COMPREHENSIVE ANALYSIS OF ENVIRONMENTAL FACTORS AFFECTING THE SURVIVAL OF MANGROVE SEEDLINGS AND CARBON STORAGE IN SANYA, HAINAN PROVINCE, CHINA: THE COMBINED IMPACTS OF PESTICIDE POLLUTION, EUTROPHICATION, AND ECOLOGICAL DEGRADATION

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Abstract. Mangrove ecosystems are essential for coastal protection and carbon sequestration but are increasingly threatened by various environmental stressors, including pesticide pollution, eutrophication, and ecological degradation. This study systematically investigates the combined effects of these factors on the survival of mangrove seedlings and carbon storage in Sanya, Hainan Province, China. We conducted field surveys and laboratory analyses to evaluate seasonal variations in pesticide residues and nutrient levels, and their impacts on mangrove seedling health. Our results indicate that pesticide concentrations in mangrove sediments peak during the dry season, with a notable reduction in the wet season, highlighting significant seasonal fluctuations. Eutrophication levels were also elevated in the dry season, exacerbating ecological stress on the seedlings. Notably, mangrove seedlings exposed to both pesticide contamination and nutrient enrichment exhibited elevated mortality rates, thereby complicating restoration initiatives. Furthermore, the invasive species *Lumnitzera racemosa* demonstrated enhanced growth relative to native species, intensifying competitive pressures. The findings underscore the critical negative impacts of combined pesticide pollution and eutrophication on the restoration of mangrove ecosystems, while the proliferation of invasive species may impede ecological recovery efforts. This research provides important insights for mangrove restoration strategies and offers evidence-based policy recommendations for conservation and management, particularly in regions of China and similar ecological contexts facing multifaceted environmental stressors.
Keywords: *mangrove restoration, coastal ecosystems, environmental contamination, aquatic pollution, carbon sequestration, tropical wetlands, Hainan Island, environmental stressors*

Introduction

Mangrove ecosystems, as one of the most critical wetland ecosystems globally, possess high biodiversity and ecological value, playing an irreplaceable role in mitigating climate change, protecting coastlines, and providing essential ecosystem services. Through their extensive root systems, mangroves effectively reduce coastal erosion, protecting shorelines from storm surges, flooding, and other natural disasters (Alongi, 2014). Additionally, mangroves are among the most significant carbon sinks on Earth. Their role in the global carbon cycle is indispensable, with studies indicating that the carbon storage capacity of mangroves is several times greater than that of terrestrial forests, and their carbon sequestration rate far exceeds that of other ecosystems, rendering them a focal point in climate change mitigation efforts (Alongi, 2009). However, with the

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intensification of human activities, particularly coastal development, pollution, and pressures from climate change, mangrove ecosystems are facing unprecedented threats.

In recent years, environmental pollution has emerged as a key factor impacting the health of mangrove ecosystems. Eutrophication, heavy metal contamination, and pesticide usage have all significantly affected the growth and survival of mangrove seedlings (Akram et al., 2023). Eutrophication typically results from excessive nitrogen and phosphorus emissions due to agricultural activities, leading to algal blooms, reduced dissolved oxygen levels, and impeded growth of mangrove roots (Chave et al., 2006; Bhagarathi and DaSilva, 2024). Concurrently, mangrove seedlings exhibit high sensitivity to heavy metal pollution. Research indicates that heavy metals such as cadmium, lead, and mercury can be absorbed through the roots, adversely affecting growth and development, and causing physiological damage (Chen et al., 2009, 2014, 2021, 2023). Furthermore, pesticides, as common environmental pollutants, have been shown to be toxic to mangrove seedlings, particularly in environments where multiple pollution sources coexist (Li et al., 2024).

While numerous studies have focused on the impact of individual pollutants on mangrove seedlings, the combined effects of multiple pollution factors on mangrove ecosystems have not received adequate attention. Interactions between different environmental factors may result in non-linear effects, further exacerbating the vulnerability of mangrove ecosystems (Lin et al., 2023). For instance, eutrophication may alter water quality conditions in ways that either enhance or diminish the toxic effects of other pollutants on mangroves. Therefore, investigating the interactions of environmental pollution factors is essential for understanding the response mechanisms of mangrove ecosystems and their carbon storage functions.

This study aims to systematically evaluate the combined effects of eutrophication, heavy metal pollution, and pesticide usage on the growth and carbon storage of mangrove seedlings in Sanya, Hainan Province. Through a three-year field study and data analysis in the Sanya region, this research not only examines the effects of individual pollutants but also explores their synergistic impacts on the survival rate, leaf growth, root development, and carbon storage capacity of mangrove seedlings. We hope that this study will provide scientific evidence for mangrove protection and restoration strategies, promote sustainable management of mangrove ecosystems, and offer new solutions for climate change mitigation.

As one of the key regions in China for mangrove distribution, Sanya in Hainan Province holds significant ecological and scientific research value. In recent years, mangrove ecosystems in Sanya have faced challenges such as eutrophication, industrial pollution, and the use of agricultural fertilizers and pesticides. Particularly in the context of global climate change and population pressures, the environmental stresses on mangrove ecosystems are becoming increasingly evident (Ma et al., 2025). Therefore, selecting Sanya as the study area will not only help uncover the growth mechanisms of mangrove ecosystems in polluted environments but also provide valuable data and insights for future mangrove protection and ecological restoration.

Methods

Experimental sites

This study was conducted in three administrative districts of Sanya City, Hainan Province, China, namely Haitang District, Tianya District, and Yazhou District. The

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Jiuyang District was excluded from the study area due to its distance from the coastline. The aforementioned three districts in Sanya City are all impacted by human activities, such as coastal development, agricultural runoff, and pollution, which have collectively influenced the health and stability of the mangrove ecosystem. The mangrove ecosystem in Sanya provides important ecological services to the local area, including coastal protection, biodiversity conservation, and carbon storage (Lin et al., 2022).

The specific study sites selected for this research represent varying levels of pollution exposure, from low to high pollution, with the aim of assessing the impact of eutrophication, heavy metal pollution, and pesticide contamination on mangrove seedling growth and ecological functions. Specifically, low-pollution areas are located in regions farther from human activities, with relatively low pollution levels; high-pollution areas are located in more urbanized zones with concentrated agricultural runoff and coastal development. The medium-pollution areas lie between these two, representing varying degrees of environmental pollution.

Sanya has a tropical monsoon climate, characterized by high temperatures and abundant rainfall year-round, with distinct wet and dry seasons. Based on the climatic characteristics, the mangrove growth season in Sanya can be divided into two main phases: the rainy season (usually from May to October) and the dry season (from November to April of the following year).

The Sanya city, which is characterized by a pronounced dry season and rainy season. The dry season typically spans from November to April, while the rainy season occurs from May to October. These seasonal variations have significant impacts on the local mangrove ecosystems, influencing factors such as soil salinity, water availability, and nutrient cycling. During the dry season, Sanya experiences lower rainfall, leading to higher soil salinity levels and reduced water availability. This period is critical for mangrove seedlings, as the limited water can stress young plants, impacting their growth and survival rates. In contrast, the rainy season brings abundant rainfall, which can lower soil salinity and increase nutrient availability. This influx of water supports the rapid growth of mangrove seedlings and helps in flushing out pollutants from the soil. This research is novel in that it specifically examines how these distinct seasonal variations affect the health and growth of mangrove seedlings. By comparing the physiological and growth responses of mangrove seedlings during the dry and rainy seasons, this study provides valuable insights into the adaptive strategies of mangroves in response to environmental stressors. Understanding these processes is crucial for the conservation and management of mangrove ecosystems in tropical coastal regions like Sanya.

Due to the fact that the site was previously used as a fish farming pond where tetracycline was applied for disinfection, and the nearby golf course used herbicides, these factors led to the detection of tetracycline and herbicides in our pollutant measurements. During the rainy season, abundant rainfall and stronger water flow cause nutrients and pollutants to enter the coastal areas through runoff, affecting mangrove growth. In the dry season, reduced rainfall and more stagnant water may lead to a more pronounced accumulation of pollutants, which could impose different environmental pressures on mangrove growth and physiological responses (*Fig. 1*).

Meteorological instrumentation

The experiment was conducted from 30 December 2022 to 30 December 2024, and details are provided in *Table 1*. The instruments were mainly installed at an 8 m height flux tower. According to the weather observation data of the weather station and the

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observation data of surface temperature data below the flux tower, the entire period was divided into two stages: rainfall season period and dry season period. Additionally, atmospheric pressure data were obtained from the nearby Mangrove Forest Ecosystem Research Station’s instruments in different areas. The dry season period was from 21 November 2023 to 28 April 2024; the rainfall season period and the dry season period was from 1 May 2024 to 28 March 2025.

Figure 1. *The experiment in the mangrove wetland sample plot*

Table 1. *Sediment information for experimental sites*

Research area	0–20 (cm depth)	20–40 (cm depth)
Sand (%)	30.7	73.9
Silt (%)	0.22	0.57
Clay (%)	2.57	2.39
Organic (%)	3.42	2.52
Bulk density (g/cm^3)	1.69	1.42

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Selection of study sites

The study was conducted across four distinct research areas in Sanya, namely Haitang Bay (E:109.70166; N:18.27174), Yalong Bay (E:109.62941; N:18.22085), Sanya Bay (E:109.44107; N:18.25765), and Yazhou Bay (E:108.95597; N:18.39672). Each of these districts contains five sampling sites, resulting in a total of 20 sampling locations for the entire study. The sampling sites were selected to represent the diverse environmental conditions within each district, ensuring that the data gathered would reflect the broader ecological variations across Sanya (*Table 2*).

Table 2. *Data collection instruments in this study*

Environmental factor	Instrument	Height (+) or depth (-)
Air temperature/humidity	Campbell Scientific HMP45C capacitance hygrometer and thermistor (USA)	+8 m
Wind speed	Met One 014A 3-cup anemometer	+1, +3, +5, +8 m
Wind fluctuations	Campbell Scientific CSAT3 ultrasonic anemometer (USA)	+8 m
Vapor fluctuations	Campbell Scientific KH_2O hygrometer (USA)	+8 m
Radiation (incoming/outgoing shortwave & longwave)	Kipp & Zonen CNR4 pyrgeometer and pyranometer (USA)	+8 m
Soil moisture	Campbell Scientific CS616 water content reflectometer (USA)	-0.05, -0.1, -0.2, -0.4 m
Soil temperature	Type-T thermocouple wire (USA)	-0.05, -0.1, -0.2, -0.4 m
Ground heat flux	Hukseflux HFT1 heat flux plate (USA)	-0.05, -0.1, -0.2, -0.4 m

At each sampling site, a fixed random sampling approach was applied. The method involved the systematic selection of specific locations within the designated sample plots, while maintaining randomness to avoid any sampling bias. This ensures that the collected data represents a true variation of the ecosystem within each area (*Fig. 2*).

In study regions were chosen due to its well-preserved mangrove ecosystems and the clear distinction between the dry and rainy seasons, which is critical for assessing seasonal impacts on mangrove seedlings. The sample collection was conducted over a period spanning both the dry and rainy seasons to capture the seasonal variations in environmental conditions and their effects on mangrove seedlings. Specifically:

Dry Season: Samples were collected from November to April.

Rainy Season: Samples were collected from May to October.

During each season, samples were collected three times per month to ensure a comprehensive dataset that reflects the temporal changes in environmental factors and mangrove seedling responses. At each sampling event, the following data were collected soil moisture, salinity, temperature, seedling height, stem diameter, and leaf chlorofluorocarbon levels were taken at each site using portable sensors and probes.

In this study, we define a mangrove seedling based on specific morphological criteria. A mangrove plant is classified as a seedling if it meets the following conditions: (1) The plant must have a height of less than 1.5 m; (2) The stem diameter at the base of the plant must be less than 2 cm; (3) The plant must be less than 2 years old, based on the annual growth rings and other age-determining techniques appropriate for mangroves.

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By utilizing this fixed random sampling method combined with diagonal sampling and a regular monthly sampling schedule, the study ensured a comprehensive and representative data set that allows for the analysis of ecological patterns and environmental changes across different districts and throughout the year.

Field sampling

Vegetation survey

A series of permanent plots (each measuring 20 m²) were established in each study site. Within each plot, the species composition, tree height, and diameter at breast height (DBH) of all mangrove trees were recorded. In each plot, a minimum of 20 individual trees were measured.

Soil carbon stock assessment

Soil samples were collected to a depth of 40 cm using a soil corer at 9 randomly selected points within each plot. The samples were analyzed in the laboratory for total organic carbon content using Komiyama et al.'s (2005) method. The soil carbon stock was calculated by multiplying the bulk density of the soil (measured in a subset of the plots) by the carbon content at different depths. Soil respiration carbon flux was observed by placing a static box in the sample plot (*Fig. 2*).

Figure 2. *The experiment in the mangrove wetland sample plot*

Hydrological data

Water salinity and tidal height were monitored by automated water level loggers and handheld refractometers for salinity measurements (Mcleod et al., 2011). These data were used to assess the impact of the changes in salinity on the mangrove environment.

Rainfall disturbance parameters

The average rainfall and temperature during the study period are shown in *Figure 3*. It can be observed that from 2022 to 2025, there was almost no rainfall during the dry season, and the temperature also decreased accordingly.

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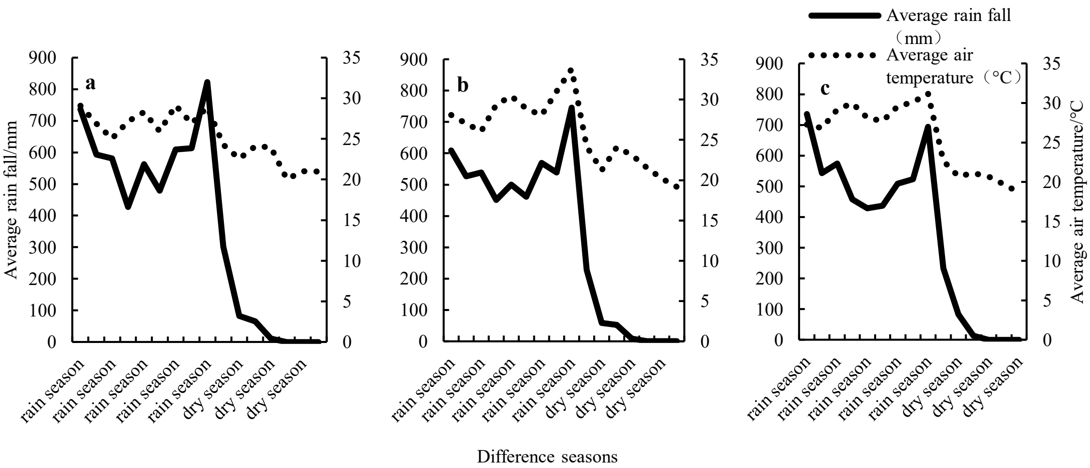

Figure 3. *The average rainfall and temperature during the study period in 2022-2025 (a) 2022-2023; (b) 2023-2024; (c) 2024-2025*

Carbon stock estimation

Soil carbon content was measured using the dry combustion method, which is a well-established technique in soil science. Briefly, soil samples were collected from different depths, air-dried, and ground. The carbon content was determined using an Elementar analyser, which measures the amount of CO2 released upon combustion at high temperatures. In our study, we modified the standard procedure by conducting the analysis on subsamples from each depth at different time intervals to capture seasonal variations in soil carbon content. The carbon stock of the mangrove ecosystem was estimated using a two-step approach:

Aboveground carbon stock (AGC)

Aboveground biomass (AGB) was estimated using allometric equations specific to mangrove species in the study region. The general equation used for mangrove AGB estimation is:

$$AGB = \beta_0 \times DBH^{\beta 1} \quad \text{(Eq.1)}$$

where DBH is the diameter at breast height of the tree, and β0, β1 are species-specific constants. A subset of mangrove trees 20 trees was measured for DBH in each site, and the biomass values were converted to carbon content using a carbon conversion factor of technical regulations for assessing carbon sequestration capacity of mangrove wetland ecosystems, China (DB 45/T 1230-2015).

Belowground carbon stock (BGC)

Belowground biomass (roots and soil organic matter) was estimated using root coring at specific points in the study sites. The root biomass of mangroves was quantified using allometric models specific to the region or derived from literature. The belowground carbon stock was also analyzed through soil carbon content as described earlier. The total carbon stock (TCS) in the mangrove ecosystem was calculated by summing the aboveground and belowground carbon stocks:

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$$TCS = AGC \times BGC \tag{Eq.2}$$

Pesticide analysis methods

This study selected the following pesticide indicators for analysis: Tetracycline, Herbicide, Diclofop-methyl, Bifenthrin, Avermectin, Triadimefon, Azoxystrobin, Epoxiconazole, Triadimefon Isomer. The pesticides were measured using High-Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), and Liquid Chromatography-Mass Spectrometry (LC-MS), all of which are standardized methods for pesticide analysis. By selecting appropriate chromatographic conditions and detectors (e.g., ultraviolet detectors, electron capture detectors), we were able to quantify the concentration and residual amounts of these pesticides.

Heavy metal analysis methods

For heavy metal analysis, the study focused on a range of elements, including Chromium (Cr), Cobalt (Co), Nickel (Ni), Copper (Cu), Zinc (Zn), Zirconium (Zr), Niobium (Nb), Molybdenum (Mo), Tin (Sn), Hafnium (Hf), Tantalum (Ta), Lead (Pb), Bismuth (Bi), and Mercury (Hg). The concentrations of these metals were measured using Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). These methods provide high sensitivity and accuracy for detecting heavy metals in water, sediments, and biological samples. Specifically, mercury analysis was performed using Cold Vapor Atomic Absorption Spectroscopy (CVAAS) or Atomic Fluorescence Spectroscopy (AFS) (Savidge et al., 2008).

Methods for assessing eutrophication

Eutrophication assessment is typically conducted through the following indicators:

Total nitrogen and total phosphorus

Measured using digestion colorimetric methods or chemical analysis instruments (such as UV spectrophotometers) to determine the concentrations of total nitrogen (TN) and total phosphorus (TP) in water samples.

Chlorophyll-a

Chlorophyll-a concentration is determined by filtering water samples and using spectrophotometric methods to reflect phytoplankton biomass.

Transparency

Water transparency is measured using a Secchi disk; lower transparency usually indicates a higher level of eutrophication.

Dissolved oxygen and biochemical oxygen demand

Dissolved oxygen (DO) and biochemical oxygen demand (BOD) are assessed using electrochemical probes or Winkler titration methods to evaluate the decomposition of organic matter in the water.

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Statistical analysis

Data were analyzed using SPSS. Descriptive statistics (mean, standard deviation) were calculated for all variables, including species composition, tree biomass, and carbon stocks. The impact of environmental factors on carbon stocks was assessed using the ANOVA to carbon stocks across the different restoration age sites. A multiple regression analysis was conducted to identify the key factors (e.g., storm surge, wind speed, salinity changes) that influenced carbon stock recovery. In addition, the relationship between restoration age and carbon stock recovery was examined using correlation analysis, with a focus on how mangroves of different restoration ages responded to the disturbance.

Results

The dynamic changes of soil microbial biomass carbon and nitrogen in study region

Between 2022 and 2024, the atmospheric carbon dioxide concentration in the study area showed a consistent increase, with the concentration measured in ppm. Sanya City, despite lacking heavy industry and being primarily based on tourism, also exhibited a general upward trend in carbon storage. Specifically, the presence of a cement plant, hospitals, and extensive farmland may all play a role. The cement plant's operations can release carbon input, while the agricultural activities, such as irrigation and the use of machinery, alongside energy consumption from hospitals, may indirectly contribute to increased carbon storage. The combined effects of these factors need to be considered when analysis the data and drawing conclusions regarding the environmental changes in the region (*Fig. 4*).

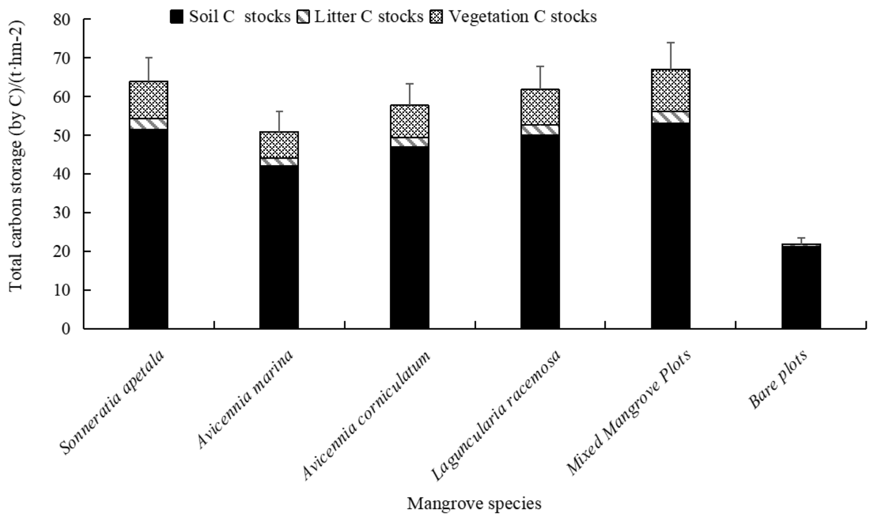

Figure 4. *Characteristic carbon storage for Hainan Province and Sanya City (2022-2024)*

Total carbon storage in the different plots decreased significant of varying intensities (*Tables 3–5*). The most substantial reductions in carbon storage were observed in the sapling plots, with the least recovery of carbon storage observed prior to pollution indicators. The primary cause of this decrease was the high mortality rate among saplings, which resulted in a marked reduction in water quality pollution indicators (*Table 3*).

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Table 3. *Water quality pollution indicators*

Pollution source	Water quality indicator	Description	Unit
Mining activities	pH Value	Reflects the acidity or alkalinity of the water, acid mine drainage often lowers pH	pH
	Heavy metal concentration (lead)	Heavy metals like lead may enter water bodies during mining activities, affecting ecosystems and health	mg/L
	Suspended solids concentration	Mining activities often release sediments and slag into the water, increasing turbidity	mg/L
Agricultural pollution	Nitrogen (N) concentration	Overuse of fertilizers leads to nitrogen entering water bodies, causing eutrophication	mg/L
	Phosphorus (P) concentration	Excess phosphorus from agricultural runoff can cause algal blooms and eutrophication	mg/L
	Organic matter concentration	Agricultural wastewater may contain organic chemicals like pesticide and fertilizer residues	mg/L
Urban infrastructure	Oil concentration	Oil from transportation, construction, and other urban activities may pollute water bodies	mg/L
	Heavy metal concentration (copper, zinc)	Construction and urban activities may introduce heavy metals like copper and zinc into water	mg/L
	pH value	Urban development might impact the water's pH level	pH
Cement plant effluents	pH value	Cement production wastewater might acidify water bodies	pH
	Heavy metal concentration (chromium, lead)	Cement production wastewater may contain heavy metals like chromium and lead	mg/L
	Suspended solids concentration	Cement production generates dust and particulate matter that may enter water bodies	mg/L
Domestic sewage	Coliform bacteria concentration	Domestic sewage may contain harmful microorganisms like E. coli, posing a health risk	CFU/100 mL
	Chemical oxygen demand (COD)	Organic matter in domestic sewage consumes oxygen in water, impacting aquatic life	mg/L

The analysis of water quality data from 2022 to 2024 reveals distinct impacts from various pollution sources. Mining activities have significantly contributed to acidic water conditions (pH below 6), high lead concentrations, and elevated levels of suspended solids, posing risks to aquatic ecosystems and human health. Agricultural runoff and domestic sewage are major contributors to nutrient pollution, with nitrogen and phosphorus levels increasing over time, potentially leading to eutrophication and harmful algal blooms. Domestic sewage also exhibits high coliform bacteria concentrations, indicating microbial contamination and the need for improved wastewater treatment. These findings underscore the urgent necessity for stricter pollution control measures, enhanced treatment technologies, and sustainable management practices to safeguard water quality and ecosystem health (*Table 4*).

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In the study area, pollution sources are mainly categorized into the following types: (1) Industrial point source pollution, including mining activities and wastewater discharge from chemical plants; (2) Agricultural non-point source pollution, including nitrogen and phosphorus runoff from fertilized farmland; (3) Urban diffuse source pollution, such as road runoff and leachate from municipal solid waste. This classification method is based on the UNEP (2004) standards for point and non-point sources and has been adjusted to fit the specific conditions of the study area.

Impact of heavy metal and pesticide concentration changes on carbon storage at different restoration stages

According to the data from 2022 to 2024, certain heavy metals (such as Cr and Cu) and pesticides (such as *Tetracycline* and *Avermectin*) showed highly significant correlations in the young restoration stage, suggesting that these pollutants may have a significant impact on carbon storage. In the Moderately Restored stage, although the effects of most pollutants were significant, some elements (such as Zr, Ni, etc.) did not show significant changes. Therefore, controlling these pollutants could potentially improve the carbon storage in mangrove restoration (*Table 5*).

The results of the LSD test showed that most heavy metals and pesticides exhibited varying levels of significance across the different restoration stages. This indicates that the differences in pollutant concentrations at different stages may be closely related to the changes in carbon storage during the restoration process. For example, in 2022 and 2023, several elements (such as Cr, Cu, Pb, etc.) in the young restoration stage showed highly significant results ($p < 0.01$), while in the mature restoration stage, there were almost no significant differences. This suggests that the accumulation of pollutants during the early stages of mangrove restoration has a considerable inhibitory effect on carbon storage (*Table 6*).

In 2022, during the early (young) stage of restoration, carbon storage showed a strong positive correlation with nitrogen ($p < 0.01$) and organic matter ($p < 0.01$), and a moderate correlation with phosphorus ($p < 0.05$). Similarly, in the moderately restored stage of 2022, carbon storage was significantly correlated with nitrogen ($p < 0.05$) and organic matter ($p < 0.01$), and displayed moderate correlation with phosphorus ($p < 0.05$). In the mature stage of the same year, carbon storage maintained significant correlations with nitrogen ($p < 0.01$) and organic matter ($p < 0.05$), though the correlation with phosphorus was not significant ($p > 0.05$).

In 2023, the young mangrove restoration stage demonstrated strong correlations between carbon storage and nitrogen ($p < 0.01$) as well as organic matter ($p < 0.01$), with a moderate correlation with phosphorus ($p < 0.05$). For moderately restored areas, carbon storage remained significantly correlated with nitrogen ($p < 0.01$) and organic matter ($p < 0.05$), while the mature stage showed significant but weaker correlations with nitrogen ($p < 0.05$) and organic matter ($p < 0.05$).

In 2024, the young stage of restoration exhibited significant correlations of carbon storage with nitrogen ($p < 0.01$) and organic matter ($p < 0.01$), and a moderate correlation with phosphorus ($p < 0.05$). The moderately restored areas in 2024 showed a strong correlation between carbon storage and phosphorus ($p < 0.01$), with significant correlations with nitrogen ($p < 0.05$) and organic matter ($p < 0.05$). In the mature stage, however, the correlations were generally weaker and not significant for phosphorus and organic matter ($p > 0.05$), with nitrogen showing a very weak and non-significant correlation ($p > 0.05$) (*Table 7*).

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Table 4. *Water quality data from 2022-2024*

Year	Pollution source	pH Value	Heavy metal concentration (lead) (mg/L)	Suspended solids concentration (mg/L)	Nitrogen (N) concentration (mg/L)	Phosphorus (P) concentration (mg/L)	Oil concentration (mg/L)	Coliform bacteria concentration (CFU/100 mL)	COD concentration (mg/L)
2022	Mining activities	4.5	0.8	150	5.2	1.2	-	-	-
	Agricultural pollution	6.8	-	30	12.3	5.4	-	-	35
	Urban infrastructure	7.2	0.1	50	-	-	0.3	-	40
	Cement plant effluents	5.8	0.3	100	-	-	-	-	50
	Domestic sewage	7.4	-	20	15	6.2	-	300	80
2023	Mining activities	4.3	0.9	160	6	1.5	-	-	-
	Agricultural pollution	7	-	40	13.1	5.8	-	-	37
	Urban infrastructure	7.3	0.2	55	-	-	0.4	-	42
	Cement plant effluents	5.7	0.4	110	-	-	-	-	55
	Domestic sewage	7.3	-	22	16	6.5	-	320	85
2024	Mining activities	4.2	1	170	6.5	1.8	-	-	-
	Agricultural pollution	6.9	-	35	14	6	-	-	40
	Urban infrastructure	7.4	0.3	60	-	-	0.5	-	45
	Cement plant effluents	5.6	0.5	120	-	-	-	-	60
	domestic sewage	7.4	-	25	17	7	-	340	90

The data analysis was performed using the LSD test. **p < 0.01, *p < 0.05, N = 15

Table 5. *Correlation analysis of heavy metal with carbon storage at different restoration stages of mangrove recovery in Hainan from 2022 to 2024*

	Recovery stage carbon storage	Cr	Co	Ni	Cu	Zn	Zr	Nb	Mo	Sn	Hf	Ta	Pb	Bi	Hg
2022	Young	0.75**	0.78**	0.53*	0.81**	0.19	0.65**	0.29	0.81**	0.1	0.53*	0.36	0.83**	0.53*	0.68**
2022	Moderately restored	0.53*	0.49*	0.44*	0.43*	0.23	0.43*	0.15	0.50*	0.27	0.46*	0.24	0.54*	0.14	0.52*
2022	Mature	0.64**	0.68**	0.54*	0.71**	0.36	0.52*	0.19	0.61*	0.16	0.61*	0.33	0.86**	0.39	0.74**
2023	Young	0.59*	0.49*	0.47*	0.43*	0.21	0.51*	0.05	0.52*	0.11	0.16	0.29	0.61*	0.54*	0.52*
2023	Moderately restored	0.69**	0.68**	0.51*	0.87**	0.14	0.54*	0.21	0.74**	0.19	0.45*	0.3	0.79**	0.59*	0.84**
2023	Mature	0.22	0.21	0.23	0.27	0.06	0.05	0.14	0.12	0.14	0.2	0.19	0.24	0.18	0.13
2024	Young	0.52*	0.49*	0.49*	0.53*	0.18	0.45*	0.11	0.53*	0.23	0.56*	0.21	0.53*	0.44*	0.52*
2024	Moderately restored	0.83**	0.69**	0.55*	0.68**	0.25	0.27	0.1	0.72**	0.18	0.51*	0.15	0.83**	0.57*	0.74**
2024	Mature	0.54*	0.50*	0.39	0.51*	0.11	0.52*	0.06	0.56*	0.28	0.48*	0.14	0.51*	0.52*	0.51*

The data analysis was performed using the LSD test. **p < 0.01, *p < 0.05, N = 15

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***Table 6.** Correlation analysis of pesticide concentrations with carbon storage at different restoration stages of mangrove recovery in Hainan from 2022 to 2024*

	Recovery stage carbon storage	Tetracycline	Herbicide	Diclofop-methyl	Bifenthrin	Avermectin	Triadimefon	Azoxystrobin	Epoxiconazole	Triadimefon isomer
2022	Young	0.43*	0.63**	0.51*	0.59**	0.45*	0.52*	0.61**	0.28	0.44*
2022	Moderately restored	0.39*	0.39*	0.33*	0.24	0.36*	0.46*	0.41*	0.34*	0.52**
2022	Mature	0.46*	0.69**	0.42*	0.58**	0.47*	0.63**	0.59**	0.21	0.42*
2023	Young	0.50*	0.39*	0.59**	0.42*	0.32*	0.33*	0.37*	0.14	0.61**
2023	Moderately restored	0.41*	0.72**	0.45*	0.75**	0.41*	0.13	0.62**	0.23	0.44*
2023	Mature	0.15	0.14	0.13	0.21	0.17	0.2	0.19	0.18	0.17
2024	Young	0.44*	0.32*	0.32*	0.43*	0.34*	0.16	0.37*	0.31*	0.32
2024	Moderately restored	0.45*	0.65**	0.53*	0.59**	0.46*	0.34*	0.62**	0.29	0.41*
2024	Mature	0.37*	0.32*	0.31*	0.39*	0.33*	0.47*	0.38*	0.35*	0.13

The data analysis was performed using the LSD test. $^{**}p < 0.01$, $^{*}p < 0.05$, N = 15

***Table 7.** Correlation analysis of eutrophication with carbon storage at different restoration stages of mangrove recovery in Hainan from 2022 to 2024*

	Recovery stage carbon storage	Nitrogen	Phosphorus	Algal bloom	Organic matter
2022	Young	0.56**	0.71**	0.42*	0.65**
2022	Moderately restored	0.46*	0.59**	0.47*	0.72**
2022	Mature	0.39*	0.41**	0.21	0.45*
2023	Young	0.59**	0.55**	0.50*	0.63**
2023	Moderately restored	0.44*	0.61**	0.45*	0.45*
2023	Mature	0.39*	0.38*	0.17	0.38*
2024	Young	0.63*	0.55**	0.40*	0.64**
2024	Moderately restored	0.41*	0.39*	0.63**	0.39*
2024	Mature	0.37*	0.12	0.16	0.13

The data analysis was performed using the LSD test. $^{**}p < 0.01$, $^{*}p < 0.05$, N = 15

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Discussion

This study explored the relationship between heavy metal and pesticide concentrations and carbon storage in mangrove forests during restoration processes from 2022 to 2024. The results demonstrated that pollutant levels significantly influenced carbon storage, especially in the early stages of mangrove restoration. Heavy metals such as Cr, Cu, and pesticides like *Tetracycline* and *Avermectin* showed significant correlations with carbon storage, indicating that pollutant accumulation in the initial restoration stages can strongly inhibit carbon sequestration. As restoration advanced, however, the impact of these pollutants seemed to diminish, suggesting that over time, the mangrove ecosystem either adapts to these pollutants or that their concentrations decrease naturally, allowing for enhanced carbon storage.

Impact of environmental factors on carbon storage

In the young restoration stage, where environmental conditions are still unstable, high concentrations of pollutants were found to suppress carbon storage significantly. The inhibitory effects of heavy metals and pesticides on mangrove growth have been well-documented in previous studies, which highlighted how pollutants interfere with plant metabolic processes, including photosynthesis, root development, and nutrient absorption (Sharma et al., 2020). Our findings support this, as the young mangrove ecosystem, still in the process of recovery, exhibits heightened sensitivity to environmental stressors, such as toxic metals and chemicals. Heavy metals, including Cr and Cu, can disrupt enzymatic activities, leading to stunted growth, reduced biomass, and consequently, lower carbon sequestration potential (Sefton et al., 2022; Selvam et al., 2022).

On the other hand, in the Moderately Restored stage, the correlation between pollutants and carbon storage was somewhat less significant. This suggests that the ecosystem may have developed some degree of resilience over time, with certain pollutants being less effective in impeding the restoration process. For instance, the decline in pollutant impacts could be attributed to the natural attenuation processes, where pollutants are either absorbed by the soil or transformed into less toxic forms by microbial communities in the ecosystem (Song et al., 2023). However, the lack of significant effects for elements such as Zr and Ni requires further investigation. These elements may have more complex interactions with the mangrove ecosystem that are not fully captured in the current study.

Specifically, pollutants like Cr, Cu, and Pb showed highly significant impacts on carbon storage ($p < 0.01$) in the young restoration stage. This finding aligns with the hypothesis that pollutant concentrations in the early stages of mangrove restoration play a critical role in determining the success of carbon sequestration. The results are consistent with previous research, which suggests that early intervention and pollutant control are crucial for the success of restoration projects (Stas et al., 2023).

In contrast, the mature restoration stage showed almost no significant differences in pollutant concentrations, highlighting the possible natural recovery mechanisms at play. As mangrove forests mature, their resilience increases, and their ability to accumulate carbon may become less influenced by the pollutants present in the environment. This resilience could be attributed to the improved capacity of mangrove trees to tolerate and detoxify pollutants, as well as the increased microbial diversity in the soil, which aids in pollutant breakdown (Temmerman et al., 2023).

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The correlation analysis reveals that during the early and moderately restored stages (2022 and 2023), there are significant positive correlations between carbon storage and eutrophication indicators such as nitrogen ($r = 0.56$ to 0.63) and organic matter ($r = 0.45$ to 0.72). This suggests that young and developing mangroves are highly responsive to nutrient inputs, likely due to their rapid growth and higher nutrient uptake rates, which enhance biomass accumulation and soil carbon storage (Alongi, 2014) However, as the mangrove ecosystems mature (2022-2024), these correlations weaken (e.g., $r = 0.12$ to 0.41 for nitrogen and $r = 0.16$ to 0.21 for phosphorus), indicating a potential shift towards nutrient saturation and stabilization of soil carbon pools (Lovelock et al., 2011).

These findings highlight the need for stage-specific nutrient management strategies in mangrove restoration. Initial restoration efforts could focus on optimizing nitrogen and organic matter inputs to maximize carbon sequestration (Adame et al., 2013). As the ecosystems mature, the focus should shift towards maintaining nutrient balance to prevent eutrophication and ensure sustainable carbon storage. This study’s results are consistent with existing literature, which also observes strong initial nutrient responses in young mangroves and complex nutrient dynamics in mature systems (Reef et al., 2010). Future research should aim at long-term monitoring to further elucidate these biogeochemical processes and refine restoration approaches (Lovelock et al., 2011).

Our findings corroborate and expand upon existing literature on the relationship between pollutants and carbon storage in coastal ecosystems. Studies have shown that heavy metals and pesticides not only harm plant growth but also alter soil properties, affecting the carbon storage potential of coastal ecosystems (Yue et al., 2021). For example, in a study by Sun and You (2024)’s study, it was found that elevated concentrations of Cu and Cr significantly reduced the growth rates of mangrove species, directly leading to lower biomass and carbon sequestration. Similarly, the effects of pesticides, particularly herbicides, have been shown to disrupt plant-pollinator interactions, which may further diminish ecosystem functions such as carbon fixation (Ellert et al., 2002; Komiyama et al., 2005; Mok et al., 2019).

By comparing our results with previous research, it becomes evident that pollutant exposure during the early stages of mangrove restoration has long-lasting effects on the ecosystem’s carbon storage capacity. The present study builds on this knowledge, emphasizing the importance of controlling pollutant levels during the early stages of restoration to optimize carbon sequestration in degraded mangrove areas.

Study limitations and future research directions

Although this study provides valuable insights, there are several limitations that must be addressed in future research. First, the observation period of three years may not be sufficient to capture the full range of changes in pollutant concentrations and carbon storage dynamics. Future studies should adopt longer time frames to monitor the long-term effects of pollutant exposure and restoration success. Longer-term studies would help to clarify whether the ecosystem’s resilience continues to improve as the mangrove forest matures, and if so, how the rates of carbon sequestration change over time.

Moreover, the spatial variability of pollutant concentrations across different mangrove restoration sites could provide more comprehensive insights into how environmental factors influence carbon storage. It would be beneficial to investigate whether the effects of pollutants vary between regions, depending on local environmental conditions, such as soil type, tidal conditions, and the presence of different mangrove species (Ellison, 2015). Additionally, research on the specific mechanisms by which pollutants like Zr and Ni

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affect mangrove ecosystems could help refine our understanding of pollutant-ecosystem interactions. In future research should explore the potential of restoration techniques that enhance the resilience of mangrove ecosystems, such as the use of *biochar* or *phytoremediation*, to accelerate the recovery of degraded areas while mitigating the negative effects of pollutants on carbon storage (Rani et al., 2018).

Conclusions

This study investigated the impact of heavy metal and pesticide concentrations on carbon storage in mangrove forests during different stages of restoration from 2022 to 2024. Our findings indicate that pollutant levels significantly influence carbon sequestration, particularly in the early stages of restoration. Specifically, heavy metals such as Cr and Cu, along with pesticides like *Tetracycline* and *Avermectin*, were found to have strong inhibitory effects on carbon storage. However, as the restoration progressed, the impact of these pollutants diminished, suggesting that the mangrove ecosystem either adapts to these pollutants or that their concentrations decrease naturally, allowing for enhanced carbon storage.

Our research highlights the critical need for stage-specific management strategies in mangrove restoration. Initial efforts should focus on controlling pollutant levels and optimizing nutrient inputs to maximize carbon sequestration. As mangrove ecosystems mature, the focus should shift towards maintaining nutrient balance to prevent eutrophication and ensure sustainable carbon storage. The study also emphasizes the importance of long-term monitoring to fully understand the effects of pollutants and refine restoration approaches. Future research should explore the spatial variability of pollutant impacts and investigate the mechanisms by which pollutants like Zr and Ni affect mangrove ecosystems. Additionally, techniques such as biochar application and phytoremediation could be explored to enhance the resilience of mangrove ecosystems and accelerate the recovery of degraded areas.

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