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International Journal for Modern Trends in Science and Technology
Volume 12, Issue 02, pages 51-56.
ISSN: 2455-3778 online
Available online at: http://www.ijmtst.com/vol12issue02.html
DOI: https://doi.org/10.5281/zenodo.18683072

Geospatial Assessment of Halophyte Ecosystems in the Cuddalore Coastal Belt, Bay of Bengal

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To Cite this Article
Mullaivendhan A, Ramanathan T & Gowarthanan R (2026). Geospatial Assessment of Halophyte Ecosystems in the Cuddalore Coastal Belt, Bay of Bengal. International Journal for Modern Trends in Science and Technology, 12(02), 51-56. https://doi.org/10.5281/zenodo.18683072

Article Info
Received: 16 January 2026; Revised: 09 February 2026; Accepted: 17 February 2026.

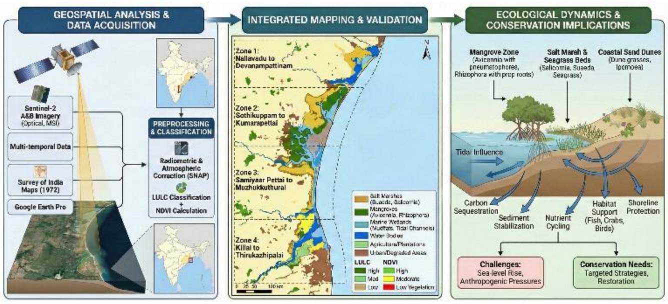
KEYWORDS

Coastal ecosystems, Cuddalore, Geospatial technology, Halophytes, Remote Sensing, Salt marsh.

ABSTRACT

Halophyte ecosystems and wetlands are vital coastal habitats that sustain biodiversity, buffer climate impacts, and enhance resilience. Along the Bay of Bengal, the Cuddalore coastline supports extensive salt marshes, mangroves, and wetlands increasingly threatened by urbanization, industrial discharge, and sea level rise. This study employed an integrated geospatial approach, combining multi-temporal Sentinel-2 imagery with rigorous ground truth validation, to assess spatial dynamics and ecological health. Using SNAP software, Land Use Land Cover (LULC) classification and Normalized Difference Vegetation Index (NDVI) analysis delineated vegetation signatures, zonation patterns, and transitional areas prone to misclassification. Results revealed distinct halophyte distributions, notably Suaeda maritima and Avicennia officinalis, with significant spatial variability driven by natural and anthropogenic factors. Integration of satellite data with extensive field surveys ensured high classification accuracy. The findings provide a robust baseline for conservation planning and highlight the urgent need for targeted strategies to protect these critical habitats.

Graphical Abstract



I. INTRODUCTION

India possesses a coastline stretching over 8,000 km, which plays a crucial role in sustaining its rich marine ecosystems. Within its exclusive economic zone, spanning approximately 2.02 million square kilometres adjoining the continental margins and offshore islands, lie diverse coastal habitats such as estuaries, lagoons, mangroves, backwaters, sand dunes, salt marshes, coral reefs, rocky shores, and sandy beaches. The Tamil Nadu coast extends for about 1,076 km, accounting for roughly 15% of India's total coastal length. These coastal regions form vital biogeographic habitats of the Indian subcontinent, shaped by distinctive biotic and abiotic processes. However, in recent decades, India has witnessed a sharp decline in marine and coastal biodiversity, raising significant ecological concerns (Venkataraman, 2003).

Geospatial technologies, particularly remote sensing and Geographic Information Systems (GIS), have emerged as powerful tools for mapping and monitoring the spatial distribution, temporal dynamics, and ecological responses of halophyte communities to environmental stressors. Understanding the biogeography and environmental drivers controlling halophyte distribution patterns is fundamental for developing effective conservation strategies, particularly as coastal ecosystems face accelerating threats from sea-level rise, anthropogenic pressures, and climate variability (Wang et al., 2023; Campbell et al., 2022).

1.1 Halophytes

Halophytic ecosystems within coastal regions serve as vital biodiversity hubs delivering crucial ecological services such as shoreline stabilization, carbon capture, and habitat support for a wide range of marine and terrestrial organisms (Belluco et al., 2006; Chenchouni, 2017). These salt-tolerant plant communities function as natural fortifications that protect coasts from environmental threats (Mullaivendhan et al., 2025). The Cuddalore coastal stretch bordering the Bay of Bengal comprises extensive salt marshes, mangrove forests, and intertidal vegetative zones featuring distinctive assemblies of halophyte species adapted to high salinity and tidal fluctuations (Badreldin & Goïta, 2015). The wetlands of Cuddalore District in Tamil Nadu hold significant ecological importance, sustaining diverse biological forms and mitigating the impacts of climate change (Ramanathan et al., 2011).

II. MATERIALS AND METHODOLOGY

2.1 Study Area

Cuddalore district lies along the Coromandel Coast, stretching between latitudes 11°11′30″ and 11°45′00″ N, and longitudes 79°28′00″ and 79°49′00″ E, as illustrated in Figure 1. The district is bordered to the east by the Bay of Bengal, to the north by the Villupuram district, to the west by the Perambalur and Ariyalur districts, and to the south by the Nagapattinam district of Tamil Nadu. Its geographical composition, featuring a vast coastline and proximity to several aquatic systems, plays a crucial role in supporting agriculture, aquaculture, and rich coastal biodiversity.

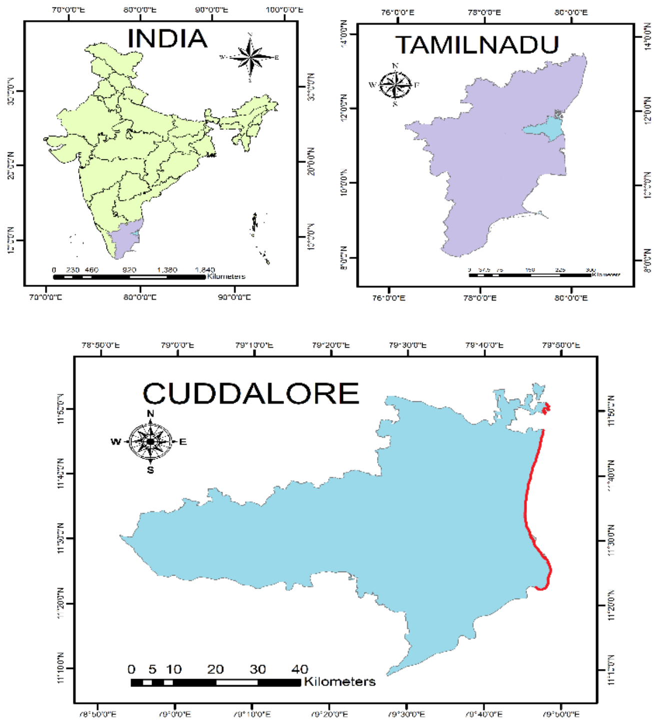


Figure 1. Description of the Study area

The Cuddalore coastline was segmented into four zones, each with 20 transects 500 meters apart. Shoreline variations were assessed using the 1972 Survey of India topographic map and multi-temporal satellite datasets from the European Space Agency's Copernicus Open Access Hub. Shorelines were manually digitized as polyline shapefiles with high visual accuracy. The U.S. Geological Survey developed the Digital Shoreline Analysis System (DSAS) to quantify shoreline dynamics. The Least Squares Regression (LRR) method was used to calculate change rates, incorporating all available data and ensuring methodological simplicity and reproducibility. Near-Infrared (NIR) bands from Landsat MSS, TM, and ETM+ sensors were used for coastline delineation following the procedure described by Lee and Jurkevich (1990).

2.2 Remote Sensing and Geospatial Data of Sentinel-2 A&B (Active Mission)

The rSentinel-2A and Sentinel-2B satellite imagery from the European Space Agency's Copernicus Program, which delivers high-resolution optical data crucial for observing both coastal and terrestrial ecosystems. The imagery, captured through the Multispectral Instrument (MSI), supports applications such as vegetation assessment, land-use mapping, and environmental change detection owing to its spatial resolution of 10–60 meters and a revisit cycle of five days. Level-2A surface reflectance products were obtained from the Copernicus Open Access Hub, ensuring globally accessible datasets for environmental monitoring and sustainable development studies.

2.3 Data Acquisition and Processing

The multispectral imagery from the Sentinel-2 mission was analyzed to evaluate variations in salt marsh extent. Cloud-free satellite images acquired from December 2024 to May 2025 were selected to capture both seasonal and yearly trends, emphasizing the dry season for clearer observation. Bands with spatial resolutions ranging from 10 to 60 meters were utilized to classify land cover types such as salt marshes, wetlands, urban regions, and agricultural fields, ensuring accurate habitat delineation while considering coastal environmental fluctuations.

2.4 Preprocessing in SNAP

The research adopted a structured preprocessing approach to maintain data reliability and uniformity. Radiometric correction converted the raw digital numbers into Top-of-Atmosphere reflectance, while atmospheric correction utilized the Scene Classification Layer for refinement. The satellite imagery was clipped according to the Cuddalore District boundary, and selected spectral bands were combined to generate composite images optimized for classification. This thorough preprocessing ensured calibrated and dependable satellite data suitable for land-use and land-cover analysis.

2.5 Study Area and Field Survey Design

Field investigations utilized a combination of geospatial technologies and ecological survey methods to ensure precise validation of salt marsh classifications. Accurate ground reference coordinates were obtained using the GPS feature of Google Earth Pro, providing dependable positional accuracy. Vegetation assessment was carried out through systematic 1 m × 1 m quadrat sampling, documenting dominant plant species such as *Suaeda maritima* and *Avicennia officinalis*, along with their percentage cover estimates. Each sampling site was further supported with geotagged photographs to record vegetation structure and substrate conditions for subsequent verification.

To correlate field data with satellite observations, ground control points were spatially matched with Sentinel-2 multispectral imagery (10 m resolution) and high-resolution Google Earth Pro base maps, facilitating visual confirmation of marsh boundaries and land cover uniformity. Spectral evaluation using SNAP software enabled the extraction of marsh vegetation LULC signatures from processed Sentinel-2 datasets, thereby validating classification accuracy. This integrated field–satellite approach established a reliable framework for assessing the precision of salt marsh mapping and detecting possible misclassifications in transitional or tidally influenced zones. Fresh plant samples from coastal salt marshes of Cuddalore District, Tamil Nadu, India, were also collected for detailed analysis.

2.6 Ground Truth Validation

Field validation was carried out through structured ground-truthing, involving the collection of more than 30 reference points across the study region. The sampling design incorporated three primary habitat categories: (1) vegetation zones encompassing dense halophytic assemblages, transitional shrub–marsh ecotones, and areas displaying clear zonation patterns; (2) unvegetated substrates, including exposed mudflats and active tidal channels; and (3) anthropogenically influenced transition areas, such as marsh–agriculture interfaces and sites affected by altered hydrological regimes. This stratified methodology ensured a thorough representation of salt marsh variability and enhanced the reliability of satellite-based classification outputs.

2.7 Field Equipment & Methods

Field investigations were carried out from December 2024 to May 2025 across nearly 42 km² of coastal wetlands in the Cuddalore District. The research centered on natural salt marsh ecosystems dominated by halophytic plants and mangrove-associated species, along with adjacent human-modified landscapes. Surveys were scheduled during the post-monsoon phase to coincide with favorable field conditions such as spring tide periods (0.2–0.5 m tidal range) enabling marsh surface exposure, peak growth phases of dominant vegetation, and stable climatic conditions (24–32°C, clear skies). To capture ecological heterogeneity, a stratified random sampling method was employed, reflecting variations in tidal elevation, vegetation composition, hydrological linkages, and degrees of anthropogenic disturbance.

III. RESULTS AND DISCUSSIONS

3.1 Land Use Land Cover (LULC)

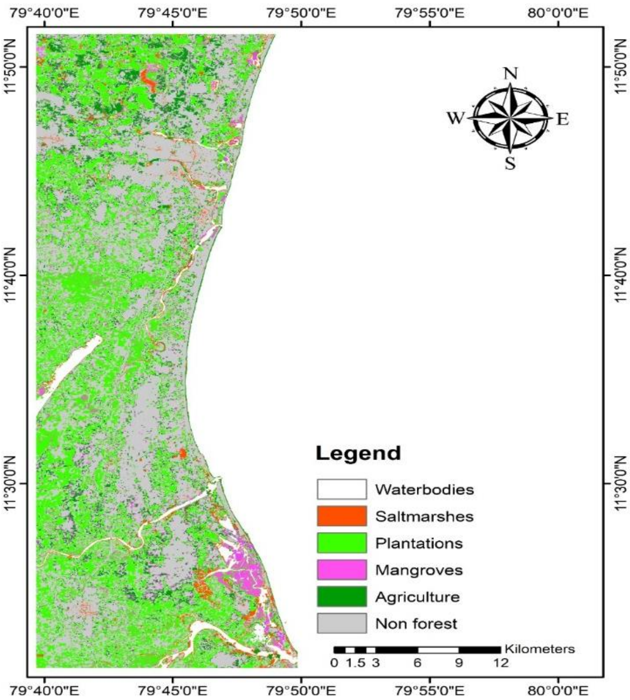


Figure 2. The LULC analysis of the Cuddalore coast

The LULC assessment of coastal ecosystems along the Cuddalore coast reveals clear spatial variations, indicating dynamic interactions between natural habitats and human-altered landscapes (Figure 2). The region is primarily characterized by salt marshes, mangroves, and plantations, which serve as key areas for nutrient cycling and coastal defense. Water bodies present potential for nature-based interventions such as halophyte-assisted phytoremediation. Urbanized and degraded non-forest areas signify strong anthropogenic influences. The restricted distribution of salt marshes and mangroves compared to human-dominated zones underlines the urgency for conservation efforts. Salt marshes, in particular, contribute significantly to nutrient dynamics, water purification, and carbon storage, supporting diverse biota adapted to saline and brackish conditions. Effective preservation demands protection of both these habitats and the ecological linkages that sustain them.

3.2 Normalized Difference in Vegetation (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a remote sensing method employed to evaluate vegetation condition, monitor land cover variations, and detect ecosystem changes. It makes use of multispectral satellite imagery along with preprocessing and classification steps to distinguish areas of dense vegetation, exposed soil, or urban regions. NDVI values typically range between -1 and +1, where higher values denote healthy vegetation, lower values signify bare ground, and negative values represent water or snow-covered surfaces. After data preprocessing, NDVI is computed using a standard mathematical formula:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Where:

- ✓ **NIR** = Reflectance in the near-infrared band
- ✓ **Red** = Reflectance in the red band

The 2024 NDVI map of the Cuddalore district illustrates vegetation vigor and density categorized into six classes. Areas with High Vegetation Density (0.282–0.438) appear as dark green zones, indicating lush growth, particularly across the central and southwestern regions. Moderate to Healthy Vegetation (0.281–0.288) is represented by lighter green to yellow-green shades, reflecting regions influenced by seasonal cropping patterns. In contrast, zones with Low Vegetation or Sparse Cover (0.0187–0.0275) display orange to light beige hues, mainly along the eastern coast and urbanized sections.

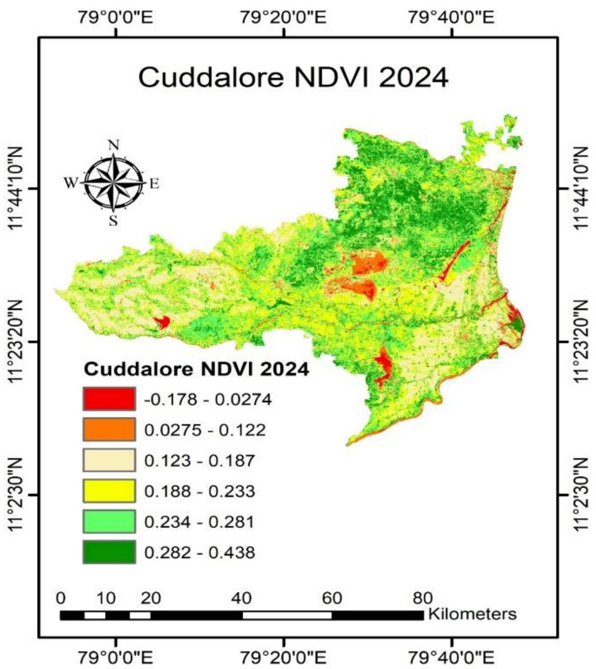


Figure 3. Normalised difference vegetative index analysis of Cuddalore Coast

The Non-Vegetated, Barren, and Water Body zones predominantly occupy coastal margins, riverbanks, and urban regions. Lower NDVI values along the eastern coastline indicate the impacts of urban expansion or limited vegetation cover. Conversely, the central and western areas display higher NDVI readings, reflecting strong agricultural productivity and healthy vegetation growth. Scattered patches with minimal NDVI values likely represent barren tracts, mining zones, or ongoing infrastructural developments.

3.3 Integration of Remote Sensing and Ground Truth Data

The coastal wetlands of Cuddalore District, Tamil Nadu, represent ecologically vital habitats supporting diverse flora and fauna while buffering climate impacts (Ramanathan et al. 2011). These systems provide ideal conditions to study halophyte zonation, sediment processes, and ecosystem functions (Kathiresan & Bingham 2001), yet face threats from urbanization, industrial discharge, and sea-level rise. To validate remote sensing outputs, representative salt marsh zones were surveyed across four clusters (Zones 1–4; Figure 4). Sentinel-2 multispectral data, integrated with Google Earth Pro basemaps and SNAP spectral analysis, confirmed vegetation signatures, NDVI, and LULC parameters. Ground truthing minimized transitional misclassifications, ensuring reliable mapping and supporting data-driven conservation and sustainable coastal management.

i) Suaeda nudiflora *ii) Heliotropium curassavicum* *iii) Salicornia brachiate*

iv) Cressa critica *v) Sesuvium portulacastrum* *vi)Suaeda fruticosa*

vii)Suaeda Monoica

Figure 4. Major Halophytes were recorded in the Ground truth analysis of the Cuddalore Coast

This study focuses on key salt marsh sites across the Cuddalore District, including zones:

Zone :1 Nallavadu, Suba Uppalavadi, Thazhanguda, Devanampattinam

Zone:2 Sothikuppam, Singarakuppam, Kayalpattu, Thiruchopuram, Reddiyar Pettai, Alapakkam, Poochimedu, Kumarapettai,

Zone:3 Samiyaar Pettai, Velliangiri Pattai, B. Mutlur, Annankoil, Parangipettai, Ponnanthittu, Mudasal odai, Muzhukkuthurai

Zone:4 Killai, Radha Vilagam, Uttama Sozhamangalam, Vadakku Pichavaram, Pichavaram, Thandavarayan Cholagan Pettai (T.S. Pettai), Kavarapattu, Kodiyampalayam, Therku Pichavaram, Thirukazhipalai.

IV. CONCLUDING SUMMARY

This study integrated Sentinel-2 remote sensing with ground validation to map halophyte ecosystems along the Cuddalore coastal belt. The land use and land cover analysis revealed the distribution of saltmarshes and mangroves, highlighting ecological fragmentation and human encroachment. Despite occasional misclassifications in transitional zones, classification accuracy was reliable, confirming the robustness of the approach. These findings emphasize the urgent need for targeted conservation strategies and adaptive coastal management to sustain Bay of Bengal ecosystems. By combining satellite data with field verification, this research establishes a strong framework for monitoring ecological change and guiding sustainable resource planning.

Acknowledgement

We would like to thank the European Space Agencies (Copernicus Hub) for providing Satellite image data for this study, and also thank Dr. Neethu and Miss. Sukanya Mandal for their help during mapping.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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