.9%, 16.1%, 28.2%, and 29.5%; Fe^{2+} by 4.1%, 12.6%, 22.4%, and 24.2%; and SO_4^{2-} by 25.3%, 42.2%, 46.1%, and 50.0% (**Table 12**).

Table 12. Relationship between water factors in planted forests.

Water Characteristics	r	P_α	K (Samples)
(1)	**(2)**	**(3)**	**(4)**
	−0.061	0.828	15
DO (mg/l)	−0.141	0.617	15
Độ mặn (‰)	−0.982	0.000	15
Al^{3+} (me/100g)	−0.977	0.000	15
Fe^{2+} (me/100g)	−0.951	0.000	15
SO_4^{2-} (me/100g)	−0.935	0.000	15

Relationship between SCI and Water Properties

Plantation growth significantly influenced water characteristics. Increasing plantation age increased , DO, salinity, Al^{3+}, Fe^{2+}, and SO_4^{2-}. However, SCI was strongly negatively correlated with salinity ($r = -0.982$; $p < 0.01$), Al^{3+} ($r = -0.977$; $p < 0.01$), Fe^{2+} ($r = -0.951$; $p < 0.01$), and SO_4^{2-} ($r = -0.932$; $p < 0.01$) (**Table 12**).

Regression Analysis

Salinity, Al^{3+}, Fe^{2+}, and SO_4^{2-} can be estimated as functions of plantation age. These models are highly significant ($p < 0.01$) with high explanatory power (R^2 = 96–98%) (**Table 13**).

Table 13. Model for estimating water factors according to forest age on site type II.

No.	Function	R^2 (%)
19	$Salinity = \sqrt{515.384 - 84.321 \times \sqrt{A}}$	98.37
20	$Al^{3+} = 0.2962 - 0.024 \times A$	95.92
21	$Fe^{2+} = 0.2054 - 0.0136 \times A$	95.89
22	$SO_4^{2-} = (0.225664 - 0.0334785 \times \sqrt{A})^2$	98.55

3.6. Relationship between the SCI Index of Planted Forests and Soil and Water Characteristics

Relationship between SCI and Soil Characteristics

On site II, the SCI index was correlated with six soil variables (N, P, K, Al, Fe, SO_4). Regression analysis indicated a strong relationship (R^2 = 56.8%; SEE = ±13.1) with five factors (N, P, K, Al, Fe) (Function 23):

$$SCI = 1.49875 + 35.2979 \times N + 30.9501 \times P + 150.295 \times K + 3.62515 \times Al - 0.266977 \times Fe - 7.7071 \times (N \times P \times K \times Al \times Fe)$$

SCI was most strongly influenced by Fe (|−0.843|), followed by Al (|0.341|), and least by P (|−0.008|).

Relationship between SCI and Water Characteristics

SCI was closely related to four water variables (salinity, Al, Fe, SO_4). Regression analysis (R^2 = 66.3%; SEE = ±25.3) followed Function 24:

$$SCI = 417.239 - 8.8789 \times salinity - 372.895 \times Al - 839.412 \times Fe + 646.916 \times SO_4 + 387.745 \times (salinity \times Al \times Fe \times SO_4)$$

SCI variation depended most on Fe (|−1.416|), followed by salinity (|−1.276|), and least on Al (|0.704|).

3.7. A Research Model on the Development of *Sonneratia alba* Forests in the Coastal Estuaries of Central Vietnam

The study on mangrove development using *Sonneratia alba* in coastal estuaries of central Vietnam (**Figure 6**) requires site adaptability, a survival rate >85%, and >75% of trees classified as good and medium quality (a, b). After 4 years, the species met research objectives compared with other regions [44]. In Vietnam, coastal reforestation is implemented by the National Center for Agricultural and Forestry Extension under the Ministry of Agriculture and Rural Development [45].

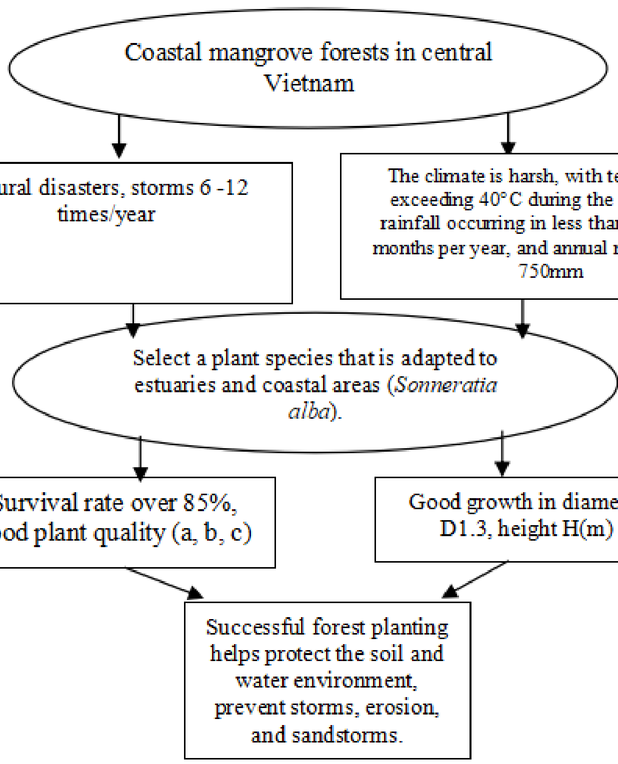


Figure 6. Study diagram of forest planting for environmental protection in central Vietnam.

Disaster prevention is critical, as central Vietnam experiences 6–12 storms annually, causing significant damage to life and property. International organizations also support forest development [46]. while national mangrove assessments indicate coastal forests are in an alarming condition [47].

Therefore, successful findings on the relationships between *Sonneratia alba* growth and soil–water environments should be rapidly scaled into a national program to increase forest cover and enhance disaster resilience in this vulnerable coastal region.

4. Conclusions

Sonneratia alba adapts well to the coastal conditions of Thua Thien Hue Province, showing the best growth at type II sites, followed by type I, and the poorest performance at type III sites. These results help identify suitable areas for planting this promising species in coastal estuaries of central Vietnam with similar climatic conditions, contributing to the mitigation of storm-related natural disasters. Soil properties under *Sonneratia alba* plantations differ significantly from those of unplanted areas. After planting, soil pH, humus, nitrogen, phosphorus, potassium, and clay content in the 0–50 cm layer increased, while Al^{3+}, Fe^{2+}, SO_4^{2-}, and the proportion of sandy and loamy soils decreased. These changes indicate improved soil fertility and reduced environmental toxicity under the plantation canopy. The growth of *Sonneratia alba* is also closely related to water characteristics. As the plantation develops, water quality improves, with significant reductions in salinity, Al^{3+}, and Fe^{2+} concentrations. These findings suggest that restoring coastal estuarine forests with *Sonneratia alba* can contribute to the remediation of environments contaminated with heavy metals.

Author Contributions

All authors contributed equally to the conception, design, data collection, analysis, and writing of this study. All authors have read and agreed to the published version of the manuscript.

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Not applicable, because this study does not involve humans or animals.

Informed Consent Statement

Not applicable. All studies only study plants and soil. It is not related to humans; it only helps the community and government to develop the economy.

Data Availability Statement

These databases are elaborated by authors. Thus, we used to study and for our article, published in the journal, can be shared by the authors' group.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Chen, L., Tam, N.F.Y., Wang, W., et al., 2013. Significant niche overlap between native and exotic Sonneratia mangrove species along a continuum of varying inundation periods. Estuarine, Coastal and Shelf Science. 117, 22–28. DOI: https://doi.org/10.1016/j.ecss.2012.09.009

[2] Trung, T.V. 1998. Tropical Forest Ecosystems in Vietnam. Science and Technology Publishing House: Hanoi, Vietnam.

[3] FAO, 1993. Mangrove for Production and Protection: A Changing Resource System: Case Study in Can Gio

District, Southern Vietnam. FAO Regional Offcie for Asia and the Pacific: Bangkok, Thailand.

[4] Brown, S., Russell, M., Cuong,C., (Eds.), 2012. Coastal Rehabilitation and Mangrove Restoration Using Melaleuca Fences: Practical Experience from Kien Giang Province. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Conservation and Development of the Kien Giang Biosphere Reserve Project: Rach Gia City, Vietnam.

[5] Setyawa, A.D., 2009. Diversity of *Sonneratia alba* in coastal area of Central Java based on isozymic patterns of esterase and peroxidase. Bioscience. 1(2), 92–103.

[6] Duarte, C.M., Thampanya, U., Terrados, J., et al., 1999. The determination of the age and growth of SE Asian mangrove seedlings from internodal counts. Mangroves and Salt Marshes. 3, 251–257. DOI: https://doi.org/10.1023/A:1009967401337

[7] Kitaya, Y., Jintana, V., Piriyayotha, S., 2002. Early growth of seven mangrove species planted at different elevations in a Thai estuary. Trees. 16(2), 150–154. DOI: https://doi.org/10.1007/s00468-002-0166-6

[8] Zeng, X., Chen, L., Tam, N.F.Y., et al., 2008. Seedling emergence and dispersal pattern of the introduced Sonneratia caseolaris in Shenzhen Bay, China. Biodiversity Science. 16(3), 236–245. (in Chinese)

[9] Chen, L., Zan, Q., Li, M., et al., 2009. Litter dynamics and forest structure of the introduced Sonneratia caseolaris mangrove forest in Shenzhen, China. Estuarine, Coastal and Shelf Science. 85(2), 241–246. DOI: https://doi.org/10.1016/j.ecss.2009.08.007

[10] Bullock, E.L., Fagherazzi, S., Nardin, W., et al., 2017. Temporal patterns in species zonation in a mangrove forest in the Mekong Delta, Vietnam, using a time series of Landsat imagery. Continental Shelf Research. 147, 144–154. DOI: https://doi.org/10.1016/j.csr.2017.07.007

[11] Liu, M., Zhang, H., Lin, G., 2018. Zonation and directional dynamics of mangrove forests derived from time-series satellite imagery in Mai Po, Hong Kong. Sustainability. 10(6), 1913. DOI: https://doi.org/10.3390/su10061913

[12] Zhang, Y., Liang, F.P., Yang, Y., et al., 2018. Allelopathic effects of leachates from two alien mangrove species, Sonneratia apetala and Laguncularia racemosa, on seed germination and seedling growth of native mangrove species Sonneratia caseolaris. Allelopathy Journal. 44(1), 119–130. Available from: https://www.allelopathyjournal.com/archive-details.php?Allelopathic-effects-of-leachates-from-two-alien-mangrove-species-Sonneratia-apetala-and-Laguncularia-racemosa-on-seed-germination-seedling-growth-and-antioxidative-activity-of-a-native-mangrove-species-Sonneratia-caseolaris-1085

[13] Sloey, T.M., Lim, K.E., Moore, J., et al., 2022. Influence of abiotic drivers on 1-year seedling survival of six mangrove species in Southeast Asia. Restoration Ecology. 30(3), e13694. DOI: https://doi.org/10.1111/rec.13694

[14] Liu, B., Wang, X., Wang, Y., et al., 2023. Review of compounds and activities from mangrove Sonneratia genus and their endophytes. Journal of Holistic Integrative Pharmacy. 4(3), 218–227. DOI: https://doi.org/10.1016/j.jhip.2023.11.003

[15] Wijayasinghe, M.M., Jayasuriya, K.M.G.G., Gunatilleke, C.V.S., et al., 2023. Seed dormancy diversity of the mangrove plant community in Sri Lanka to assist in direct seeding and seedling transplanting restoration. Seed Science Research. 33(2), 107–117. DOI: https://doi.org/10.1017/S0960258523000120

[16] Latuconsina, A.S.R., Tuahatu, J.W., Rahma, R., 2025. Estimation of litterfall production of *Sonneratia alba* and its contribution to carbon accumulation in mangrove sediments in Kailolo Village, Maluku, Indonesia. Asian Journal of Research in Agriculture and Forestry. 11(1), 214–225. DOI: https://doi.org/10.9734/ajraf/2025/v11i1378

[17] Wang'ondu, V.W., Bosire, J.O., Kairo, J.G., et al., 2014. Litter fall dynamics of restored mangroves (*Rhizophora mucronata* Lamk. and *Sonneratia alba* Sm.) in Kenya. Restoration Ecology. 22(6), 824–831. DOI: https://doi.org/10.1111/rec.12149

[18] Pradisty, N.A., Sidik, F., Bimantara, Y., et al., 2022. Litterfall and associated macrozoobenthic communities of restored mangrove forests in abandoned aquaculture ponds. Sustainability. 14(13), 8082. DOI: https://doi.org/10.3390/su14138082

[19] Li, T., Ke, X., Bai, H., et al., 2025. A Population structure and flowering traits in endangered *Sonneratia* mangroves: Conservation implications on Hainan Island, China. Global Ecology and Conservation. 59, e03483. DOI: https://doi.org/10.1016/j.gecco.2025.e03483

[20] Khanbo, S., Naktang, C., Kongkachana, W., et al., 2026. Genetic diversity and population structure in two mangrove species (*Sonneratia alba* and *Sonneratia caseolaris*) across coastal areas of Thailand. Biology. 15(2), 141. DOI: https://doi.org/10.3390/biology15020141

[21] Cheng, C., Ke, X., Lang, T., et al., 2023. Current status and potential invasiveness evaluation of an exotic mangrove species, *Laguncularia racemosa* (L.) C.F.

Gaertn., on Hainan Island, China. Forests. 14(10), 2036. DOI: https://doi.org/10.3390/f14102036

[22] Zhang, Y., Chen, H., Lin, X., et al., 2022. Introduction of exotic species *Sonneratia apetala* alters diazotrophic community and stimulates nitrogen fixation in mangrove sediments. Ecological Indicators. 142, 109179. DOI: https://doi.org/10.1016/j.ecolind.2022.109179

[23] Chen, Y., Lin, X., Zhang, H., et al., 2023. High site elevation enhanced nitrogen fixation and the stability of diazotrophic community in planted *Sonneratia apetala* mangrove sediments. Applied Soil Ecology. 191, 105059. DOI: https://doi.org/10.1016/j.apsoil.2023.105059

[24] Chapin, F.S., Matson, P.A., Vitousek, P.M., 2011. Principles of Terrestrial Ecosystem Ecology, 2nd ed. Springer: New York, NY, USA. DOI: https://doi.org/10.1007/978-1-4419-9504-9

[25] Hoang, V.S., Nguyen, H.H., Tran, T.M.S., et al., 2024. Mangrove Forests in the Red River Delta. Agricultural Publishing House: Hanoi, Vietnam.

[26] Liu, L., Li, F., Yang, Q., et al., 2014. Long-term differences in annual litter production between alien (*Sonneratia apetala*) and native (*Kandelia obovata*) mangrove species in Futian, Shenzhen, China. Marine Pollution Bulletin. 85(2), 747–753. DOI: https://doi.org/10.1016/j.marpolbul.2014.04.047

[27] Cooray, P.L.I.G.M., Jayawardana, D.T., Gunathilake, B.M., et al., 2021. Characteristics of tropical mangrove soils and relationships with forest structural attributes in the northern coast of Sri Lanka. Regional Studies in Marine Science. 44, 101741. DOI: https://doi.org/10.1016/j.rsma.2021.101741

[28] Asbridge, E., Lucas, R., Accad, A., et al., 2015. Mangrove response to environmental changes predicted under varying climates: Case studies from Australia. Current Forestry Reports. 1, 178–194. DOI: https://doi.org/10.1007/s40725-015-0018-4

[29] Yang, Y., Li, J., Yang, S., et al., 2017. Effects of Pleistocene sea-level fluctuations on mangrove population dynamics: A lesson from *Sonneratia alba*. BMC Evolutionary Biology. 17, 22. DOI: https://doi.org/10.1186/s12862-016-0849-z

[30] Sarno, Suwignyo, R.A., Dahlan, Z., et al., 2017. Short communication: The phenology of *Sonneratia alba* J. Smith in Berbak and Sembilang National Park, South Sumatra, Indonesia. Biodiversitas. 18(3), 909–915. DOI: https://doi.org/10.13057/biodiv/d180307

[31] Teng, Z., Lin, X., 2024. Sediment nitrate reduction processes affected by non-native *Sonneratia apetala* plantation in South China. Science of the Total Environment. 906, 167523. DOI: https://doi.org/10.1016/j.scitotenv.2023.167523

[32] Ahmed, S., Sarker, S.K., Kamruzzaman, M., et al., 2025. Soil nutrients and leaf area index interact with species and structural diversity to buffer mangrove productivity against salinity. Soil Ecology Letters. 7, 250299. DOI: https://doi.org/10.1007/s42832-025-0299-x

[33] Chen, Y., Lin, X., Zhang, H., et al., 2025. Microbial community structure and functional diversity affected by soil depth, tidal levels, and stand ages in restored *Sonneratia apetala* mangroves. Estuarine, Coastal and Shelf Science. 319, 109276. DOI: https://doi.org/10.1016/j.ecss.2025.109276

[34] Pello, F.S., Tupan, C.I., Huliselan, N.V., 2025. Nitrate and phosphate content in mangrove leaf litter of Rhizophora apiculata and *Sonneratia alba* in Ambon Bay, Indonesia. Egyptian Journal of Aquatic Biology and Fisheries. 29(4), 135–147.

[35] Bui, K.N.T., Vien, N.N., Nguyen, N.T., et al., 2025. Biomass, carbon stock, carbon uptake, and oxygen production of *Sonneratia alba*: Estimating values for mangrove forest environmental service in Can Gio, Vietnam. Journal of Tropical Forest Science. 37(4), 463–474. DOI: https://doi.org/10.26525/jtfs2025.37.4.463

[36] Feng, X., Xu, S., Li, J., et al., 2020. Molecular adaptation to salinity fluctuation in tropical intertidal environments of a mangrove tree *Sonneratia alba*. BMC Plant Biology. 20, 178. DOI: https://doi.org/10.1186/s12870-020-02395-3

[37] Yu, C., Feng, J., Liu, K., et al., 2020. Changes of ecosystem carbon stock following the plantation of exotic *Sonneratia apetala* in Qi'ao Island, China. Science of the Total Environment. 717, 137142. DOI: https://doi.org/10.1016/j.scitotenv.2020.137142

[38] Rahman, M.M., Hossain, M.L., Roy, S.K., et al., 2024. Ecosystem carbon accumulation of *Sonneratia apetala* mangroves along an afforestation chronology in Bangladesh. Ocean & Coastal Management. 259, 107466. DOI: https://doi.org/10.1016/j.ocecoaman.2024.107466

[39] Ismail, M., Johany, S.A., Dey, T., et al., 2026. Carbon stock assessment in *Sonneratia apetala* afforested mangroves: A case study from Cox’s Bazar, Bangladesh. Applied Environmental Research. Available from: https://ph01.tci-thaijo.org/index.php/aer/article/view/263980

[40] He, Z., Sun, H., Peng, Y., et al., 2020. Colonization by native species enhances the carbon storage capacity of exotic mangrove monocultures. Carbon Balance and

Management. 15, 28. DOI: https://doi.org/10.1186/s13021-020-00165-0

[41] Isnaini, S., Amin, B., Efriyeldi, E., 2020. Comparison of carbon reserves in mangrove *Sonneratia alba* and Nypa fruticans in Bengkalis District, Indonesia. Journal of Coastal and Ocean Sciences. 1(1), 41–50.

[42] Ainindya, D.G., Rarasti, K.A., Farikha, K.N., et al., 2024. Characteristics of mangroves and carbon stock estimation in Sampang and Pamekasan Districts, Madura Island, Indonesia. International Journal of Bonorowo Wetlands. 14(1), 19–24. DOI: https://doi.org/10.13057/bonorowo/w140103

[43] Robinson, A.P., Hamann, J.D., 2011. Forest Analytics with R: An Introduction. Springer: New York, NY, USA. DOI: https://doi.org/10.1007/978-1-4419-7762-5

[44] Affandi, N.A.M., Kamali, B., Rozainah, M.Z., et al., 2010. Early growth and survival of Avicennia alba seedlings under excessive sedimentation. Scientific Research and Essays. 5(18), 2801–2805.

[45] Hai, N.T., Dell, B., Phuong, V.T., et al., 2020. Towards a more robust approach for the restoration of mangroves in Vietnam. Annals of Forest Science. 77, 18. DOI: https://doi.org/10.1007/s13595-020-0921-0

[46] International Federation of Red Cross and Red Crescent Societies, 2011. Planting Protection: Evaluation of Community-Based Mangrove Reforestation and Disaster Prevention Programs, 2006–2010. International Federation of Red Cross and Red Crescent Societies: Geneva, Switzerland.

[47] Nguyen, X.H., Pham, T.L., Nguyen, X.T., 2010. Status of Mangrove Forest in the Coastal Waters of South Central Vietnam from Da Nang to Ninh Thuan Provinces. Vietnam Institute of Oceanography: Nha Trang, Vietnam.