EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(2), 109–124
https://doi.org/10.12912/27197050/216574
ISSN 2719–7050, License CC-BY 4.0

Received: 2025.12.14
Accepted: 2026.01.18
Published: 2026.02.07

Spatial modelling of coral reefs habitat under climate scenario in coral triangle area of East Java

Maulinna Kusumo Wardhani[1], Herlambang Aulia Rachman[1*], Zainul Hidayah[1], Achmad Fachruddin Syah[1], Dedi Irawan[1], Abd. Rahman As-syakur[2]

[1] Department of Marine Science and Fisheries, Faculty of Agriculture, University of Trunojoyo Madura, Jalan Raya Telang No 02, Kamal – Bangkalan, East Java 69162, Indonesia
[2] Department of Marine Science, Faculty of Marine and Fisheries, Udayana University, Bukit Jimbaran Campus, Bali 80361, Indonesia
* Corresponding author's e-mail: herlambang.rachman@trunojoyo.ac.id

ABSTRACT

Coral reef ecosystems within the Coral Triangle (CT) represent global biodiversity hotspots but are increasingly threatened by climate change and anthropogenic pressures. This study was purposes to assess the current and future condition spatial distribution of coral reef habitat suitability in the Kangean Archipelago, East Java, Indonesia, located at the westernmost boundary of the CT areas. Coral reef occurrence data were integrated with ten key oceanographic and biogeochemical variable using a maximum entropy (MaxEnt) modelling framework. Habitat suitability was evaluated under present environmental conditions and projected climate conditions for 2050 based on the low-emission Shared Socioeconomic Pathways (SSP) 1-1.9 scenario from Intergovermental Panel of Climate Changes (IPCC) Sixth Assessment Report (AR6). Model performance was robust, achieving an area under the curve (AUC) value of 0.775. The results identified four primary drivers of coral reef habitat suitability based on their relative importance: seawater pH (21.1%), current velocity (16.7%), sea surface temperature (15.6%), and chlorophyll-a concentration (14.6%). Under current conditions, areas classified as very suitable and suitable cover a total of 31,521.14 ha (7.98%) and 58,772.96 ha (14.89%), respectively. These areas are primarily distributed around Raas Island, eastern Kangean Island, and the Sepanjang Archipelago. However, future projection reveal a pronounced decline in habitat suitability, with more than 90% of the study area shifting to the not suitable category by 2050, even under this optimistic climate scenario. These findings highlight the high vulnerability of coral reefs in East Java to climate-driven oceanographic changes and emphasize the urgent need to prioritize remaining suitable habitats as climate refugia within marine spatial planning and adaptive conservation strategies.

Keywords: coral reefs, maximum entropy, Coral Triangle, oceanographic variables, climate changes.

INTRODUCTION

Coral reef ecosystems serve as critical habitats for foraging, breeding, and nursery grounds for numerous marine organisms, while also contributing substantially to the local economy and coastal resilience (McClanahan et al., 2002; Viehman et al., 2023). The ecological and economic values of these reefs highlight their role as vital natural resources for sustaining both biodiversity and human livelihoods. Coral reefs are some of the most susceptible coastal ecosystems and exhibit significant sensitivity to alterations in their environmental conditions (Foster and Attrill, 2021; Hoegh-Guldberg, 2010; Mentzel et al., 2024). Climate change effects, including elevated sea surface temperature and ocean acidification, might impair coral reefs by decreasing calcification rates, thereby limiting their capacity to generate calcium carbonate (Kleypas et al., 2005; Kleypas and Yates, 2009; Lam et al., 2019). Moreover, anthropogenic influence including coastal development, terrestrial pollution, and many deleterious human activities can exacerbate the destruction of coral reef ecosystems. In Indonesia, shifts in coral composition and reef decline have been observed across multiple sites, reflecting the combined stress of climate and human-driven disturbances (Januar et al., 2023).

The Kangean Islands are situated in the waters east of Java Island and west of Bali Island. The Kangean Islands are administratively included in East Java Province, despite their separation from the main island of Java. This location is located inside the Coral Triangle (CT) region, marking the westernmost edge of the CT. The CT is internationally acknowledged as a critical marine biodiversity hotspot, encompassing over five hundred species of reef-building corals and providing essential support to millions of coastal communities through fisheries, tourism, and coastal protection services (Hughes et al., 2017; Veron et al., 2009). The CT region spans the middle area of Indonesia to Papua New Guinea, covering over seven countries. The westernmost tip of the CT is located in East Java Province and is part of the Makassar Strait ecoregion (Veron et al., 2011). The nearest location of the CT to the mainland of Java Island is the Kangean Archipelago. Java Island is recognised as one of the most densely populated islands globally, characterised by a significant degree of human activity (Liu and Yamauchi, 2014; White, 2023). This condition results in human-induced stresses that may endanger coastal ecosystems, particularly coral reefs.

However, coral reefs are highly vulnerable to environmental stressors, particularly under the growing impacts of global climate change (Mumby and Van Woesik, 2014). Increasing concentrations of atmospheric greenhouse gasses have driven significant warming of the oceans and intensified ocean acidification, both of which impose severe physiological stress on reef-building corals (Bove et al., 2022). Elevated sea surface temperatures disrupt the symbiotic relationship between corals and their zooxanthellae, often resulting mass coral bleaching events that reduce coral growth, reproductive capacity, and survival (Khalil et al., 2023). Concurrently, ocean acidification lowers seawater pH and carbonate ion availability, thereby diminishing calcification rates and weakening the structural integrity of coral calcium carbonate skeletons (Doney et al., 2009; Guinotte and Fabry, 2008). Additionally, anthropogenic pressures such as coastal development, land-based pollution, and destructive fishing practices exacerbate reef degradation, altering coral community structures and threatening long-term ecosystem stability (Edinger et al., 1998; Hughes et al., 2003).

To address these multifaceted challenges, scientific approaches that integrate climate projections with spatial ecological modelling have become increasingly essential for informing effective coral reef conservation and management strategies. By coupling present-day environmental conditions with future climate scenarios, such approaches enable the assessment of habitat suitability, vulnerability, and potential spatial shifts in reef ecosystems under changing climatic regimes (Freeman et al., 2013; Januar et al., 2023; Shen et al., 2026). Species distribution models (SDMs) provide a robust and widely adopted framework for predicting the geographic distribution of species and habitats by quantifying relationships between biological occurrences and environmental drivers (Elith and Leathwick, 2009; Benson et al., 2017). In coral reef studies, SDMs are particularly valuable for identifying areas of persistence, contraction, or expansion under both current and projected environmental conditions (Yuen et al., 2023). Among the available SDM techniques, the maximum entropy (MaxEnt) model has emerged as one of the most commonly applied tools for modelling marine biota (Anderson et al., 2016; He et al., 2022; Tong et al., 2023). Its ability to effectively utilize presence-only data makes it especially suitable for coral reef research, where absence data are often unreliable or unavailable. Furthermore, MaxEnt has demonstrated strong predictive performance even with limited occurrence records, while offering clear measures of variable importance and response curves that enhance ecological interpretability (Bedia et al., 2011; Kramer-Schadt et al., 2013; Srivastava et al., 2019).

In this study, spatial modelling of coral reef habitat suitability in East Java, a strategically important region within the CT, is conducted under both present-day environmental conditions and projected future climate scenarios for the year 2050. Future projections are derived from the Shared Socioeconomic Pathway (SSP) 1–1.9, as presented in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). This pathway represents a strong global mitigation scenario characterized by rapid reductions in greenhouse gas emissions, sustainable development trajectories, and limited global warming, making it broadly comparable to the Representative Concentration Pathway (RCP) 2.6 scenario from the IPCC Fifth Assessment Report (AR5) (Bodeker et al., 2022; Riahi et al., 2017). While previous studies have examined coral reef responses to climate changes at broader regional scales, there is still limited knowledge on how future environmental changes will specifically alter the spatial distribution and suitability of coral reef habitats in East Java. This study addresses that gap by integrating oceanographic, climatic, and biogeochemical variable to evaluate how habitat suitability may shift over time, identify potential areas of habitat loss and climate refugia and assess the influence of key environmental drivers. The purpose of this research is to generate new spatial evidence on projected coral reef habitat dynamics under a strong mitigation scenario, with the expectation that warming and changing environmental conditions will reduce suitability in vulnerable zones while allowing some areas to remain stable. The findings are intended to support climate-adaptive conservation planning, marine spatial management, and policy development in East Java and the wider CT region.

MATERIAL AND METHODS

Study location

This study focuses on the area of the CT region that lies within the jurisdiction of East Java Province, commonly referred to as the Kangean Islands. These island groups, administratively part of Sumenep Regency, are identified as being within the CT region based on the CT map defined by (Veron et al., 2009). According to CT map, the area is classified within the Makassar Strait zone, located at the southwestern boundary of the CT. Geographically, the Kangean Islands are situated at the easternmost part of Java Island and to the north of Bali Island. Major islands within this cluster include Kangean, Sapudi, Raas, Poteran, and Sepanjang, along with approximately more than 20 smaller islands (Figure 1). Previous studies have reported that coral reef cover in this region remains relatively healthy and is distributed across the islands (Handoko et al., 2025; Rizal et al., 2022). From an oceanographic perspective, this area is also influenced by the Indonesian throughflow (ITF), with water masses flowing from the Makassar Strait toward the Lombok Strait (Gordon and Fine, 1996).

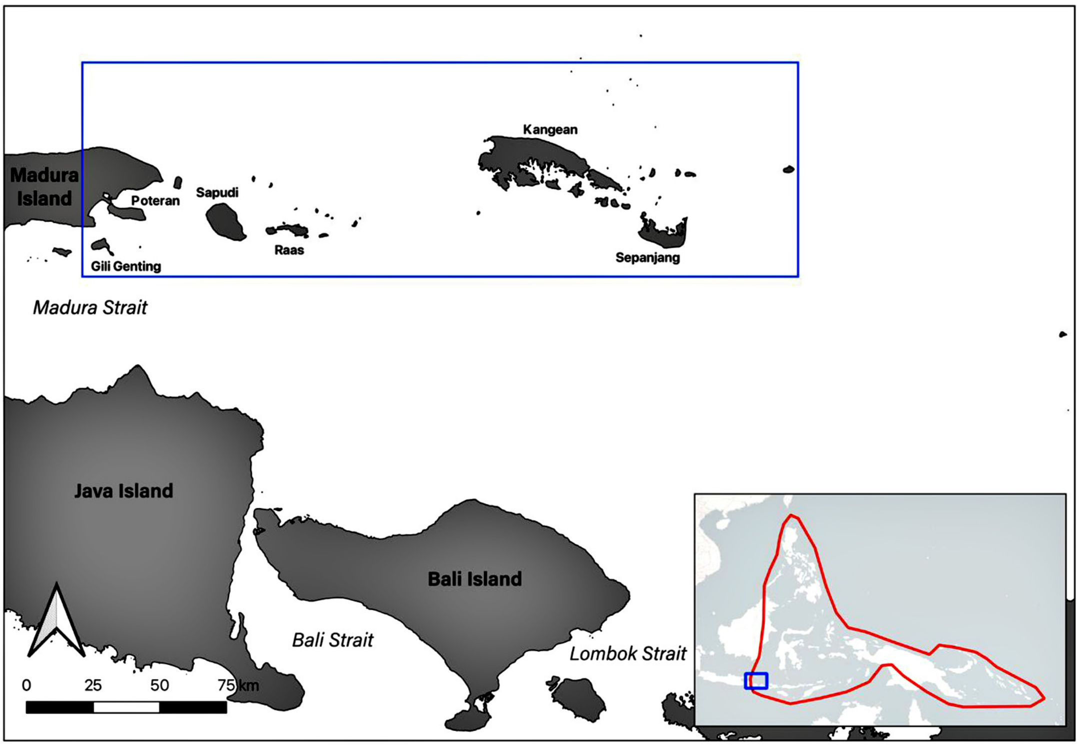


Figure 1. Study location in CT area of East Java, Indonesia

Material

Distribution of coral reef

The research focuses on predicting the geographical distribution of coral reefs in relation to various environmental factors, with the objective of understanding their present condition and potential future distribution under different climate scenarios. The modelling method aims to establish a baseline for current reef distribution and predict possible alterations or reductions in these ecosystems due to environmental changes, such as variations in sea surface temperature, ocean acidification, and other climate-related events. To build a solid and reliable model, it is vital to have accurate and high-resolution spatial data on coral reef distribution in the study area. The main source of this information is the Allen Coral Atlas (https://allencoralatlas.org), which is a global collection made up of high-resolution satellite images from PlanetScope and PlanetDove. The spatial distribution of coral reef data in this study is derived from satellite image analysis that integrates multi-resolution imagery using an object-based analysis (OBA) approach and machine-learning classifications, informed by input data provided by multiple domain experts (Lyons et al., 2020). This analysis produced a unified spatial dataset of benthic habitats (including coral reefs), which was subsequently used as model input. We also conducted a comparative assessment with several external data sources, including the Global Biodiversity Information Facility (GBIF) and the Ocean Biodiversity Information System (OBIS), using records corresponding to selected hard coral (Scleractinia) taxa distributed across Indonesia. However, the availability of GBIF and OBIS data in the form of point-based coordinates was limited and insufficient to support robust model development. Therefore, additional enrichment was carried out using a more comprehensive dataset, namely the Allen Coral Atlas. The spatial distribution of coral reef ecosystem cover within the study area is presented in Figure 1. For model construction, the spatial dataset was required to be converted into point-sample data, which served as input for the Maximum Entropy (MaxEnt) modelling process. The polygon-based coral reef features were converted into random point samples using QGIS software.

Environmental parameters

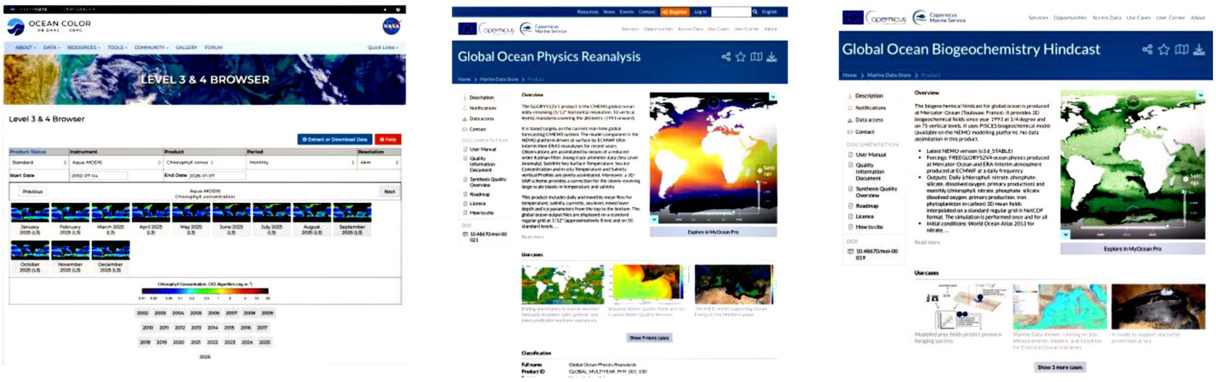
Coral reefs are among the ecosystems most vulnerable to changes in environmental parameters. According to numerous studies, the distribution of coral reefs is strongly influenced by factors such as sea surface temperature, salinity, nutrient levels, dissolved oxygen, pH, and ocean current velocity (Januar et al., 2023; Li et al., 2024; Shen et al., 2026). In addition, indicators of water fertility such as chlorophyll-a concentration and primary productivity are also included as critical parameters. In this study, several datasets used as inputs for developing the model were obtained from various sources, particularly those representing current and future environmental conditions. The complete list of environmental parameters used in this study, along with their corresponding data sources, is presented in Table 1.

For the present-condition analysis, three primary data sources were employed, consisting of reanalysis and numerical modelling products from Marine Copernicus and satellite-derived datasets from MODIS through the Ocean Color program. All environmental variables were processed as multi-year averages covering the period 2020–2024, which corresponds to the temporal range of the benthic habitat occurrence records obtained from the Allen Coral Atlas. This temporal alignment ensures consistency between environmental inputs and species occurrence data used in the modelling process. Sea surface temperature (SST) and chlorophyll-a data were derived from moderate resolution imaging spectroradiometer (MODIS) Ocean Colour products, accessible at the following website https://oceandata.sci.gsfc.nasa.gov/l3/ (Figure 2a). The data used in this research represent the one-year climatological average for 2020 to 2024 with a spatial resolution of 4 km (Level 3 data).

Salinity and current velocity data were obtained from Marine Copernicus, specifically from the Global Ocean Physics Reanalysis (GLORYS12V1) dataset, which is a reanalysis product with a spatial resolution of 1/12°. This dataset results from data assimilation performed using the Nucleus for European Modelling of the Ocean (NEMO) numerical model platform, combined with satellite observations, including altimetry and optical sensors. Detailed documentation of this model product can be found at: https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description (Figure 2b).

Table 1. List of environmental parameters used in developing the coral reef habitat suitability model

Data	Sources	
	Current	SSP 1.19 (2050)
Sea Surface Temperature	MODIS Ocean Color Sources : https://oceandata.sci.gsfc.nasa.gov/l3/	BIO-ORACLE V3.2 Environmental Project Sources : https://bio-oracle.org/downloads-to-email.php
Chlorophyll-a Concentration		
Current Velocity	GLORYS12V1 Reanalysis data from Marine Copernicus Sources : https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/description	
Salinity		
Dissolve Oxygen	Biogeochemical Hindcast (PISCES-NEMO) from Marine Copernicus Sources : https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_BGC_001_029/description	
Phosphate		
Primary Productivity		
Nitrate		
Silicate		
pH		



a b c

Figure 2. Capture of each environmental parameter were obtained from (a) MODIS Ocean Colour; (b) GLORYS12V1 from Copernicus Marine Service; and (c) Global Ocean Biogeochemistry from Copernicus Marine Service

For several biogeochemical parameters, such as dissolved xygen (DO), nutrient levels (nitrate, phosphate, and silicate), and water fertility indicators (primary productivity and Chlorophyll-a), we used biogeochemical hindcast model data from Marine Copernicus. This model is based on the Pelagic Interaction Scheme for Carbon and Ecosystem Studies (PISCES) biogeochemical platform within the NEMO framework (Figure 2c). The dataset has a spatial resolution of 0.25°, available in both monthly and daily formats. In this study, we used the multiyear average from 2020–2024. The averaging processes for all datasets described above were conducted using the Climate Data Operators (CDO) platform.

For modelling future scenarios, we used datasets corresponding to the same environmental variables applied in constructing the current-condition model. To generate projections of future coral reef distribution, we employed data from BIO-Oracle version 3.2 (https://bio-oracle.org), which provides ensemble environmental parameter outputs derived from the Coupled Model Intercomparison Project Phase Six (CMIP6) (Figure 3). These datasets are integrated with the Shared Socioeconomic Pathway (SSP) framework, allowing the incorporation of both biophysical and socioeconomic dimensions of future climate conditions. Further details on how these data were generated can be found in the following research outputs (Assis et al., 2024). In this study, the projections were based on the SSP1-1.9 scenario for the year 2050. The SSP1-1.9 pathway reflects a sustainability-oriented development trajectory

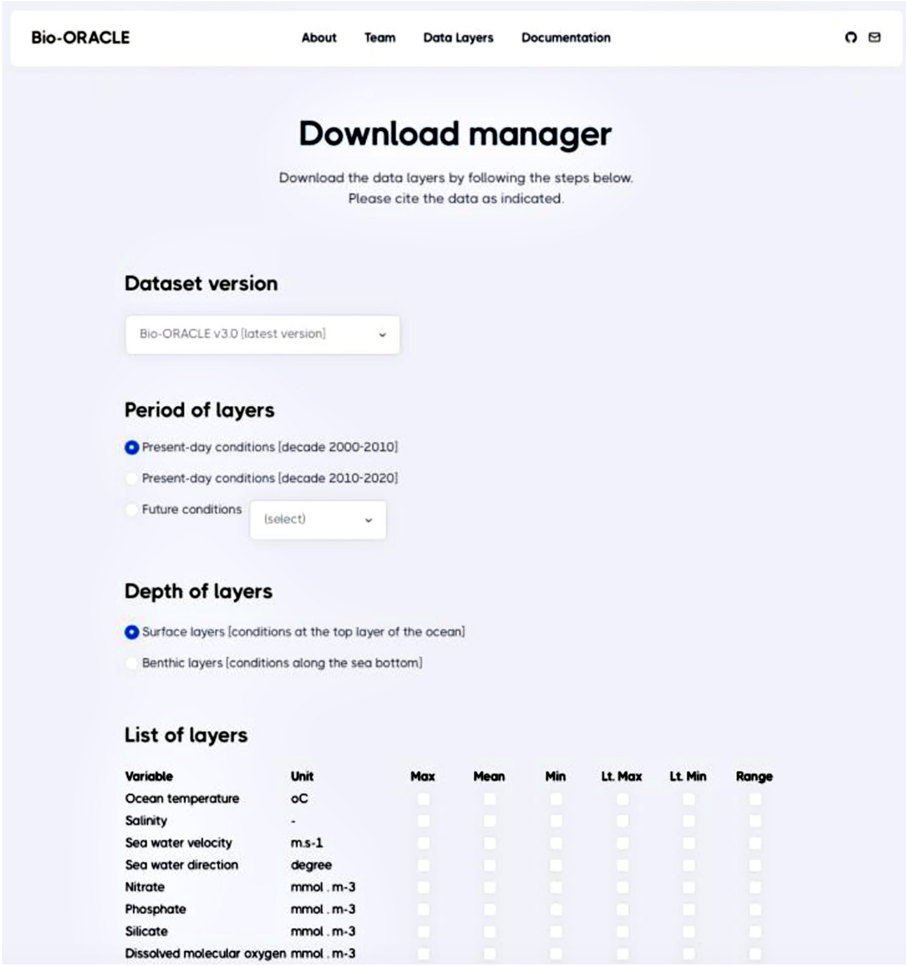


Figure 3. Dashboard of Bio-Oracle platform for accessing the future scenario of environmental data

characterized by low population growth, rapid adoption of clean technologies, reduced global inequality, and strong international cooperation toward climate solutions. Under this scenario, stringent climate policies are applied to keep warming below 1.5 °C, reducing environmental degradation and anthropogenic stress on coral reefs, with 2050 serving as a key mid-century benchmark for evaluating future climate and socioeconomic impacts in conservation-priority areas.

Habitat modelling

Habitat suitability modelling was carried out the maximum entropy (MaxEnt) algorithm that implemented in MaxEnt Software version 3.4.4, following the procedures by (Phillips and Dudík, 2008). The objective of this modelling was to estimate the probability of suitable coral reef habitats based on occurrence record and set of environmental predictors variables. The model seeks the probability distribution p(x) that is closest to uniform while still satisfying the empirical expectation of environmental features:

$$Maximize\ H(p) = -\sum p(x) \ln p(x) \quad (1)$$

For each environmental variable f_j follow this equation :

$$\sum p(x) f_j(x) = \mu_j \quad (2)$$

where: $fj(x)$ represent environmental predictors and mj is the empirical averages of fj at occurrence locations.

In the MaxEnt modeling analysis to identify suitable habitat areas for coral reef ecosystems, several sequential stages were conducted, including dataset preparation, MaxEnt model configuration, as well as classification of model outputs and map generation. The overall workflow of the data processing and analysis procedures is illustrated in the flowchart presented in Figure 4.

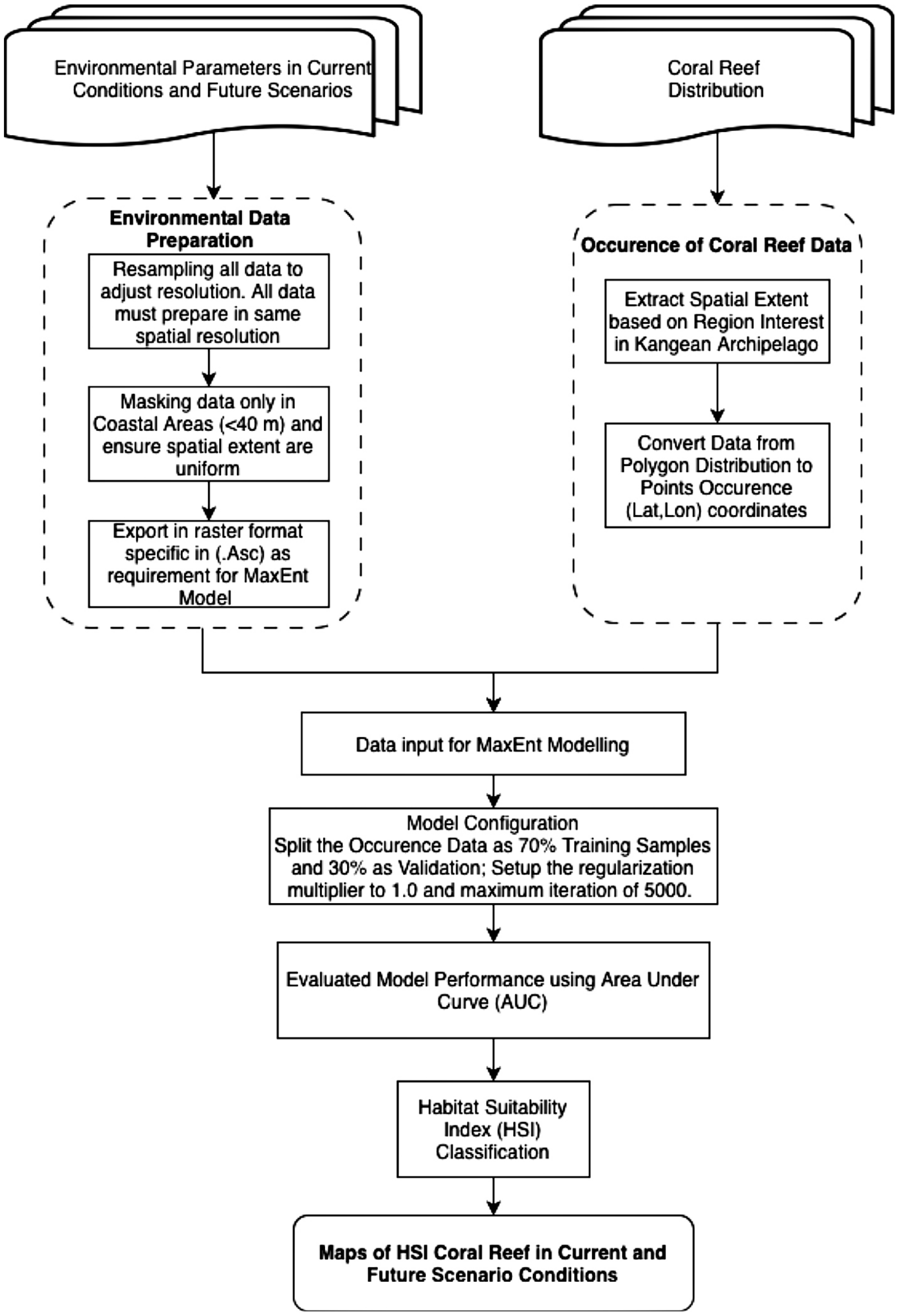


Figure 4. Flowchart of anaylis data of habitat modelling using MaxEnt model

Data preparation

The equation 1 is implemented using presence-only occurrence records and environmental predictors, where the constraint term of $\Sigma p(x)f_j(x)$ is derived from spatially explicit environmental conditions at coral reef locations. Therefore, carefull preparation of both occurrence data and predictor layers was required to ensure valid estimation of the empirical feature expectations used in the model. The presence data for coral reefs were derived from polygon-based reef distribution datasets, which were subsequently converted into point features by extracting the centroid of each polygon. These centroid points were recorded in geographic coordinates using decimal degrees (latitude and longitude) to ensure consistency with other spatial datasets. To minimize potential sources of sampling bias, several data refinement steps were undertaken. Duplicate records and spatially overlapping points were removed, and points located too close to land or within terrestrial areas were excluded to avoid misrepresentation of true reef habitats. The resulting dataset represents a cleaner and more spatially independent set of reef occurrence locations. Finally, the processed point data were exported in CSV format, making them compatible for use as presence-only input in the MaxEnt modelling framework.

Environmental predictors were selected based on ecological relevance to coral reef suitability including as we show in Table 1. All environmental layers were processed using QGIS 3.3 to ensure spatial consistency and analytical compatibility. Because the source datasets originated from different spatial resolutions and coordinate systems, a standardized preprocessing workflow was applied in which all raster were reprojected to the WGS84 corrdinate system, clipped the spatial extent of study area, and resampled to spatial resolution of 0.005° using bilinear interpolation to preserve spatial continuity. To constrain the analysis ecologically plausible reef supporting environments, each predictor layer was subsequently masked using bathymetry that downloaded from www.tanahairku.go.id, retaining only marine areas within the 0–40 depth range where shallow water coral reefs most likely to occur. Multicollinearity among predictors was evaluated using Pearson correlation analysis, and in cases where strong correlations were detected ($|r| \geq 0.7$), the variable with lower ecological interpretability or weaker theoretical relevance was excluded to reduce redundancy and improve model robustness. The final predictor set therefore consisted of a refined group of independent environmental variables that provided a meaningful representation of the biophysical conditions influencing coral reef habitat suitability in the study area.

In the coral reef habitat modelling process, a future projection analysis was also undertaken for the year 2050 using the Shared Socioeconomic Pathway (SSP) 1–1.9 scenario. This projection was designed to assess the potential shifts in habitat suitability under low-emission climate mitigation trajectories. The environmental predictor variables employed in the future scenario were consistent with those used in the current condition model (Table 1), thereby ensuring methodological comparability between temporal assessments. All predictor datasets for the 2050 projection were subjected to an identical preprocessing workflow, which included resampling to a spatial resolution of 0.005° to maintain uniform grid consistency, followed by spatial clipping restricted to marine areas with depths of less than 40 m. This depth threshold reflects the ecologically relevant depth range for shallow-water coral reef ecosystems and aligns with the ecological assumptions of the modelling framework. Through this approach, the future projection aims to produce a robust and comparable assessment of potential changes in coral reef habitat suitability under projected climate conditions.

Model configuration

Within the MaxEnt framework, species distribution is estimated by maximizing entropy subject to environmental constraints, where the optimization process is numerically approximated through iterative evaluation of the model gain function. The gain reflects the degree to which the predicted distribution of occurrence points differs from a uniform background, thereby indicating how effectively the model concentrates probability in environmentally suitable regions. In this study, modelling was conducted using MaxEnt version 3.4.4, with the regularization multiplier set to 1.0, a maximum of 5000 iterations, and automatic feature class selection enabled to allow the algorithm to determine the most appropriate feature combinations based on the structure of the data. A cross-validation approach was implemented by randomly partitioning occurrence records into 70% training data and 30% testing data, following the sampling scheme described by (Syah et al., 2016). Model performance was evaluated using the Area Under the Receiver Operating Characteristic Curve (AUC), which provides a threshold-independent measure of discriminatory ability (Elith et al., 2006; Phillips et al., 2006). To better understand the relative influence of environmental predictors, heuristic contribution and permutation importance metrics were examined, enabling interpretation of how each variable contributes to overall model gain. In addition, response curves were generated to visualize the marginal effect of individual predictors on habitat suitability, offering ecological insight into how environmental gradients shape the probability of coral reef occurrence.

Habitat suitability classifications

The continuous probability surface generated by MaxEnt represents the estimated habitat suitability function $p(x)$, where values approaching 1 indicate highly suitable environmental conditions and values approaching 0 reflect areas of low or no suitability. To enhance interpretability and enable spatial quantification of suitability classes, the continuous habitat suitability index (HSI) values were discretized into ecologically meaningful categories. Raster outputs were imported into QGIS 3.3 and reclassified into five suitability levels following the classification scheme of (Januar et al., 2023), with minor modification: not suitable ($R < 0.2$), less suitable ($0.2 \leq R < 0.4$), suitable ($0.4 \leq R < 0.6$), more suitable ($0.6 \leq R < 0.8$), and very suitable ($R \geq 0.8$). The resulting classified maps were then used to calculate the spatial extent of each suitability class and to assess changes in area coverage between the present-day baseline conditions and the projected 2050 scenarios.

RESULT AND DISCUSSION

Result

This study's primary outcome is the spatial distribution of predicted coral reef habitats based on environmental parameter data under both current conditions and future scenarios. The model produced an AUC value of 0.775, indicating strong performance and a reliable ability to differentiate between suitable and unsuitable coral reef habitats (Figure 5). The contribution of each environmental variable provides valuable insight into the primary drivers influencing coral reef distribution. As shown in Table 2, pH is the most influential factor, accounting for 21.1% of the model's explanatory power, highlighting the importance of seawater acidity stability for coral reef viability. This is followed by current velocity (16.7%), temperature (15.6%), chlorophyll-a (14.6%), and dissolved oxygen (12.8%). In contrast, variables such as fertilizer concentration and salinity contribute less than 10%, suggesting they exert only a minimal effect on habitat suitability in the context of this modelling framework.

Figure 6 illustrates the regional distribution of the four parameters that most significantly influenced the MaxEnt coral reef ecosystem model: pH, current velocity, temperature, and chlorophyll-a. The comparison between current conditions and the 2050 projection under the SSP 1.19 scenario reveals significant changes across all dimensions. The current pH readings indicate that the seas near Madura Island are considerably more alkaline than those in the Kangean Archipelago. In contrast, the 2050 estimate indicates a significant reduction in pH values throughout the study area, reflecting a trend towards heightened ocean acidity in the future. The following parameter is the present velocity. The Kangean Archipelago is profoundly affected by the Indonesian throughflow (ITF). The velocities in the western area of the region, particularly around Madura Island, are rather low, generally ranging from 0 to 0.007 m/s. The highest velocities are recorded at the western coast of Kangean Island, exceeding 0.03 m/s. The 2050 projection forecasts an elevation in current velocities across most of the region, with the exception of areas adjacent to Madura Island, where speeds are expected to remain comparatively lower. The eastern region of the archipelago is expected to have average current velocities above 0.1 m/s throughout a substantial area of its shallow seas. Changes in current velocity are anticipated to influence the dynamics of water mass transfer in the region.

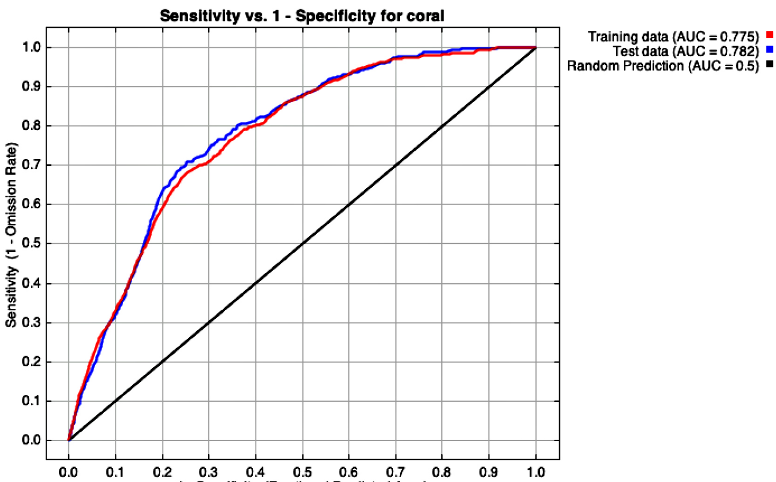


Figure 5. AUC values pada penyusunan model

Table 2. Percentage contribution of variables in constructing the spatial habitat distribution model of coral reefs

Variable	Percent contribution (%)
pH	21.1%
Current velocity	16.7%
Temperature	15.6%
Chlorophyll-a	14.6%
Dissolve oxygen	12.8%
Phosphate	8.4%
Primary productivity	4.2%
Salinity	3.7%
Nitrate	2.5%
Silicate	0.5%

The research area also shows significant fluctuations in sea surface temperature (SST). Sea surface temperature estimates usually fluctuate between 28 and 29 °C. Higher temperatures are often seen at the coasts of large landmasses, such as Madura Island and Kangean Island. The observed increase in temperature is likely caused by water runoff from larger landmasses. This process could then magnify the warming seen in certain areas. Based on the SSP 1.19 projection for 2050, a considerable increase in sea surface temperature is projected, particularly along the Kangean Archipelago. Figure 6 shows that average SST are expected to reach about 29–30 °C by 2050, indicating a rise of almost 1 °C over the following 25 years. The increase in temperature is linked to a decline in marine productivity, as shown by lower levels of chlorophyll-a. Currently, chlorophyll-a concentrations in coastal waters are often high, frequently topping 1 mg/m^3. In contrast, future estimates indicate a considerable reduction in chlorophyll-a, with concentrations expected to be very low by 2050. These losses are likely connected to higher sea surface temperatures and changes in regional currents. These factors can impact the availability of nutrients and the overall productivity of primary producers.

Figure 7 depicts the spatial configuration of coral reef habitat suitability generated through MaxEnt modelling using ten key oceanographic variables, with Figure 7a (left) reflecting present-day conditions and Figure 7b (right) illustrating projected patterns under the SSP 1.19 scenario for the year 2050. The comparative analysis between these two temporal states reveals HSI values and red (warm colours) denotes lower suitability. The western portion of the study area, particularly Poteran Island and Gili Genting Island, consistently exhibits low suitability, remaining predominantly within the not suitable class, with only localized segments transitioning into the less suitable category, including minor patches along the northern coastline of Kangean Island. Conversely, areas demonstrating elevated suitability classified as more suitable and very suitable are largely concentrated around Raas Island, the eastern margin of Kangean Island, and the northern expanse of the Sepanjang Archipelago.

The habitat modelling outcomes under the 2050 climate scenario suggest a pronounced overall decline in coral reef habitat suitability across the study area. The projections indicate that the entire Kangean Archipelago will predominantly transition into the Not suitable and Less suitable classes, reflecting a substantial reduction in environmental favourability for coral reef persistence. Several zones that previously exhibited higher suitability classified as more suitable or very suitable under present-day conditions are projected to deteriorate to the less suitable category, underscoring the sensitivity of these habitats to future oceanographic changes. The western sector, particularly the regions surrounding Poteran and Gili Genting, is expected to remain relatively unchanged, maintaining its current status within the not suitable and less suitable classes, which suggests that the underlying limiting factors in this area persist irrespective of future climate forcing. In contrast, more pronounced and spatially extensive shifts are anticipated in the vicinity of Sapudi and Raas Islands, where previously very suitable zones are projected to decline to Suitable, indicating a marked reduction in optimal habitat conditions. The most dramatic transformation is expected across the broader Kangean region, where modelling suggests a widespread collapse of suitable habitat, with all areas shifting toward lower suitability classes. These findings collectively highlight the increasing vulnerability of coral reef ecosystems in the region under future climate trajectories and emphasize the need for adaptive management strategies to mitigate projected habitat losses.

Table 3 presents the area-based analysis of each HSI class derived from the habitat suitability models for both the current condition and the 2050 projection under the SSP1.19 scenario. The calculated area coverage corresponds to the spatial extent of marine zones within the 0–40

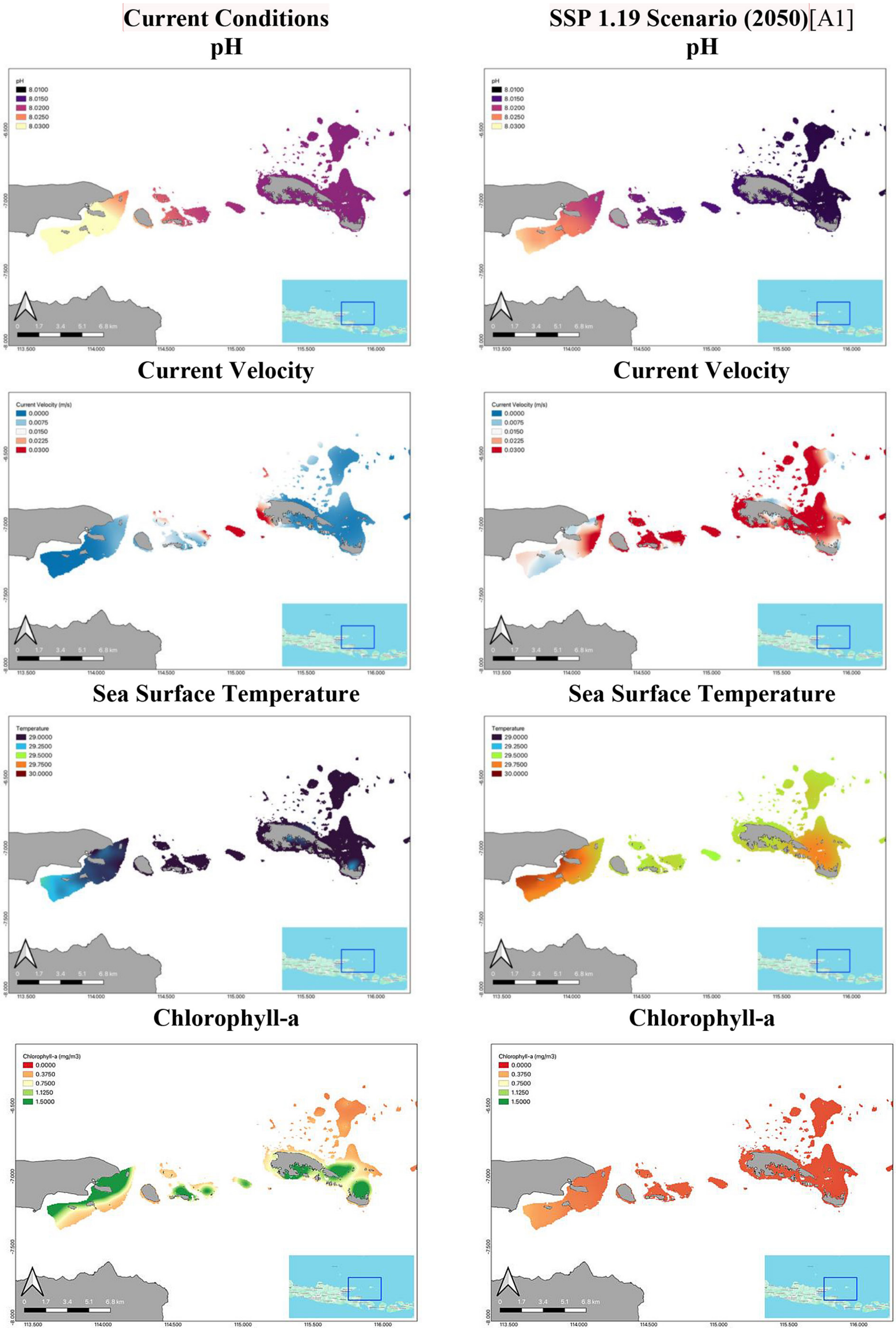
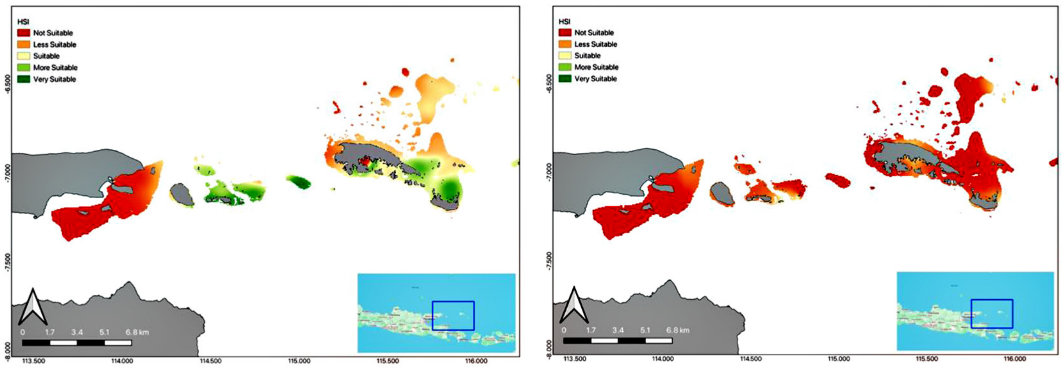


Figure 6. The parameters showing the greatest contribution to the MaxEnt modelling are pH, current velocity, temperature, and chlorophyll-a



a b

figure 7. spatial distribution of predicted coral reef habitat modelling for the current condition (left) and future prediction in 2050 (right)

Table 3. Area of each HSI category for coral reef habitat based on maximum entropy modelling results

HSI category	Area (Ha)	
	Current	Future (2050)
Not suitable	121517.80	360925.08
Less suitable	85484.14	31867.18
Suitable	97389.53	1649.13
More suitable	58772.96	-
Very suitable	31521.14	-

m depth range, consistent with the methodological criteria established for defining suitable coral reef environments. Under present-day conditions, approximately 31,521.14 ha (7.98%) of the study area is classified as very suitable for supporting coral reef ecosystems, while more than 150,000 ha are categorized as suitable and more suitable, aligning spatially with the distribution shown in Figure 7. The current model also indicates that about 30.78% of the total area has already shifted into the Not Suitable category, reflecting considerable environmental pressures limiting coral reef viability. In contrast, projections under the SSP1.19 scenario for 2050 show a marked intensification of unsuitable habitat conditions, with an estimated 91.50% of the total area (370,925.08 ha) falling into the not suitable class. Only a minimal proportion of the region approximately 0.41% or 1,649.13 ha is expected to remain within the suitable category.

DISSCUSSION

The MaxEnt modelling results indicate that the spatial distribution of coral reefs in the Kangean Archipelago is strongly shaped by several key oceanographic variables most notably pH, current velocity, temperature, and chlorophyll-a concentration which emerged as the primary predictors of habitat suitability. The model achieved an AUC of 0.775, demonstrating robust predictive skill and reliability, consistent with previous SDM applications in Indonesia and the broader CT, where AUC values typically range from 0.7 to 0.85 (Januar et al., 2023; Shen et al., 2026; Syah et al., 2016). Among these predictors, pH exerted the greatest influence, underscoring the critical role of seawater acidity in coral calcification, with ocean acidification widely recognized as a key driver of reduced skeletal growth and weakened reef structure (Hoegh-Guldberg, 2010; Kleypas and Yates, 2009). The model further confirmed that ocean acidification significantly shapes coral habitat suitability (Freeman et al., 2013). Current velocity also contributed substantially, reflecting the importance of hydrodynamic processes in enhancing nutrient exchange, maintaining water quality, and reducing thermal stress factors that collectively support coral productivity and overall ecosystem resilience (Drake et al., 2025).

Regions identified as suitable to very suitable are primarily concentrated around Raas Island, the eastern waters of Kangean Island, and the Sepanjang Archipelago. These zones are characterized by relatively stable oceanographic conditions and reduced human disturbance, consistent with earlier assessments of coral reef health in the Kangean region (Handoko et al., 2025). Conversely, the western portion of the study area including Poteran and Gili Genting consistently exhibits low suitability. This trend is likely driven by stronger terrestrial influences originating from Madura and Java, such as sedimentation, nutrient loading, and coastal modification, all of which are widely recognized as major drivers of coral degradation in densely populated Indonesian coastal systems (Edinger et al., 1998; Risk, 2014). Notably, Raas Island lies approximately 70 km from the Madura mainland, whereas the easternmost site, Sepanjang Island, is situated more than 150 km away. These spatial differences highlight the heightened vulnerability of nearshore reefs to cumulative anthropogenic pressures.

Future projections under the SSP1–1.9 scenario reveal a substantial decline in coral reef habitat suitability by 2050, even though this scenario represents the most optimistic global mitigation pathway. The model suggests that more than 90% of the study area will shift into the not suitable category, leaving only about 1.649 ha (0.41%) potentially capable of supporting coral survival. This drastic reduction aligns with global assessments predicting severe coral reef losses as ocean warming approaches 1.5 °C, driven by rising sea surface temperatures, declining pH, and reduced ocean productivity (Hughes et al., 2017; Lam et al., 2019). The projected temperature increase of approximately 1 °C, together with significant decreases in chlorophyll-a, points to potential disruptions in primary productivity and nutrient cycling, which would further diminish habitat quality (Hill et al., 2013). Notably, the offshore shifts in suitability particularly the contraction of previously very suitable areas near Raas and Kangean highlight how intensifying climate pressures may increasingly favor open-ocean conditions over nearshore ecosystems.

These findings carry important implications for coral reef management and marine spatial planning in the Kangean Archipelago. Areas currently classified as suitable to very suitable under present condition should be prioritized as climate refugia and integrated into existing or newly designated marine protected area (MPA), with management strategies explicity incorporating climate change projections. Protecting these remaining high-suitablity zones is critical to maintanining ecological connectivity, larval dispersal pathways, and genetic diversity accros the Java-Bali-NTB reef network, which are essential for post-disturbance recovery (Magris et al., 2014; McLeod et al., 2009). In parralel, reducing local scale stressors such as sedimentation, eutrophication, destructive fishing practice, and coastal development remains a key adaptive strategy to enhance coral resilience to climate driven stressors (Anthony et al., 2011; Good and Bahr, 2021). For nearshore reefs, particularly around Poteran and Gili Genting, integrated land–sea management approaches are urgently needed to control land-based sources of pollution from Madura and Java, which may otherwise accelerate the loss of already marginal habitats.

From a broader scientific perspective, this study reinforces growing evidence that even under low-emission scenarios such as SSP1–1.9, coral reef ecosystems face profound risks, emphasizing the limited capacity of mitigation alone to safeguard reef persistence without strong local adaptation measures. The dominance of pH and temperature as predictors of suitability highlights the necessity of incorporating biogeochemical variables into future species distribution and habitat suitability models (Bleuel et al., 2021; Guan et al., 2015), particularly in tropical reef systems where ocean acidification and warming act synergistically (Dove et al., 2020; Hu et al., 2024). Future research should integrate adaptive capacity indicators such as coral species composition, thermal tolerance, and acclimatization potential alongside socio-ecological dimensions to better identify reefs with higher survival prospects (Beyer et al., 2018; Van Hooidonk et al., 2014). Long-term monitoring combined with high-resolution remote sensing and coupled ocean–biogeochemical models will be essential to refine projections and support evidence-based conservation planning, ensuring that limited management resources are directed toward reefs with the greatest potential for long-term persistence under accelerating climate change.

CONCLUSIONS

This study demonstrates that coral reef habitat suitability in the Kangean Archipelago, East Java, is strongly controlled by key oceanographic and biogeochemical variables, particularly seawater pH, current velocity, sea surface temperature, and chlorophyll-a concentration. The MaxEnt model exhibited reliable predictive performance (AUC = 0.775), confirming its effectiveness for assessing coral reef distribution using presence-only data in data-limited tropical marine environments. Under present conditions, areas classified as suitable to very suitable are mainly concentrated around Raas Island, eastern Kangean waters, and the Sepanjang Archipelago, reflecting relatively stable environmental conditions and reduced terrestrial influence. Future projections under the low-emission SSP1–1.9 climate scenario for 2050 indicate a substantial decline in coral reef habitat suitability across the study area. More than 90% of the shallow marine zone (0–40 m depth) is projected to shift into the not suitable category, with only a small fraction remaining marginally suitable for coral persistence. This decline is driven primarily by increasing sea surface temperatures, declining seawater pH, and reductions in ocean productivity, highlighting the sensitivity of coral reef ecosystems even under optimistic climate mitigation pathways. The findings emphasize that global emission reductions alone may be insufficient to safeguard coral reef ecosystems in the western CT without strong local and regional adaptation measures. Areas currently identified as suitable and very suitable should be prioritized as climate refugia and integrated into marine spatial planning and marine protected area networks. Simultaneously, reducing local stressors such as sedimentation, eutrophication, coastal pollution, and destructive fishing practices is essential to enhance coral resilience under accelerating climate change. Overall, this study provides spatially explicit scientific evidence to support climate-informed coral reef conservation and adaptive management strategies in East Java and contributes to broader efforts to sustain coral reef ecosystems within the CT region.

Acknowledgement

We gratefully acknowledge the Ministry of Higher Education, Science, and Technology of Indonesia, through the Directorate General of Research and Development, for providing financial support for this study under the Regular Fundamental Research (PFR) scheme for the 2025 fiscal year (Contract No. B/041/UN46.1/PT.01.03/BIMA/PL/2025). We also extend our sincere appreciation to the data providers supporting this research, including Bio-ORACLE, GBIF, and OBIS, for making available oceanographic datasets and coral reef occurrence records for the study area.

REFERENCES

1. Anderson, O. F., Guinotte, J. M., Rowden, A. A., Tracey, D. M., Mackay, K. A., Clark, M. R. (2016). Habitat suitability models for predicting the occurrence of vulnerable marine ecosystems in the seas around New Zealand. *Deep Sea Research Part I: Oceanographic Research Papers*, *115*, 265–292.
2. Anthony, K. R., A. Kleypas, J., Gattuso, J. (2011). Coral reefs modify their seawater carbon chemistry–implications for impacts of ocean acidification. *Global Change Biology*, *17*(12), 3655–3666.
3. Assis, J., Fernández Bejarano, S. J., Salazar, V. W., Schepers, L., Gouvêa, L., Fragkopoulou, E., Leclercq, F., Vanhoorne, B., Tyberghein, L., Serrão, E. A. (2024). Bio-ORACLE v3. 0. Pushing marine data layers to the CMIP6 Earth System Models of climate change research. *Global Ecology and Biogeography*, *33*(4), e13813.
4. B. Lyons, M., M. Roelfsema, C., V. Kennedy, E., M. Kovacs, E., Borrego-Acevedo, R., Markey, K., Roe, M., M. Yuwono, D., L. Harris, D., R. Phinn, S., Asner, G. P., Li, J., E. Knapp, D., S. Fabina, N., Larsen, K., Traganos, D., J. Murray, N. (2020). Mapping the world's coral reefs using a global multiscale earth observation framework. *Remote Sensing in Ecology and Conservation*, *6*(4), 557–568. https://doi.org/10.1002/rse2.157
5. Beyer, H. L., Kennedy, E. V., Beger, M., Chen, C. A., Cinner, J. E., Darling, E. S., Eakin, C. M., Gates, R. D., Heron, S. F., Knowlton, N. (2018). Risk-sensitive planning for conserving coral reefs under rapid climate change. *Conservation Letters*, *11*(6), e12587.
6. Bleuel, J., Pennino, M. G., Longo, G. O. (2021). Coral distribution and bleaching vulnerability areas in Southwestern Atlantic under ocean warming. *Scientific Reports*, *11*(1), 12833.
7. Bodeker, G., Tait, A., Morgenstern, O., Noone, D., Revell, L., McDonald, A., Cullen, N., Renwick, J., Katurji, M. (2022). *Aotearoa New Zealand climate change projections guidance: Interpreting the latest IPCC WG1 report findings*.
8. Bove, C. B., Davies, S. W., Ries, J. B., Umbanhowar, J., Thomasson, B. C., Farquhar, E. B., McCoppin, J. A., Castillo, K. D. (2022). Global change differentially modulates Caribbean coral physiology. *Plos One*, *17*(9), e0273897.
9. Dove, S. G., Brown, K. T., Van Den Heuvel, A., Chai, A., Hoegh-Guldberg, O. (2020). Ocean warming and acidification uncouple calcification from calcifier biomass which accelerates coral reef decline. *Communications Earth & Environment*, *1*(1), 55.
10. Drake, M. A., Noonan, S. H., Alvarez-Noriega, M., Rashid, A. R., Fabricius, K. E. (2025). Current

velocity, water quality, and benthic taxa as predictors for coral recruitment rates on the Great Barrier Reef. *PloS One*, *20*(3), e0319521.

11. Edinger, E. N., Jompa, J., Limmon, G. V., Widjatmoko, W., Risk, M. J. (1998). Reef degradation and coral biodiversity in Indonesia: Effects of land-based pollution, destructive fishing practices and changes over time. *Marine Pollution Bulletin*, *36*(8), 617–630.
12. Elith, J., H. Graham*, C., P. Anderson, R., Dudík, M., Ferrier, S., Guisan, A., J. Hijmans, R., Huettmann, F., R. Leathwick, J., Lehmann, A. (2006). Novel methods improve prediction of species' distributions from occurrence data. *Ecography*, *29*(2), 129–151.
13. Foster, N. L., Attrill, M. J. (2021). Changes in coral reef ecosystems as an indication of climate and global change. In *Climate change* 427–443. Elsevier.
14. Freeman, L. A., Kleypas, J. A., Miller, A. J. (2013). Coral reef habitat response to climate change scenarios. *PloS One*, *8*(12), e82404.
15. Good, A. M., Bahr, K. D. (2021). The coral conservation crisis: Interacting local and global stressors reduce reef resiliency and create challenges for conservation solutions. *SN Applied Sciences*, *3*(3), 312.
16. Gordon, A. L., Fine, R. A. (1996). Pathways of water between the Pacific and Indian oceans in the Indonesian seas. *Nature*, *379*(6561), 146–149.
17. Guan, Y., Hohn, S., Merico, A. (2015). Suitable environmental ranges for potential coral reef habitats in the tropical ocean. *PloS One*, *10*(6), e0128831.
18. Handoko, A., Hidayah, Z., Saptarini, D., Wiyanto, D. B., Nurdini, J. A., Setiawan, D., Vieira, L. D. O. (2025). Assessment of coral reef health and resilience in Saobi and Sapapan Islands, Kangean Archipelago, Indonesia. *Biodiversitas Journal of Biological Diversity*, *26*(7).
19. He, Y., Zhao, L., Liu, S., Zhao, X., Wang, Y., Jiang, X. (2022). Delineation of estuarine ecological corridors using the MaxEnt model to protect marine fishery biodiversity. *Frontiers in Marine Science*, *9*, 966621.
20. Hill, S. L., Phillips, T., Atkinson, A. (2013). Potential climate change effects on the habitat of Antarctic krill in the Weddell quadrant of the Southern Ocean. *PloS One*, *8*(8), e72246.
21. Hoegh-Guldberg, O. (2010). The impact of climate change on coral reef ecosystems. In: *Coral reefs: An ecosystem in transition* 391–403. Springer.
22. Hu, N., Bourdeau, P. E., Hollander, J. (2024). Responses of marine trophic levels to the combined effects of ocean acidification and warming. *Nature Communications*, *15*(1), 3400.
23. Hughes, T. P., Barnes, M. L., Bellwood, D. R., Cinner, J. E., Cumming, G. S., Jackson, J. B., Kleypas, J., Van De Leemput, I. A., Lough, J. M., Morrison, T. H. (2017). Coral reefs in the Anthropocene. *Nature*, *546*(7656), 82–90.
24. Januar, H. I., Hidayah, I., Humaida, N., Iswani, S., Hidayat, A. (2023). Habitat suitability modeling of *Acropora* spp. distribution in coral triangle area of Maluku Waters, Indonesia under influence of future climate change and coastal pollution. *Agriculture and Natural Resources*, *57*(5), 869–876.
25. Khalil, I., Muslim, A. M., Hossain, M. S., Atkinson, P. M. (2023). Modelling and forecasting the effects of increasing sea surface temperature on coral bleaching in the Indo-Pacific region. *International Journal of Remote Sensing*, *44*(1), 194–216.
26. Kleypas, J. A., Feely, R. A., Fabry, V. J., Langdon, C., Sabine, C. L., Robbins, L. L. (2005). *Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research*. *18*(2005), 20.
27. Kleypas, J. A., Yates, K. K. (2009). Coral reefs and ocean acidification. *Oceanography*, *22*(4), 108–117.
28. Lam, V. W., Chavanich, S., Djoundourian, S., Dupont, S., Gaill, F., Holzer, G., Isensee, K., Katua, S., Mars, F., Metian, M. (2019). Dealing with the effects of ocean acidification on coral reefs in the Indian Ocean and Asia. *Regional Studies in Marine Science*, *28*, 100560.
29. Li, T., Feng, J., Zhao, L., Wang, D., Fan, R. (2024). Geographical distribution of coral reefs and their responses to environmental factors in the South China Sea. *Ecological Indicators*, *158*, 111485.
30. Liu, Y., Yamauchi, F. (2014). Population density, migration, and the returns to human capital and land: Insights from Indonesia. *Food Policy*, *48*, 182–193.
31. Magris, R. A., Pressey, R. L., Weeks, R., Ban, N. C. (2014). Integrating connectivity and climate change into marine conservation planning. *Biological Conservation*, *170*, 207–221.
32. McClanahan, T., Polunin, N., Done, T. (2002). Ecological states and the resilience of coral reefs. *Conservation Ecology*, *6*(2).
33. McLeod, E., Salm, R., Green, A., Almany, J. (2009). Designing marine protected area networks to address the impacts of climate change. *Frontiers in Ecology and the Environment*, *7*(7), 362–370.
34. Mentzel, S., Nathan, R., Noyes, P., Brix, K. V., Moe, S. J., Rohr, J. R., Verheyen, J., Van den Brink, P. J., Stauber, J. (2024). Evaluating the effects of climate change and chemical, physical, and biological stressors on nearshore coral reefs: A case study in the Great Barrier Reef, Australia. *Integrated Environmental Assessment and Management*, *20*(2), 401–418.
35. Mumby, P. J., Van Woesik, R. (2014). Consequences of ecological, evolutionary and biogeochemical

uncertainty for coral reef responses to climatic stress. *Current Biology*, *24*(10), R413–R423.

36. Phillips, S. J., Anderson, R. P., Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, *190*(3–4), 231–259.
37. Phillips, S. J., Dudík, M. (2008). Modeling of species distributions with Maxent: New extensions and a comprehensive evaluation. *Ecography*, *31*(2), 161–175.
38. Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change*, *42*, 153–168.
39. Risk, M. J. (2014). Assessing the effects of sediments and nutrients on coral reefs. *Current Opinion in Environmental Sustainability*, *7*, 108–117.
40. Rizal, A., Siagian, H., Farahdita, W. (2022). Sebaran dan Kondisi Terumbu Karang di Kepulauan Kangean. *Jurnal Kelautan Nasional*, *16*(3), 237–248.
41. Shen, C., Ruan, X., Tao, Z., Xu, C., Zhu, J. (2026). Predicting coral reef habitat distribution in the South China Sea under climate change using MaxEnt modeling. *Marine Pollution Bulletin*, *223*, 119087.
42. Syah, A. F., Saitoh, S.-I., Alabia, I. D., Hirawake, T. (2016). Predicting potential fishing zones for Pacific saury (Cololabis saira) with maximum entropy models and remotely sensed data. *Fishery Bulletin*, *114*(3).
43. Tong, R., Yesson, C., Yu, J., Luo, Y., Zhang, L. (2023). Key factors for species distribution modeling in benthic marine environments. *Frontiers in Marine Science*, *10*, 1222382.
44. Van Hooidonk, R., Maynard, J. A., Manzello, D., Planes, S. (2014). Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. *Global Change Biology*, *20*(1), 103–112.
45. Veron, J. E., Devantier, L. M., Turak, E., Green, A. L., Kininmonth, S., Stafford-Smith, M., Peterson, N. (2009). Delineating the coral triangle. *Galaxea, Journal of Coral Reef Studies*, *11*(2), 91–100.
46. Veron, J. E., DeVantier, L. M., Turak, E., Green, A. L., Kininmonth, S., Stafford-Smith, M., Peterson, N. (2011). The coral triangle. *Coral Reefs: An Ecosystem in Transition*, 47–55.
47. Viehman, T. S., Reguero, B. G., Lenihan, H. S., Rosman, J. H., Storlazzi, C. D., Goergen, E. A., Canals Silander, M. F., Groves, S. H., Holstein, D. M., Bruckner, A. W. (2023). Coral restoration for coastal resilience: Integrating ecology, hydrodynamics, and engineering at multiple scales. *Ecosphere*, *14*(5), e4517.
48. White, B. (2023). Population, involution and employment in rural Java. In *Rural Development* 300–320. Routledge.
49. Yuen, B., Stuart, C. E., Pittman, S. J., Green, S. J., Henderson, L. M., Wedding, L. M. (2023). Habitat suitability models of elkhorn coral provide ecological insight to support coral reef restoration. *Restoration Ecology*, *31*(5), e13953.