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Mapping dominant mangrove genera using SPOT-6 imagery and Maximum Likelihood Classification for conservation planning in Langsa City, Aceh, Indonesia

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Abstract. *Rahmadi MT, Damayani WN, Harefa MS. 2026. Mapping dominant mangrove genera using SPOT-6 imagery and Maximum Likelihood Classification for conservation planning in Langsa City, Aceh, Indonesia. Asian J For 10 (1): r100120. https://doi.org/10.13057/asianjfor/r100120.* Mangrove forests are among the world's most productive and ecologically significant coastal ecosystems, providing essential services such as shoreline stabilization, carbon sequestration, and habitat provision. Indonesia accounts for approximately 19.5% of the global mangrove area, underscoring its critical role in coastal resilience and in supporting coastal communities. Despite their importance, these ecosystems face increasing pressures from anthropogenic activities, land-use change, and climate change, necessitating accurate and up-to-date information for effective monitoring and restoration planning. While remote sensing is indispensable, mangrove mapping at the genus level remains limited. Such detailed data are essential for robust zoning-based conservation planning and targeted strategies. This study addresses this gap by characterizing the distribution of dominant mangrove genera in Langsa City, Aceh, an area with mangrove representation. Utilizing high-resolution SPOT-6 imagery and the Maximum Likelihood Classification method, supported by comprehensive field validation with 30 control points, we produced a genus-level classification map. The total mangrove area identified in Langsa City is 5,837.46 ha, distributed across five sub-districts. Based on the classification and field data, three dominant mangrove genera were reliably identified: *Rhizophora* (2,216.01 ha), *Avicennia* (2,086.34 ha), and *Ceriops* (1,535.11 ha), which collectively account for 95% of the mangrove area, with *Rhizophora* being the most dominant. The overall accuracy and kappa coefficient achieved were 83% and 76%, respectively, indicating robust and reliable mapping results. This up-to-date, genus-level spatial information is invaluable for effective, zoning-based mangrove management, targeted conservation planning, and sustainable resource utilization in Langsa City and similar coastal regions. The findings underscore the potential of high-resolution SPOT-6 imagery for precise mapping of mangrove genera and support evidence-based conservation efforts.

Keywords: Genus-level classification, Langsa City, mangrove mapping, remote sensing, SPOT 6

INTRODUCTION

Mangrove forests are highly productive and ecologically significant coastal ecosystems worldwide, providing essential services such as shoreline stabilization, carbon sequestration, and habitat provision (Yunus et al. 2023; Middleton et al. 2024). Indonesia has approximately 3.3 million hectares of mangrove forests, approximately 19.5% of the global total, underscoring their crucial role in maintaining coastal resilience and supporting the livelihoods of millions of people living in coastal communities (Mulyanto and Kamal 2024).

Despite their importance, mangrove ecosystems continue to face increasing pressures from anthropogenic activities, land-use change, and environmental disturbances. The extensive conversion of mangrove areas for aquaculture, agriculture, and urban expansion has led to substantial habitat loss and degradation (Sulaiman et al. 2023). Furthermore, climate-related stressors, such as sea-level rise, rising temperatures, and changes in hydrological regimes, pose significant risks, particularly to mangrove forests, pushing them near their ecological tolerance limits (Hickey and Radford 2022; Baubekova et al. 2023). These threats have resulted in significant reductions in mangrove forest area, biodiversity, and ecological functions across Indonesia and globally (Pham et al. 2019; Ashton 2022; Akram et al. 2023). Specifically in Langsa City, studies have highlighted multiple threats to mangrove ecosystems and their significant impacts on coastal biodiversity, underscoring the urgent need for effective mangrove management strategies (Rahmadi et al. 2023).

Given these challenges, accurate and up-to-date information on mangrove distribution and composition is crucial for effective monitoring, restoration planning, and sustainable management (Chan-Bagot et al. 2024). Remote sensing technology has become an indispensable tool for large-scale mangrove assessments due to its ability to capture consistent, repeatable, and spatially comprehensive data, even in difficult-to-access areas (Kamal and Phinn 2011; Sawant et al. 2024). Advances in multispectral, hyperspectral, and radar sensors have improved the ability to detect structural and compositional differences within mangrove communities (Rosmasita et al. 2019; Hati et al. 2022). However, most mangrove mapping studies in Indonesia still emphasize general land-cover or ecosystem-level classifications. Efforts to identify mangrove species at finer taxonomic levels, such as genus or species, are still limited (Viennois et al. 2016; Pham et al. 2019). Previous studies, such as a study mapping mangrove distribution using satellite imagery in Langsa City, provide baseline data for the region (Rahmadi et al. 2021). Although previous studies have mapped mangrove extent in Langsa City, Indonesia, genus-level spatial information derived from high-resolution satellite imagery remains unavailable, limiting zoning-based conservation and restoration planning.

Addressing this significant gap, this study presents the first genus-level mangrove map of Langsa City using high-resolution SPOT-6 imagery, a critical advance for robust conservation. Mangrove mapping at the genus or species level is crucial for understanding ecological patterns, monitoring vegetation dynamics, and directly guiding targeted, zoning-based conservation and restoration strategies (Koedsin and Vaiphasa 2013; Wang et al. 2018; Wulandari et al. 2018). Detailed taxonomic information supports precise zoning, habitat suitability assessment, and species-specific restoration planning, all of which are crucial for long-term ecosystem resilience. However, achieving accurate genus-level classification is challenging due to spectral similarities among mangrove taxa, environmental complexity, and the limitations of medium-resolution satellite imagery commonly used in previous studies (Sanjoto et al. 2021; Huang et al. 2024). High-resolution sensors such as SPOT-6, which provides 1.5 m panchromatic and 6 m multispectral resolution, offer better capabilities for distinguishing mangrove genera based on canopy structure, texture, and spectral variation (Wang et al. 2015)

Langsa City, located on the east coast of Aceh Province, is one of the most important mangrove areas in western Indonesia. This region is home to a diverse range of mangrove genera, including *Rhizophora* spp., *Sonneratia* spp., and *Avicennia* spp., which play ecologically important roles in sediment stabilization, coastal protection, and habitat provision (Iswahyudi et al. 2020). However, existing mangrove maps for Langsa are often outdated, lack detailed taxonomic information, and do not fully support zoning-based conservation or restoration planning. The limited availability of genus-level spatial data poses challenges to the effective management and prioritization of critical mangrove zones in the region.

Therefore, there is an urgent need to develop accurate, high-resolution, genus-level mangrove maps for Langsa City. Langsa was specifically selected as a research location due to its extensive, diverse, and ecologically significant mangrove forests, making it a priority area for mangrove conservation in Aceh Province. The city has representative mangrove stands, with dominant genera such as *Rhizophora* spp., *Sonneratia* spp., and *Avicennia* spp., and exhibits a variety of habitat conditions influenced by tidal dynamics, sedimentation patterns, and anthropogenic pressures (Iswahyudi et al. 2020). Its mangrove ecosystem has undergone conservation initiatives amid increasing human disturbance, underscoring the need for detailed, up-to-date spatial information to support sustainable management. Given these conditions, the use of SPOT-6 imagery combined with field-based validation offers an opportunity to address previous limitations in mangrove mapping in the region. Therefore, the objective of this study was to map the spatial distribution of dominant mangrove genera in Langsa City using SPOT-6 imagery and the Maximum Likelihood Classification method, supported by field data. The results are expected to provide a strong foundation for targeted zoning-based conservation, restoration planning, and sustainable mangrove management in Langsa City and other similar coastal areas in Indonesia.

MATERIALS AND METHODS

Study area

This research was conducted in Langsa City (Figure 1). Langsa City is located in the eastern part of Aceh Province, Indonesia. Geographically, Langsa City is located at 04024'35.68 "N - 04024'35.68"N and 97-53'14.59"E - 98004'42.16" E. Based on the Qanun of Langsa City No. 12 of 2013, Langsa City has an area of 239.83 km and is divided into five sub-districts, namely Langsa Kota, Langsa Lama, Langsa Baro, West Langsa, and East Langsa. Langsa City was selected as the study area due to its extensive and ecologically significant mangrove forest, which serves as a critical habitat and provides numerous ecosystem services. The area exhibits a diverse array of mangrove species, including *Rhizophora* spp., *Sonneratia* spp., and *Aevicennia* spp., which are among the most dominant genera (Iswahyudi et al. 2020). These mangrove communities thrive in dynamic coastal environments, influenced by tidal conditions, sedimentation patterns, and varying salinity gradients. The complex interactions of these factors contribute to unique ecological zonation and canopy characteristics, which ultimately significantly influence the spectral reflectance properties of the mangrove canopy. For example, differences in leaf morphology, canopy architecture (dense *Rhizophora* stands versus more open *Avicennia* canopies), and physiological stress (salinity or waterlogging) can alter spectral response, making detailed mapping challenging but providing insights into ecological gradients.

Satellite data acquisition and pre-processing

This study used high-resolution SPOT-6 imagery acquired on September 6, 2021, at 7:30:15:00 AM local time. The imagery includes a panchromatic band with a 1.5 m spatial resolution and four multispectral bands with a 6 m spatial resolution. The imagery has a reported cloud cover of 11.20%. A comprehensive pre-processing workflow was carefully implemented to ensure the imagery was radiometrically and geometrically corrected and suitable for accurate classification. This workflow includes:

Radiometric calibration: Raw digital values from the SPOT-6 sensor were converted to Peak Atmospheric

Reflectance values using absolute calibration coefficients provided in the imagery metadata. This step corrects the sensor gain and offset, ensuring consistent spectral response across bands and minimizing sensor-induced variability.

Atmospheric correction: TOA reflectance values were further corrected to Surface Reflectance using the Fast Line-of-Sight Atmospheric Analysis module of the Spectral Hypercube. This process reduces the effects of atmospheric scattering and absorption by aerosols and water vapor, which can significantly alter spectral signatures, particularly over vegetated surfaces such as mangrove canopies.

Geometric correction: The imagery underwent precise geometric correction to accurately align it with real-world coordinates. This was achieved using a high-accuracy basemap (Google Earth imagery with known high positional accuracy) and a carefully selected set of Ground Control Points. A second-order polynomial transformation and the Nearest Neighbor resampling method were used to ensure that the mangrove features retained their original spectral values while being accurately georeferenced. The Mean Squared Error (RMSE) was consistently maintained below 0.5 pixels to ensure high positional accuracy suitable for detailed mapping.

Reprojection: The geometrically corrected imagery was then reprojected to the Universal Transverse Mercator (UTM) coordinate system (WGS84, Zone 48N) to ensure consistency with other spatial datasets and to support accurate area calculations and spatial analysis.

Cloud cover and interpolation: Areas affected by cloud cover and its shadow were manually digitized and masked to prevent spectral contamination in the classification process. The criterion for cloud cover was any pixel with visible cloud cover or shadow that directly impacted the mangrove canopy. Given the relatively limited extent of cloud cover (11.20%) and its primary impact on non-mangrove areas or small, isolated patches within the study area, spectral interpolation was deemed unnecessary to avoid introducing artificial spectral information and maintain the integrity of the original data for the main mangrove stands.

Mangrove classification

After preprocessing, mangrove classification was performed using the Maximum Likelihood Classification (MLC) algorithm in QGIS. MLC was chosen for its strong probabilistic foundation, established stability, and proven performance in mangrove mapping, especially when reliable training data from field surveys is available. This parametric classifier assumes that the statistics for each class in each band follow a normal distribution and calculates the probability that a given pixel belongs to each class based on these statistics. The pixel is then assigned to the class with the highest probability. The methodological rationale for choosing MLC acknowledges this underlying assumption. Although alternative machine learning classifiers (e.g., Random Forest, Support Vector Machine) are gaining popularity for their robustness to non-normal distributions and high accuracy, their optimal performance often depends on larger, more balanced training datasets. Given the relatively limited number of field-based training samples available for a given genus, MLC was deemed more appropriate because it is less sensitive to sample-size variability within well-defined classes and provides a clearer interpretation of class probability distributions, enabling a more direct understanding of classification decisions.

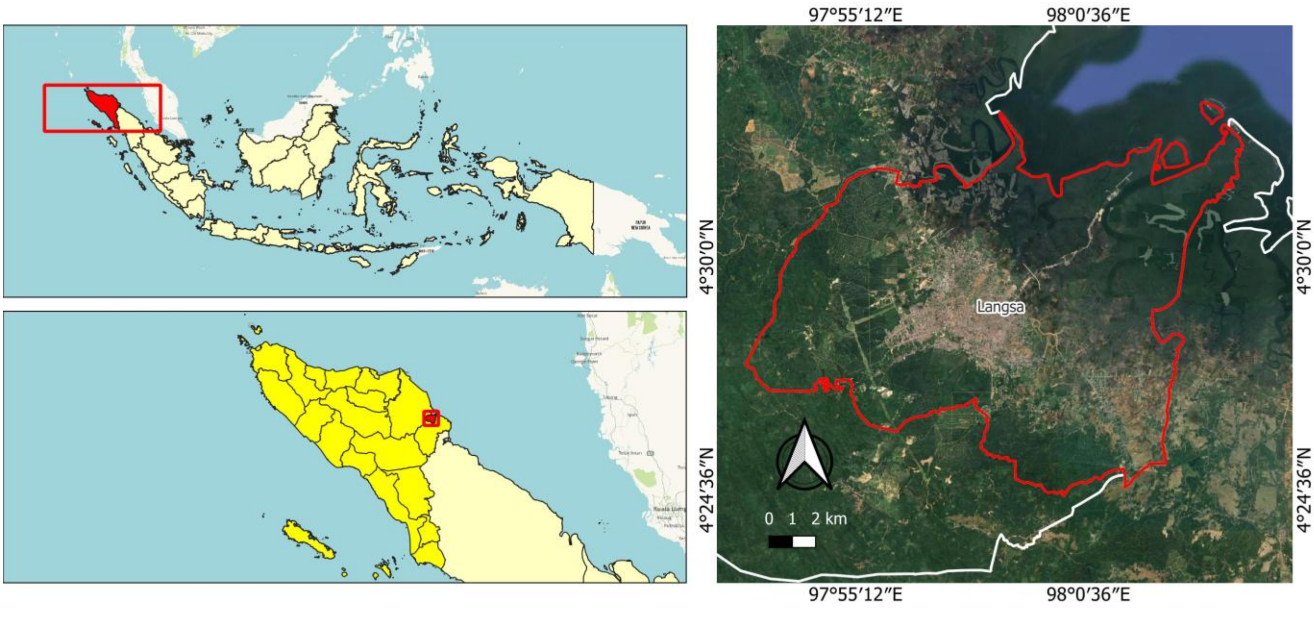

Figure 1. Research location map in Langsa City, Aceh, Indonesia

Regions of Interest (ROI)

Regions of Interest (ROIs) for each target mangrove genus (*Rhizophora*, *Avicennia*, *Ceriops*) and non-mangrove land cover type were carefully defined. This was based on detailed field surveys conducted concurrently with image acquisition and subsequent visual interpretation, combined with spectral signature analysis.

Number of ROIs: For each of the three dominant mangrove genera (*Rhizophora*, *Avicennia*, *Ceriops*), a minimum of 15-20 homogeneous polygons, each containing at least 50 pixels, were digitized across the study area. This resulted in approximately 50-60 ROIs for each mangrove class. Non-mangrove classes (e.g., water bodies, bare land, built-up areas, other vegetation) were represented by an additional 30-40 ROIs.

Selection criteria: ROIs were selected from visually homogeneous areas within the SPOT-6 imagery, ensuring clear boundaries and representing pure pixel clusters of their respective land cover/genus. Field notes, precise GPS coordinates of dominant genera, and corresponding field photographs were used extensively to guide ROI delineation. Efforts were made to distribute these ROIs geographically across sub-districts to capture spectral variability within each class that may arise from local environmental factors (e.g., substrate, micro-topography).

Separability analysis: Prior to classification, a spectral separability analysis was performed on the selected ROIs to assess spectral differences between classes. The Transform Divergence metric was calculated. TD values ranged from 0 to 2, with values above 1.8 generally indicating good separability. Classes with TD values below 1.8 were carefully reviewed; The ROIs were refined by removing spectrally ambiguous pixels or, if inherent spectral overlap remained, considering merging with other spectrally similar classes. This analysis confirmed that *Rhizophora*, *Avicennia*, and *Ceriops* exhibited sufficient spectral distinction for reliable classification in the SPOT-6 multispectral bands. In contrast, other genera, such as *Sonneratia* and *Bruguiera*, although present in the field, exhibited significant spectral overlap with the main genera, leading to their exclusion from direct genus-level mapping as independent classes. This decision overcomes the assumption of class separability by ensuring that only spectrally distinguishable classes are used for MLC.

Zonation analysis

In addition to classification, this study incorporated zonation analysis to understand ecological patterns within the mangrove landscape. Mangrove zonation was obtained by interpreting the classified SPOT-6 output in conjunction with field ecological data. Zonation was determined from the spatial dominance of each genus in the classification map and was supported by field measurements of salinity, inundation frequency, and substrate characteristics collected across the main mangrove stand. These environmental variables are known determinants of mangrove distribution and are used to interpret ecological gradients and patterns in Langsa City. The resulting zonation scheme reflects each genus's ecological preferences, allowing differentiation into central, intermediate, and outer/back zones. Although the field survey identified 13 mangrove species belonging to multiple genera, only those genera that showed clear spectral separation in the SPOT-6 multispectral bands were included in the final classification. This constraint ensured that the mapped classes represented taxa that could be reliably distinguished within the available spatial and spectral resolutions. Consequently, mapping focused on dominant genera that could be distinguished with acceptable accuracy.

Accuracy assessment

To validate the classification results, a confusion matrix was constructed by comparing the classified pixels with independent ground truth points collected during the field survey. A total of 30 validation points were collected specifically for the mapped mangrove genera (*Rhizophora, Avicennia, Ceriops*), and an additional 25 points were collected for non-mangrove land cover categories (e.g., water, bare land, built-up areas).

Sampling strategy and justification: A stratified random sampling approach was used to collect validation points. Strata were defined based on initial classification results, known ecological zones (e.g., areas typically dominated by *Rhizophora* vs. *Avicennia*), accessibility constraints within dense mangrove environments, and representation of different habitat types. This strategy ensured adequate geographic coverage of key mangrove areas and minimized sampling bias across Langsa City's diverse landscape. The relatively limited number of validation points (30 for the mangrove genera) was primarily justified by logistical challenges in accessing dense, often impenetrable mangrove areas, as well as the need to prioritize points that were highly reliable and easily identifiable in the field. Each point represents a homogeneous plot of the corresponding class.

Geographic distribution of validation points: Validation points for the mangrove genus were evenly distributed among the three classified genera (e.g., 10 points for *Rhizophora*, 10 for *Avicennia*, 10 for *Ceriops*), ensuring that each class was represented. These points were geographically distributed across the five sub-districts of Langsa City, reflecting the actual distribution patterns of the genera. Non-mangrove points were similarly distributed across water bodies, vacant land, and agricultural areas. All validation points were spatially independent from the training data used for classification, ensuring an unbiased assessment. These points were recorded using a high-precision GPS receiver (accuracy <5 m).

Metrics: A confusion matrix was used to calculate standard accuracy metrics: Overall Accuracy, User Accuracy, Producer Accuracy, and Kappa coefficient, which collectively assess the reliability and consistency of the classification. The scientific names of all identified genera and species are italicized in accordance with standard taxonomic conventions.

Mangrove zonation maps were generated by analyzing the spatial distribution of dominant genera in relation to associated environmental gradients. This ecological interpretation follows the approach described by (Koedsin and Vaiphasa 2013). All spatial analysis, map generation, and data visualization were performed using QGIS. Images were generated with standard symbols, clear scale bars, and north arrows to ensure cartographic consistency and clarity.

RESULTS AND DISCUSSION

Mangrove cover and distribution in Langsa City

Classification of SPOT-6 images processed using the Maximum Likelihood Classification algorithm identified a total mangrove forest area of 5,837.46 hectares in Langsa City. This mangrove forest area is unevenly distributed among the five sub-districts. Langsa Timur Sub-district shows the largest mangrove forest area, namely 2,841.78 ha, which is 48.68% of the total mangrove forest area. Then followed by Langsa Barat with 1,910.07 ha (32.72%), Langsa Baro with 702.9 ha (12.04%), Langsa Lama with 359.94 ha (6.17%), and Langsa Kota with the smallest proportion of 22.77 ha (0.39%). The detailed distribution by sub-district is presented in Table 1. The overall spatial distribution of mangrove forests and other land cover types in Langsa City is visualized in Figure 2. This map provides a comprehensive overview of the coastal landscape, distinguishing mangrove forests (dark green) from other features, including built-up land, fisheries ponds, water bodies, and various vegetation types across the sub-district.

Mangrove genera composition

From the field verification results, a total of 13 mangrove species were identified, namely *Rhizophora apiculata*, *Rhizophora mucronata*, *Rhizophora stylosa*, *Acanthus ilicifolius*, *Ceriops tagal*, *Sonneratia alba*, *Avicennia lanata*, *Avicennia alba*, *Bruguiera gymnorrhiza*, *Bruguiera cylindrica*, *Xylocarpus granatum*, *Hibiscus tiliaceus*, and *Nypa fruticans*. Although the field verification identified 13 mangrove species representing several genera, only three genera (*Rhizophora*, *Avicennia*, and *Ceriops*) could be reliably mapped from SPOT-6 imagery. This result reflects the inherent spectral limitations of SPOT-6 multispectral bands, which are often unable to separate genera with highly overlapping spectral signatures, such as *Sonneratia*, *Bruguiera*, and *Xylocarpus*. These genera exhibit spectral variations that are insufficiently distinguishable at the available spatial and spectral resolutions, preventing consistent classification. Therefore, this study focused on genera that could be distinguished with acceptable accuracy: *Rhizophora*, *Avicennia*, and *Ceriops*, which collectively dominate the mangrove composition in Langsa City and cover over 95% of its mangrove area. This refinement ensures that the resulting "mangrove types" remain ecologically meaningful and spatially reliable, aligning with the goal of providing robust genus-level information for conservation and management.

Field verification and spectral analysis revealed that several genera exhibit substantial spectral overlap in the available SPOT-6 multispectral bands, leading to confusion between classes. Genera such as *Sonneratia* and *Bruguiera* have similar reflectance characteristics to *Rhizophora* and *Avicennia*, particularly in the red and near-infrared bands, which limits their separation at 6 m spatial resolution. This spectral similarity has been widely reported in previous studies, where medium-resolution optical imagery often fails to distinguish between mangrove taxa with comparable canopy structure, leaf chemistry, and water content (Koedsin and Vaiphasa 2013; Wang et al. 2018)

Due to these limitations, the Maximum Likelihood Classification (MSC) algorithm could only separate three genera with the most distinct and consistent spectral signatures. *Rhizophora* occupied the largest area, followed by *Avicennia* and *Ceriops*. This finding aligns with field observations and the ecological dominance of these genera in Langsa City, indicating that although some taxa were misclassified or combined due to spectral confusion, the classification successfully captured the main mangrove types that could be distinguished using SPOT-6 imagery. The area and proportion of these main genera are detailed in Table 2, and their spatial distribution across Langsa City is illustrated in Figure 3.

Table 1. Mangrove Area Distribution by sub-district in Langsa City, Aceh, Indonesia

Land cover	Wide (Ha)	Percentage
Langsa Barat	1,910.07	32.72%
Langsa Timur	2,841.78	48.68%
Langsa Baro	702.9	12.04%
Langsa Lama	359.94	6.17%
Langsa Kota	22.77	0.39%
Total	5,837.46	100%

Table 2. Area and proportion of major genera in Langsa City, Aceh, Indonesia

Genus	Area (Ha)	Percentage (%)
Rhizophora	2,216.01	38
Avicennia	2,086.34	36
Ceriops	1,535.11	26
Total	5,837.46	100

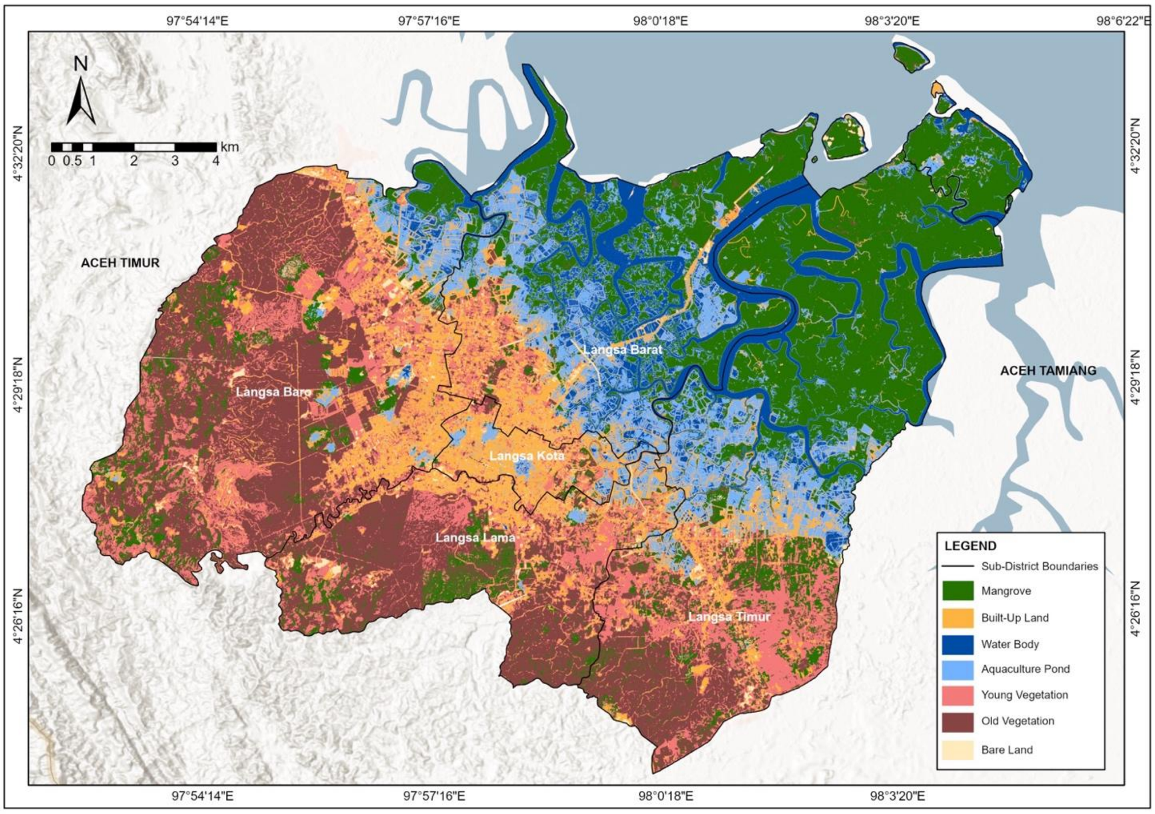

Figure 2. Map of mangrove distribution in Langsa City, Aceh, Indonesia. Source: Data Processing (2024)

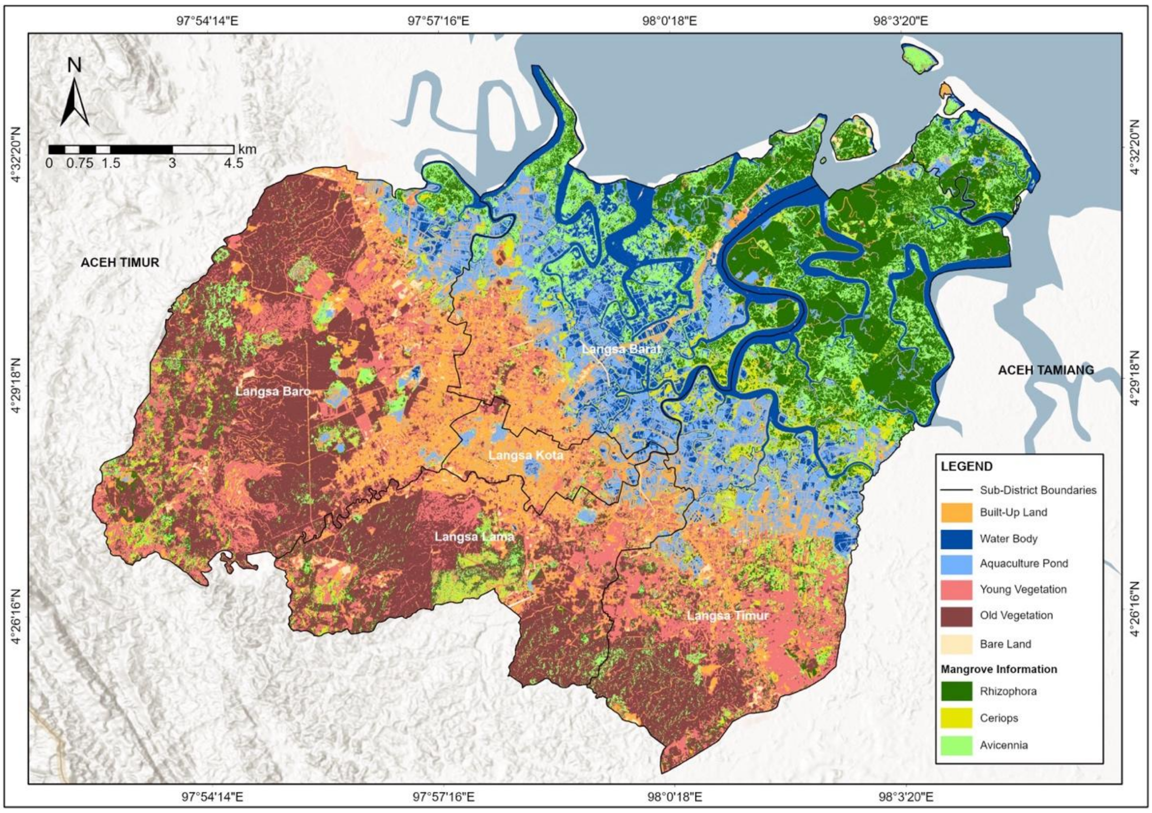

Figure 3. Map of mangrove type distribution in Langsa City, Aceh, Indonesia. Source: Data Processing (2024)

Zonation of mangrove types

Based on spectral patterns, classification results, and field observations, mangrove zoning in Langsa City is divided into three ecological zones, as depicted in Figure 4. These zones are: Zone 1 (central zone of *Avicennia-Sonneratia*), Zone 2 (central/eastern zone of *Rhizophora*), and Zone 3 (outer/back zone of *Bruguiera*). Zoning is determined by the spatial dominance of each genus, supported by field measurements of key environmental variables, including salinity, inundation frequency, and substrate stability. The central zone (Zone 1, red on the map), which is dominated by *Avicennia* and *Sonneratia*, is characterized by higher salinity levels and frequent tidal waves, conditions that correspond to the physiological tolerance and pneumatophore-based adaptation of these genera. The central/eastern zone (Zone 2, yellow on the map) is dominated by *Rhizophora*, which thrives in areas with regular but not too extreme tidal influences and in muddy, unstable substrates suitable for stabilizing the supporting roots. The outer/back zone (Zone 3, light blue on the map), where *Bruguiera* was recorded during the field survey, corresponds to areas with a more stable substrate, lower salinity, and reduced inundation frequency. This zoning pattern reflects the ecological strategies and habitat preferences of each genus and is consistent with previous research on mangrove ecological gradients (Koedsin and Vaiphasa 2013; Tran et al. 2024).

Discussion

This study successfully demonstrated that high-resolution SPOT-6 imagery, combined with the Maximum Likelihood Classification (MSCL), can effectively map the spatial distribution and dominant mangrove genera in Langsa City. The accuracy assessment, detailed in Table 3, showed an Overall Accuracy of 83% and a Kappa coefficient of 76%. This indicates that the classification performed reliably at the genus level, providing robust results for mapping the major mangrove genera present in the study area. These accuracy values are comparable to those of previous studies using similar remote sensing approaches for mangrove classification, confirming the robustness of the methodology for genus-level discrimination. Specifically, *Avicennia* demonstrated excellent User Accuracy (100%), while *Rhizophora* and *Ceriops* also demonstrated strong User and Producer Accuracy, demonstrating the reliability of their mapping.

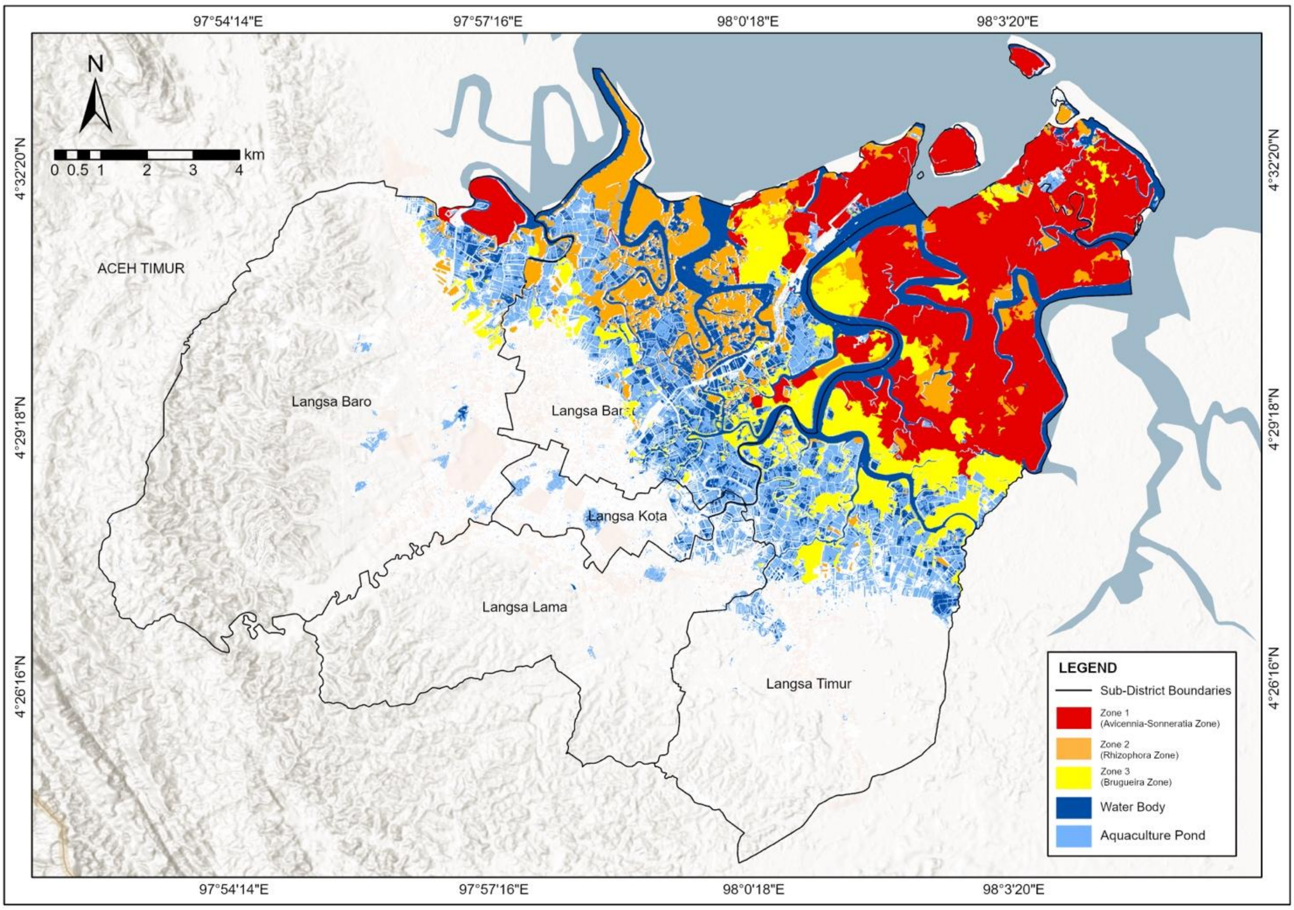

Figure 4. Langsa City mangrove zoning map. Source: Data Processing (2024)

Table 3. Accuracy test of confusion matrix mangrove genera

Classification Class	Rhizophora	Avicennia	Ceriops	Total	User's Accuracy (%)	Errors Commission
Rhizophora	10	-	1	11	91%	9%
Avicennia	-	5	-	5	100%	-
Ceriops	2	-	5	7	71%	29%
Pond	-	1	-	1	-	-
Total	12	6	6	24		
Producer's Accuracy (%)	83%	83%	83%		Overal Accuracy	83%
Errors Commission	17%	17%	17%		Kappa	76%

Spatial analysis indicates that Rhizophora is the most dominant genus in Langsa City, consistent with findings from North Sumatra and Southeast Asia, where *Rhizophora* are widely recognized for their ecological resilience and prevalence in restoration programs. This observation has been highlighted by Koedsin and Vaiphasa (2013) and Iswahyudi et al. (2020), who both reported that *Rhizophora* tend to dominate areas with stable tidal regimes and high sediment accumulation. The widespread distribution of *Avicennia* and *Ceriops* also aligns with their ecological roles along tidal gradients and their adaptive strategies to cope with salinity and sediment instability, as described by Middleton et al. (2024). The clear zonation pattern in Langsa City, consisting of *Avicennia-Sonneratia* in the central part, *Rhizophora* in the eastern part, and *Bruguiera* in the outer part, closely matches measured environmental gradients, including salinity, inundation frequency, and substrate conditions. This relationship supports the ecological framework described by Bengen (2002). Environmental measurements collected during field observations also strengthen this relationship and indicate that the spatial distribution of the genus in Langsa City is strongly influenced by hydrological and sedimentation processes. A similar zonal interaction between environmental gradients and mangrove distribution was highlighted by Katili et al. (2017) Gorontalo, who documented how degradation rates were strongly influenced by local hydrology, freshwater input, and substrate characteristics.

The results of this study have important implications for conservation and restoration strategies in Langsa City. The dominance of *Rhizophora* in East and West Langsa highlights areas suitable for strict protection because they provide shoreline stabilization, nursery habitat, and ecological connectivity. Transition zones dominated by *Avicennia* and *Ceriops* are strategic areas for restoration, particularly in locations experiencing salinity fluctuations or sediment imbalance. This recommendation is consistent with the findings of Tran et al. (2024), who showed that restoration success is significantly increased when species adapt to the specific ecological characteristics of each habitat zone. Integrating genus-level mapping with community-based conservation approaches can further enhance the long-term sustainability of mangrove protection efforts. Community engagement plays a central role in the success of mangrove rehabilitation programs in Indonesia, as social acceptance and local involvement often determine the survival of restored stands. These findings highlight the importance of involving local stakeholders in mangrove management initiatives in Langsa City.

The need for sustainable management is further reinforced by studies of long-term degradation and successful rehabilitation efforts in other mangrove areas. These studies demonstrate that long-term degradation can only be reversed when conservation zoning, ecological monitoring, and community engagement are combined within a coordinated approach and management framework. This evidence supports the application of genus-level maps in Langsa City for improved zoning design, targeted restoration, and long-term monitoring. Although SPOT-6 imagery offers advantages for high-resolution mapping, this study found spectral confusion in distinguishing certain genera, particularly *Bruguiera* and *Sonneratia*. This limitation is consistent with previous research, which found that some mangrove genera exhibit overlapping spectral characteristics, reducing the ability to distinguish species in multispectral imagery (Wang et al. 2015). Seasonal hydrological dynamics can also affect spectral reflectance, leading to discrepancies between image acquisition conditions and field surveys.

Future research in Langsa City would benefit from multi-temporal satellite imagery to capture seasonal variations and canopy dynamics, thereby improving the robustness of genus-level mangrove discrimination. Time-series imagery is highly effective for detecting long-term mangrove fluctuations. Furthermore, integrating structural datasets, such as drone hyperspectral or LiDAR data, can significantly improve mangrove classification, especially for spectrally overlapping genera. This data can be used to classify mangrove vegetation structure with high accuracy. These findings align with regional mangrove conservation literature and provide practical guidance for sustainable mangrove ecosystem management in Langsa City. The genus-level mapping generated in this study can serve as an important basis for spatial planning, ecological zoning, restoration prioritization, and community-based conservation programs.

In conclusion, this study successfully mapped the distribution and classified the dominant mangrove genera in Langsa City using high-resolution SPOT-6 imagery and the Maximum Likelihood Classification method. The study identified a total mangrove area of 5,837.46 hectares, with *Rhizophora*, *Avicennia*, and *Ceriops* as the main genera, collectively covering more than 95% of the mapped mangrove area. The classification achieved a reliable

Overall Accuracy of 83% and a Kappa coefficient of 76% through rigorous field validation.

The resulting genus-level map provides important and up-to-date spatial information previously unavailable for the Langsa region. This detailed mapping is invaluable for understanding mangrove distribution patterns and ecological zoning, and supporting effective spatial planning for conservation. It enables specific zone-based conservation planning and targeted restoration efforts, ensuring that interventions are ecologically appropriate and resource allocation is optimized for long-term mangrove resilience.

It is recommended that local governments, conservation organizations, and coastal planners utilize this genus-level map and the presented methodology to guide mangrove forest management and restoration in Langsa City. Further research should explore integrating multi-temporal satellite imagery, drone hyperspectral data, and LiDAR datasets to improve spectral discrimination of overlapping mangrove genera and monitor the long-term dynamics of this vital ecosystem, including at the species level. Furthermore, expanding field validation efforts across multiple mangrove locations will further improve the accuracy and reliability of future classification models.

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