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Spectral Reflectance Characteristics of Mangrove Species in Mundupesisir Cirebon, Indonesia

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Abstract. In the Mundupesisir mangrove ecosystem, only a few dominant mangrove species are present, each with unique spectral reflectance characteristics. Accurate identification and classification of these species are essential for effective management and conservation. Low-resolution satellite imagery often struggles with mixed pixels, limiting species-level identification. This study addresses that limitation by utilising hyperspectral radiometers to collect reflectance data, thereby improving classification accuracy. Ground-based hyperspectral sensing was conducted using the USSIMO Hyperspectral Remote Sensing System, covering the 305-115 nm spectral range. The Red-Edge (700-750 nm) and near-infrared (>800 nm) regions were most informative for distinguishing species. These results provide a sensor-compatible foundation for scalable mangrove monitoring using remote sensing. *Rhizophora stylosa* showed the highest NIR and Red-Edge reflectance values (0.594 and 0.522, respectively), while *Acanthus ilicifolius* showed the lowest (0.2653 and 0.2385). These results enabled the construction of species-specific spectral libraries. Reflectance values were also resampled to match multispectral bands from UAVs and satellites, facilitating practical application. Species-specific reflectance patterns were visualised, highlighting the most distinguishable bands. The findings enhance species spectral separability in spectrally complex environments and provide a scalable, sensor-compatible foundation for operational mangrove ecosystem monitoring through remote sensing platforms.

1. Introduction

The Mundupesisir mangrove ecosystem in northern Cirebon presents a straightforward floristic structure dominated by just four species. *Rhizophora stylosa* and *Rhizophora apiculata* form the main canopy, while *Avicennia marina* occupies tidal channels and *Acanthus ilicifolius* dominates the landward margins. These mangroves provide exceptional ecosystem services, with measured carbon storage exceeding 1,000 megagrams per hectare and significant coastal protection value [1, 2].



Accurate species spectral separability in this ecosystem faces three primary challenges. First, morphological convergence creates nearly identical leaf structures among species. Second, spectral characteristics show minimal separation in visible wavelengths. Third, dense canopy conditions produce severe spectral mixing, blurring species signatures [3, 4].

Despite significant advances, current satellite-based monitoring systems continue to face substantial limitations in achieving sufficient spectral separability among morphologically similar mangrove species at the species level. Medium-resolution multispectral imagery, such as Landsat-8, generally achieves classification accuracies of approximately 68%. At the same time, Sentinel-2 performs slightly better, reaching around 71%, primarily because it includes Red-Edge bands that enhance vegetation detection. Nevertheless, both sensors remain limited in capturing fine-scale intra-species spectral variability. The achieved accuracies are still lower than those obtained from very high-resolution data such as Pléiades-1 (approximately 79%), indicating that the insufficient spatial and spectral resolution of medium-resolution sensors, such as Landsat-8 and Sentinel-2, still lacks the spatial and spectral capability for accurate mangrove species mapping. [5].

This study employed the USSIMO hyperspectral system, covering the 305 to 1150 nm range, to overcome these constraints. Analysis focused on two key spectral regions: the Red-Edge region between 700 and 730 nm, where species-specific reflectance differences reached 12% to 15%, and the near-infrared zone from 800 to 900 nm, where distinct canopy structural patterns were observed. These findings are consistent with previous research [6], which demonstrated the high effectiveness of these wavelengths for mangrove species dominant in Southeast Asia.

For operational implementation, spectral resampling was conducted to emulate the spectral characteristics of standard multispectral sensors. The DJI Phantom 4 Multispectral demonstrated the ability to capture up to 78% of the key hyperspectral features, whereas Sentinel-2 detected approximately 65% of the relevant spectral markers. These detection rates align with previous findings on mangrove species classification using both airborne and satellite-based sensors, which similarly reported moderate accuracies for Sentinel-2 and Landsat-8 due to their limited spectral resolution [5, 7].

The resulting spectral libraries support multiple conservation applications. They allow for species-specific restoration, accurate carbon stock monitoring, and more precise assessments of ecosystem health. These capabilities are essential for maintaining the integrity of Mundupesisir's vulnerable coastal systems [1, 2].

2. Methodology

2.1 Study site

This study was conducted in a 10-hectare mangrove area located in Mundupesisir Village, Mundu District, Cirebon Regency, West Java Province, Indonesia (Figure 1). The site, part of the northern coast of Java, faces ecological pressure from reclamation, land-use change, and industrial development. The mangrove community is dominated by *Acanthus ilicifolius*, *Rhizophora apiculata*, *Avicennia marina*, and *Rhizophora stylosa*, distributed naturally and through rehabilitation projects. Despite restoration efforts, species-level spectral monitoring remains limited. To address this gap, the study collected leaf-level reflectance data from representative stands to build a localised spectral library, enhancing the accuracy of remote-sensing-based

species classification and conservation planning. This approach complements prior findings on the limitations of UAV and WorldView-3 imagery for mangrove species mapping [8].

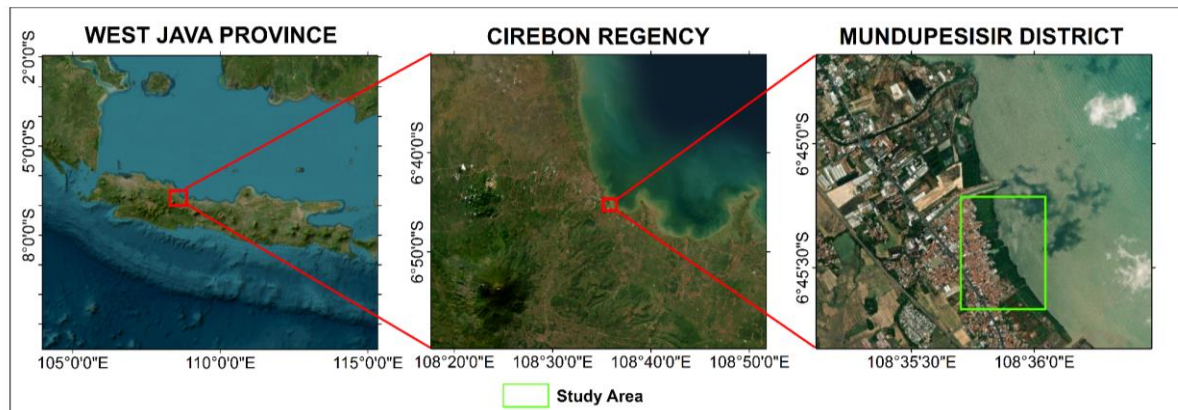


Figure 1. Map of the study area

2.2. Spectral Data Acquisition

Spectral reflectance was recorded in situ using a USSIMO hyperspectral radiometer (305-1150 nm; resolution 3-5 nm), under clear sky conditions between 08:30 and 09:30 local time to ensure radiometric consistency and reduce atmospheric interference [9, 10].

The target species included four dominant mangrove taxa: *Acanthus ilicifolius*, *Rhizophora apiculata*, *Avicennia marina*, and *Rhizophora stylosa* (Figure 2). Healthy, sunlit, and fully open leaves were measured at nadir orientation, with a 15 cm sensor distance and stable geometry, using a special mounting frame.



Figure 2. (a) *Acanthus ilicifolius* leaf, (b) *Rhizophora apiculata* leaf, (c) *Avicennia marina* leaf, (d) *Rhizophora stylosa* leaf.

Hyperspectral measurements were acquired in fast-burst mode with approximately 15-minute sessions at each site to maximise temporal sampling and minimise illumination variability. The data collection procedure and field setup are illustrated in Figure 3 [11, 12].



Figure 3. Collection of spectral reflectance data of mangrove leaves in the Mundupesisir area, Cirebon.

Calibration was performed before and after sampling using a Spectralon 99% reference and dark current correction. A minimum of five replicates was recorded for each species. Sampling sites were georeferenced using GNSS (± 3 cm), and metadata on temperature, humidity, and cloud cover were documented [13].

2.3. Preprocessing and Reflectance Calculation

Raw spectral data exported from the USSIMO Hyperspectral Radiometer were processed to ensure radiometric consistency and calibration accuracy before analysis. The radiance measurements from the target object (L_{obj}) were corrected using dark current and a Spectralon white reference panel (reflectance = 0.99), measured at the start and end of each session.

Following established radiometric calibration procedures, the object reflectance was calculated using the equation:

$$R_{obj} = \pi \frac{L_{obj}(\lambda)}{E(\lambda)} \left(\frac{1}{R_{white}(\lambda)} \right)$$

Where $L_{obj}(\lambda)$ is the radiance from the object at wavelength λ , $E(\lambda)$ is the incident irradiance measured from a white reference panel, and $R_{white}(\lambda)$ the constant π accounts for Lambertian surface correction. The term $R_{white}(\lambda)$ acts as a scaling factor to normalise the measured radiance to known reference values, ensuring accurate and consistent reflectance outputs.

This formulation corrects for variability in sunlight intensity or sensor settings, enabling more reliable inter-sample comparison [14]. The reflectance data were smoothed using a Savitzky-Golay filter (window size = 11, polynomial order = 2) to enhance spectral quality further, effectively reducing high-frequency noise while preserving spectral feature integrity. Bands outside the 350-1050 nm range were excluded due to high noise near sensor boundaries and reduced signal-to-noise ratio.

Final reflectance curves were averaged per species to reduce measurement redundancy and form a baseline for spectral library development. Key vegetation-sensitive spectral regions were identified, including the chlorophyll absorption trough (~670 nm), the Red-Edge transition (700-740 nm), and NIR reflectance features (>800 nm).

2.4. Spectral Library and Visualisation

Field-based hyperspectral data were collected using the USSIMO hyperspectral radiometers (305-1150 nm), following standardised protocols for vegetation spectral acquisition. Only healthy leaves exposed to sunlight from the dominant mangrove species were selected for spectral measurements. To adequately capture intraspecific variability, several replicate measurements were taken for each species. The mean reflectance and standard deviation were calculated across all wavelength ranges to determine characteristic spectral signatures [15].

To enhance operational applicability, hyperspectral data were resampled to the spectral response functions of Sentinel-2 MSI, Landsat-8 OLI, and DJI Phantom 4 MS. This enabled comparisons between hyperspectral precision and multispectral performance and the identification of diagnostic bands. Reflectance profiles were visualised for all species and validated against established spectral libraries from previous mangrove studies.

2.5. Simulation with Multispectral Bandwidths

To evaluate the operational applicability of hyperspectral data, spectral simulations were conducted by resampling field-measured reflectance to match the spectral response characteristics of commonly used multispectral sensors: Sentinel-2 MSI, Landsat-8 OLI, and DJI multispectral drone sensors. The hyperspectral signatures collected from the USSIMO radiometer were convolved with each platform's sensor response profiles, focusing on vegetation-sensitive regions such as blue, green, red, Red-Edge, and near-infrared [16, 17].

This simulation aimed to estimate how the distinct spectral traits of mangrove species would appear under real-world sensor configurations with broader spectral bandwidths. By bridging hyperspectral precision with multispectral practicality, this approach enables species-level spectral separability insights using widely available satellite and drone data [18].

The simulation supports the identification of optimal sensor configurations for mangrove classification and provides insights for extending spectral library applications to scalable, remote-sensing-based ecosystem monitoring.

3. Results and Discussion

3.1 Spectral Characterisation of Dominant Mangrove Species

Hyperspectral reflectance profiles of four dominant mangrove species in Mundupesisir were acquired using the USSIMO sensor (380-900 nm) to quantify interspecific spectral variability, particularly within the Red-Edge (RE) and near-infrared (NIR) domains. Reflectance was derived from normalised radiance-to-irradiance ratios to isolate species-specific optical responses.

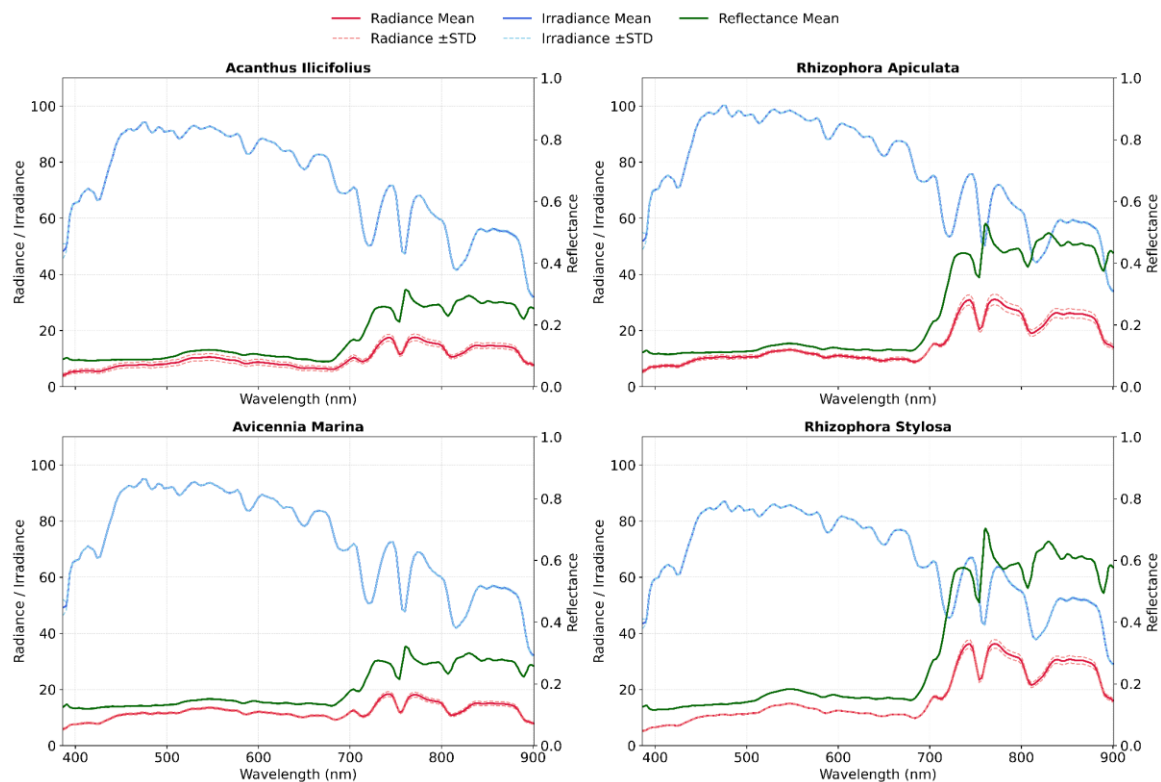


Figure 4. Spectral Profile of Mangrove Species

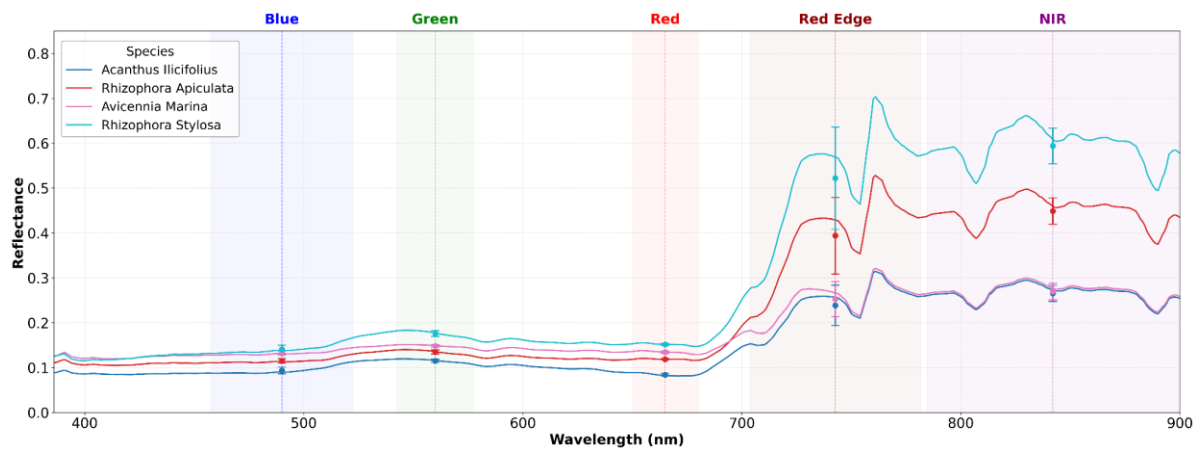
Rhizophora stylosa exhibited the highest NIR reflectance (~ 0.6) with a pronounced Red-Edge transition near 700-750 nm, indicative of dense mesophyll tissue and vigorous canopy structure. *Rhizophora apiculata* displayed moderately lower NIR reflectance (~ 0.45) and greater variability within the Red-Edge region, reflecting structural heterogeneity at the canopy level. In contrast, *Avicennia marina* and *Acanthus ilicifolius* exhibited subdued NIR responses (< 0.35) and flattened spectral trajectories, consistent with high leaf water content and irregular canopy architecture.

As shown in Figure 4, the Red-Edge (RE) and near-infrared (NIR) regions exhibited the highest potential for spectral separability among mangrove species, highlighting their diagnostic importance for optical separability. These findings confirm the Red-Edge region as a critical domain of spectral separability in operational mangrove mapping and reinforce the integration of field-derived spectral signatures into satellite-based and machine-learning classification frameworks for large-scale coastal monitoring [19, 20, 21].

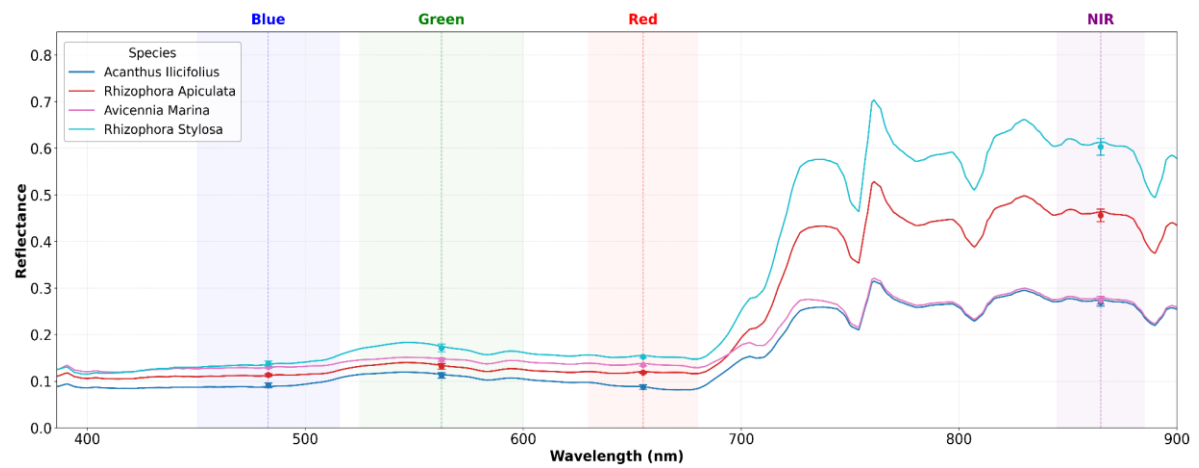
3.2 Simulated Multispectral Reflectance from Hyperspectral Data

To bridge field-based hyperspectral observations with operational multispectral platforms, hyperspectral reflectance (305-1150 nm) acquired with the USSIMO sensor was resampled to emulate the spectral configurations of Sentinel-2 MSI, Landsat-8 OLI, and DJI Phantom 4 MS. Reflectance values were averaged across the Blue, Green, Red, Red-Edge, and NIR bands to enable cross-platform comparison and evaluation of species-level separability among *Rhizophora stylosa*, *Rhizophora apiculata*, *Avicennia marina*, and *Acanthus ilicifolius* (Figure 5).

(a)



(b)



(c)

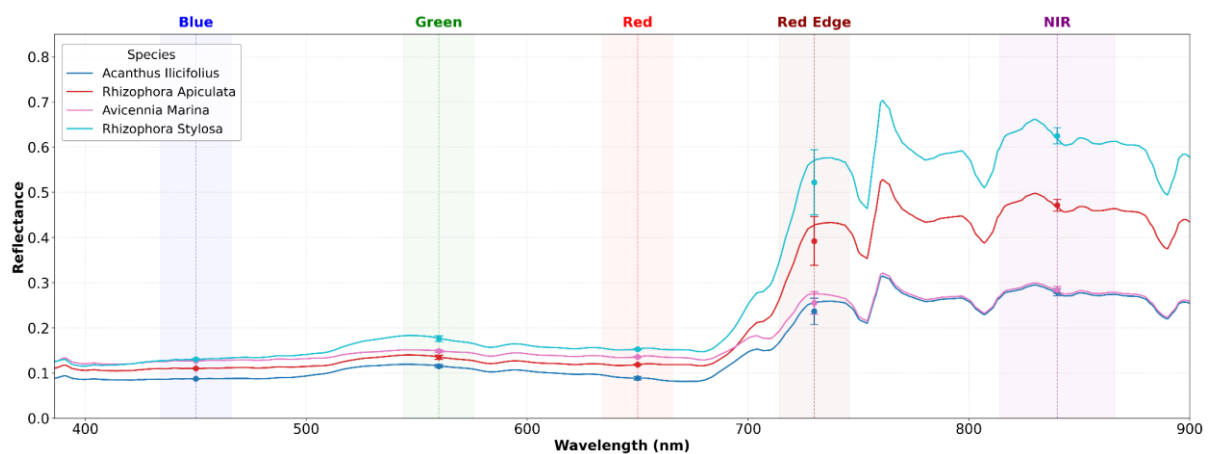


Figure 5. Simulated reflectance curves of mangrove species, (a) Sentinel-2 MSI, (b) Landsat-8 OLI, (c) DJI Phantom 4 MS (UAV).

To facilitate intersensor comparison and assess species-level spectral divergence, mean reflectance values were extracted across five key vegetation-sensitive bands: blue, green, red, Red-Edge, and near-infrared from simulated datasets representing Sentinel-2 MSI, Landsat-8 OLI, and UAV-based DJI Phantom 4 MS. These values, compiled for four dominant mangrove species (*Rhizophora stylosa*, *Rhizophora apiculata*, *Avicennia marina*, and *Acanthus ilicifolius*), are summarised in Tables 1 - 3, providing a basis for evaluating interspecific separability and the diagnostic strength of each spectral region the supplementary material details full statistical descriptors, including standard deviation, minimum, and maximum reflectance values.

Table 1. Reflectance statistics (mean) per band Sentinel-2 MSI.

Species	Blue	Green	Red	Red-Edge	NIR
<i>Acanthus ilicifolius</i>	0.0914	0.0814	0.0845	0.2385	0.2653
<i>Rhizophora stylosa</i>	0.1196	0.1146	0.1146	0.522	0.594
<i>Avicennia marina</i>	0.1425	0.1418	0.1453	0.2523	0.2696
<i>Rhizophora apiculata</i>	0.1157	0.1105	0.1136	0.394	0.4488

Table 2. Reflectance statistics (mean) per band Landsat-8 OLI.

Species	Blue	Green	Red	Red-Edge	NIR
<i>Acanthus ilicifolius</i>	0.0928	0.0837	0.0892	0.2292	0.2476
<i>Rhizophora stylosa</i>	0.1213	0.1172	0.1184	0.4992	0.5323
<i>Avicennia marina</i>	0.1287	0.1278	0.1314	0.2336	0.2483
<i>Rhizophora apiculata</i>	0.1149	0.1074	0.1094	0.3680	0.4102

Table 3. Reflectance statistics (mean) per band DJI Phantom 4 MS (UAV).

Species	Blue	Green	Red	Red-Edge	NIR
<i>Acanthus ilicifolius</i>	0.0871	0.1114	0.0884	0.2357	0.2196
<i>Rhizophora stylosa</i>	0.1186	0.1152	0.1161	0.5053	0.5591
<i>Avicennia marina</i>	0.1275	0.1310	0.1322	0.2435	0.2596
<i>Rhizophora apiculata</i>	0.1137	0.1072	0.1103	0.3583	0.3972

Across all platforms, *Rhizophora stylosa* exhibited the highest NIR reflectance (Sentinel-2: 0.5940; Landsat-8: 0.5323; DJI: 0.5591), attributable to its multilayered canopy and strong

internal scattering. *Acanthus ilicifolius* consistently showed the lowest NIR reflectance (< 0.27), reflecting compact, dark-green leaves and reduced scattering efficiency, enabling reliable distinction from *Rhizophora* species. *Rhizophora apiculata* and *Avicennia marina* exhibited intermediate NIR reflectance and greater variability, linked to differences in canopy density and internal water content [19, 20, 21].

Among sensors, Sentinel-2 demonstrated superior spectral separability capacity through its strategically positioned Red-Edge bands (705-783 nm), clearly separating *Rhizophora stylosa* (0.5220) from *Acanthus ilicifolius* (0.2385). Landsat-8 maintained NIR sensitivity (~ 865 nm) but lacked Red-Edge coverage, whereas DJI Phantom 4 MS provided enhanced spatial resolution, facilitating intra-species spectral separability in fragmented stands.

Empirical thresholds derived from reflectance distributions (NIR > 0.45 for *Rhizophora*; < 0.30 for *Acanthus ilicifolius* and *Avicennia marina*) demonstrated robust separability across sensors. These results confirm the stability and transferability of field spectra across platforms and reinforce their suitability for both rule-based and machine-learning classification of mangrove species [18, 22, 23, 24].

3.3 Comparison with Existing Spectral Libraries

The comparison of average NIR and Red-Edge reflectance across dominant mangrove species reported in previous studies is shown in Table 4. Mean reflectance profiles were broadly consistent with established mangrove spectral libraries, although *Avicennia marina* and *Acanthus ilicifolius* exhibited significant divergence in the NIR and Red-Edge domains. The NIR reflectance of *Avicennia marina* (0.2696) and *Acanthus ilicifolius* (0.2653) was markedly lower than reported values (~ 0.51 - 0.52), while Red-Edge reflectance (0.2523 and 0.2385) fell below literature ranges (~ 0.30 - 0.32) [25, 26]. These deviations are attributed to structural rather than hydric effects, as NIR reflectance is primarily governed by mesophyll thickness, tissue compactness, and intercellular scattering geometry [27]. The reduction in Red-Edge magnitude further suggests lower chlorophyll concentration or photosynthetic activity associated with physiological stress or phenological variation [28].

Table 4. Cross-study comparison of average NIR and Red-Edge reflectance in the dominant mangrove species.

Species	NIR (This Study)	RE (This Study)	NIR (Previous Studies)	RE (Previous Studies)	References
<i>Acanthus ilicifolius</i>	0.2653	0.2385	~ 0.52	~ 0.32	[29]
<i>Rhizophora apiculata</i>	0.4488	0.394	~ 0.45	~ 0.4	[22]
<i>Avicennia marina</i>	0.2696	0.2523	~ 0.51	~ 0.295	NIR [25] & Red-Edge [26]
<i>Rhizophora stylosa</i>	0.594	0.522	~ 0.58	~ 0.51	[30]

Conversely, *Rhizophora stylosa* recorded the highest spectral response, consistent with previously reported values [30], reflecting loose mesophyll structure, enhanced scattering efficiency, and high pigment content. *Rhizophora apiculata* exhibited intermediate but stable values, in close agreement with reference datasets [22], indicating uniform canopy structure and stable physiological function [14, 29].

The interspecific divergence observed in the NIR and Red-Edge regions reflects inherent anatomical and biochemical heterogeneity rather than instrumentation bias. The spectral stability of *Rhizophora stylosa* and *Rhizophora apiculata* substantiates their suitability as spectral endmembers for calibrating hyperspectral and multispectral classification models in mangrove ecosystems.

4. Conclusion

This study demonstrates the effectiveness of ground-based hyperspectral radiometry in addressing the persistent challenges of species-level mangrove classification within the spatially heterogeneous Mundupesisir ecosystem. Traditional satellite-based methods are often constrained by mixed-pixel contamination and broad spectral bandwidths, limiting their ability to achieve sufficient spectral separability among morphologically similar mangrove species. By employing the USSIMO Hyperspectral Remote Sensing System, this research successfully acquired high-resolution spectral reflectance profiles for five dominant taxa, thereby developing a localised, high-fidelity spectral library. The Red-Edge (700-750 nm) and NIR regions were consistently identified as the most diagnostic spectral domains, with *Rhizophora stylosa* and *Acanthus ilicifolius* exhibiting maximal interspecific contrast due to differences in canopy density, foliar structure, and internal scattering properties.

Simulations of the hyperspectral dataset under the spectral response functions of Sentinel-2 MSI, Landsat-8 OLI, and DJI Phantom 4 MS demonstrated strong translational compatibility. Among these, Sentinel-2 exhibited the highest spectral separability power due to its strategically positioned Red-Edge bands, which captured subtle physiological variations, particularly in *Rhizophora apiculata* and *Avicennia marina*. UAV-based multispectral data contributed valuable spatial granularity, especially for species with fragmented distributions. Diagnostic thresholds such as NIR reflectance >0.45 for *Rhizophora spp.* were consistently observed across platforms and validated through cross-study comparisons. These results reinforce the utility of hyperspectral-to-multispectral translation for operational mangrove monitoring, offering a scalable and sensor-compatible framework for biodiversity assessment, habitat mapping, and evidence-based coastal conservation.

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Data availability statement

All data supporting this study's findings are included in the supplementary section of the article.

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Supplementary

Table 1. Reflectance statistics per band Sentinel-2 MSI

Species	Band	Min	Max	Mean	Std
<i>Acanthus ilicifolius</i>	Blue	0.0871	0.1125	0.0934	0.0076
	Green	0.1074	0.1194	0.115	0.0037
	Red	0.0814	0.0887	0.084	0.0028
	Red-Edge	0.2387	0.3145	0.2385	0.0451
	NIR	0.2196	0.295	0.2653	0.0178
<i>Rhizophora apiculata</i>	Blue	0.1105	0.1295	0.1149	0.0049
	Green	0.1258	0.1399	0.1346	0.0045
	Red	0.1161	0.1204	0.1186	0.0012
	Red-Edge	0.1204	0.5282	0.394	0.0853
	NIR	0.3747	0.4976	0.4488	0.0293
<i>Avicennia marina</i>	Blue	0.1275	0.1439	0.1318	0.0043
	Green	0.1425	0.1512	0.1483	0.0025
	Red	0.1288	0.1343	0.1343	0.0026
	Red-Edge	0.1378	0.3211	0.2523	0.0389
	NIR	0.2233	0.2996	0.2696	0.0181
<i>Rhizophora stylosa</i>	Blue	0.1317	0.1657	0.1409	0.0089
	Green	0.1634	0.183	0.1758	0.0064
	Red	0.1473	0.1551	0.1516	0.0023
	Red-Edge	0.1551	0.7035	0.522	0.114
	NIR	0.4939	0.6615	0.594	0.0397

Table 2. Reflectance statistics per band Landsat-8 OLI

Species	Band	Min	Max	Mean	Std
<i>Acanthus ilicifolius</i>	Blue	0.0869	0.1061	0.091	0.005
	Green	0.1023	0.1194	0.1123	0.0057
	Red	0.0814	0.0972	0.0872	0.0049
	NIR	0.237	0.2771	0.2692	0.0084
<i>Rhizophora apiculata</i>	Blue	0.1095	0.1227	0.1131	0.0028
	Green	0.1206	0.1399	0.1316	0.0061
	Red	0.1161	0.1204	0.1184	0.0013
	NIR	0.4036	0.4686	0.4557	0.0135
<i>Avicennia marina</i>	Blue	0.1265	0.1387	0.1302	0.0026
	Green	0.137	0.1512	0.146	0.004
	Red	0.1288	0.1384	0.1349	0.0024
	NIR	0.2413	0.2818	0.2738	0.0085
<i>Rhizophora stylosa</i>	Blue	0.1299	0.1551	0.1376	0.0058
	Green	0.1567	0.183	0.1713	0.0084
	Red	0.1473	0.1562	0.1521	0.0022

	NIR	0.5328	0.6201	0.6028	0.0179
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Table 3. Reflectance statistics per band DJI Phantom 4 MS (UAV)

Species	Band	Min	Max	Mean	Std
<i>Acanthus ilicifolius</i>	Blue	0.0859	0.0878	0.0871	0.0005
	Green	0.1083	0.1194	0.1151	0.0035
	Red	0.0819	0.0884	0.0884	0.0035
	Red-Edge	0.0956	0.2589	0.1664	0.0289
	NIR	0.2659	0.2950	0.2790	0.0077
<i>Rhizophora apiculata</i>	Blue	0.1093	0.1115	0.1103	0.0006
	Green	0.1268	0.1399	0.1348	0.0043
	Red	0.1166	0.1184	0.1184	0.0012
	Red-Edge	0.1204	0.4330	0.2607	0.0536
	NIR	0.4504	0.4976	0.4715	0.0130
<i>Avicennia marina</i>	Blue	0.1254	0.1285	0.1271	0.0008
	Green	0.1435	0.1512	0.1484	0.0023
	Red	0.1342	0.1357	0.1357	0.0012
	Red-Edge	0.1378	0.2755	0.1917	0.0429
	NIR	0.2698	0.2996	0.2835	0.0078
<i>Rhizophora stylosa</i>	Blue	0.1269	0.1334	0.1303	0.0018
	Green	0.1647	0.1830	0.1760	0.0061
	Red	0.1508	0.1527	0.1527	0.0014
	Red-Edge	0.1551	0.5762	0.3442	0.0720
	NIR	0.5982	0.6615	0.6249	0.0180