Correlation of Bio-physicochemical Factors with the Expansion of Mangrove Forests in Laikang Bay, Indonesia

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Abstract

The bio-physicochemical conditions of seawater are critically important in the rate of expansion of mangrove forests. This study aims to assess the driving factors of mangrove forest expansion with bio-physicochemical water quality analysis using the Maximum Entropy (MaxEnt) method in Laikang Bay, Indonesia. Water quality analysis included measurements of NO_3, PO_4, kH, salinity, current speed, brightness (D3), NO_2, pH, and chlorophyll-a levels (bio-physicochemical factors). This research adopts quantitative methods, with data collected from 42 specific locations between 12:00 a.m. and 3:00 p.m. The observation data was gathered using the stratified random sampling method. Spatial distribution mapping of mangroves and observation data were analyzed using Euclidean nearest neighbor distance with ArcGIS software version 8.1. The MaxEnt method was applied to investigate the percentage contribution of water quality on the distribution of mangroves. The results of this study indicate that the most significant factor contributing to the growth and expansion of mangrove forests in Laikang Bay is the PO_4 content, with a contribution value of 47.4%. The PO_4 concentration ranges from 0.10 to 1.40 mg.100g^{-1}, with a concentration of approximately 0.10 mg.100g^{-1} having the greatest impact. Meanwhile, the less influential factor is brightness (D3), with a contribution value of 0.3%. These results indicate that to maintain the growth and expansion of mangrove forests in Laikang Bay, it is necessary to maintain the levels of these influential variables.

Keywords: *mangrove expansion, mangrove ecosystem, Bio-physicochemical Factors, water quality, MaxEnt*

Introduction

Indonesia has a sea area of 6.4 million km^2, with 108,000 km of coastline and a diversity of potential coastal and marine resources, including mangroves, coral reefs, seagrass beds, seaweed, and fisheries (Mitra and Zaman, 2016). The potential of coastal and marine resources has a significant role as an economic and ecological function, especially mangroves. It offers a starting point for exploring the role of higher plant species diversity in modulating biogeochemical functions (production, nutrient cycling), ecological functions (habitat for organisms at different tropic levels), and anthropogenic functions (fisheries maintenance, sediment management) on a range of time scales (Sari and Soeprobowati, 2021).

Mangrove ecosystems also have physical functions as a natural barrier to dampen waves and hurricanes, protect against abrasion, retain silt, and trap sediment. Several methods have been developed to maintain mangrove ecosystems, including conservation (Handayani *et al.,* 2021). The conservation not only significantly impacts mangrove abundance, but also the sustainable management and development of mangroves related to maintaining the hydrogeochemical characteristics of the system (Eddy *et al.,* 2016). Water quality plays an essential role in maintaining the ability of mangroves to support habitat diversity and species composition that inhabit the environment.

Laikang Bay, located on the southern coast of Indonesia, is home to a rich and diverse mangrove ecosystem. However, there are several cases can affect the existence of mangrove systems in Laikang Bay, including the utilization of marine space on the coast of the Bay. The conversion of mangrove areas into shrimp ponds is the main factor contributing to the destruction of mangrove ecosystems and has a negative impact on aquaculture (Risanti and Marfai, 2020).

Despite several conflicts of interest in utilizing marine space in Laikang Bay, the development of mangrove growth continues to develop naturally.

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Based on survey results of Mulyani (2021) with spatial analysis in the report Optimizing Aquaculture Management and Conservation in the Coastal Area of Laikang Bay, Jeneponto Regency, the presence of *Rhizospora* sp. in Laikang Bay continues to grow naturally from 7.69 hectares in 10 years or 0.76 hectares per year. The natural development of mangrove growth rate can be caused by bio-physicochemical factors of water quality (Mahmudi *et al.,* 2022).

However, research on the specific bio-physicochemical factors affecting mangrove growth in Laikang Bay is still limited. Previous research has highlighted the importance of mangroves in mitigating climate change impacts and enhancing coastal resilience (Agustina and Ramli, 2022; Arifanti *et al.,* 2022). There still needs to be more understanding of the factors underlying mangrove expansion in this region. Overcoming these knowledge gaps is essential for informed conservation efforts and managing mangrove ecosystems.

Numerous studies have examined the factors influencing the presence or habitat of various species by employing the MaxEnt method. In a prior study conducted by Cobos *et al.* (2019) and Lifeng et al. (2024), the MaxEnt algorithm was utilized to assess the environmental suitability and potential geographic distribution of four mangrove species. Consequently, our research employs the MaxEnt method approach to identify the factors influencing the expansion of mangrove ecosystems in Laikang Bay.

Based on existing literature and phenomena, this study aims to identify bio-physicochemical factors of water quality and their correlations that influence the expansion of mangrove forests in Laikang Bay, Indonesia. In addition, this study also identifies the biophysicochemical factors that are primarily responsible for mangrove forest expansion. The biophysicochemical factors of water quality used in this study including salinity, PO_4, pH, NO_2, NO_3, kH, current velocity, brightness (D3), and chlorophyll-a using the MaxEnt method. Through rigorous scientific analysis, we aim to elucidate the complex relationships in this unique ecosystem. Understanding these relationships is essential for the conservation and sustainable management of mangrove ecosystems in Laikang Bay and can be a valuable model for other coastal areas.

Materials and Methods

Laikang Bay is located in Jeneponto Regency, South Sulawesi, Indonesia. The total area of Jeneponto Regency is 749.79 km^2 (BPS-Statistics of Jeneponto Regency, 2021) or approximately 1.64% of the total area of South Sulawesi Province. Geographically, Jeneponto Regency is positioned between 5° 23'12" - 5° 42'1.2" South Latitude (SL) and 119° 29' 12" - 119° 56' 44.9" East Longitude (EL). The research location of Laikang Bay, Jeneponto Regency, is shown in Figure 1.

Laikang Bay has a mangrove area of 17.57 ha in 2022. This marked an increase of 6.85 ha from the year 2012 when the mangrove forest covered an area of 10.75 ha. The selection of this research location was guided by its potential for rapid expansion of mangrove ecosystems within Laikang Bay, making it a viable choice for local government efforts to sustain the growth of mangrove ecosystems. This mangrove forest serves as a crucial resource for climate regulation, carbon storage, and the enhancement of coastal biodiversity, all of which contribute to the economic well-being of the local population in Laikang Bay (BPS-Statistics of Jeneponto Regency, 2021). The precise location of the Mangrove Ecosystem in Laikang Bay can be seen in Figure 2.

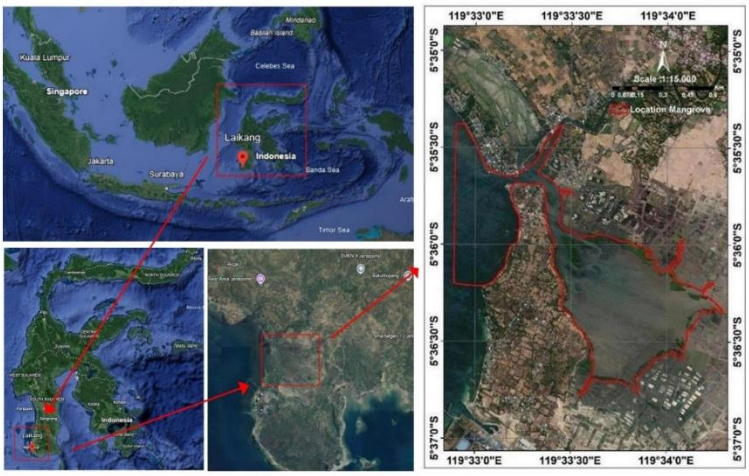


Figure 1. The study site of Laikang Bay, Jeneponto Regency, Indonesia

The collection of seawater samples was carried out during June - July 2022, between 12:00 a.m. and 3:00 p.m. Determination of geographical points for sampling using GPS. A total of 42 sampling sites were used for seawater sample collection, as shown in Figure 3. In addition, data collection on mangrove expansion was done using satellite imagery and digital elevation models (DEM) to analyze topography that affects water distribution.

Seawater samples were taken using a sample bottle at a depth of 30 cm above sea level at each sampling site. The collected water quality data included salinity, PO_4, pH, NO_2, NO_3, kH, current speed, brightness (D3), and chlorophyll-a. Current speed was measured using a Virtual Hydromet ABS Water Current Meter, salinity was measured with a refractometer (RRHS-28-ATC), brightness was measured using a Secchi disk, PO_4 using a test kit from Sera GmbH.D, pH, NO_2, kH, and NO_3 were analyzed using a test kit from JBL GmbH & Co.KG, and chlorophyll-a levels were measured using UV-Vis Spectrophotometry at the Hasanudin University water quality laboratory.

The analysis of chlorophyll-a was obtained using the Prasasti *et al.* (2022) method. One liter of seawater sample was filtered using Nitrocellulose Membrane (0.45 ɣm HA) supported by a vacuum pump. The filtered sample water was added with aquabides to maintain the temperature during the filtering process (preventing chlorophyll-a damage). Filter paper containing chlorophyll-a was folded and filed in aluminum foil. Filter paper that contains chlorophyll-a samples were stored in a refrigerator at 4°C.The filter paper of the stored chlorophyll-a sample was added with 15 ml of 90% acetone and dissolved until evenly homogenized. The chlorophyll-a sample was transferred into a test tube and stored in a refrigerator at 4°C for 24 h. The chlorophyll-a sample was added with 2-3 ml of 90% acetone and centrifuged at 500 rpm for 1-15 min. Furthermore, the chlorophyll-a sample was transferred to a 1 cm cuvette and analyzed using UV-Vis spectrophotometry with wavelengths of 630, 645, and 665 nm.

Data analysis

Data analysis was conducted using a quantitative approach. The observation data were collected using the stratified random sampling, with specific attention given to the distribution of mangroves (Dewiyanti *et al.,* 2021). Mangrove forest expansion data were analyzed using statistical geospatial analysis with geographical information systems (GIS) to map changes in mangrove forest areas over time. Correlation analysis of bio-physicochemical factors affecting the spatial distribution of mangrove mangroves was conducted by calculating the aggregate value of Euclidean nearest neighbor distance (Toosi *et al.,* 2022; Hilmi *et al.,* 2021). The Euclidean nearest neighbor distance calculation employs a structural equation, which is presented as follows:

$$ED_{jk} = \sqrt{\sum_{i=1}^{s}(xij - xik)^2} \qquad (1)$$

$$D\ (j,k)h = a1\ D(j,h) + a2D(k,h) + \beta D(j,k) \qquad (2)$$

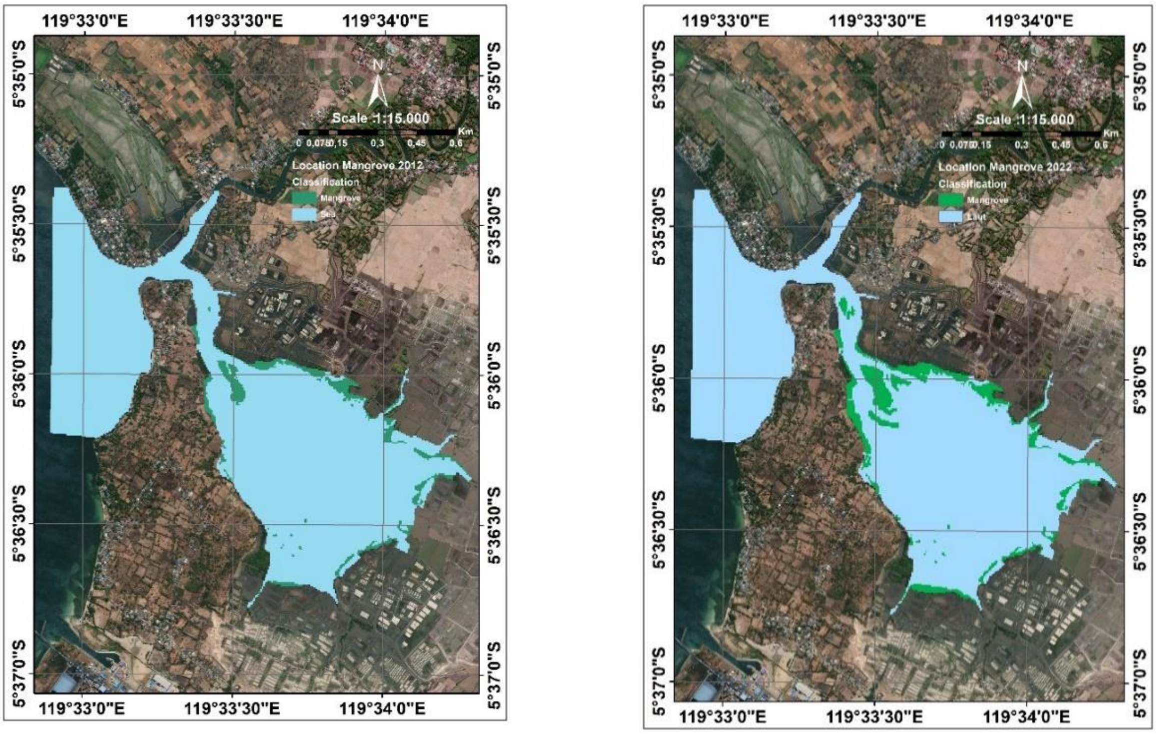
Note: ED_{jk} = Euclidean distance of the bio-physicochemical variables of seawater; i = seawater biophysical and chemical variables; xij = density of j-station; xik = density of the k-station; D= distance; $a1$= equal to 0.625; $a2$= equal to 0.625; β = equal to 0-0.25.

Mapping data obtained from samples through the Euclidean nearest neighbor distance method was analyzed using ArcGIS software version 8.1 In examining the percentage contribution of bio-physicochemical factors behind the expansion of mangrove forests, this research adopts the Maximum Entropy (MaxEnt). Shannon (1948) defines entropy as "a measure of the extent of 'choice' involved in the selection of an event." In this context, distributions with higher entropy levels offer more potential choices. The fundamental principle of the MaxEnt is to ensure that the estimation meets all constraints present at unknown locations. In other words, the estimated probability distribution at unknown locations has fewer limitations but offers a broader array of options (Wang, 2007; Rodríguez-Medina *et al.,* 2020; Das *et al.,* 2022). The structural equation employed in the MaxEnt method is as follows:

$$H\ (\pi) = -\sum_{x \in X} \pi(x) In\pi(x) \qquad (3)$$

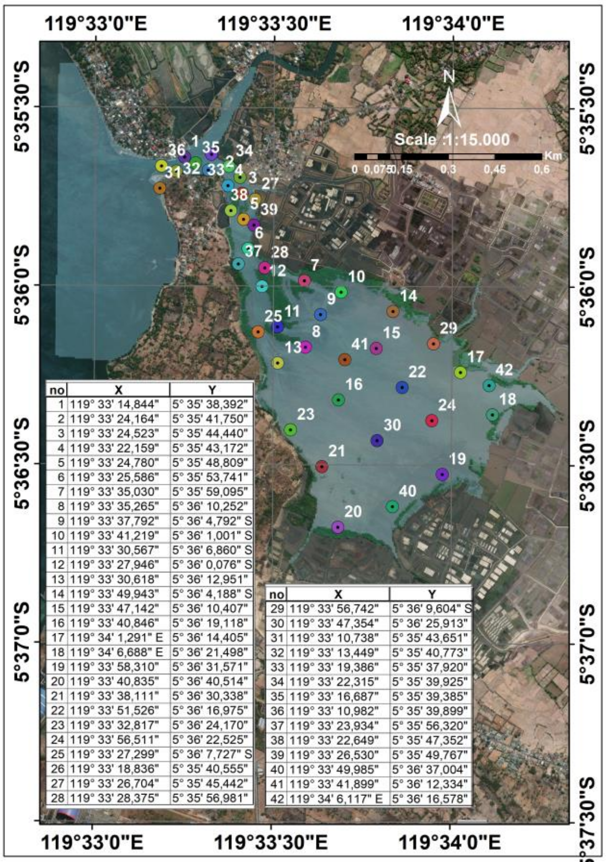
Note: H (π)= Mgen probability distribution; x = set of pixels in the study area; (x) = non-negative probability to each point x.

The sample data used is 75% of the total sample data selected using the random method. The test data used is 25% of the sample data used. The regularization multiplier value used is 0.1 to avoid over-fitting results (Phillips, 2004). The background value used was limited to 5000. Model superiority was measured using the area under the receiver operator curve (AUC). The contribution of each factor driving the expansion of mangrove forests in Laikang Bay was calculated using the Jackknife test. The Jackknife test was used to calculate habitat suitability curves for each variable and systematically eliminate each variable to determine the most relevant variable in assessing the potential distribution of mangrove forests. Mapping of limiting variable was also used to determine which bio-physicochemical variable had



a. 2012 b. 2022

Figure 2. Distribution of Mangrove Ecosystem in Laikang Bay



no	X	Y
1	119° 33' 14,844"	5° 35' 38,392"
2	119° 33' 24,164"	5° 35' 41,750"
3	119° 33' 24,523"	5° 35' 44,440"
4	119° 33' 22,159"	5° 35' 43,172"
5	119° 33' 24,780"	5° 35' 48,809"
6	119° 33' 25,586"	5° 35' 53,741"
7	119° 33' 35,030"	5° 35' 59,095"
8	119° 33' 35,265"	5° 36' 10,252"
9	119° 33' 37,792"	5° 36' 4,792" S
10	119° 33' 41,219"	5° 36' 1,001" S
11	119° 33' 30,567"	5° 36' 6,860" S
12	119° 33' 27,946"	5° 36' 0,076" S
13	119° 33' 30,618"	5° 36' 12,951"
14	119° 33' 49,943"	5° 36' 4,188" S
15	119° 33' 47,142"	5° 36' 10,407"
16	119° 33' 40,846"	5° 36' 19,118"
17	119° 34' 1,291" E	5° 36' 14,405"
18	119° 34' 6,688" E	5° 36' 21,498"
19	119° 33' 58,310"	5° 36' 31,571"
20	119° 33' 40,835"	5° 36' 40,514"
21	119° 33' 38,111"	5° 36' 30,338"
22	119° 33' 51,526"	5° 36' 16,975"
23	119° 33' 32,817"	5° 36' 24,170"
24	119° 33' 56,511"	5° 36' 22,525"
25	119° 33' 27,299"	5° 36' 7,727" S
26	119° 33' 18,836"	5° 35' 40,555"
27	119° 33' 26,704"	5° 35' 45,442"
28	119° 33' 28,375"	5° 35' 56,981"

no	X	Y
29	119° 33' 56,742"	5° 36' 9,604" S
30	119° 33' 47,354"	5° 36' 25,913"
31	119° 33' 10,738"	5° 35' 43,651"
32	119° 33' 13,449"	5° 35' 40,773"
33	119° 33' 19,386"	5° 35' 37,920"
34	119° 33' 22,315"	5° 35' 39,925"
35	119° 33' 16,687"	5° 35' 39,385"
36	119° 33' 10,982"	5° 35' 39,899"
37	119° 33' 23,934"	5° 35' 56,320"
38	119° 33' 22,649"	5° 35' 47,352"
39	119° 33' 26,530"	5° 35' 49,767"
40	119° 33' 49,985"	5° 36' 37,004"
41	119° 33' 41,899"	5° 36' 12,334"
42	119° 34' 6,117" E	5° 36' 16,578"

Figure 3. Sampling location

the most significant influence on the differences in predictions across the study area. The final potential species distribution map had a value range from 0 to 1, which was regrouped into three classes of potential mangrove suitability: high potential (0.62-1.00), medium potential (0.23-0.61), and low potential (0.00-0.22).

Result and Discussion

Euclidean nearest neighbor distance model

The results of the Euclidean nearest neighbor distance model from the results of sampling sites of mangrove forest suitability variables can be seen in Figure 4. The Euclidean nearest neighbor distance model results indicate that the highest concentration of NO_3 in the waters of Laikang Bay is 9.99 mg.L^{-1}, while the lowest concentration is 1.00 mg.L^{-1}. The highest PO_4 content in Laikang Bay is 1.49 mg.100 g^{-1}, and the lowest is 0.1 mg.100 g^{-1}. The kH content in the seawater of Laikang Bay ranges from 178.05 to 356.96 mg.L^{-1}. The salinity content in the seawater of Laikang Bay varies from 15.02 to 26 ppt. The ocean current speed in Laikang Bay ranges from 1.91 to 31.8 m.s^{-1}. The water clarity (D3) values in Laikang Bay range from 0.23 to 62.35 m. The NO_2 values in the seawater of Laikang Bay are in the range of 0.1 to 1.50 g.Nm^{-3}. The pH values in Laikang Bay range from 7.8 to 9, and the Chlorophyll-a content ranges from 0.5 to 1.7 mg.L^{-1}.

Maximum entropy (MaxEnt)

The results of estimating the relative contribution of each variable to the location of mangrove forests can be seen in Table 1. Based on the results of Maximum Entropy (MaxEnt), the variable that most affects the growth of mangrove forests in Laikang Bay is the PO_4 concentration in seawater, with a contribution percentage of 47.4% and a permutation importance value of 36.1%. However, the variable with the lowest influence is the brightness level (D3), with a contribution percentage value of 0.3 % and a permutation importance value of 0.5%.

The relationship of influence between variables in mangrove growth in Laikang Bay can be seen from the results of the Jackknife test in Figure 5. Based on the results of the Jackknife test, PO_4 is in the medium potential class (0.23-0.61), while other variables such as salinity, pH, NO_3, NO_2, kH, current speed, brightness (D3), and chlorophyll-a level are in the low potential class (0.00-0.22). These results indicate PO_4 as the most influential variable for mangrove expansion in Laikang Bay compared to other variables.

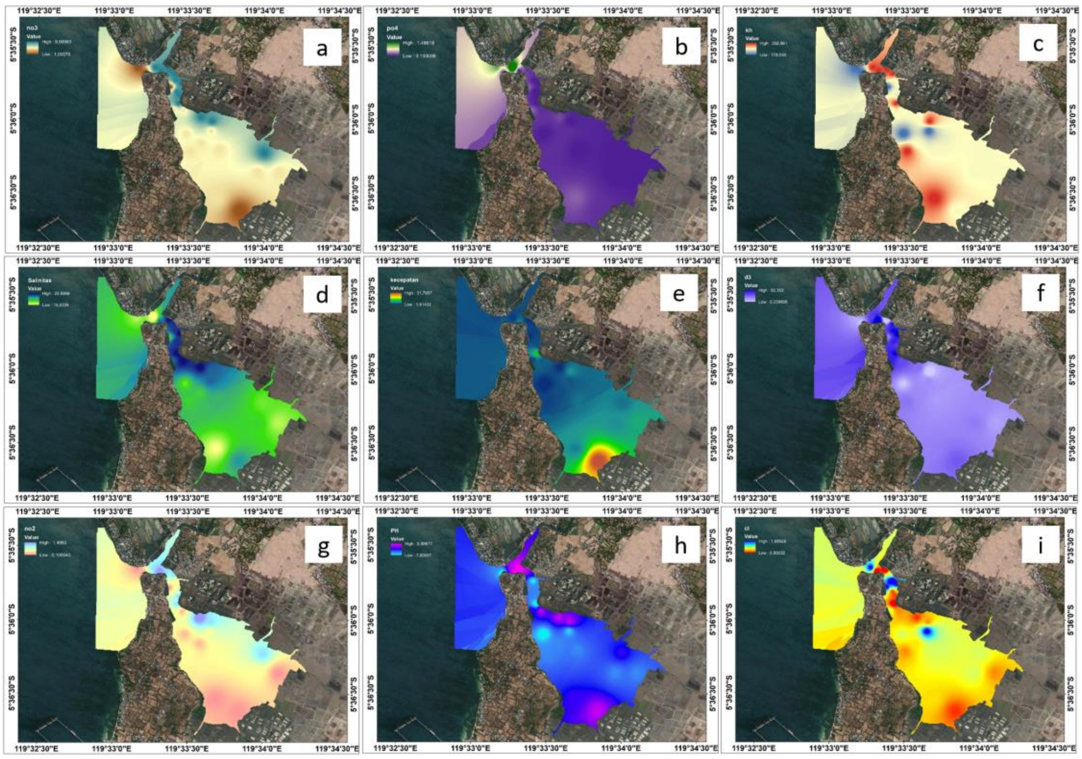


Figure 4. The Euclidean nearest neighbor distance model of a) NO_3, b) PO_4, c) kH, d) salinity, e) current speed, f) brightness, g) NO_3, h) pH, i) chlorophyll-a

Table 1. The contribution value of variables and Their Permutation Importance

Variable	Percent Contribution (%)	Permutation Importance (%)
PO_4	47.4	36.1
Salinity	16.9	0.2
Chlorophyll-a	15	17.2
NO_2	7.8	13.4
Current Speed	4.7	8.4
NO_3	4	14.6
pH	3	6.7
kH	0.9	2.9
Brightness (D3)	0.3	0.5

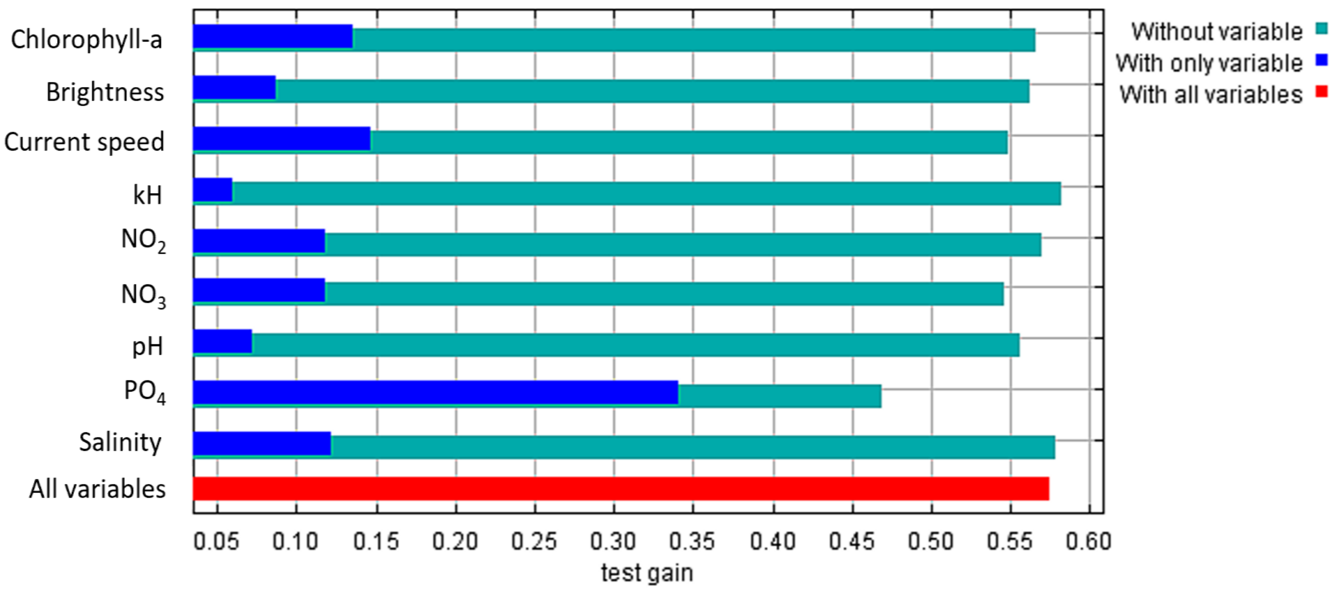


Figure 5. The Jackknife Test for the Contribution of Each Variable to the Model

The results of the AUC test value of 0.793 with the AUC training data value of 0.831 can be seen in Figure 6. These results indicate that the model used in this study has good accuracy and is acceptable. According to Zhang *et al.* (2021), the model performance on MaxEnt is acceptable if $0.8 \leq AUC < 0.9$.

The contribution curves of each variable to mangrove growth in Laikang Bay can be seen in Figure 7. These curves show how each variable affects the MaxEnt prediction. Based on the findings, the areas with the potential for mangrove forest expansion are areas with the characteristics of each variable's concentration, as seen in Table 2.

The condition of mangroves in Laikang Bay predicted in this study from the driving variables can be seen in Figure 8. Figure 8 is a representation of the MaxEnt model for mangrove expansion areas. Warmer colors indicate areas with good water quality for mangrove forest expansion (1-0). The white dots represent the existing locations used for planning, while the purple dots represent the research locations.

Dominant species

In Laikang Bay, the dominant mangrove genus, including *Rhizophora* spp., *Avicennia* spp., and *Sonneratia* spp. (Agustina and Ramli, 2022) adapt to biophysical chemical factors. Such adaptation is essential for mangrove survivability and maintaining the balance of coastal ecosystems. Human activities, sedimentation, and nutrient inputs from river flows also affect mangrove distribution and development (Agustina and Ramli, 2022).

Phosphate (PO_4) contribution to mangrove forest expansion

The waters of Laikang Bay was examined and found that PO_4 levels in this area ranging from 0.10-1.40 $mg.100g^{-1}$. The research findings presented in Figure 7a indicate that mangrove vegetation tends to thrive and expand in areas where PO_4 levels are at the lower end of this range, particularly around 0.1 mg.100 g^{-1}. PO_4 levels contribute significantly to the suitability of the mangrove ecosystem, with a contribution of 47.4% compared to other variables. Figure 4 demonstrates that areas adjacent to urban villages have high PO_4 levels, while lower PO_4 values are observed around salt ponds. These results suggest that mangrove vegetation flourishes in water areas with low PO_4 levels, approximately 0.10 mg.100g^{-1}, or regions more distant from human settlements.

Supriyantini *et al.* (2018) emphasized the importance of phosphate for the growth of mangroves. The research findings suggested that when the phosphate content in the water is higher, there is a decrease in mangrove vegetation. Excessive phosphate levels can lead to eutrophication (Kumararaja *et al.,* 2019). Eutrophication can be a trigger for algal bloom (Abbas *et al.,* 2023). These algal blooms can result in reduced dissolved oxygen levels in the seawater, a deterioration in seawater quality, and a decrease in biodiversity (Kumararaja *et al.,* 2019; Lin *et al.,* 2020).

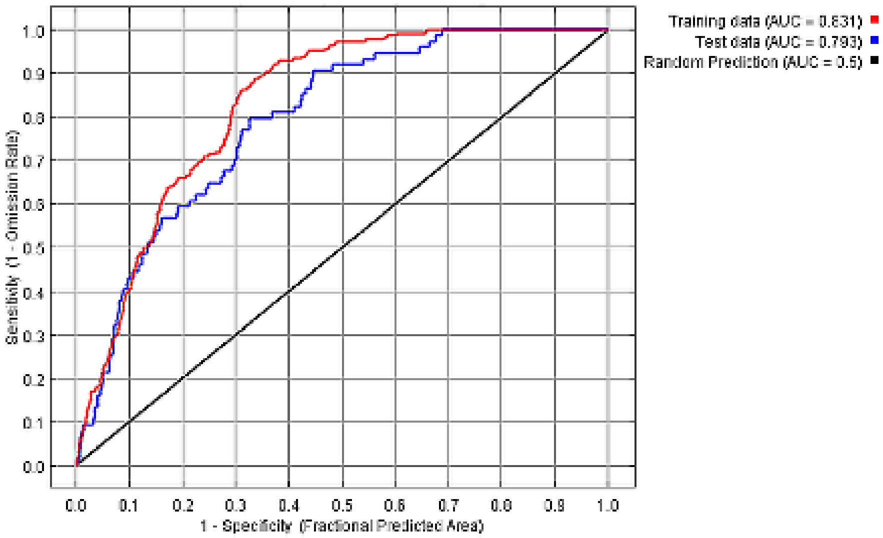


Figure 6. AUC Accuracy Model

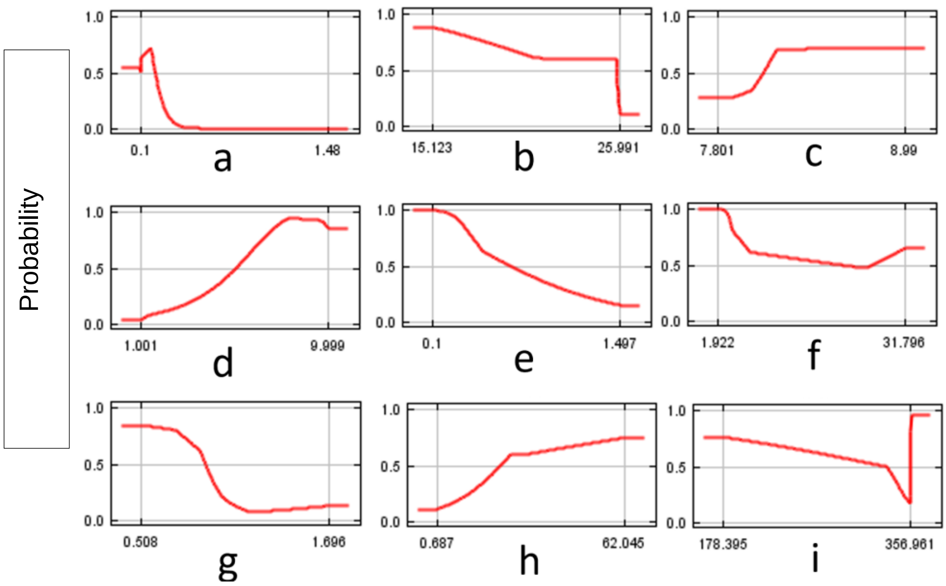


Figure 7. The response curve for the influential variables in the MaxEnt model for the growth and expansion of mangrove forest in Laikang Bay, a) PO_4 (mg.100g^{-1}), b) Salinity (ppt), c) pH, d) NO_3 (mg.L^{-1}), e) NO_2 (g.Nm-3), f) Current speed (m.s^{-1}), g) Chlorophyll-a (mg.L^{-1}), h) Brightness (D3) (m), i) kH (mg.L^{-1})

Table 2. The results of the concentration range of each variable that supports the expansion of mangrove forests

Variable contribution	Concentration
PO_4	0.10 - 0.20 mg.100g^{-1}
Salinity	14 - 15 ppt
Chlorophyll-a	0.4 - 0.8 mg g^{-1}
NO_2	0.1 – 0.2 gNm^{-1}
Current Speed	0.1 – 2.58 m.s^{-1}
NO_3	8.00 – 9.00 mg.L^{-1}
pH	8.20 - 9.00
kH	360 - 380 mg.L^{-1}
Brightness (D3)	60 - 62.35 m

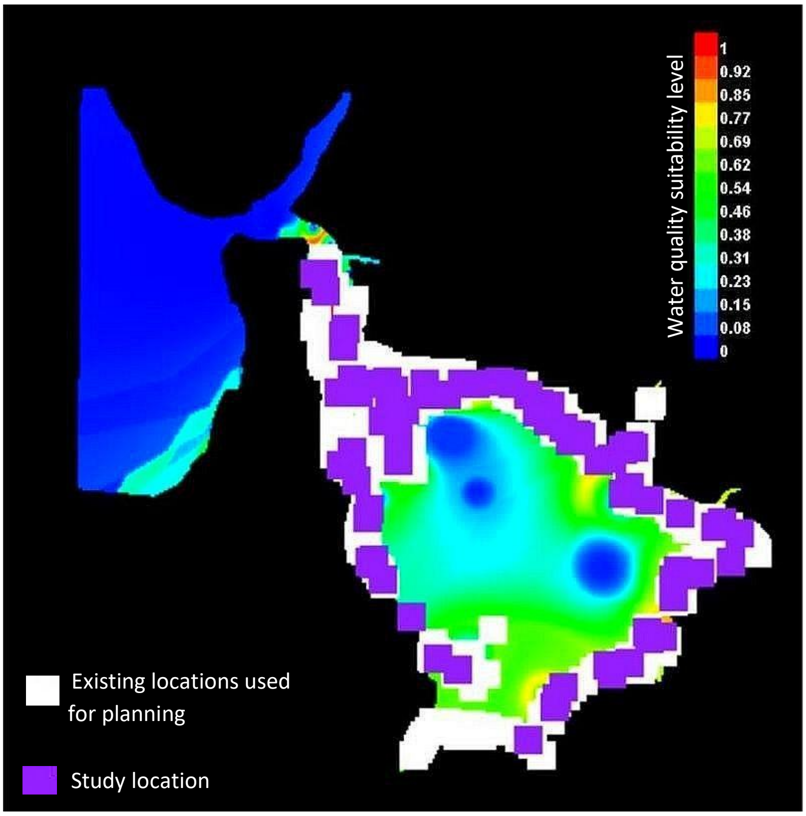


Figure 8. Predictions of mangrove forest expansion site in Laikang Bay as influenced by all water quality variables

PO_4 (phosphate) content is the most crucial factor in the growth and expansion of mangrove forests because it is an essential nutrient for various biological processes, especially photosynthesis and tissue growth. PO_4 is the macronutrient most needed by plants for the synthesis of ATP (adenosine triphosphate) in the formation of nucleic acids and cell membranes (Ahmed *et al.,* 2023). Adequate phosphate availability can greatly affect the rate of plant growth and expansion of vegetation areas, especially in environments rich in organic matter, such as Laikang Bay.

In many mangrove ecosystems, phosphate is often a limiting factor. It means that even if other bio-physicochemical factors such as salinity, pH, and temperature are at an optimal range and well collaborated, mangrove forest expansion can still be limited if phosphate availability is poor (Sun *et al.,* 2023). Conversely, sufficient phosphate will spur biomass production and mangrove root development, ultimately favoring forest expansion. Phosphates can also interact with microorganisms in mangrove sediments, such as bacteria and fungi, which help break down organic materials and release nutrients into a form that plants more easily absorb (Wainwright *et al.*, 2023).

Each location has unique bio-physicochemical characteristics. In Laikang Bay, other physical conditions can already support mangrove growth, making the variability in phosphate content more significant than other factors. Phosphate supports plant growth by accelerating the uptake of other necessary nutrients, such as nitrogen. In the Laikang Bay area, the phosphate that may come from natural or anthropogenic sources (such as agricultural runoff) can increase the fertility of the soil around the mangroves (Zhao *et al*., 2019). This condition accelerates the rate of mangrove colonization and growth in new areas.

Salinity contribution to mangrove forest expansion

In our study, the waters of Laikang Bay exhibited a range of salinity levels, with values ranging from 15.00–26 ppt. Figure 7b illustrates that mangrove vegetation predominantly thrived and expanded in areas with lower salinity levels (<15.02 ppt). Moreover, the study identified that the salinity levels played a significant role, contributing to 16.9% of the suitability for mangrove habitat. These findings align with the research Kodikara *et al.* (2018), which demonstrated that mangrove seedlings growing in high-salinity seawater exhibited notably reduced performance ($P<0.05$). This reduction was observed in various aspects, including survival rate, cumulative shoot height, average growth rate, average total leaf area, and average dry weight, compared to water with moderate and high salinity levels (Ahmed *et al.,* 2023; Kodikara *et al.,* 2018).

pH contribution to mangrove forest expansion

In our study, the waters of Laikang Bay exhibited pH levels ranging from 7.8–9.0. Figure 7c shows that mangrove vegetation develops and spreads over waters with high pH levels (pH >8.20). Furthermore, in Table 1, the pH level shows a relatively low contribution value (3%) in influencing the expansion of mangrove forests compared to other variables. These findings suggest that pH levels have a limited impact on the suitability of mangrove ecosystems. Nevertheless, based on the pH values, it can be inferred that mangroves can thrive within a range of neutral to alkaline pH levels. Seawater with an alkaline pH can accelerate bacterial growth and decomposition of organic matter needed for mangrove ecosystems (Widawati *et al.,* 2022). According to Jayachandran *et al.* (2018), the high pH level of seawater can decrease the harmful effects of heavy metals like Cu, thereby promoting improved growth of mangroves.

Nitrate (NO_3) contribution to mangrove forest expansion

In our study, the waters of Laikang Bay displayed a range of NO_3 (nitrate) levels, ranging from 1.00–10.00 mg.L^{-1}. As demonstrated in Figure 7d, mangrove vegetation thrives and expands in areas characterized by high NO_3 levels (8.00–9.00 mg.L^{-1}). Furthermore, in Table 1, the NO_3 level shows a low contribution value (4%) in influencing the expansion of mangrove forests compared to other variables. These results suggest that NO_3 levels have a limited impact on the suitability of mangrove ecosystems. However, based on the NO_3 values, it can be concluded that mangroves tend to thrive in environments with higher NO_3 levels.

The process of nitrification can impact the availability of necessary nitrate in the sediment of mangrove soil. Nitrifying bacteria convert the ammonium (NH_4^+) content in the sediments into nitrate (NO_3^-) (Taillardat *et al.,* 2020). Because the supply of nitrate in mangrove sediments is limited, the reduction of nitrate is considered a minor microbial pathway in the breakdown of organic matter derived from mangroves. Therefore, NO_3 levels will be higher in locations around mangrove vegetation. The sites with high NO_3 levels can be seen in Figure 4.

According to Alongi (2018), excessive levels of NO_3 in mangrove sediments can adversely affect the ecosystem's balance. Rapid increase in nitrate levels can trigger algal blooms (Wadnerkar *et al.,* 2019). This situation leads to a competition for nutrients between algae and mangrove roots, impacting the availability of dissolved oxygen and other essential nutrients. Moreover, algal blooms can heighten sedimentation, causing deposited solid particles to obstruct the roots' absorption (Wang *et al.,* 2023).

Nitrogen Dioxide (NO_2) contribution to mangrove forest expansion

In our study, the waters of Laikang Bay displayed a range of NO_2 (nitrogen) levels, ranging from 0.1 g.Nm^{-3} – 1.49 g.Nm^{-3}. As demonstrated in Figure 7e, mangrove vegetation thrives and expands in areas characterized by low NO_2 levels (0.1–0.2 g.Nm^{-3}). Furthermore, in Table 1, the NO_2 level shows a low contribution value (7.8%) in influencing the expansion of mangrove forests compared to other variables. These results suggest that NO_2 levels have a limited impact on the suitability of mangrove ecosystems. However, based on the NO_2 values, it can be concluded that mangroves tend to thrive in environments with lower NO_2 levels.

The nitrogen cycle in the soil involves a series of intricate transformation processes. These processes are primarily carried out by specialized groups of bacteria and archaea, such as ammonium oxidizers, cyanobacteria, nitrate reducers, and nitrite oxidizers. The nitrogen cycle encompasses various pathways of oxidation and reduction in both oxygen-rich and oxygen-deficient environments, especially in marine sediments and waterlogged saline soils. Multiple factors, including temperature, soil fertility, microbial community composition, plant metabolic processes, root activity, bioturbation, intertidal location, and salinity, influence microbial nitrogen metabolism activity. Alongi (2020) observed other bacterial and archaeal groups responsible for nitrogen modification in mangrove soils. However, data on the rates of methane denitrification, nitrite oxidation, and phototrophic nitrate oxidation were not available in the study.

Based on the system assessment, NO_2 emissions are expected to increase from 20% to 51% by 2030 and from 27% to 74% by 2050. These projections underscore the importance of improving nitrogen capture management strategies (Mao *et al.,* 2021). Mangroves are reported to be able to sequester anthropogenic nitrogen and other heavy metals. This ability allows mangroves to act as a barrier in protecting marine ecosystems from terrestrial contaminants (Lugendo and Kimirei, 2021).

Current speed contribution to mangrove forest expansion

In our study, the waters of Laikang Bay showed ocean current speeds ranging from 0.1–31.76 $m.s^{-1}$. As shown in Figure 7f, mangrove vegetation thrived and extended over areas characterized by low current speeds (0.1–2.58 $m.s^{-1}$). Furthermore, in Table 1, the current speed shows a relatively low contribution value (4.7%) in influencing mangrove forest expansion compared to other variables. However, referring to the current speed, it can be concluded that mangroves can grow better at low current speeds. The existence of mangrove forests influences the low speed of the current, which becomes a barrier to the current on the coast.

These results are supported by Chang *et al.* (2019) research, which showed the prevalence of low current speeds along the vertical profile within the mangrove forest. The vertical profile analysis revealed a consistent reduction in speed as the height above the mangrove base increased. This pattern is due to the vertical increase of the inhibition force by the tree trunk and canopy on the ocean's current speed.

Chlorophyll-a contribution to mangrove forest expansion

In our study, Laikang Bay waters showed chlorophyll-a contents ranging from 0.5–1.7 $mg.L^{-1}$. As shown in Figure 7g, mangrove vegetation thrives and expands in areas with chlorophyll-a content ranging from 0.6 to 0.8 $mg.L^{-1}$. Furthermore, in Table 1, chlorophyll-a levels show a low contribution value (15%) in influencing mangrove forest expansion compared to other variables. These results suggest that chlorophyll-a levels have a limited impact on the suitability of mangrove ecosystems.

In photosynthesis, chlorophyll-a is a phytoplankton pigment that plays an important role (Mancheño *et al.,* 2021). It is considered the primary photosynthetic pigment to distribute the absorbed light energy for photosynthesis. The chlorophyll-a concentration in the seawater can indicate water fertility for mangrove growth. In addition, chlorophyll-a concentration can be used to estimate primary productivity, which is the amount of organic matter produced by autotrophic organisms with the help of sunlight, usually through photosynthesis. Therefore, chlorophyll-a is an important pigment that can maintain estuaries and mangrove ecosystems (Utami *et al.,* 2021; Salma *et al.,* 2022)

Brightness (D3) contribution to mangrove forest expansion

In our study, the waters of Laikang Bay showed brightness values (D3) ranging from 0.23 to 62.35 m. As shown in Figure 7h, mangrove vegetation thrives and expands in areas with brightness values ranging from 60 to 62.35 m. Furthermore, in Table 1, the brightness value shows a low contribution value (0.3%) in influencing the extent of mangrove forest compared to other variables. This result indicates that the brightness value has a limited impact on the suitability of the mangrove ecosystem.

Brightness (D3) derived from sunlight exposure significantly contributes to the mangrove photosynthesis process. Sunlight exposure can impact the sea water temperature. The intensification of sunlight exposure due to deforestation can elevate the sea surface temperature, leading to oxidative stress and harm to plant tissues (da Silva and Maiab, 2022). Conversely, diminished sunlight exposure can lower the sea surface temperature, thereby impeding photosynthesis and hindering the dispersal of mangrove seedlings through seawater (Ximenes *et al.*, 2018). Consequently, human intervention to provide 50% shading becomes imperative for the growth of seedlings and the rejuvenation of deforested regions (da Silva and Maiab, 2019).

Potassium Hydride (kH) contribution to mangrove forest expansion

In our study, the waters of Laikang Bay showed kH concentrations ranging from 178.05 to 356.96 $mg.L^{-1}$. As shown in Figure 7i, mangrove vegetation thrives and expands in areas with kH concentrations ranging from 360 to 380 mg.L^{-1}. Furthermore, in Table 1, KH concentration showed a low contribution (0.9%) in influencing mangrove forest area compared to other variables. This result indicates that kH concentration has minimal impact on mangrove ecosystem suitability.

kH (carbonate hardness) or carbonate hardness is commonly referred to as alkalinity, meaning the ability of water to bind acidity (ions capable of binding H^+). Alkalinity refers to the water's capacity to neutralize acids, also known as Acid Neutralizing Capacity (ANC). It is characterized as the presence of anions (-) in water that can counterbalance the cations (+) of hydrogen (Qomariyah *et al.*, 2021). Alkalinity can also be described as the water's ability to resist changes in acidity (pH). Various ions, including bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), hydroxide (OH^-), sulfide (HS^-), silicate (HSiO), ammonia (NH_3), borate and phosphate $(PO_4)^{3-}$ ions, can contribute to the alkalinity of water (Huljani and Rahma, 2019). Among these ions, hydroxide, carbonate, and bicarbonate are the primary contributors to alkalinity and are commonly present in water (Mashadi *et al.,* 2018).

Alkalinity plays a crucial role in determining water's capacity to support the growth of algae and other aquatic life forms. Elevated levels of alkalinity often lead to increased water hardness. Soil acidity is influenced by the chemical alteration of various nutrients. The majority of mangrove sediments act as effective buffers, maintaining a pH level typically ranging from 6 to 7 (Nath *et al.,* 2013; Mei *et al.,* 2020).

Bio-physicochemical factors are essential in supporting the growth and distribution of mangrove forests. Mangroves have a unique tolerance to extreme environmental conditions, such as high salinity and low oxygen levels in muddy soils. These bio-physicochemical variables interact complexly to create conditions promoting optimal growth. In coastal ecosystems, bio-physicochemical factors interact and often affect mangrove growth synergistically. For example, although PO_4 content is significant in supporting mangrove growth, too high salinity or inappropriate pH can inhibit nutrient uptake and reduce phosphate effectiveness (Kammann *et al.*, 2022; Yurek *et al.*, 2023) Therefore, it is essential to understand the correlation between all these factors, as they do not function in isolation but work in a complex and dynamic manner

This study provides an in-depth insight into how environmental variables interact to support mangrove growth. The significant influence of phosphate content, interactions with other biophysicochemical factors such as salinity and pH, and human activities contribute to a better understanding of this coastal ecosystem. This research is vital for conservation strategies locally in Laikang Bay and for the global interest in mangrove conservation. This research also contributes to the global understanding of mangrove ecosystem dynamics. Due to climate change and human activities, coastal ecosystems worldwide are under increasing pressure. Results from the Laikang Bay study may provide important insights that can be applied to other coastal areas, particularly in Southeast Asia and other tropical regions.

Conclusion

The rapid growth of the mangrove forest in Laikang Bay can be attributed to various bio-physicochemical factors. Among these factors, the highest contributor to the growth is the PO_4 content in seawater. On the other hand, the levels of brightness and kH content contribute the least. These results indicate the increasing trend of mangrove forest in Laikang Bay. It is necessary to maintain the levels of these influential factors. For future research, it is advisable to prioritize the study of additional factors, such as water current patterns, human activities, soil quality, and fluctuations in water temperature, to assess their external influence on the expansion of the mangrove forests in Laikang Bay. Furthermore, the diversity of mangrove species might have an impact on the ecology they form. As a result, it is critical to analyze and compare the seawater quality within each variety of mangroves in its ecosystems.

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