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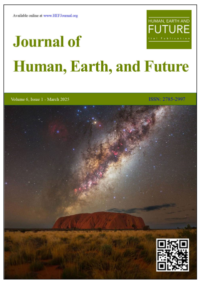

Mapping Mangrove Species Distribution and Density Using Sentinel-2 Satellite Imagery and Spectral Analysis

Lalu Muhamad Jaelani [1*], Dwi Sugma Safitri [1], Naomy Elliana Kristian [1], Aldea Noor Alina [1], Muhammad Aldila Syariz [1], Hartanto Sanjaya [2], Abdul Rauf Abdul Rasam [3]

[1] *Department of Geomatics Engineering, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia.*

[2] *Research Center for Geoinformatics, National Research and Innovation Agency (BRIN), Jakarta Pusat 10340, Indonesia.*

[3] *College of Built Environment, Malaysia Institute of Transport, Universiti Teknologi MARA, Shah Alam, Selangor 40450, Malaysia..*

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Abstract

This study aimed to conduct a comprehensive analysis and mapping of mangrove species distribution and density in conservation areas of Surabaya, Indonesia. The investigation focused on assessing the current state of mangrove ecosystems using Sentinel-2 satellite imagery and advanced spectral analysis methods, which were crucial for climate regulation, food security, and poverty reduction. Moreover, Linear Spectral Unmixing (LSU) was used to accurately classify mangrove species and individual densities. The methodology included the use of radiometrically corrected Sentinel-2A imagery and spectral library data obtained from various national agencies. The findings showed that the Pamurbaya protected area covered 7,965,971 m^2, with Avicennia Marina accounting for 74% of the mangrove, followed by Rhizophora Mucronata (24%) and Rhizophora Apiculata (2%). Additionally, this study showed significant density variations, with 83% of the area densely populated, and also provided novel insights by applying LSU, indicating a significant advancement in environmental monitoring. The outcome offered critical information for policymakers and stakeholders to develop effective conservation and management strategies to ensure the long-term sustainability of critical coastal ecosystems. Finally, the findings showed the urgency of systematic conservation efforts to address the impact of deforestation and land-use changes on mangrove habitats worldwide.

Keywords: Linear Spectral Unmixing; Mangrove; Pamurbaya; Remote Sensing; Sustainability.

1. Introduction

Mangrove ecosystems are important coastal habitats characterized by tidal wetland ecosystems that are mostly found on tropical and subtropical coasts [1]. These ecosystems are classified as facultative halophytes, showing individual ability to tolerate a range of salinity levels. Studies have shown that optimal growth occurs when saltwater concentrations range from 5% to 75% [2]. While mangroves can endure freshwater conditions, the trees are not considered to thrive in purely freshwater environments. This classification reflects the substantial study conducted on mangroves over the past century [3]. Mangrove ecosystems play a crucial role in providing essential benefits that contribute to human well-being, such as climate regulation, food security, and poverty reduction [4]. Following this discussion, wetland habitats offer various advantages, including supporting fisheries, maintaining clean water, as well

* Corresponding author: lmjaelani@its.ac.id

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as safeguarding against erosion and severe weather events. Mangroves act as natural barriers, protecting assets and reducing community vulnerability. Despite its exceptional carbon storage capabilities, the value of mangroves is often underestimated, leading to depletion exceeding global deforestation rate [5–8].

As integral components of blue carbon ecosystems, mangroves are included in numerous international programs and are distinguished for their capacity to store three to five times more carbon than other ecosystems [9–13]. However, the ability of the tree to mitigate and adapt to climate change varies depending on species, influenced by factors such as erosion rates, nutrient availability, temperature tolerance, and species composition [14, 15]. Some species may migrate poleward but face habitat loss, with Central America and the Caribbean projected to experience significant species decline [16]. According to a publication from LIPI in 2021, Indonesia has up to 3.3 million hectares of mangrove forests, representing 22.6% of the global total. Following this discussion, the country has documented at least 202 mangrove species. In Surabaya Mangrove Botanical Garden, part of the Pamurbaya area, at least 59 species have been identified as of 2023. Effective management and conservation of these ecosystems require detailed data on species distribution and density. However, these forests face threats from deforestation, land-use changes, and anthropogenic activities, necessitating strong monitoring and mapping strategies to support conservation efforts [5, 17–19].

Recent advancements in mangrove mapping methods, driven by technological progress and the need for accurate monitoring, have revolutionized the study of these ecosystems. Traditional on-site surveys are precise but require labor-intensive effort and cover only a small area. Relating to this discussion, the advent of remote sensing technologies, particularly high-resolution satellite imagery, has transformed mangrove mapping. The Sentinel-2 satellite, launched by the European Space Agency as part of the Copernicus program, offers high-resolution multispectral imagery with a spatial resolution of up to 10 meters, facilitating detailed and cost-effective mapping of mangrove forests. This technology enables the assessment of mangrove distribution, density, and species composition over time through spectral analysis methods [20–24].

This method allows the direct measurement of spectral characteristics using a spectrometer, spectral libraries, and image-based reflectance extraction methods. Therefore, this study aimed to address gaps in the literature by conducting a comprehensive analysis and mapping of mangrove species distribution as well as density in the conservation areas of Surabaya, Indonesia, using Sentinel-2 satellite imagery and spectral analysis methods.

2. Material and Methods

This study was conducted in the Pamurbaya protected area at the East Coast Area of Surabaya with geographic coordinates of 120°47'52.52" E - 120°50'47.34" E and 7°15'30" S - 7°20'45" S (Figure 1). According to the Surabaya Environmental Agency, the predicted mangrove ecosystems in this area reached 916.743 hectares out of the total predicted area of 1,108.823 hectares, which was approximately 82.68%. Furthermore, Surabaya Regional Regulation No. 12 of 2014 concerning the Surabaya Spatial Plan of 2014-2034 stated that the Pamurbaya area was a marine protected area aimed at guarding the environment, potential, and resources in the coastal and marine waters areas from activities leading to damage and pollution. In this area, development and land use activities capable of damaging the environment were prohibited.

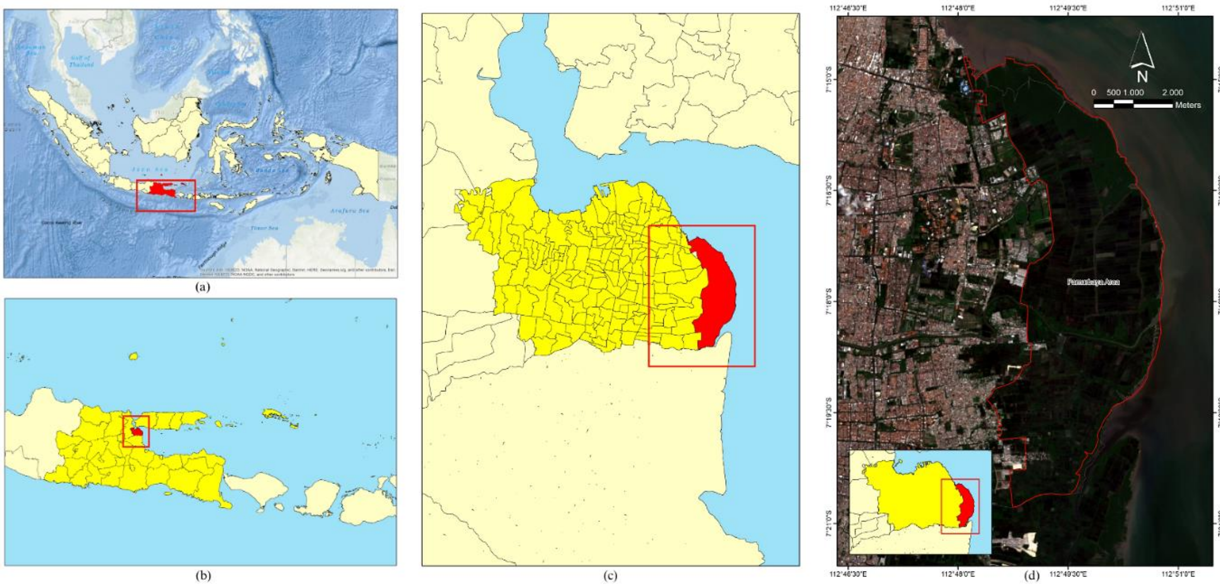


Figure 1. Study Area: (a) Indonesia, (b) East Java Province, (c) Pamurbaya Area in Surabaya, and (d) Satellite Imagery of Pamurbaya Area

The investigation used a radiometrically corrected Sentinel-2A image from the Sentinel Hub EO Browser website and followed the steps shown in Figure 2. In this context, the image was acquired on February 9, 2024, but it had a low cloud pixel percentage of 4.3%. Following this discussion, spectral library data for four different mangrove species were obtained from the Agency for the Assessment and Application of Technology (BPPT), Ministry of Marine Affairs and Fisheries (KKP), as well as the National Study and Innovation Agency (BRIN). Subsequently, the endmember spectral values were recorded using a field remote sensing instrument and the OceanOptics USB4000+ spectrometer. To focus on the Pamurbaya area, vector data of the area was applied. SNAP—Earth Online (2020) was used for LSU processing, while spatial data processing software was considered for layout preparation and data analysis.

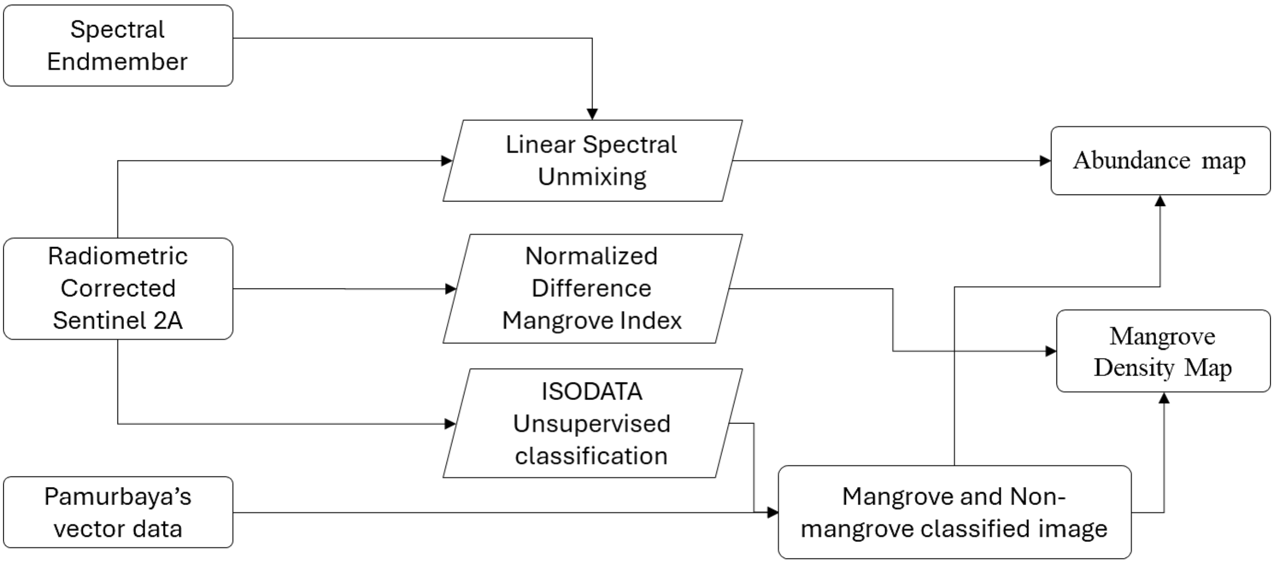


Figure 2. Study flow

The study process included several stages, beginning with the identification of mangrove forest area in Pamurbaya. This outcome was achieved by performing ISODATA unsupervised land cover classification based on a radiometrically corrected Sentinel-2A image [25, 26]. After a subset with vector data of the area, the results were then used as base data for all processing results as shown in Figure 3.

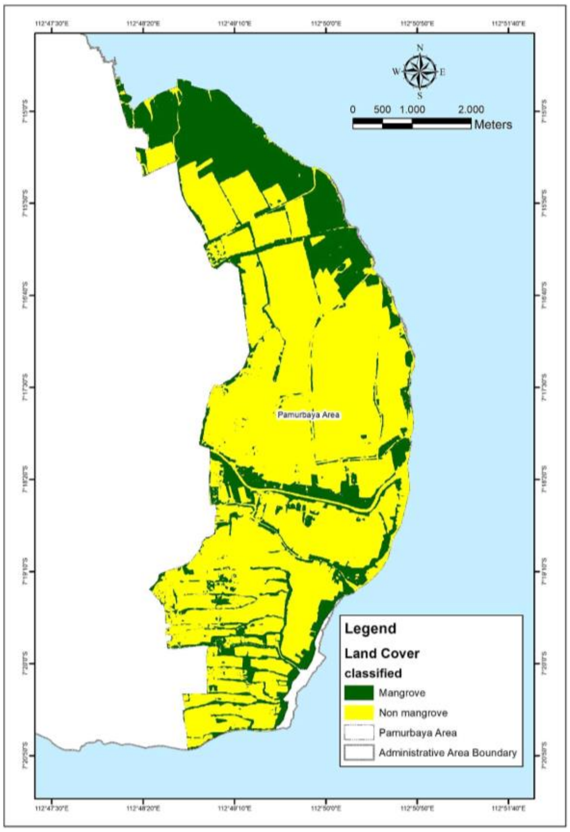


Figure 3. Landcover Classification: Mangrove vs non-mangrove area

The calculated area of mangrove forest coverage from the classified image was 8,319,459.5 m², which was less than the predicted area of 9,167,430 m². This difference was attributed to factors such as recent changes in vegetation cover or potential inaccuracies in the initial prediction.

The second step was performing Linear Spectral Unmixing (LSU), a sub-pixel analysis method that showed abundance of endmembers in mixed pixels and was separated using a linear model [27–33]. This process signified that the reflectance in each image pixel was a linear combination of the reflectance of endmembers present in the pixel. The spectral unmixing tool in SNAP software was used, which contained three different algorithms, including Unconstrained LSU, Constrained LSU, and Fully Constrained LSU. In the unconstrained LSU method, abundance was not constrained and could be used for any numerical value. This process showed that the abundance value was negative or exceeded 1. In the constrained LSU method, the sum of endmember abundances was equal to 1, which was the most used method. Additionally, the fully constrained LSU method used by the data processing in this study signified that the sum of all endmember abundances was equal to 1 and abundance values were not less than zero. This method needed spectral values of each endmember, which were trimmed according to the Sentinel-2A band wavelength range as shown in Table 1 and Figure 4.

Table 1. Endmember (in % reflectance) of Mangrove Species

Species	Sentinel 2 Band Number				
	B2	**B3**	**B4**	**B5**	**B8**
Avicennia Marina	6.072	13.599	4.994	14.028	29.910
Rhizophora Apiculata	4.778	10.280	4.088	11.047	35.428
Rhizophora Mucronata	5.296	9.497	3.757	10.855	48.353
Sonneratia Alba	9.663	20.742	7.543	20.075	33.345

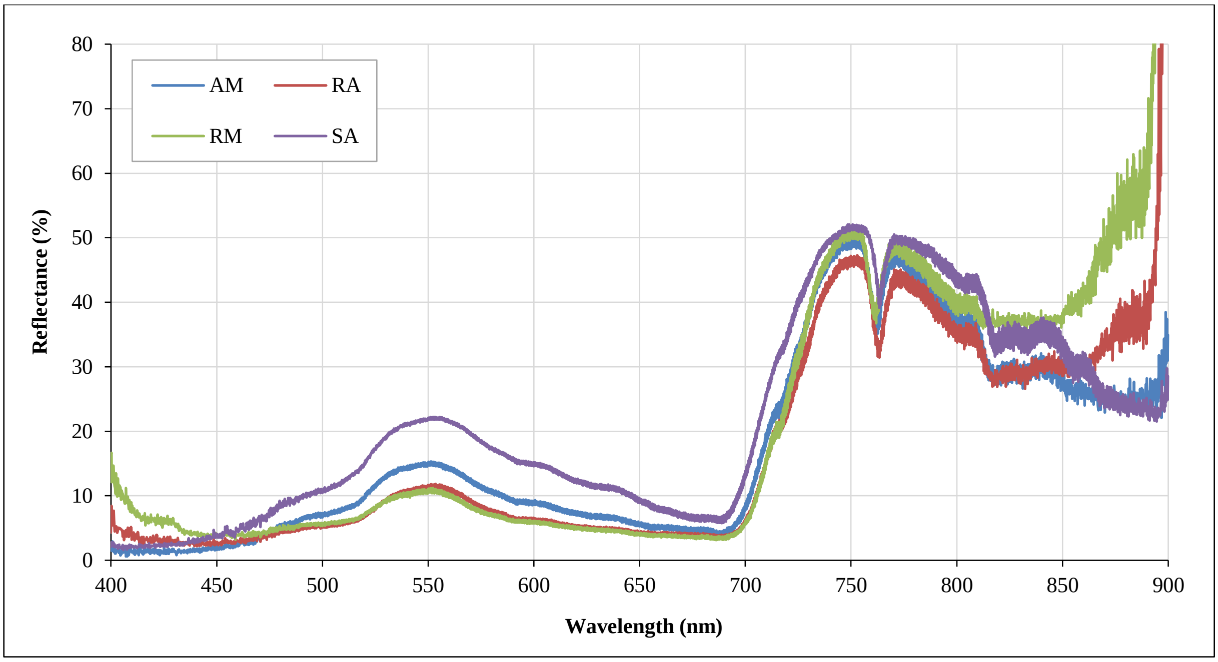


Figure 4. Spectral endmember of mangrove species according to Sentinel 2 spectral bands: Avicennia Marina (AM), Rhizophora Apiculata (RA), Rhizophora Mucronata (RM), and Sonneratia Alba (SA)

LSU calculated the abundance value of each end member for every pixel. The number of endmembers was less than the number of spectral channels. Moreover, the unmixing results were highly dependent on the endmembers used, and changing these endmembers affected the results. The algorithm for LSU was shown in the following equation.

$$R_k = \sum_{i}^{n} a_i \cdot E_{i,k} + \varepsilon_k \tag{1}$$

where, R_k = Reflectance value at wavelength k; $E_{k,i}$ = Endmember i value at wavelength k, a_i =Abundance value of endmember i, ε_k =Error value at wavelength k, and k = Bands: blue, green, red, and near-infrared. i = The number of endmembers, which were endmembers of Avicennia Marina, Rhizopora Apiculata, Rhizopora Mucronata, and Sonneratia Alba.

The investigation performed a classification to separate mangrove density into dense, medium, and sparse vegetation using the *Normalized Difference Mangrove Index* (NDMI) [34, 35]. This process allowed the study to generate a map of distribution and density levels of mangrove in the Pamurbaya conservation area, Surabaya, Indonesia. The NDMI index was shown in Equation 2:

$$NDMI = \frac{(\rho NIR - \rho SWIR1)}{(\rho NIR + \rho SWIR1)} \quad (2)$$

where, ρNIR =reflectance at Near Infrared (NIR) band, and $\rho SWIR1$ = reflectance at Short-wave infrared 1 band

3. Results and Discussion

The different endmembers of Avicennia marina, Rhizophora Apiculata, Rhizophora Mucronata, and Sonneratia Alba were shown in Figure 4. This result was a graph of data collected from spectral libraries of BPPT, KKP, and BRIN, where each species showed unique spectral values. There was a slight increase in reflectance in the wavelength range around 500-600 nm, as well as a significant decrease in the range of 750-770 nm, leading to a steep slope in the spectral graph. Figure 4 showed the average reflectance values of endmembers at the center wavelengths of Sentinel-2A and signified unique reflectance patterns for each mangrove species. Subsequently, LSU processing was performed using only average reflectance values of each endmember for each band. The endmember of each species for the individual band of Sentinel-2 data was shown in Table 2, which was used as an input for LSU.

Table 2. Area and Density of Mangrove Species

No.	Species	Area				Density
		m²	%	m²	%	
1	Avicennia Marina	5,926,659	74	652,546	11	Sparse
				416,173	07	Moderate
				4,857,939	**82**	**Dense**
2	Rhizophora Apiculata	119,645	02	31,345	26	Sparse
				41,120	34	Moderate
				47,180	**39**	**Dense**
3	Rhizophora Mucronata	1,919,667	24	131,952	07	Sparse
				49,631	03	Moderate
				1,738,083	**91**	**Dense**
4	Sonneratia Alba	0	0	**0**	**0**	**0**

The abundance maps generated through the spectral unmixing algorithm showed the percentage of each endmember in each pixel, ranging from 0% to 100%. The maps shown in Figure 5 signified the spatial distribution of Avicennia Marina, Rhizophora Apiculata, Rhizophora Mucronata, and Sonneratia Alba species in the Pamurbaya area. During the study, bright green to dark green implied LSU percentages ranging from 50-100%, while red to yellow showed the range of 0-50%. Avicennia Marina species dominated the Pamurbaya protected area and were commonly found in Gunung Anyar and Wonorejo Mangrove Botanical Gardens, with a percentage range of 50-100%. This outcome showed the important role the species played in the mangrove ecosystem structure of the area. However, there were some areas during the study with a lower percentage range. Avicennia Marina species were mostly found in tidal areas and also as pioneer species in protected coastal areas with high tolerance to salinity levels. The species were common mangrove, that occupied the open mangrove zone (Figure 5a).

Figure 5b showed the spatial distribution of Rhizophora Apiculata species across the Pamurbaya area. The majority of the area signified an abundance range of 0-40%. This result implied that in individual pixels, other mangrove species were more dominant. The outcome showed that Rhizophora Apiculata species did not dominate the Pamurbaya protected area. However, a small portion of the area signified a higher percentage range of 50-60% for these species.

Different from Rhizophora Apiculata, the spatial distribution of Rhizophora Mucronata species (Figure 5c) showed a dominance range of 0-50% in the majority with a minimal area in the range of 50-100%. The outcome signified that Rhizophora Mucronata species had high abundance and were dominant in each pixel in some areas, even though it was less than the dominance of Avicennia Marina. Compared to the three previous species, the last species (Figure 5d), Sonneratia Alba, was not strongly observed, with a percentage of abundance mainly in the 0-10% range. This value showed that the species were not observed in the Pamurbaya protected area.

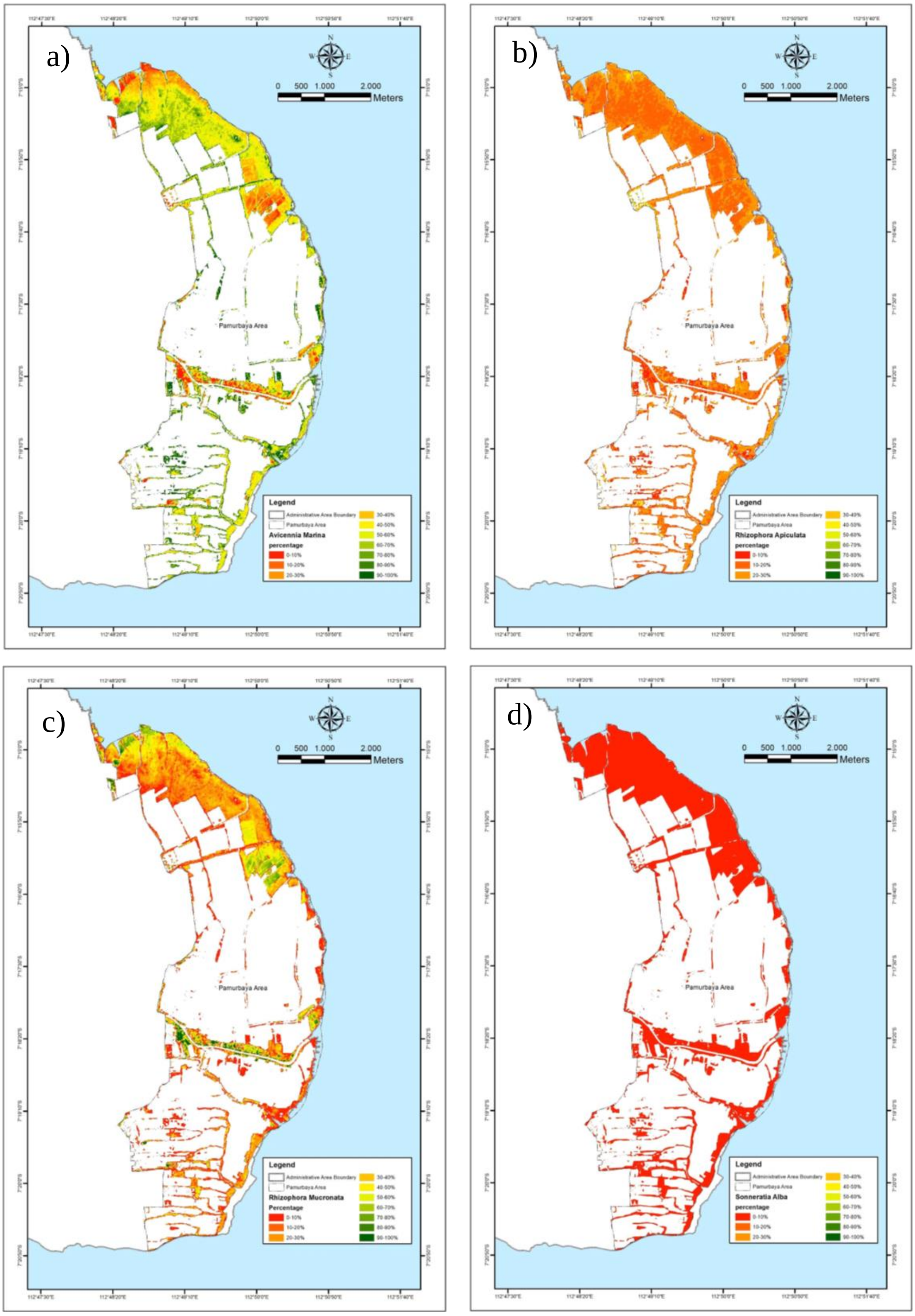


Figure 5. Abundance map: (a) Avicennia Marina, (b) Rhizophora Apiculata, (c) Rhizophora Mucronata, (d) Sonneratia Alba

Figure 6 showed the spatial distribution of dominant mangrove species in the Pamurbaya protected area. The mapping results, supported by Table 2, showed that Avicennia Marina was the primary species, covering an area of 5,926,659 m², which constituted approximately 74% of the total mangrove area. These species were predominantly found in areas with dense vegetation, approximately 82% of its coverage. The significant presence of Avicennia marina signified its ecological importance as a pioneer species capable of thriving in saline environments, thereby playing a crucial role in the stability and resilience of mangrove ecosystems. Figure 7 showed a detailed view of mangrove density across the study area, categorized into sparse, moderate, and dense vegetation. According to the data, Rhizophora Mucronata occupied 1,919,667 m², with 91% of its area classified as densely vegetated. The high density signified adaptability of the species and contribution to the structural complexity of the habitat. Consequently, Rhizophora Apiculata covered a smaller area of 119,645 m², with a mixed density distribution of sparse, moderate, and dense vegetation. The absence of significant areas for Sonneratia Alba showed its limited presence in the area. Moreover, Wonorejo Mangrove Botanical Garden and Gunung Anyar signified a more diverse mix among the three main mangrove species, showing areas of high biodiversity. These figures collectively improved understanding about mangrove ecosystems by providing spatial insights into species distribution and density.

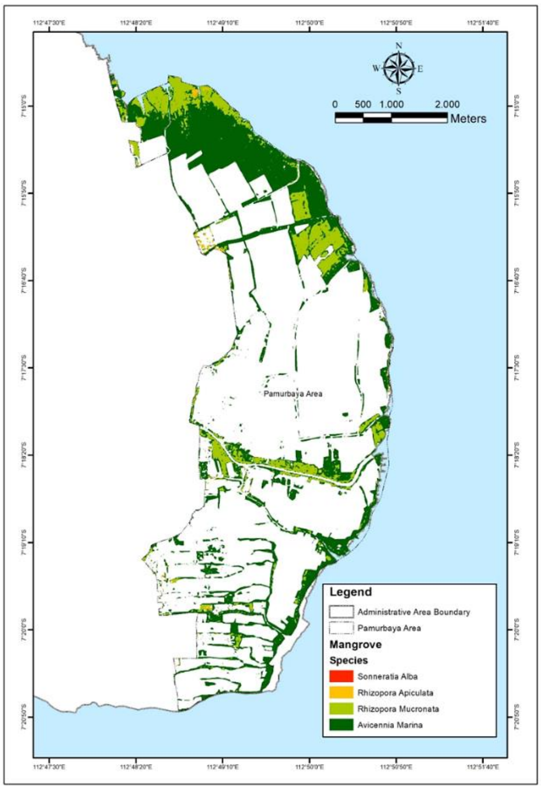
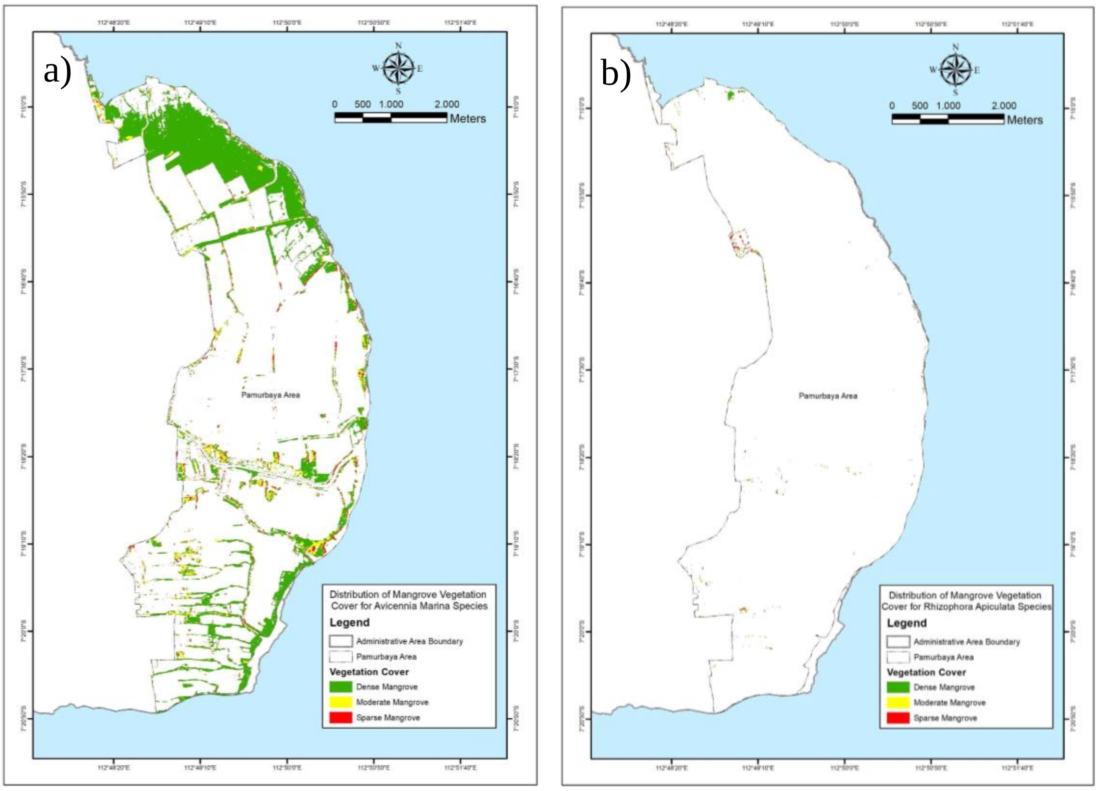


Figure 6. Dominant Mangrove variety map



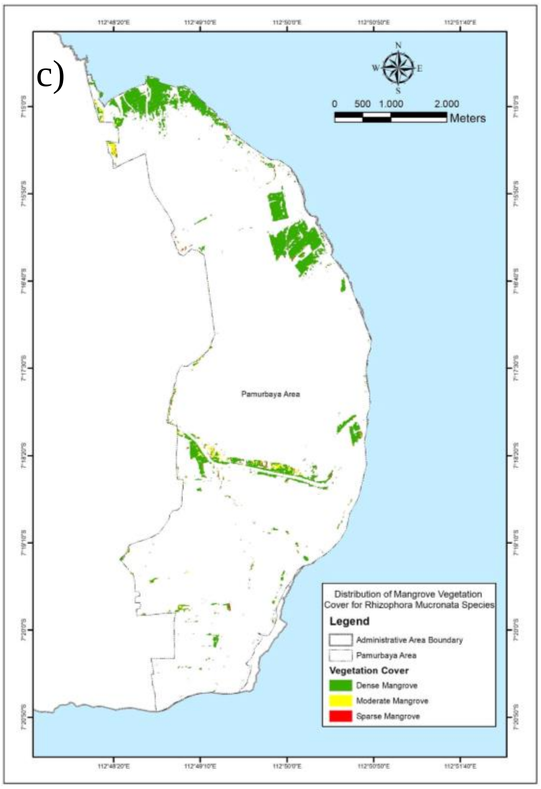


Figure 7. Mangrove density map: (a) Avicennia Marina, (b) Rhizophora Apiculata, (c) Rhizophora Mucronata

The study using Sentinel-2 satellite images and LSU gave very useful information about where and how many mangrove species are in the Pamurbaya protected area. The calculated mangrove forest coverage from the classified image was 8,319,459.5 m², slightly less than the predicted area of 9,167,430 m². This discrepancy was due to recent changes in vegetation cover or potential inaccuracies in the initial prediction. The mapping results showed that Avicennia Marina was the primary species, covering a significant portion of the area, followed by Rhizophora Mucronata as the second most prevalent species. In addition, spatial distribution and density of these species were critical for understanding the ecological dynamics and resilience of mangrove ecosystems.

The results showed the need for aimed conservation strategies, particularly for Avicennia Marina and Rhizophora Mucronata, due to individual substantial coverage as well as density. These species were crucial for carbon storage and coastal protection [36-41]. The study showed the use of LSU and Sentinel-2 imagery for large-scale mangrove mapping, providing a strong framework for ongoing monitoring as well as management.

4. Conclusion

In conclusion, this study conducted a comprehensive analysis of mangrove species distribution and density in the Pamurbaya protected area using Sentinel-2 satellite imagery and LSU methods. The calculated mangrove forest coverage from the classified image was 8,319,459.5 m², which was less than the predicted area of 9,167,430 m². This discrepancy was caused by recent changes in vegetation cover or potential inaccuracies in initial predictions. The spectral library data showed unique spectral characteristics for each mangrove species, with reflectance values signifying a slight increase in the 500-600 nm range and a significant decrease in the 750-770 nm range, leading to a steep spectral curve. Following the discussion, LSU analysis identified Avicennia Marina as the dominant species, covering 5,926,659 m² (74% of the total mangrove area) with 82% dense vegetation, while Rhizophora Mucronata occupied 1,919,667 m², having 91% dense coverage. Rhizophora Apiculata and Sonneratia Alba had smaller coverage, with Rhizophora Apiculata covering 119,645 m² with mixed density. During the analysis, Wonorejo Mangrove Botanical Garden and Gunung Anyar signified a more diverse mix among the three main mangrove species.

This study showed the use of LSU in large-scale mangrove species mapping, offering critical insights for conservation and management efforts. Despite the critical insights for conservation and management, it is essential to validate the findings through ground-truthing. Following this discussion, the results provided a strong framework for policymakers and stakeholders to develop effective strategies to ensure the long-term sustainability of Pamurbaya mangrove ecosystems, addressing significant threats from deforestation as well as land-use changes. Future studies should focus on validating these findings through ground-truthing and exploring the incorporation of additional remote sensing data to improve the accuracy and scope of mangrove mapping efforts. In addition, the insights achieved from this study could impact policymakers and stakeholders in developing effective strategies to ensure the long-term sustainability of mangrove ecosystems, showing individual ecological as well as socio-economic significance.

4.1. Limitations and Future Study

While the study provided valuable insights, the absence of ground-truthing showed a limitation that should be addressed in future studies. Ground-truthing would validate remote sensing results and improve the accuracy of spectral analysis. Additionally, incorporating environmental factors such as salinity and tidal patterns could further explain the drivers of species distribution and density variations. By addressing these limitations and expanding the scope of analysis, future studies could build on these findings to support the sustainable management of mangrove ecosystems in Surabaya.

5. Declarations

5.1. Author Contributions

Conceptualization, L.M.J.; methodology, L.M.J.; software, D.S.F. and N.E.K.; validation, A.N.A.; formal analysis, L.M.J., M.A.S., and A.N.A.; investigation, D.S.F., N.E.K., and A.N.A.; resources, L.M.J., H.S., and A.R.A.; data curation, L.M.J., D.S.F., and N.E.K.; writing—original draft preparation, L.M.J., D.S.F., and N.E.K.; writing—review and editing, L.M.J.; visualization, D.S.F. and N.E.K.; supervision, L.M.J. and M.A.S.; project administration, L.M.J.; funding acquisition, L.M.J. and A.R.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

Data sharing did not apply to this article.

5.3. Funding

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5.4. Acknowledgments

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5.5. Institutional Review Board Statement

Not applicable.

5.6. Informed Consent Statement

Not applicable.

5.7. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

6. References

[1] Jusoff, K. (2008). Geospatial Information Technology for Conservation of Coastal Forest and Mangroves Environment in Malaysia. Computer and Information Science, 1(2), 129. doi:10.5539/cis.v1n2p129.

[2] van Bochove, J. W., Sullivan, E., Nakamura, T., & Drakou, E. G. (2014). The importance of mangroves to people: a call to action. United Nations Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), Cambridge, United Kingdom.

[3] Alappatt, J. P. (2018). Structure and species diversity of mangrove ecosystem. Biodiversity and Climate Change Adaptation in Tropical Islands, 127–144. doi:10.1016/B978-0-12-813064-3.00005-3.

[4] Warfield, A. D., & Leon, J. X. (2019). Estimating mangrove forest volume using terrestrial laser scanning and UAV-derived structure-from-motion. Drones, 3(2), 1–17. doi:10.3390/drones3020032.

[5] Friess, D. A., Rogers, K., Lovelock, C. E., Krauss, K. W., Hamilton, S. E., Lee, S. Y., Lucas, R., Primavera, J., Rajkaran, A., & Shi, S. (2019). The State of the World's Mangrove Forests: Past, Present, and Future. Annual Review of Environment and Resources, 44(1), 89–115. doi:10.1146/annurev-environ-101718-033302.

[6] Islam, K., Sarker, S., Morsad, G., Khan, M. F., Chowdhury, A., & Islam, S. L. U. (2024). Spatial–temporal changes of shoreline and Vegetation: Impacts on mangrove cover along the Sundarbans area, Bangladesh. Journal of Coastal Conservation, 28(1). doi:10.1007/s11852-023-01016-z.

[7] Dong, H., Gao, Y., Chen, R., & Wei, L. (2024). MangroveSeg: Deep-Supervision-Guided Feature Aggregation Network for Mangrove Detection and Segmentation in Satellite Images. Forests, 15(1), 127. doi:10.3390/f15010127.

[8] Ginting, D. N. B., Setiawan, K. T., Anggraini, N., Suardana, A. P., Nandika, M. R., Ulfa, A., Aziz, K., & Dewanti, R. (2024). Comparison between top and bottom of atmosphere Sentinel-2 image for mangrove mapping in Balikpapan Bay, East Kalimantan. BIO Web of Conferences, 89. doi:10.1051/bioconf/20248907003.

[9] Alongi, D. M. (2014). Carbon cycling and storage in mangrove forests. Annual Review of Marine Science, 6, 195–219. doi:10.1146/annurev-marine-010213-135020.

[10] Rovai, A. S., Twilley, R. R., Worthington, T. A., & Riul, P. (2022). Brazilian Mangroves: Blue Carbon Hotspots of National and Global Relevance to Natural Climate Solutions. Frontiers in Forests and Global Change, 4. doi:10.3389/ffgc.2021.787533.

[11] Richards, D. R., Thompson, B. S., & Wijedasa, L. (2020). Quantifying net loss of global mangrove carbon stocks from 20 years of land cover change. Nature Communications, 11(1), 4260. doi:10.1038/s41467-020-18118-z.

[12] Chatting, M., Al-Maslamani, I., Walton, M., Skov, M. W., Kennedy, H., Husrevoglu, Y. S., & Le Vay, L. (2022). Future Mangrove Carbon Storage under Climate Change and Deforestation. Frontiers in Marine Science, 9. doi:10.3389/fmars.2022.781876.

[13] Chatting, M., LeVay, L., Walton, M., Skov, M. W., Kennedy, H., Wilson, S., & Al-Maslamani, I. (2020). Mangrove carbon stocks and biomass partitioning in an extreme environment. Estuarine, Coastal and Shelf Science, 244. doi:10.1016/j.ecss.2020.106940.

[14] Tengku Hashim, T. M. Z., & Suratman, M. N. (2021). Mangroves as a Carbon Sink/Stocks. In Mangroves: Ecology, Biodiversity and Management. Springer Singapore. doi:10.1007/978-981-16-2494-0_7.

[15] Alongi, D. M. (2008). Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuarine, Coastal and Shelf Science, 76(1), 1–13. doi:10.1016/j.ecss.2007.08.024.

[16] Alongi, D. M. (2015). The Impact of Climate Change on Mangrove Forests. Current Climate Change Reports, 1(1), 30–39. doi:10.1007/s40641-015-0002-x.

[17] Giri, C. (2016). Observation and monitoring of mangrove forests using remote sensing: Opportunities and challenges. Remote Sensing, 8(9), 783. doi:10.3390/rs8090783.

[18] Gandhi, S., & Jones, T. G. (2019). Identifying mangrove deforestation hotspots in South Asia, Southeast Asia and Asia-Pacific. Remote Sensing, 11(6), 728. doi:10.3390/RS11060728.

[19] Carter, H. N., Schmidt, S. W., & Hirons, A. C. (2015). An international assessment of mangrove management: Incorporation in integrated coastal zone management. Diversity, 7(2), 74–104. doi:10.3390/d7020074.

[20] Dahdouh-Guebas, F. (2002). The use of remote sensing and GIS in the sustainable management of tropical coastal ecosystems. Environment, Development and Sustainability, 4(2), 93–112. doi:10.1023/A:1020887204285.

[21] Maurya, K., Mahajan, S., & Chaube, N. (2021). Remote sensing techniques: mapping and monitoring of mangrove ecosystem—a review. Complex and Intelligent Systems, 7(6), 2797–2818. doi:10.1007/s40747-021-00457-z.

[22] Pham, T. D., Yokoya, N., Bui, D. T., Yoshino, K., & Friess, D. A. (2019). Remote sensing approaches for monitoring mangrove species, structure, and biomass: Opportunities and challenges. Remote Sensing, 11(3), 230. doi:10.3390/rs11030230.

[23] Yudha, G. D., & Purnama, S. M. (2018). Analysis of dissemination methods for remote sensing information in maritime field to support the local government. IOP Conference Series: Earth and Environmental Science, 162(1), 12046. doi:10.1088/1755-1315/162/1/012046.

[24] Wang, L., Jia, M., Yin, D., & Tian, J. (2019). A review of remote sensing for mangrove forests: 1956–2018. Remote Sensing of Environment, 231. doi:10.1016/j.rse.2019.111223.

[25] Melesse, A. M., & Jordan, J. D. (2002). A comparison of fuzzy vs. augmented-ISODATA classification algorithms for cloud-shadow discrimination from Landsat images. Photogrammetric Engineering and Remote Sensing, 68(9), 905–911.

[26] Kantakumar, L. N., & Neelamsetti, P. (2015). Multi-temporal land use classification using hybrid approach. Egyptian Journal of Remote Sensing and Space Science, 18(2), 289–295. doi:10.1016/j.ejrs.2015.09.003.

[27] Keshava, N., & Mustard, J. F. (2002). Spectral unmixing. IEEE Signal Processing Magazine, 19(1), 44–57. doi:10.1109/79.974727.

[28] Kärdi, T. (2007). Remote sensing of urban areas: Linear spectral unmixing of Landsat Thematic Mapper images acquired over Tartu (Estonia). Proceedings of the Estonian Academy of Sciences: Biology, Ecology, 56(1), 19–32. doi:10.3176/eco.2007.1.02.

[29] Cipta, I. M., Jaelani, L. M., & Sanjaya, H. (2022). Identification of Paddy Varieties from Landsat 8 Satellite Image Data Using Spectral Unmixing Method in Indramayu Regency, Indonesia. ISPRS International Journal of Geo-Information, 11(10). doi:10.3390/ijgi11100510.

[30] Cipta, I. M., Jaelani, L. M., & Sanjaya, H. (2024). A phenology-based linear spectral unmixing method for rice varieties identification from Landsat 8 Satellite Image in Ngawi District, East Java, Indonesia. Biodiversitas, 25(4), 1691–1702. doi:10.13057/biodiv/d250439.

[31] Kusoiry, M. R., Jaelani, L. M., & Sanjaya, H. (2024). Using satellite image data to identify rice varieties through linear spectral unmixing method (case study: Karangjati Sub District, Ngawi Regency). Advances in Modern Agriculture, 5(2), 2538. doi:10.54517/ama.v5i2.2538.

[32] Xu, X., Tong, X., Plaza, A., Zhong, Y., Xie, H., & Zhang, L. (2017). Using Linear Spectral Unmixing for Subpixel Mapping of Hyperspectral Imagery: A Quantitative Assessment. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 10(4), 1589–1600. doi:10.1109/JSTARS.2016.2624560.

[33] Yu, J., Chen, D., Lin, Y., & Ye, S. (2017). Comparison of linear and nonlinear spectral unmixing approaches: a case study with multispectral TM imagery. International Journal of Remote Sensing, 38(3), 773–795. doi:10.1080/01431161.2016.1271475.

[34] Green, E. P., Clark, C. D., Mumby, P. J., Edwards, A. J., & Ellis, A. C. (1998). Remote sensing techniques for mangrove mapping. International Journal of Remote Sensing, 19(5), 935–956. doi:10.1080/014311698215801.

[35] Jensen, J. R., Lin, H., Yang, X., Ramsey, E., Davis, B. A., & Davis, C. W. (1991). The measurement of mangrove characteristics in southwest florida using spot multispectral data. Geocarto International, 6(2), 13–21. doi:10.1080/10106049109354302.

[36] Inoue, T., Kohzu, A., Akaji, Y., Miura, S., & Baba, S. (2024). Diazotrophic nitrogen fixation through aerial roots occurs in Avicennia marina: implications for adaptation of mangrove plant growth to low-nitrogen tidal flats. New Phytologist, 241(4), 1464–1475. doi:10.1111/nph.19442.

[37] Ramesh, C., Muthukumar, C., Koushik, S., Shunmugaraj, T., & Mallavarapu Venkata Ramana, M. (2024). Hypersalinity and Low Nitrogen Levels Cause Dwarf Growth in Mangrove Avicennia marina (Forssk.) Vierh. Proceedings of the National Academy of Sciences India Section B - Biological Sciences, 94(2), 331–336. doi:10.1007/s40011-023-01532-w.

[38] Friis, G., Smith, E. G., Lovelock, C. E., Ortega, A., Marshell, A., Duarte, C. M., & Burt, J. A. (2024). Rapid diversification of grey mangroves (Avicennia marina) driven by geographic isolation and extreme environmental conditions in the Arabian Peninsula. Molecular Ecology, 33(4), e17260. doi:10.1111/mec.17260.

[39] Sitepu, B. S., Chasani, A. R., Mukhlisi, M., Atmoko, T., Adman, B., & Prihatini, I. (2024). Camptostemon philippinensis, a new record of endangered mangrove species in the Balikpapan Bay, East Kalimantan, Indonesia. F1000Research, 12, 1394. doi:10.12688/f1000research.140887.2.

[40] Kinya, G., Kairo, J. G., Nyoike, R. N., Nguu, J. G., Githinji, B. K., & Githaiga, M. N. (2024). Eco-Engineering Mangrove Restoration at Gazi Bay, Kenya. Diversity, 16(3), 135. doi:10.3390/d16030135.

[41] Nimsi, K. A., Arya, H., Manjusha, K., & Kathiresan, K. (2024). Multifarious plant growth-promoting traits of mangrove yeasts: growth enhancement in mangrove seedlings (Rhizophora mucronata) for conservation. Archives of Microbiology, 206(4), 192. doi:10.1007/s00203-024-03913-9.