



Assessment of Heavy Metal Concentrations and Biological Blue Carbon Sequestration Process in Mangrove Forest Ecosystems

Natthawat Wisaiprom^{1*}, Apichart Thammajarn¹, Kittinut Kaewthong¹, Suchada Chaisawasdi¹, Padoung Boonpetch², and Natthawan Phonthong²

¹ Energy Environment Safety and Health Center, King Mongkut's University of Technology Thonburi, Bangkok, 10140, Thailand

² KMUTT Bangkhuntien Facility Management Office, King Mongkut's University of Technology Thonburi, Bangkhuntien Campus, Bangkok, 10150, Thailand

* Corresponding author: Natthawat.wisai@kmutt.ac.th

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Abstract: Mangrove forests play a critical role in coastal carbon sequestration and act as natural filters for heavy metal contaminants. This study investigated the physicochemical characteristics, heavy metal distribution, and carbon dynamics of *R. apiculata* and *Avicennia spp* (*A. alba*) in the Bangkhunthian mangrove ecosystem over three years. Surface water and sediment analyses revealed elevated concentrations of Hg, Cd, Cr, Cu, Ni, Pb, and Zn at upstream stations, with sediments serving as the primary metal reservoir due to their high organic matter and clay content. Physicochemical parameters, including pH (6.8–7.6), color (16–25 Pt-Co), and turbidity (124–145 NTU), indicated a near-neutral, turbid environment that promotes metal adsorption and organic carbon retention. Above-ground biomass carbon (AGBC) and below-ground biomass carbon (BGBC) of both species increased exponentially, with *R. apiculata* AGBC rising from 0.15 to 2.49 Mg C/ha and BGBC from 0.019 to 0.848 Mg C/ha, and *Avicennia spp* (*A. alba*) showing similar trends. The total carbon stock (TCS) steadily increased, reaching 15.94 Mg C/ha for *R. apiculata* and 17.60 Mg C/ha for *Avicennia spp* (*A. alba*) by the third year. These findings highlight the high carbon sequestration potential of young mangrove stands and underscore the importance of mangrove restoration and conservation for climate change mitigation and coastal ecosystem management.

Keywords: Mangrove ecosystem; total carbon stocks (TCS); above-ground biomass (AGB); below-ground biomass (BGB); surface water

1. Introduction

Mangrove forests are among the most productive and carbon-rich ecosystems on Earth, serving as critical components of the global "blue carbon" network [1-2]. They sequester and store large quantities of organic carbon in both their aboveground biomass and anoxic sediments, which makes them highly effective in mitigating climate change and reducing greenhouse gas (GHG) emissions [3-4]. Globally, mangrove ecosystems can store up to 1,000 Mg C ha⁻¹, significantly higher than most terrestrial forests [5]. Beyond carbon storage, mangroves contribute to shoreline protection, nutrient cycling, water purification, and biodiversity support, forming an essential buffer between marine and terrestrial systems [6-7]. Despite their ecological importance,

mangrove areas have declined substantially worldwide due to anthropogenic pressures such as coastal development, aquaculture expansion, and pollution [8-9]. In Thailand, nearly 50% of mangrove forests were lost between 1960 and 2000 [10-11], particularly in urbanized coastal provinces like Samut Sakhon and Bangkok. This loss not only reduced biodiversity and fisheries productivity but also diminished mangroves' potential to act as long-term carbon sinks. Consequently, restoring and expanding mangrove ecosystems has become an urgent priority for both ecological and climate policy [12-13].

Expanding mangrove areas enhances carbon sequestration through increased biomass accumulation and sedimentary carbon burial [14-15]. In addition, restored mangroves promote the reestablishment of ecological functions such as soil stabilization, hydrological balance, and habitat regeneration [7]. Empirical studies across Southeast Asia have demonstrated that up to 80% of natural carbon stocks can be recovered within two to three decades [16-17]. Moreover, mangrove expansion supports biodiversity by providing critical habitats for juvenile fish, crustaceans, and migratory birds [18-19], thereby improving ecological resilience and overall ecosystem productivity. The Bangkhunthian coastal zone, located along the western Gulf of Thailand, is a highly dynamic estuarine environment influenced by tidal actions, sediment deposition, and human activities [20]. In this area, the King Mongkut's University of Technology Thonburi (KMUTT) Bangkhunthian Campus has undertaken several initiatives to enhance carbon neutrality and environmental stewardship, aligning with Thailand's national roadmap toward net-zero greenhouse gas emissions). The expansion of mangrove areas surrounding the KMUTT coastal campus presents a valuable opportunity to assess how localized restoration efforts contribute to carbon sequestration and ecosystem recovery within a managed coastal system. Therefore, this research assesses the potential of mangrove area expansion to improve carbon sequestration and ecological restoration in the Bangkhunthian coastal zone. The study aims to evaluate the capacity of mangrove ecosystems to absorb and store atmospheric carbon, including their contribution to GHG emission reduction, and to examine the ecological impacts of mangrove expansion in terms of biodiversity enhancement and ecosystem restoration processes. By integrating carbon flux measurement, soil organic carbon analysis, and biodiversity assessment, this research contributes to the broader understanding of blue carbon dynamics and restoration ecology in tropical coastal systems. The outcomes are expected to provide evidence-based recommendations for sustainable coastal management and policy formulation, supporting Thailand's commitments under the Paris Agreement and the Sustainable Development Goals (SDGs 13 and 15) (UNEP, 2020; IPCC, 2021).

Mangrove ecosystems play a highly significant role in mitigating the impacts of climate change due to their exceptional capacity for carbon sequestration in both biomass and soil organic matter. Carbon storage in mangrove ecosystems occurs through several interrelated mechanisms. Mangrove trees absorb atmospheric carbon dioxide (CO₂) through photosynthesis and store carbon within their tissues, including trunks, branches, leaves, and roots. Subsequently, a portion of this carbon is transferred to the soil through the decomposition of organic materials such as fallen leaves, roots, and plant litter. The soils in mangrove ecosystems are typically characterized by deep layers of organic-rich sediments formed under waterlogged and anaerobic conditions. These low-oxygen environments slow decomposition, allowing carbon to accumulate and remain stored for centuries or even millennia as peat, a dense, carbon-rich material derived from partially decomposed plant matter. Numerous studies have reported that mangrove forests can store up to four times more carbon per unit area than tropical rainforests, demonstrating their outstanding efficiency as natural carbon sinks. However, mangrove ecosystems worldwide are increasingly threatened by anthropogenic activities such as deforestation, aquaculture expansion, and coastal development. The loss or degradation of mangrove forests not only reduces their carbon storage capacity but also releases the stored soil carbon into the atmosphere, thereby increasing greenhouse gas concentrations and accelerating global warming.

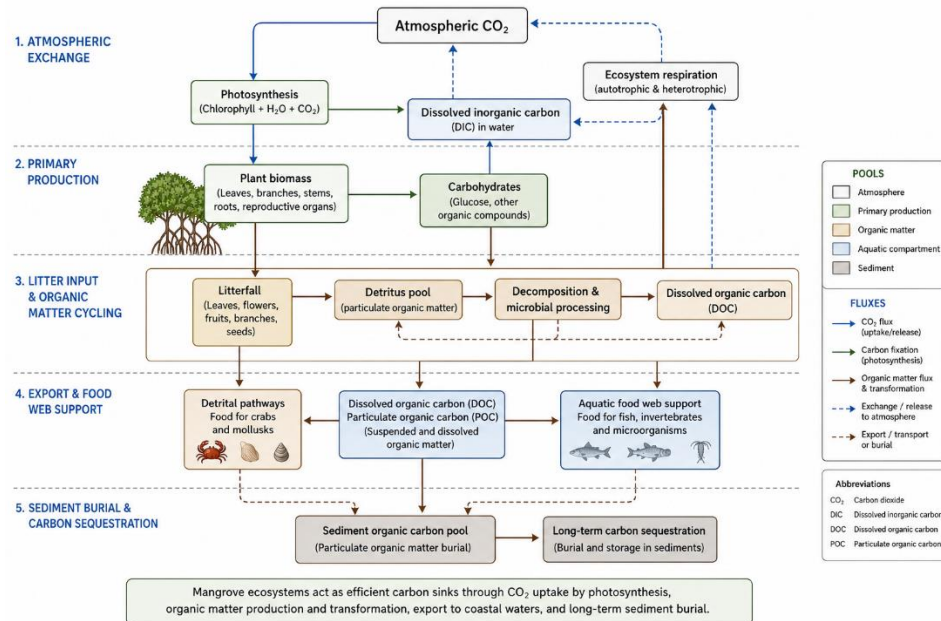


Figure 1. Overall carbon cycling processes in the mangrove ecosystems

Therefore, conserving and restoring mangrove ecosystems is essential to maintaining their natural carbon sequestration potential. Such actions not only contribute to climate change mitigation but also enhance ecosystem resilience, protect coastal areas from erosion, and support local communities' sustainable livelihoods. Thus, the sustainable management and preservation of mangrove ecosystems represent a crucial nature-based solution for addressing global climate change and promoting long-term environmental sustainability. Given the critical role of mangrove ecosystems in carbon sequestration, understanding how environmental stressors, such as heavy metal contamination, may affect their carbon storage capacity is important. Heavy metals can accumulate in mangrove soils and plant tissues due to both natural processes and anthropogenic activities, such as industrial discharge, agricultural runoff, and urbanization. These contaminants may impair mangrove plant physiology, alter microbial activity in sediments, and ultimately influence the efficiency of blue carbon sequestration. Therefore, the present study, Assessment of heavy metal concentrations and the biological blue carbon sequestration process in mangrove forest ecosystems, aims to investigate the interplay between heavy metal accumulation and carbon storage in mangrove soils and vegetation. Understanding these relationships is crucial for evaluating the sustainability of carbon sequestration in polluted mangrove areas, informing restoration and conservation strategies, and supporting the development of evidence-based management practices that enhance both ecosystem health and climate change mitigation.

2. Materials and methods

2.1 Study Area

The study was conducted in the Bangkhunthian mangrove forest, located along the western coast of the Gulf of Thailand (Latitude: 13°32'31.39"N), (Longitude: 100°24'51.56"E) within the vicinity of King Mongkut's University of Technology Thonburi (KMUTT) Bangkhunthian Campus (Figure 2). The area is characterized by a tropical estuarine climate with semidiurnal tidal patterns, moderate freshwater inflow, and high anthropogenic influence from urban and industrial activities. Dominant mangrove species include *R. apiculata* and *Avicennia spp* (*A. alba*), both of which are widely distributed along the intertidal zones and are representative of early successional mangrove communities in Southeast Asia [1, 21]



Figure 2. Graphical location of the mangrove forest in Bangkhunthian campus.

2.2 Sampling Design

Sampling was conducted over three years (Year 1–3) to investigate temporal variations in heavy metal accumulation and carbon stock dynamics within the mangrove ecosystem. Ten sampling stations (A1–A10) were established along a longitudinal gradient from upstream to downstream to account for potential spatial variations in sediment characteristics, physicochemical properties, and contaminant inputs. Sediment sampling was conducted during the dry season each year to minimize the influence of extreme flooding events and seasonal hydrological fluctuations. [22, 23].

2.3 Physicochemical Analysis

The measured water quality parameters included pH, color, and turbidity, which influence heavy metal speciation, sediment adsorption, and organic carbon stabilization [3, 6]. pH was measured in situ using a calibrated portable pH meter (Hach HQ40d) with ± 0.01 precision. Color was determined spectrophotometrically following the Pt-Co method [24], and turbidity was measured using a turbidimeter (Hach 2100Q), as reported in NTU. Sediment texture and organic content were characterized using the hydrometer method for particle size distribution and loss-on-ignition (LOI) at 550°C to determine the organic matter content [25, 26].

2.4 Measurement of Above-Ground Biomass Carbon (AGBC), Below-Ground Biomass Carbon (BGBC), and Total Carbon Stock (TCS)

The carbon stocks of mangrove forests were quantified by assessing the above-ground biomass carbon (AGBC), below-ground biomass carbon (BGBC), and total carbon stock (TCS), including both biomass and sediment carbon pools. These measurements are essential for evaluating mangroves' role in carbon sequestration and climate change mitigation. Methodology: Representative trees were randomly selected across each plot (30 trees per species). DBH (Diameter at Breast Height) was measured at 1.3 m above ground using a diameter tape. Tree height was measured using a laser hypsometer (Vertex IV, Hagl f Sweden).

2.4.1 Above-ground biomass (AGB)

Calculated using species-specific allometric equations [27, 28]

$$\text{AGB} = 0.251 \times \rho \times D^{2.46} \quad (1)$$

where ρ is wood density (g cm^{-3})

D is the DBH (cm)

AGBC was calculated as 47–50% of AGB, following the IPCC guidelines.

2.4.2 Below-ground biomass (BGB) Estimated using root-to-shoot ratios specific to the mangrove species

Estimated using root-to-shoot ratios specific to mangrove species.

$$\text{BGB} = \text{AGB} \times \text{R/S} \quad (2)$$

where $\text{R/SR/S} = 0.24 - 0.31$ for *R. apiculata* and *Avicennia spp (A. alba)* [21, 29]. BGBC was calculated as 47–50% of BGB.

2.4.3 Total Carbon Stock (TCS)

TCS represents the sum of AGBC and BGBC to a depth of 1 m. Method: elemental analyzer (e.g., Shimadzu TOC-L).

$$\text{TCS} = \text{AGBC} + \text{BGBC} \quad (3)$$

Hypsometer (Vertex IV): Measures tree height using laser distance technology with ± 0.1 m accuracy. Diameter tape: Non-destructive measurement of DBH. Weighing balance (OHAUS) for calibrating biomass samples, precision 0.01 g.

2.5 Heavy metal analysis

The concentrations of heavy metals mercury (Hg), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) in both surface water and sediment samples were quantified to assess the contamination levels and evaluate the ecological and environmental risks in the mangrove ecosystem. Heavy metals are of particular concern due to their persistence, bioaccumulation potential, and toxicity even at low concentrations [30].

2.5.1 Sample Collection and Preservation

Surface water samples were collected in acid-washed polyethylene bottles, taking care to avoid contamination from tools or containers. Immediately after collection, samples were acidified to pH <2 using ultrapure nitric acid (HNO_3 , 2% v/v) to prevent metal precipitation and microbial activity. Sediment samples were collected from the top 0–10 cm layer using a stainless steel corer. Samples were transferred to pre-cleaned containers and stored on ice during transport to the laboratory.

2.5.2 Sample Preparation

Water samples: Filtered through 0.45 μm membrane filters to remove suspended particulates. Acidified samples were directly analyzed or stored at 4°C for short-term storage (<1 week). Sediment samples: Oven-dried to a constant weight at 60°C to remove moisture without causing metal loss. Ground and homogenized using an agate mortar and pestle to achieve a uniform particle size (<63 μm). Approximately 0.5 g of sediment was digested using a HNO_3 -HCl-HF- HClO_4 acid mixture. This multi-acid digestion ensures the complete breakdown of silicate matrices and liberation of heavy metals for analysis. The digested solutions were diluted with ultrapure water to a final volume suitable for ICP-MS measurement. Instrumental Analysis: Inductively Coupled Plasma Mass Spectrometry (ICP-MS, Agilent 7700x) was used for trace metal quantification. ICP-MS offers high sensitivity, multi-element detection capability, and low detection limits (ng/L for water, mg/kg for sediment) [31]. Operating principle. The Samples are nebulized into an argon plasma (~10,000 K), where atoms are ionized. The resulting ions were separated by mass-to-charge ratio (m/z) and quantified using a mass spectrometer detector. Instrument calibration was performed using multi-element standard solutions prepared in the same acid matrix as the samples.

2.5.3 Quality Assurance and Quality Control (QA/QC)

To ensure data reliability and accuracy, blanks and reagent blanks were analyzed to account for any contamination from acids or labware. Duplicates. To evaluate analytical precision, 10% of the samples were analyzed in duplicate. Certified Reference Materials (CRM): Standard reference sediments and waters (e.g., NIST 1646a for sediments) were analyzed to validate accuracy. Recovery rates ranged between 92–105%, indicating acceptable precision and method reliability. Detection limits and sensitivity: Detection limits for water samples were typically 0.01–0.05 $\mu\text{g/L}$ for most metals, while sediment detection limits ranged from 0.01–0.1 mg/kg.

2.5.4 Data Interpretation

The concentrations were reported in $\mu\text{g/L}$ for water and mg/kg dry weight for sediments. To evaluate contamination levels, data were compared against national water quality standards (e.g., Thailand Ministry of Natural Resources and Environment) and international sediment quality guidelines. Statistical analyses, such as correlation matrices and enrichment factors, were applied to assess the potential sources of heavy metals and their environmental risks.

3. Results and discussion

3.1 Heavy metal contents in sediments and surface water in the mangrove forest area.

The heavy metal analysis in the mangrove forest area reveals distinct spatial patterns in both surface water and sediment samples collected from stations A1 to A10. In general, the concentrations of all analyzed heavy metals, such as Hg, Cd, Cr, Cu, Ni, Pb, and Zn, showed a decreasing trend. Figure 3. showed a decreasing trend from upstream (A1–A3) toward downstream (A8–A10), indicating dilution and dispersion of pollutants toward the coastal zone. Moreover, metal concentrations were consistently higher in sediments than in surface water, suggesting that mangrove sediments act as a natural sink and long-term reservoir for heavy metals due to their high content of organic matter, clay minerals, and sulfide phases, which have strong adsorption and complexation capacity [25–26].

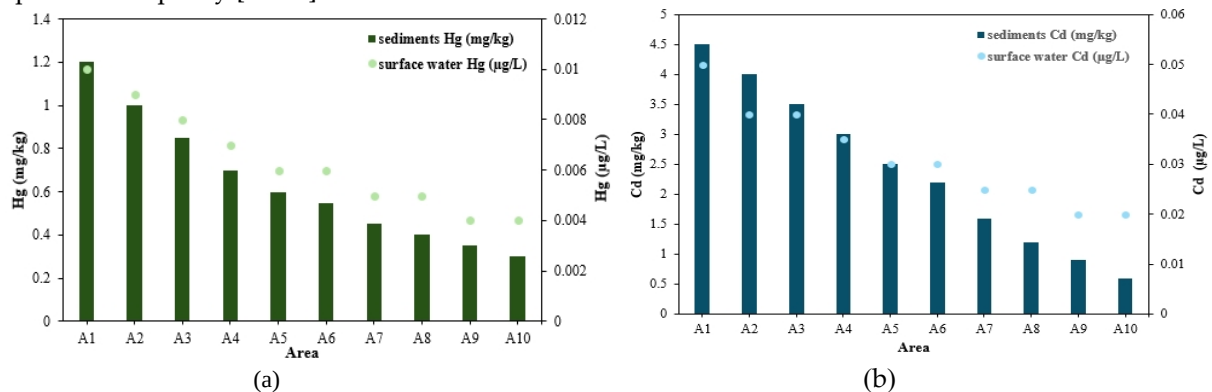


Figure 3. Heavy metal contents (a) Hg (b) Cd in sediments and surface water of the mangrove forest.

Figure 3. (a) Mercury levels in surface water ranged from 0.004 to 0.01 $\mu\text{g/L}$, while in sediments they ranged between 0.3 and 1.2 mg/kg . The highest concentration was recorded at station A1 and decreased gradually downstream. This pattern indicates that mercury contamination likely originates from anthropogenic sources, such as industrial wastewater, municipal discharge, or atmospheric deposition. The high sediment-to-water ratio confirms that mercury is predominantly retained in sediments through adsorption to organic matter and iron-manganese oxides, forming insoluble complexes under reducing conditions typical of mangrove soils [32–34]. Demonstrated that mangrove muds can act as both a sink and a secondary source of mercury under fluctuating redox conditions. Figure3. (b) Cadmium concentrations in surface water ranged from 0.02 to 0.05 $\mu\text{g/L}$, and in sediments from 0.6 to 4.5 mg/kg , with the highest values at A1 and A2. Sediment Cd concentrations at these stations exceeded the USEPA (1999) guideline of 3 mg/kg , implying potential ecological risks. Cadmium contamination in mangrove zones often results from agricultural runoff (fertilizers, pesticides), electroplating, and the plastics industry [36–37]. Cd has a strong affinity to sulfides and organic complexes, which stabilize it in sediments under anoxic conditions but can be released under oxidation, posing potential threats to benthic organisms [23].

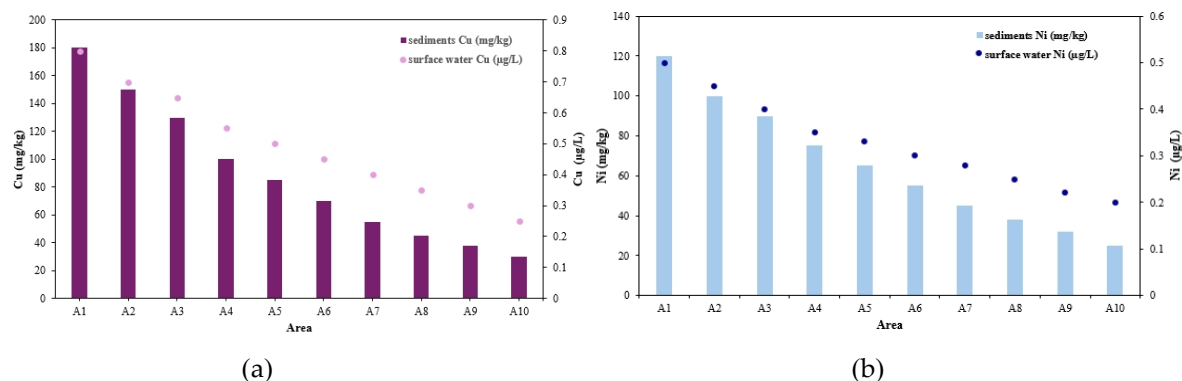


Figure 4. Heavy metal contents (a) Cu (b) Ni in sediments and surface water of the mangrove forest.

Figure 4. (a) Copper concentrations in surface water ranged from 0.25 to 0.8 µg/L, and in sediments from 30 to 180 mg/kg, with the highest levels at A1–A3. Cu accumulation is typically associated with urban wastewater, antifouling paints, and industrial discharge. Cu is an essential micronutrient but becomes toxic at high concentrations. The recorded values above 70 mg/kg exceed the NOAA (1999) guideline, indicating potential effects on benthic invertebrates. The strong correlation between Cu and organic matter indicates that organic complexation plays a major role in Cu retention in mangrove sediments [25]. The decline toward downstream sites suggests dilution and lower anthropogenic pressure (Figure 4b). Nickel concentrations in surface water ranged from 0.2 to 0.5 µg/L, and in sediments from 25 to 120 mg/kg, showing a pattern similar to Cu. The elevated Ni levels near A1 and A2 likely result from industrial corrosion, fertilizers, or oil residues [30]. Nickel can form stable complexes with clay minerals and humic substances, contributing to its long-term accumulation. However, excessive Ni concentrations can affect sediment microbial activity and enzyme function, disrupting mangrove root metabolism [35]. The gradual decrease downstream suggests flocculation and sedimentation processes that immobilize Ni along the estuary.

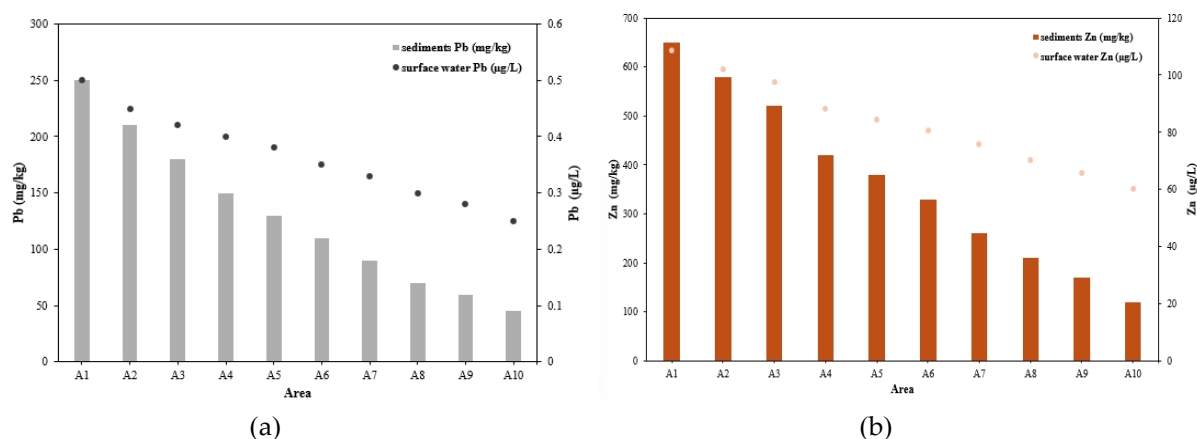


Figure 5. Heavy metal contents (a) Pb (b) Zn in sediments and surface water of the mangrove forest.

Figure 5. (a) Lead concentrations in surface water ranged from 0.25 to 0.5 µg/L, and in sediments from 45 to 250 mg/kg, with higher values at A1–A3. Pb levels above 112 mg/kg [38] may pose probable ecological effects, particularly on benthic fauna. The elevated Pb content can be attributed to vehicular emissions, leaded gasoline residues, and industrial discharge, as Pb strongly adsorbs to fine sediments and organic matter [22]. Lead's persistence in sediments indicates limited mobility but potential bioavailability under acidification or oxidation conditions. The observed gradient suggests both historical and ongoing contamination inputs at upstream zones. Figure 5(b) shows that zinc (Zn) exhibited the highest concentrations among all analyzed heavy metals, ranging from 60.2 to 108.53 µg/L in surface water and from 120 to 650 mg/kg in sediments. When compared with Thailand's Surface Water Quality Standards, which specify a maximum allowable Zn concentration of 1.0 mg/L (1,000 µg/L), the Zn concentrations measured in surface water at all

sampling stations were substantially below the national guideline value. This indicates that dissolved Zn in the water column does not currently pose a direct risk to water quality or aquatic organisms. However, Zn concentrations in sediments reached as high as 650 mg/kg, and several stations exceeded 300 mg/kg, a level commonly associated with potential adverse effects on benthic organisms. These findings suggest that Zn tends to accumulate in sediments rather than remain in the water column. Consequently, mangrove sediments serve as an important sink for heavy metals through adsorption onto fine sediment particles, organic matter, and sulfide compounds under anoxic conditions, thereby promoting the long-term retention and stabilization of Zn within the sediment matrix.

Table 1. Chromium (Cr) content in sediments and surface water of the mangrove forest.

Area	Surface water Cr ($\mu\text{g/L}$)	Cr sediments (mg/kg)
A1	ND	190
A2	ND	160
A3	ND	140
A4	ND	120
A5	ND	100
A6	ND	85
A7	ND	75
A8	ND	68
A9	ND	60
A10	ND	22

ND is not detected

Table 1. Chromium content was not detected (ND) in surface water but was present in sediments ranging from 60 to 220 mg/kg. The highest concentration was found at A1, exceeding the Canadian Sediment Quality Guideline TEL = 52.3 mg/kg [38], suggesting contamination from industrial sources or surface runoff containing metal waste. The absence of detectable Cr in water indicates that most Cr is particle-bound and deposited with sediments. Cr(III) tends to bind strongly to organic matter, while Cr (VI), a more toxic form, is often reduced to Cr(III) in the oxygen-depleted mangrove sediments, decreasing its solubility [39]. The decreasing trend from A1 to A10 reflects both adsorption efficiency and hydrodynamic sorting of sediments along the estuarine gradient. The results indicate that mangrove sediments act as the primary reservoir of heavy metals, while surface water contains relatively low concentrations due to continuous tidal flushing. The dominance of high metal content at upstream stations (A1–A3) reflects anthropogenic influences, including urban wastewater, industrial effluents, and agricultural discharges, while the lower levels at downstream stations (A8–A10) suggest natural attenuation and pollutant dispersion in the estuarine system. Physicochemical processes governing metal behavior include adsorption, complexation, ion exchange, precipitation, and redox reactions, which are strongly influenced by mangrove sediment properties such as pH, salinity, cation exchange capacity, and organic carbon content [28]. Overall, the spatial distribution pattern and metal enrichment suggest that the mangrove forest serves as both a sink and a potential secondary source of heavy metals. Continuous monitoring and sediment quality assessment are crucial to manage contamination risks and preserve the ecological function of mangrove ecosystems as natural coastal filters and carbon sinks.

3.2 Physicochemical characteristics.

The physicochemical parameters of the mangrove surface water (Table 2) provide crucial insights into the hydrological and biogeochemical dynamics of the Bangkhunthian mangrove ecosystem. The measured pH ranged from 6.8 to 7.6, the color from 16 to 25 Pt-Co, and the turbidity from 124 to 145 NTU. These values reflect the combined influence of freshwater inflow, tidal exchange, and organic matter decomposition, all characteristic features of mangrove-dominated estuarine systems.

Table 2. Physicochemical characteristics of mangrove forest.

Area	pH	Color (Pt-Co)	Turbidity (NTU)
A1	6.8	18	124
A2	6.9	16	126
A3	7	17	125
A4	7.1	16	134
A5	7.2	20	136
A6	7.1	21	135
A7	7.6	23	137
A8	7.5	25	141
A9	7.4	24	140
A10	7.6	25	145

3.2.1 pH

The pH values (6.8–7.6) indicate a neutral to slightly alkaline environment, consistent with natural mangrove estuaries reported globally, such as in Malaysia (6.5–7.8 [33]) and Indonesia (6.7–7.5 [23]). This near-neutral pH range facilitates the precipitation and immobilization of trace metals by promoting the conversion of toxic ionic forms into less soluble species [28]. In particular, chromium (Cr) occurs predominantly as Cr (III) under such conditions, which has low solubility and tends to adsorb onto sedimentary organic matter and clay minerals [39]. This finding aligns with Table 1, where Cr was not detected in surface water but accumulated significantly in sediments (22–190 mg/kg). The gradual increase in pH from upstream (A1) to downstream (A10) also suggests an enhanced influence of seawater intrusion, which is naturally slightly alkaline due to the presence of bicarbonate and carbonate ions [6]. Similar estuarine gradients have been documented in the Mekong Delta and the Sundarbans, where tidal mixing dilutes acidic organic compounds from mangrove litter, resulting in stable pH buffering [18, 40]. Maintaining this near-neutral condition is ecologically important because it supports microbial mineralization, nutrient cycling, and the retention of organic carbon in anaerobic sediments [3].

3.2.2 Color

The color intensity of the mangrove water, ranging between 16 and 25 Pt-Co, is typical for tropical estuarine waters enriched with dissolved organic carbon (DOC) and humic substances derived from decomposing mangrove litter and root exudates. [25], mangrove waters often exhibit elevated coloration due to high concentrations of tannins and lignin phenols, which leach from leaves and woody debris under anaerobic conditions. The slight increase in color downstream (from 16 Pt-Co at A2 to 25 Pt-Co at A10) reflects the accumulation and recirculation of organic-rich materials within the tidal zone. This pattern is consistent with findings in the Matang mangrove forest, Malaysia, where surface-water color increased seaward due to enhanced decomposition of detrital material and limited freshwater dilution [39]. High color intensity also correlates with greater carbon storage potential, as colored dissolved organic matter (CDOM) represents an intermediate pool of labile and refractory carbon compounds. Therefore, the color profile in this study not only reflects biogeochemical activity but also indicates the mangrove's role as a source and sink of organic carbon within the blue carbon framework.

3.2.3 Turbidity

The observed turbidity levels (124–145 NTU) are relatively high compared to other coastal systems but are characteristic of mangrove estuaries. Such high turbidity results from intense sediment resuspension during tidal cycles and root disturbance, coupled with high organic detritus loads [22, 35]. The gradual increase in turbidity toward the downstream stations (A7–A10) can be attributed to flocculation and fine-sediment deposition under reduced water-flow velocity near the coastal boundary [26]. High turbidity has significant implications for metal dynamics and carbon storage. Suspended particulate matter (SPM) provides abundant adsorption sites for heavy metals such as Cr, Pb, and Zn, effectively reducing their dissolved concentrations in surface water and promoting their sequestration in sediments [30]. This mechanism explains

the “not detected” status of Cr in water samples, as metals are preferentially bound to colloidal particles and subsequently settle into the anoxic sediment layer [23]. Moreover, turbid waters enhance light attenuation, reducing photodegradation of dissolved organic matter and facilitating long-term organic carbon retention [3]. In addition, elevated turbidity is often associated with nutrient-rich environments that sustain microbial respiration and carbon cycling within mangrove sediments. While high turbidity might limit photosynthetic productivity in pelagic systems, in mangrove environments it contributes positively to sediment accretion, supporting mangrove root stability and coastal protection [17].

3.3 AGBC and BGBC of the mangrove ecosystem

3.3.1 AGBC and BGBC of *R. apiculata*

The continuous increase in AGBC across the three-year growth period reflects the physiological development of *R. apiculata* from seedling to sapling stage, characterized by increased stem diameter, canopy expansion, and photosynthetic activity. During the early growth phase, mangrove trees primarily invest energy in vertical growth and leaf production, resulting in accelerated above-ground carbon accumulation (Komiya et al., 2008). AGBC increased nearly fivefold between the first and second years, followed by another fivefold increase from the second to third years, indicating that *R. apiculata* enters a phase of rapid biomass accumulation once its root system becomes well established. These results are consistent with previous studies in Southeast Asian mangrove plantations. Moreover, the AGBC of 2.49 Mg C ha⁻¹ observed in the third year aligns closely above-ground carbon stocks of 2–4 Mg C ha⁻¹ in young *R. apiculata* plantations across the Indo-Pacific region. The increase in above-ground biomass indicates the species' high photosynthetic efficiency, structural development, and adaptability to intertidal conditions, contributing directly to atmospheric CO₂ removal and long-term carbon sequestration.

BGBC values increased from 0.019 Mg C ha⁻¹ in year one to 0.848 Mg C ha⁻¹ in year three, marking a more than 44-fold increase over the growth period. Although the absolute carbon content below ground is lower than that above ground, the relative growth rate of BGBC is higher, signifying that root biomass develops substantially once above-ground structures are established. Root proliferation in mangrove species like *R. apiculata* serves multiple ecological and biogeochemical roles, including sediment stabilization, nutrient uptake, and anaerobic carbon burial [2, 7]. The development of prop roots and pneumatophores in response to tidal inundation enhances the plant's anchorage and facilitates gas exchange in anoxic soils, thereby promoting below-ground carbon storage in root tissues and adjacent sediments demonstrated that young *R. apiculata* species in restored mangroves of India exhibited exponential increases in root carbon after the second year of establishment. The proportional growth of BGBC relative to AGBC suggests that carbon allocation shifts progressively toward below-ground tissues as the tree matures, a critical adaptation for long-term carbon retention in mangrove ecosystems.

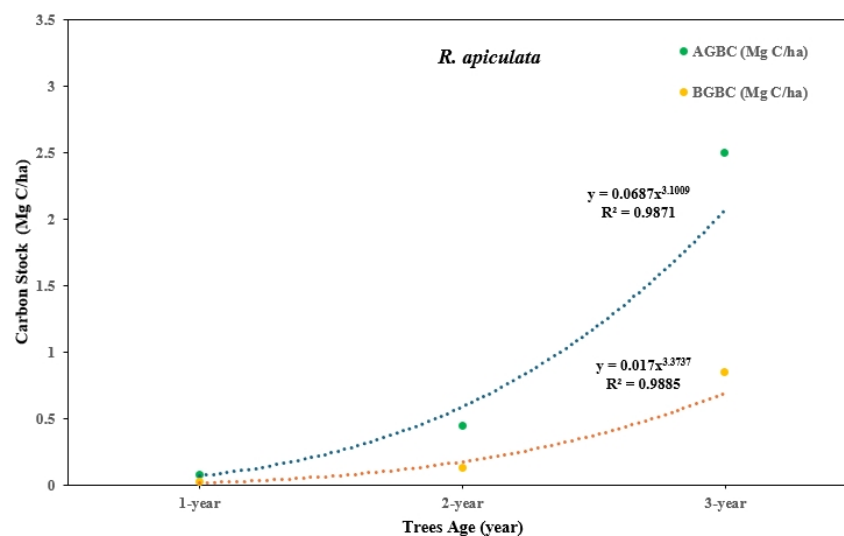


Figure 6. AGBC and BGBC of *R. apiculata*

The relationship between AGBC and BGBC indicates a strong positive correlation, implying that root development scales proportionally with canopy expansion. The AGBC:BGBC ratio decreased from approximately 4.0 in year one to 2.9 in year three, reflecting an increasing allocation of carbon to below-ground biomass as structural and physiological demands evolve. Where carbon allocation patterns in mangroves shift toward roots with increasing age and size. Such proportional increases in root carbon are essential for maintaining tree stability in high-energy coastal environments and for enhancing the soil's carbon sequestration capacity through organic matter accumulation and sediment trapping [25]. Furthermore, the balance between above- and below-ground carbon accumulation represents a key ecological mechanism underlying the blue carbon potential of mangroves. While above-ground carbon contributes to short-term CO₂ capture through biomass growth, below-ground carbon ensures long-term sequestration by transferring organic carbon into sediments under oxygen-poor conditions.

3.3.2 AGBC and BGBC of *Avicennia spp* (*A. alba*)

The biomass carbon accumulation of *Avicennia spp.* (*A. alba*) demonstrates a clear temporal increase in both above-ground (AGBC) and below-ground (BGBC) compartments over the three-year observation period. The AGBC increased from 0.26 Mg C/ha in the first year to 3.99 Mg C/ha in the third year, representing a more than 15-fold increase. Similarly, BGBC increased from 0.05 Mg C/ha to 0.99 Mg C/ha, roughly a 20-fold increase over the same period. These results indicate that the carbon sequestration potential of *Avicennia spp* (*A. alba*) accelerates with age, reflecting rapid growth and biomass accumulation during early successional stages of mangrove development. The observed AGBC: BGBC ratio (~4:1 across the three years) is consistent with previous studies on mangrove species, where above-ground biomass typically constitutes the dominant fraction of total biomass carbon [12]. This pattern is expected for *Avicennia spp.* (*A. alba*), which allocate substantial carbon to stem and branch growth to support structural stability and light acquisition, while root biomass grows proportionally to maintain nutrient and water uptake [29]. Moreover, the increasing trend in both AGBC and BGBC aligns with other studies reporting that mangrove carbon stocks accumulate exponentially during early stand development before approaching a plateau in mature forests. The relatively higher proportional increase in BGBC suggests that root system development may lag initially but intensifies as the above-ground structure becomes more complex, supporting sediment stabilization and resilience to tidal inundation.

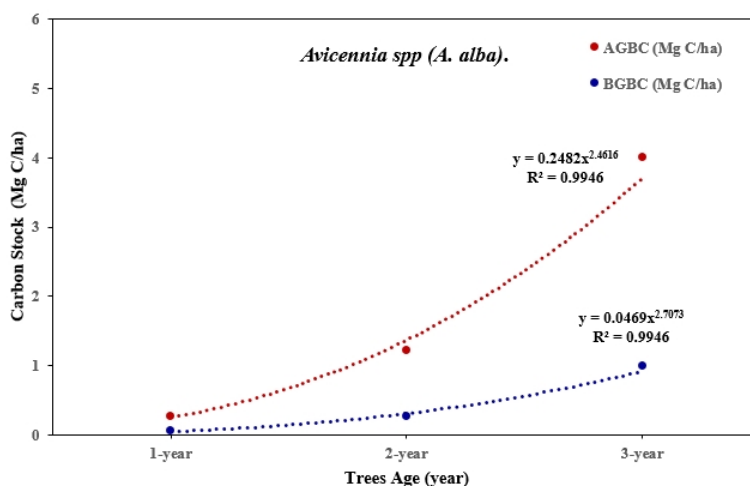


Figure 7. AGBC and BGBC of *Avicennia spp* (*A. alba*).

3.4 Total Carbon Stock (TCS) in Mangrove Ecosystems

The total carbon stock (TCS) of *R. apiculata* and *Avicennia spp* (*A. alba*) exhibited a consistent increase over the three-year observation period. For *R. apiculata*, TCS rose from 4.51 Mg C/ha in the first year to 15.94 Mg C/ha in the third year, while *Avicennia spp* (*A. alba*) showed a slightly higher accumulation, from 4.72 Mg C/ha to 17.60 Mg C/ha. These results indicate that both species have substantial carbon sequestration potential, with *Avicennia spp* (*A. alba*) displaying slightly faster accumulation, particularly during the second and third

years. The steady increase in TCS reflects the rapid biomass growth of these mangrove species during early successional stages, a pattern consistent with prior studies on tropical mangrove forests [21]. The higher TCS observed in *Avicennia spp* (*A. alba*) may be associated with its vigorous root and shoot development, which enhances both above- and below-ground carbon storage. Moreover, the three-year trend highlights the importance of early-stage mangrove restoration and afforestation for maximizing carbon sequestration benefits, as carbon accumulation in young mangrove stands can be rapid before reaching maturity. Overall, the results demonstrate that both *R. apiculata* and *Avicennia spp* (*A. alba*) play crucial roles in coastal carbon storage, with implications for climate change mitigation strategies through mangrove conservation and reforestation programs.

Based on the findings of this study, the concentrations of heavy metals, including Hg, Cd, Cr, Cu, Ni, Pb, and Zn, were highest at the upstream stations (A1–A3) and were consistently much greater in sediments than in surface water. In particular, Zn reached concentrations of up to 650 mg/kg, Pb up to 250 mg/kg, Cr up to 190 mg/kg, and Cu up to 180 mg/kg, indicating that mangrove sediments function as highly effective sinks for heavy metals through adsorption, complexation with organic matter, and precipitation under anoxic conditions. At the same time, the water's physicochemical characteristics, including a pH range of 6.8–7.6 and turbidity values of 124–145 NTU, provide favorable conditions for both heavy metal immobilization and long-term organic carbon retention. These findings suggest a close relationship between heavy metal accumulation and carbon sequestration processes in mangrove ecosystems. Many heavy metals can bind strongly to organic matter, humic substances, and fine sediment particles, resulting in the simultaneous accumulation of both heavy metals and organic carbon within the sediment matrix. Consequently, mangrove sediments serve as stable, long-term carbon reservoirs. Despite the relatively high concentrations of heavy metals observed in the study area, both *Rhizophora apiculata* and *Avicennia alba* demonstrated continuous increases in carbon accumulation throughout the three-year study period. The above-ground biomass carbon (AGBC) of *R. apiculata* increased from 0.15 to 2.49 Mg C ha⁻¹, while below-ground biomass carbon (BGBC) increased from 0.019 to 0.848 Mg C ha⁻¹. Similarly, *A. alba* exhibited an increase in AGBC from 0.26 to 3.99 Mg C ha⁻¹ and in BGBC from 0.05 to 0.99 Mg C ha⁻¹. As a result, the total carbon stock (TCS) increased to 15.94 Mg C ha⁻¹ for *R. apiculata* and 17.60 Mg C ha⁻¹ for *A. alba*. These results indicate that heavy metal contamination in the study area has not yet reached a threshold sufficient to inhibit mangrove growth or biomass carbon accumulation significantly.

In contrast, sediment conditions that promote the immobilization of both heavy metals and organic carbon may enhance long-term carbon sequestration through organic matter accumulation and carbon burial. Therefore, this study highlights the dual ecological function of the Bangkhunthian mangrove ecosystem as both a heavy metal sink and a blue carbon sink. The interaction among heavy metals, organic matter, and mangrove sediments appears to be a key mechanism supporting carbon stabilization and enhancing the long-term carbon sequestration potential of this coastal ecosystem. Both *R. apiculata* and *Avicennia spp* (*A. alba*) exhibited substantial increases in above-ground biomass carbon (AGBC) and below-ground biomass carbon (BGBC) over the three years, with total carbon stocks (TCS) reaching 15.94 Mg C/ha and 17.60 Mg C/ha, respectively. The proportional increase in below-ground biomass emphasizes the importance of root systems for long-term carbon storage, sediment stabilization, and ecosystem resilience, aligning with prior reports that root biomass plays a crucial role in blue carbon accumulation and coastal protection. The slightly higher carbon accumulation in *Avicennia spp* (*A. alba*) reflects species-specific growth and carbon allocation strategies, regarding interspecific differences in mangrove biomass development.

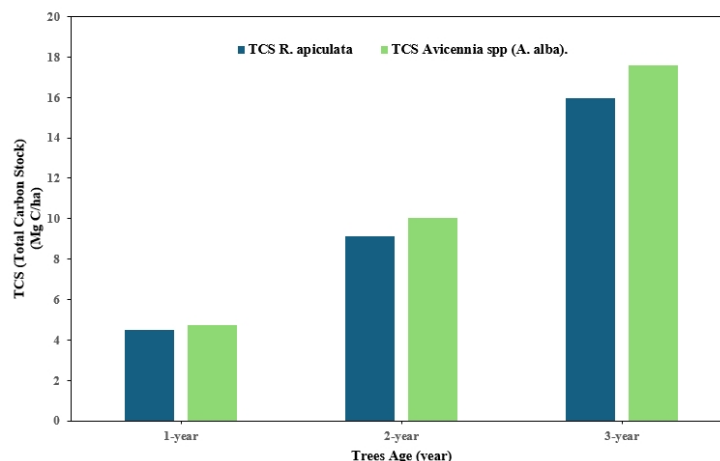


Figure 8. TCS of *R. apiculata* and *Avicennia* spp (*A. alba*).

4. Conclusion

The present study demonstrates that the Bangkhunthian mangrove ecosystem functions as both a natural sink for heavy metals and a significant carbon reservoir. Sediment analyses revealed that Hg, Cd, Cr, Cu, Ni, Pb, and Zn were predominantly retained in sediments, particularly at upstream stations, indicating strong anthropogenic influence and highlighting the sediment's role in long-term metal sequestration. These findings are consistent with previous studies reporting that mangrove sediments act as sinks for trace metals due to high organic matter content, clay minerals, and sulfide phases, which promote adsorption and stabilization. The present study demonstrates that the Bangkhunthian mangrove ecosystem functions as both a natural sink for heavy metals and a significant carbon reservoir. Sediment analyses revealed that Hg, Cd, Cr, Cu, Ni, Pb, and Zn were predominantly retained in sediments, particularly at upstream stations, indicating strong anthropogenic influence and highlighting the sediment's role in long-term metal sequestration. These findings are consistent with previous studies reporting that mangrove sediments act as sinks for trace metals due to high organic matter content, clay minerals, and sulfide phases, which promote adsorption and stabilization. Both *R. apiculata* and *Avicennia* spp (*A. alba*) exhibited substantial increases in above-ground biomass carbon (AGBC) and below-ground biomass carbon (BGBC) over the three years, with total carbon stocks (TCS) reaching 15.94 Mg C/ha and 17.60 Mg C/ha, respectively. The proportional increase in below-ground biomass emphasizes the importance of root systems for long-term carbon storage, sediment stabilization, and ecosystem resilience, aligning with prior reports that root biomass plays a crucial role in blue carbon accumulation and coastal protection. The slightly higher carbon accumulation in *Avicennia* spp (*A. alba*) reflects species-specific growth and carbon allocation strategies regarding interspecific differences in mangrove biomass development.

Based on the findings of this study, the concentrations of heavy metals, including Hg, Cd, Cr, Cu, Ni, Pb, and Zn, were highest at the upstream stations (A1–A3) and were consistently much greater in sediments than in surface water. In particular, Zn reached concentrations of up to 650 mg/kg, Pb up to 250 mg/kg, Cr up to 190 mg/kg, and Cu up to 180 mg/kg, indicating that mangrove sediments function as highly effective sinks for heavy metals through adsorption, complexation with organic matter, and precipitation under anoxic conditions. At the same time, the water's physicochemical characteristics, including a pH range of 6.8–7.6 and turbidity values of 124–145 NTU, provide favorable conditions for both heavy metal immobilization and long-term organic carbon retention. These findings suggest a close relationship between heavy metal accumulation and carbon sequestration processes in mangrove ecosystems. Many heavy metals can bind strongly to organic matter, humic substances, and fine sediment particles, resulting in the simultaneous accumulation of both heavy metals and organic carbon within the sediment matrix. Consequently, mangrove sediments serve as stable, long-term carbon reservoirs. Despite the relatively high concentrations of heavy metals observed in the study area, both *Rhizophora apiculata* and *Avicennia alba* demonstrated continuous increases in carbon accumulation throughout the three-year study period. The above-ground biomass carbon (AGBC) of *R.*

apiculata increased from 0.15 to 2.49 Mg C ha⁻¹, while below-ground biomass carbon (BGBC) increased from 0.019 to 0.848 Mg C ha⁻¹. Similarly, *A. alba* exhibited an increase in AGBC from 0.26 to 3.99 Mg C ha⁻¹ and in BGBC from 0.05 to 0.99 Mg C ha⁻¹. As a result, the total carbon stock (TCS) increased to 15.94 Mg C ha⁻¹ for *R. apiculata* and 17.60 Mg C ha⁻¹ for *A. alba*. These results indicate that heavy metal contamination in the study area has not yet reached a threshold sufficient to inhibit mangrove growth or biomass carbon accumulation significantly. In contrast, sediment conditions that promote the immobilization of both heavy metals and organic carbon may enhance long-term carbon sequestration through organic matter accumulation and carbon burial. Therefore, this study highlights the dual ecological function of the Bangkhunthian mangrove ecosystem as both a heavy metal sink and a blue carbon sink. The interaction among heavy metals, organic matter, and mangrove sediments appears to be a key mechanism supporting carbon stabilization and enhancing the long-term carbon sequestration potential of this coastal ecosystem.

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Author Contributions: Natthawat Wisaiprom led the overall research project and was primarily responsible for the conceptualization and design of the study, development of the research methodology, planning and coordination of the three-year field investigation, supervision of sample collection and laboratory analyses, data analysis and interpretation, assessment of heavy metal concentrations and carbon sequestration, and integration of the research findings. He also took the primary responsibility for drafting, developing, revising, and finalizing the manuscript and supervised the overall research process and critically reviewed the manuscript, and approved the final version of the manuscript. Apichart Thammajarn and Kittinut Kaewthong contributed to the development of the research methodology, field investigation, sample collection, laboratory analysis, interpretation of the results, and critical revision of the manuscript. Kittinut Kaewthong contributed to field investigation, sample collection, data processing and analysis, interpretation of heavy metal and carbon-related results, and manuscript revision and Suchada Chaisawasdi, Padoung Boonpetch, and Natthawan Phonthong contributed to field investigation, sample collection, data organization, analysis, interpretation of the findings.

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Conflicts of Interest: The authors declare that there are no conflicts of interest associated with this manuscript.

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