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REMOTE SENSING FOR COASTAL ECOSYSTEM MONITORING: A PRACTICAL SENSOR SELECTION FRAMEWORK

PENGINDERAAN JAUH UNTUK PEMANTAUAN EKOSISTEM PESISIR: KERANGKA PRAKTIS PEMILIHAN SENSOR

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Abstract

Coastal habitats require monitoring strategies that can capture changes in their extent, ecological characteristics, and surrounding environmental conditions. Although satellite and unmanned aerial vehicle observations offer diverse capabilities, selecting an appropriate sensor remains challenging because monitoring objectives, observation scales, and environmental constraints differ among ecosystems. This study synthesizes published evidence to develop a practical framework for selecting observation technologies for mangroves, seagrass meadows, coral reefs, and coastal environments. A structured narrative literature review was conducted using a Scopus search in September 2026, supplemented by relevant publications and technical documentation. The initial search identified 1,969 records; 95 priority candidates were screened further, and 47 publications underwent abstract-level relevance assessment. Of these, 28 were retained for the main qualitative synthesis. Evidence was organized according to monitoring objectives, sensor characteristics, environmental and operational constraints, and validation requirements. The synthesis shows that sensor suitability depends primarily on the intended monitoring product rather than nominal spatial or spectral resolution alone. Historical satellite archives support long-term habitat-change assessment, while high-resolution optical and unmanned aerial vehicle observations can provide finer spatial detail for localized applications. Radar offers complementary information where optical observations are constrained, whereas submerged habitat mapping requires particular attention to water-column effects, depth, and reference data. These findings were translated into a qualitative Sensor Selection Matrix linking monitoring objectives with candidate observation strategies and their principal limitations. The proposed framework supports context-dependent planning and transparent interpretation of monitoring outputs without establishing universal sensor rankings or transferable accuracy guarantees.

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Keywords : Mangrove Mapping, Seagrass Meadows, Coral Reef Habitats, Multisensor Integration, Field Validation.

Abstrak

Habitat pesisir memerlukan strategi pemantauan yang mampu mengidentifikasi perubahan luasan, karakteristik ekologis, dan kondisi lingkungan di sekitarnya. Meskipun pengamatan satelit dan wahana udara nirawak menawarkan beragam kemampuan, pemilihan sensor masih menjadi tantangan karena tujuan pemantauan, skala pengamatan, dan kendala lingkungan berbeda antar-ekosistem. Penelitian ini menyintesis bukti ilmiah untuk mengembangkan kerangka praktis pemilihan teknologi pengamatan pada mangrove, padang lamun, terumbu karang, dan lingkungan pesisir. Kajian dilakukan melalui tinjauan pustaka naratif terstruktur menggunakan penelusuran Scopus pada September 2026, yang dilengkapi publikasi relevan dan dokumentasi teknis. Penelusuran awal menghasilkan 1.969 rekaman bibliografis; sebanyak 95 kandidat prioritas diseleksi lebih lanjut dan 47 publikasi menjalani penilaian relevansi berdasarkan abstrak. Dari jumlah tersebut, 28 publikasi dipertahankan untuk sintesis kualitatif utama. Bukti ilmiah dikelompokkan berdasarkan tujuan pemantauan, karakteristik sensor, kendala lingkungan dan operasional, serta kebutuhan validasi. Hasil sintesis menunjukkan bahwa kesesuaian sensor terutama ditentukan oleh keluaran pemantauan yang dituju, bukan semata-mata oleh resolusi spasial atau spektral. Arsip citra satelit mendukung analisis perubahan habitat jangka panjang, sedangkan citra optik beresolusi tinggi dan pengamatan wahana udara nirawak menyediakan detail spasial untuk kajian lokal. Radar memberikan informasi pelengkap ketika pengamatan optik terkendala, sementara pemetaan habitat bawah air memerlukan perhatian khusus terhadap pengaruh kolom air, kedalaman, dan data referensi. Temuan tersebut dirumuskan menjadi Matriks Pemilihan Sensor kualitatif yang menghubungkan tujuan pemantauan dengan alternatif strategi pengamatan dan keterbatasan utamanya. Kerangka ini mendukung perencanaan yang sesuai konteks dan interpretasi hasil pemantauan secara transparan, tanpa menetapkan peringkat sensor yang berlaku universal atau menjanjikan tingkat akurasi yang dapat diterapkan pada semua lokasi.

Kata Kunci : Pemetaan Mangrove, Padang Lamun, Habitat Terumbu Karang, Integrasi Multisensor, Validasi Lapangan.

1. INTRODUCTION

Coastal ecosystems provide essential ecological functions and support human activities, including fisheries, coastal protection, and tourism. Mangroves, seagrass meadows, and coral reefs are particularly important because their ecological conditions influence habitat availability, biodiversity, and the sustainability of coastal resources. However, these ecosystems are exposed to environmental changes and human pressures that require reliable and continuous monitoring. Understanding changes in habitat extent, vegetation condition, benthic composition, and coastal environmental characteristics is therefore necessary for effective ecosystem assessment and management (Kuenzer et al., 2011; Hedley et al., 2016).

Remote sensing provides an important complement to field-based monitoring by enabling environmental observations across broader spatial and temporal scales. Satellite imagery supports repeated observations of coastal habitats, while unmanned aerial vehicles (UAVs) provide detailed information for localized assessments. Developments in multispectral, hyperspectral, radar, and other remote-sensing technologies have expanded the range of environmental characteristics that can be investigated. Nevertheless, remote sensing does not replace field observations, particularly when

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detailed ecological information or independent validation is required (Hedley et al., 2016; Makumbura et al., 2026).

The effectiveness of remote sensing depends on the relationship between sensor characteristics and monitoring objectives. Mangrove monitoring may require information on vegetation extent, canopy structure, or environmental change. Seagrass and coral reef monitoring involves additional challenges because underwater habitats are affected by water-column properties, depth, and spectral mixing. Consequently, a sensor suitable for mapping broad habitat distributions may not provide sufficient information for distinguishing detailed benthic components. Reviews of seagrass and coral reef remote sensing have demonstrated that observation requirements and environmental conditions strongly influence the information obtainable from different technologies (Hossain et al., 2015; Hedley et al., 2016; Smart et al., 2026).

Sensor selection also involves practical considerations beyond spatial resolution. Spectral characteristics, observation frequency, data availability, acquisition costs, and processing requirements influence whether a technology can support a particular monitoring program. For example, hyperspectral imagery provides detailed spectral information that can improve the discrimination of certain benthic components, but its application remains constrained by spectral mixing, data accessibility, and the need for appropriate analytical workflows. Similarly, UAV observations provide detailed spatial information but face operational constraints that can limit their application across extensive coastal areas (Smart et al., 2026; Makumbura et al., 2026). These considerations indicate that higher spatial or spectral resolution does not automatically make a sensor appropriate for every monitoring objective.

Existing reviews provide substantial knowledge concerning remote-sensing applications in individual ecosystems and technological domains. Kuenzer et al. (2011) reviewed remote sensing of mangrove ecosystems, Hossain et al. (2015) examined applications in seagrass environments, and Hedley et al. (2016) synthesized remote-sensing approaches for coral reef monitoring and management. More recent reviews have examined hyperspectral observations of coral reefs and seagrasses and UAV applications across coastal ecosystems (Smart et al., 2026; Makumbura et al., 2026).

Although these studies provide important technological and ecosystem-specific insights, a practical synthesis that directly connects monitoring objectives, sensor characteristics, environmental constraints, and management information needs across multiple coastal ecosystems remains useful. The present review addresses this need by organizing existing evidence into a common decision framework.

From a coastal social–ecological perspective, sensor selection is not merely a technical decision. The information produced by remote sensing contributes to how environmental changes are identified, interpreted, and communicated to resource managers. Inappropriate sensor selection may produce observations that are insufficiently detailed, spatially incomplete, or unsuitable for the intended management question. Conversely, a monitoring approach aligned with the required environmental information can support habitat assessment, change detection, and the identification of areas requiring further investigation. The relevance of remote sensing to coastal management therefore depends not only on technological capabilities but also on whether the resulting information addresses specific ecological and management needs (Hedley et al., 2016; Smart et al., 2026).

Accordingly, this review aims to develop a practical decision framework for selecting remote-sensing sensors for coastal ecosystem monitoring. Specifically, it seeks to: (1) synthesize the capabilities and limitations of major remote-sensing technologies; (2) examine their applications in mangrove, seagrass, coral reef, and coastal environmental monitoring; (3) identify the environmental and operational factors influencing sensor suitability; and (4) develop an evidence-based Sensor Selection Matrix linking monitoring objectives with candidate technologies and their supporting literature. The proposed framework is intended to assist students, researchers, and coastal resource

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managers in selecting observation technologies according to their information needs, while recognizing that sensor suitability is context-dependent rather than universal.

2. RESEARCH METHOD

Review Design

This study employed a structured narrative literature review to synthesize scientific evidence on remote-sensing sensor selection for coastal ecosystem monitoring. This approach was adopted to integrate findings from studies involving different sensor technologies, ecosystem characteristics, spatial scales, and monitoring objectives. The review followed the principles of transparent literature identification, evidence appraisal, and qualitative synthesis described by Grant and Booth (2009) and Snyder (2019).

The review focused on four interconnected aspects: sensor characteristics, ecosystem-specific applications, environmental and operational constraints, and management information needs. These aspects provided the conceptual basis for developing a practical Sensor Selection Matrix. Rather than establishing a universal ranking of remote-sensing technologies, the review aimed to identify context-dependent sensor options supported by published scientific evidence.

Literature Search Strategy

The primary literature search was conducted using the Scopus database in September 2026. The search was performed within article titles, abstracts, and keywords using the following search string: ("remote sensing" OR "satellite imagery" OR "UAV" OR "synthetic aperture radar" OR "hyperspectral") AND ("mangrove" OR "seagrass" OR "coral reef" OR "coastal ecosystem") AND ("monitoring" OR "mapping" OR "sensor selection" OR "change detection").

The search covered Scopus records assigned publication years from 2015 to 2027 and was restricted to English-language journal articles, including final publications and articles in press. The upper year limit reflected the bibliographic years recorded in Scopus at the time of the September 2026 search, rather than a search conducted in 2027. Two records assigned a 2027 publication year were present in the initial search export; neither was included in the 47-publication shortlist. The search yielded 1,969 bibliographic records, which were exported in BibTeX format for subsequent screening and evidence assessment.

Additional relevant publications were identified through Google Scholar, ResearchGate, and publisher websites. These supplementary sources were used to identify studies addressing sensor characteristics, coastal ecosystem monitoring, and management applications. Official technical documentation from satellite data providers was also consulted when necessary to verify sensor specifications and environmental data products.

Literature Selection and Eligibility Criteria

The literature selection process was conducted in stages. The initial Scopus search identified 1,969 bibliographic records. Preliminary screening of titles, abstracts, and bibliographic metadata yielded 95 priority candidates. Further relevance assessment produced a shortlist of 47 publications. All 47 shortlisted publications underwent abstract-level assessment and were classified according to their relevance to the review objectives. Of these, 28 publications were retained for the main qualitative synthesis, 15 were designated as conditional supporting literature, and four were excluded from the main synthesis.

Publications were considered relevant when they addressed remote-sensing technologies, demonstrated applications in coastal ecosystems, or provided evidence concerning sensor capabilities and limitations. Priority was given to studies involving mangroves, seagrasses, coral reefs, and coastal environmental monitoring. Studies focusing primarily on algorithm development without a clear connection to sensor selection or coastal monitoring were assigned lower priority. Conditional supporting literature was considered where its reported findings directly addressed a specific monitoring objective, sensor characteristic, environmental constraint, or management application.

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The selection and classification of the 47 shortlisted publications were based on bibliographic information and available abstracts. Comprehensive full-text examination was not documented for all shortlisted publications. Accordingly, abstract-level information was distinguished from evidence verified through publisher-provided article content or full texts, where available. This distinction was maintained to avoid presenting preliminary relevance assessments as equivalent to comprehensive full-text reviews.

Additional relevant publications were identified through supplementary searches and reference checking, including Google Scholar, ResearchGate, and publisher websites. These sources were considered separately from the primary Scopus selection and assessed for their relevance to coastal monitoring objectives and sensor characteristics. Official technical documentation from satellite data providers was also consulted where necessary to support the interpretation of sensor specifications and environmental data products.

Evidence Extraction and Synthesis

The qualitative synthesis was developed primarily from the 28 publications retained for the main synthesis. Conditional supporting literature and supplementary sources were considered where they provided directly relevant contextual or technical information. Evidence was organized into a structured matrix containing publication details, ecosystem type, sensor technology, monitoring objective, reported capabilities, environmental limitations, and potential management applications.

The synthesis was organized into four categories: mangrove monitoring, seagrass monitoring, coral reef monitoring, and coastal environmental monitoring. Within each category, the available evidence was examined in relation to monitoring objectives and the characteristics of the observation technologies employed. Particular attention was given to spatial, spectral, and temporal characteristics; atmospheric and water-column effects; data accessibility; and field validation requirements.

Evidence interpretation accounted for the level of source verification. Information obtained from abstracts was limited to findings explicitly reported in those abstracts, whereas more detailed methodological or performance-related statements required support from accessible article content or other identifiable sources. Sensor capabilities demonstrated in individual studies were distinguished from broader interpretations developed through comparison across the literature.

The synthesis focused on identifying practical relationships between monitoring objectives, candidate sensor technologies, and environmental constraints. These relationships informed the development of the Sensor Selection Matrix. Supporting references were retained to maintain traceability between the proposed selection considerations and their scientific sources. The synthesis was qualitative; no meta-analysis, pooled accuracy assessment, or independent sensor performance validation was performed.

Development of the Sensor Selection Matrix

A practical Sensor Selection Matrix was developed through qualitative synthesis of the reviewed literature. The matrix connected monitoring objectives with candidate sensors, their selection rationale, environmental constraints, and supporting references.

Sensor suitability was considered in relation to the target environmental variable, ecosystem characteristics, spatial and temporal requirements, and operational conditions. These considerations were used to distinguish between technologies suitable for broad-scale habitat monitoring, detailed ecosystem characterization, and environmental change assessment.

The framework did not assign numerical scores or establish a universal ranking of sensors. Instead, it identified context-dependent options based on documented sensor capabilities and limitations. Where relevant, multisensor approaches were considered to address complementary monitoring requirements.

Each recommendation was linked to scientific literature or official technical documentation. The resulting matrix was intended to support research design, sensor selection, and the interpretation of remotely sensed information for coastal ecosystem management.

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3. RESULT AND DISCCUSSION

Monitoring continuity. Spatial resolution should consequently be matched to the size and heterogeneity of the target and the intended mapping scale (Kuenzer et al., 2011; Hedley et al., 2016; Carpenter et al., 2022).

Spectral characteristics determine the extent to which a sensor can distinguish targets with different reflectance properties. Multispectral observations provide information for vegetation mapping, land-cover classification, and broad habitat discrimination. Hyperspectral observations offer more detailed spectral sampling and may support the differentiation of selected vegetation or benthic components when their spectral properties are sufficiently distinct. Nevertheless, additional spectral bands do not necessarily produce more reliable ecological classifications. Spectral mixing, atmospheric effects, sensor signal quality, and, for submerged habitats, attenuation within the water column can limit the information retrieved. The required spectral characteristics should therefore be determined by the environmental variable being investigated and the conditions under which its signal can be observed (Hedley et al., 2016; Muller-Karger et al., 2018).

Empirical evidence further demonstrates that spectral characteristics must be interpreted in relation to the environmental variable and measurement scale. Zhao et al. (2019) investigated hyperspectral estimation of chlorophyll content in mangrove leaves with different thicknesses, illustrating the potential of detailed spectral observations for a specific biochemical indicator. However, spectral relationships established at the leaf level should not be assumed to transfer directly to satellite-scale canopy observations. For submerged environments, Wei et al. (2018) evaluated atmospheric correction approaches for Landsat-8 observations of coral reefs and turbid coastal waters using concurrent in situ reflectance measurements. Their study highlights the importance of obtaining reliable reflectance products before undertaking habitat or environmental analysis. These examples indicate that spectral capability, measurement scale, and preprocessing requirements should be evaluated together.

Temporal resolution is important when monitoring objectives involve seasonal variability, habitat conversion, or long-term environmental change. Repeated satellite observations can provide consistent records for detecting spatial and temporal patterns. However, nominal revisit frequency should be distinguished from the frequency of observations that are usable for ecological analysis. Cloud cover, atmospheric conditions, tidal stage, and water clarity may reduce the availability of suitable optical imagery. In intertidal and shallow-water environments, images acquired under different tidal or water-column conditions may also represent different observation states rather than ecological change alone. Sensor selection should consequently consider the effective observation frequency and the consistency of acquisition conditions required by the monitoring objective (Kuenzer et al., 2011; Muller-Karger et al., 2018).

Observation timing is particularly important in intertidal environments. Gao and Zhou (2023) examined multitemporal changes in mangrove-covered tidal flats, while Wen et al. (2024) integrated Sentinel-2 time-series imagery with tide-height information for tidal-flat mapping. These applications illustrate why variations in observed water extent must be interpreted in relation to tidal conditions before being attributed to habitat change. Consequently, selecting a sensor with frequent observations is insufficient unless the monitoring design also considers the environmental conditions represented by the acquired images.

Radiometric characteristics and environmental conditions further influence the reliability of remotely sensed measurements. Sensor sensitivity, signal quality, and appropriate calibration affect the detection of differences in recorded radiation. These considerations are particularly relevant in aquatic environments, where the signal associated with the water surface or submerged substrate may be influenced by atmospheric interference, suspended materials, and water-column properties. Water depth, turbidity, and surface reflection can further constrain optical observations of seagrass and coral reef habitats. Accordingly, the suitability of an optical sensor for submerged monitoring cannot be established solely from its nominal spatial or spectral resolution. The feasibility of obtaining

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interpretable measurements under the expected environmental conditions must also be assessed (Hedley et al., 2016; Muller-Karger et al., 2018; Wei et al., 2018).

Sensor selection must also account for differences between observation technologies. Synthetic aperture radar (SAR) provides microwave observations that can complement optical imagery, particularly where persistent cloud cover limits the availability of optical data. However, radar backscatter is influenced by factors such as vegetation structure, moisture, inundation, and surface characteristics; it should not be interpreted as an interchangeable measure of optical reflectance. The integration of Sentinel-1 and Sentinel-2 observations for mangrove mapping illustrates the potential value of combining complementary information sources (Hu et al., 2020). Light detection and ranging (LiDAR), by contrast, provides geometric and structural information relevant to terrain elevation and vegetation structure. These technologies should be considered according to the specific information required rather than treated as universal substitutes for one another (Kuenzer et al., 2011; Maurya et al., 2021).

Operational feasibility introduces a further set of selection criteria. Data accessibility, acquisition costs, processing requirements, technical expertise, and the availability of field observations influence whether a monitoring approach can be implemented and maintained. Freely accessible satellite archives may facilitate repeated regional assessments, whereas commercial imagery and specialized airborne surveys can involve additional acquisition and operational requirements. Multisensor approaches may also require spatial alignment, temporal coordination, and additional validation. For example, the integration of UAV observations with Sentinel-2 imagery for seagrass-cover estimation demonstrates how observations at different scales can provide complementary information, while requiring appropriate procedures to connect field measurements, UAV products, and satellite pixels (Carpenter et al., 2022). Operational suitability should therefore be evaluated alongside technical capability, particularly when monitoring must be repeated consistently over time.

Validation requirements should be defined according to the intended monitoring product. Habitat extent, percentage cover, structural characteristics, and environmental indicators represent different types of information and may require different reference observations. Independent field measurements or other appropriate reference data are important for evaluating classification performance and measurement uncertainty. The availability and quality of such data affect the confidence with which remotely sensed products can be interpreted. Sensor selection should therefore consider not only whether a technology can produce the intended map or measurement, but also whether its reliability can be assessed adequately for the proposed application (Hedley et al., 2016; Carpenter et al., 2022).

Taken together, these considerations support a sequential approach to sensor selection. The monitoring objective and target environmental variable should first be defined. The spatial, spectral, temporal, radiometric, or structural information required to observe that variable can then be identified. Environmental constraints, operational feasibility, and validation requirements should subsequently be examined before selecting an observation strategy. Table 1 summarizes these criteria as decision considerations rather than as a ranking of sensor technologies.

Table 1. Principal sensor characteristics and practical selection criteria for coastal ecosystem monitoring

Selection criterion	Main consideration	Implication for sensor selection
Spatial resolution	Target size, habitat heterogeneity, and mapping scale	Match spatial detail to the target while considering mixed pixels and coverage.
Spectral characteristics	Reflectance differences associated with the target variable	Select spectral information appropriate to the required habitat or environmental discrimination.

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Selection criterion	Main consideration	Implication for sensor selection
Temporal resolution	Frequency and consistency of usable observations	Match effective observation frequency to environmental dynamics and change-detection needs.
Radiometric characteristics	Sensor sensitivity, signal quality, and calibration	Assess whether the target signal can be measured reliably.
Environmental constraints	Cloud cover, tidal stage, water depth, turbidity, and surface reflection	Determine whether acquisition conditions permit interpretable observations.
Complementary sensor information	Requirements for optical, microwave, or structural measurements	Combine technologies where they address distinct information needs.
Data accessibility	Data availability, acquisition conditions, and archive continuity	Consider whether observations can be obtained consistently and reproducibly.
Operational feasibility	Costs, expertise, processing demands, and acquisition logistics	Match the monitoring strategy to available resources.
Validation requirements	Availability and suitability of independent reference observations	Establish how product accuracy and uncertainty will be assessed.

Source: Qualitative synthesis based on Kuenzer et al. (2011), Hedley et al. (2016), Muller-Karger et al. (2018), Hu et al. (2020), Maurya et al. (2021), and Carpenter et al. (2022).

Sensor Applications across Coastal Ecosystems

The suitability of remote-sensing technologies varies across coastal ecosystems because the environmental variables of interest, habitat characteristics, and observation constraints differ. Mangrove monitoring may require information on forest extent, canopy condition, or vegetation structure. Seagrass and coral reef monitoring must additionally account for water-column effects and the difficulty of distinguishing submerged components. Coastal environmental monitoring often focuses on shoreline position, intertidal exposure, land-cover change, or water-quality variables. Consequently, sensor selection should be guided by the intended information product and its validation requirements rather than by ecosystem type alone.

Mangrove Monitoring

Mangrove monitoring commonly involves mapping habitat extent, detecting land-cover change, and characterizing vegetation condition or structure. Multispectral satellite imagery supports repeated observations of mangrove distribution, while higher-resolution imagery can help delineate narrow or fragmented vegetation patches. Radar observations offer complementary information, particularly where persistent cloud cover limits optical acquisition. Nevertheless, mangrove boundaries, canopy characteristics, and physiological indicators represent distinct monitoring products that may require different observation strategies (Kuenzer et al., 2011; Maurya et al., 2021).

Empirical studies demonstrate the value of combining complementary observations for mangrove extent mapping. Abdel-Hamid et al. (2018) integrated polarimetric SAR and high-resolution optical imagery to map mangroves along the Egyptian Red Sea coast. Their results showed that the combination of radar and optical information improved habitat discrimination under the conditions evaluated. Hu et al. (2020) likewise investigated the integration of Sentinel-1 and Sentinel-2 observations for mangrove mapping. More recently, Dong et al. (2026) combined Sentinel-1 and Sentinel-2 observations with multiyear training to improve mapping consistency in a tropical intertidal estuary. The reported overall accuracy of 0.89 represents the performance of that particular study and should not be generalized without independent validation. Collectively, these applications indicate

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that multisensor integration can address complementary information needs, although its contribution depends on the habitat, reference data, and classification design.

For mangrove condition monitoring, the distinction between habitat extent and vegetation properties is particularly important. Zhao et al. (2019) examined hyperspectral estimation of chlorophyll content in mangrove leaves, whereas Sun et al. (2023) investigated high-resolution mangrove mapping using habitat and tidal information. The former addresses a biochemical indicator at the leaf scale; the latter addresses spatial habitat discrimination. Their monitoring products are not interchangeable, and a sensor suitable for delineating forest boundaries cannot automatically be assumed suitable for estimating physiological condition. Leaf-level spectral relationships also require additional evaluation before being transferred to canopy- or satellite-scale observations.

The Lombok mangrove study by Isdianto et al. (2026) provides a further example of applying remote-sensing observations to a defined local monitoring objective. Its contribution should be interpreted in relation to the study's mapped variables, spatial scale, and reference observations rather than as evidence that one sensor configuration is universally suitable. For repeated mangrove monitoring, the practical choice is therefore between—and sometimes the integration of—observations that can consistently represent habitat extent, structural properties, or condition indicators.

Seagrass Monitoring

Seagrass monitoring requires the observation of submerged vegetation through a water column whose optical properties vary with depth, turbidity, and acquisition conditions. Multispectral satellite imagery can support the mapping of seagrass distribution over relatively extensive areas, but its performance depends on whether sufficient information from the seabed reaches the sensor. Atmospheric correction, water-column effects, tidal stage, and the availability of suitable reference data must therefore be considered alongside spatial and spectral resolution (Hossain et al., 2015; Traganos et al., 2018).

Evidence from tropical intertidal environments illustrates the importance of acquisition conditions. Trinh et al. (2023) evaluated Sentinel-2 imagery for mapping a turbid seagrass meadow in southern Vietnam. In that study, water-column correction increased overall classification accuracy from 80.4% to 80.6%, whereas a multitemporal composite increased it to 88.6%. These results demonstrate that the contribution of a processing procedure must be evaluated in its environmental and methodological context. They do not establish that multitemporal compositing will produce the same improvement at other sites.

UAV observations provide a complementary strategy where finer spatial detail or more localized vegetation discrimination is required. Carpenter et al. (2022) demonstrated the integration of UAV and satellite observations for seagrass-cover estimation. Elma et al. (2024) used UAV-based multispectral imagery in an intertidal seagrass environment and reported overall classification accuracies of 84–91% across the evaluated habitat maps. Oiry et al. (2024) investigated the discrimination of seagrasses and green macroalgae using high-resolution multispectral drone imagery. These applications distinguish two monitoring objectives: delineating general seagrass distribution and separating vegetation components that may have similar spectral characteristics. The latter requires a classification scheme and reference observations capable of supporting that distinction.

Optical and radar observations may also be combined for particular intertidal mapping tasks. Wang et al. (2025) investigated a rule-based approach integrating optical and synthetic aperture radar imagery. Such an approach broadens the available observation strategies, but its suitability depends on local tidal conditions, habitat characteristics, and the intended output. Radar observations should not be interpreted as direct substitutes for the optical information used to identify submerged vegetation.

Overall, seagrass sensor selection should begin by specifying whether the required product is habitat extent, percentage cover, or discrimination among vegetation components. The selection of

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satellite, UAV, or combined observations should then follow from the required spatial detail, water conditions, acquisition opportunities, and validation design.

Coral Reef Monitoring

Coral reef monitoring involves a range of products, including reef extent, benthic habitat classes, structural characteristics, and environmental exposure. Optical satellite observations support broad-area mapping, whereas high-resolution imagery and underwater observations can provide more detailed information at smaller spatial scales. However, spectral similarity among benthic components, variable water depth, and water-column attenuation constrain habitat discrimination. These limitations mean that increased spatial or spectral resolution does not, by itself, guarantee a more ecologically informative product (Hedley et al., 2016; Lyons et al., 2024).

Structural information can complement spectral observations where habitat classes differ in their geomorphic characteristics. Nieuwenhuis et al. (2022) incorporated geomorphometric variables derived from a UAV-based digital elevation model into object-based image analysis of shallow coral reef habitats. Their findings illustrate how elevation-derived information can contribute to habitat classification when the intended classes have relevant structural differences. The benefit of these additional variables should nevertheless be assessed against the information already available from the imagery.

The contribution of multisensor integration is also product-specific. Dumpati (2026) combined Sentinel-2 imagery and ICESat-2 satellite laser bathymetry for benthic habitat classification in the Florida Keys. The integrated approach achieved an overall classification accuracy of 89.25%, compared with 89.91% for the spectral-only model. Bathymetric information contributed improvements for selected habitat classes rather than increasing overall accuracy. This distinction is important: an additional dataset may be valuable for a particular classification problem even when it does not improve the aggregate performance metric.

Detailed benthic observations require a further distinction between sensor capability and ecological validation. Mills et al. (2024) combined temporal photoquadrat observations with underwater hyperspectral imaging to assess benthic communities in Guam. Their approach illustrates the value of linking detailed spectral measurements with ecological reference information. Underwater hyperspectral measurements, however, operate under different illumination, viewing, and water-column conditions from satellite observations; relationships established using one observation configuration should not be transferred to another without evaluation.

Thermal monitoring introduces a separate information requirement. Satellite-derived sea surface temperature products can support assessments of thermal exposure, but nominal pixel size does not necessarily indicate how well a product represents the thermal conditions experienced at a reef. Lachs et al. (2025) compared satellite temperature products in a western Pacific coral reef system and found that finer nominal spatial resolution did not necessarily provide a better representation of local thermal conditions or historical bleaching patterns. Temperature-product selection should therefore consider the relevant thermal environment, temporal characteristics, and available validation observations rather than spatial resolution alone.

These studies indicate that coral reef monitoring requires an explicit distinction among benthic composition, structural information, and thermal exposure. Each product involves different observation mechanisms and validation requirements. Multisensor integration is justified when the additional data address a defined information gap, not simply because more data sources are available.

Coastal Environmental Monitoring

Coastal environmental monitoring encompasses shoreline and tidal-flat dynamics, coastal land-cover change, and aquatic environmental variables. These applications differ in the physical processes being observed and the reference information needed for interpretation. Repeated satellite observations can support assessments over extensive areas, but acquisition conditions must be considered when the observed boundary or surface changes with tides, water level, or seasonal

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conditions. Murray et al. (2019), for example, demonstrated the value of satellite observations for assessing changes in tidal-flat extent.

Empirical tidal-flat studies further illustrate the need to distinguish environmental variability from persistent spatial change. Jia et al. (2021) used Sentinel-2 time-series imagery for automated tidal-flat mapping in China, while Wen et al. (2024) incorporated tide-height information into a related monitoring approach. These applications support the use of multitemporal observations, provided that differences in tidal conditions are addressed during image selection and interpretation. An apparent change in exposed surface area should not automatically be interpreted as a change in habitat extent.

Coastal land-surface temperature monitoring presents a different scale-matching problem. Anggraini et al. (2026) examined cross-resolution consistency between UAV thermal observations and Landsat 8 thermal imagery in a tropical coastal–industrial setting. This application illustrates the importance of evaluating whether observations acquired at different spatial scales represent comparable thermal information. A finer-resolution thermal image may resolve local heterogeneity that is averaged within a coarser satellite pixel; consequently, differences between products require interpretation in relation to measurement scale and acquisition conditions.

Water-quality monitoring requires an observation and validation strategy distinct from habitat mapping. Ahmadi et al. (2025) evaluated the retrieval of colored dissolved organic matter using Sentinel-2 observations and field measurements in coastal waters of the Persian Gulf. Their study illustrates the importance of matching satellite-derived estimates with in situ measurements of the target variable. Such retrievals should not be interpreted as direct measurements of overall ecological condition without additional supporting evidence. Sensor suitability depends on whether the target parameter has an observable optical relationship under the prevailing water conditions and whether that relationship can be validated.

Across these applications, coastal environmental monitoring should distinguish changes in the observed physical state from changes in the underlying environmental condition. Revisit frequency, spatial resolution, and spectral capability are relevant only insofar as they support a clearly defined variable, consistent acquisition conditions, and an appropriate validation strategy.

Cross-Ecosystem Synthesis

The empirical evidence indicates that remote-sensing sensor selection should begin with the monitoring objective rather than the ecosystem category alone. Mangrove extent mapping, seagrass cover estimation, reef habitat classification, and coastal temperature assessment require different observation properties and validation approaches. The studies reviewed here demonstrate the value of matching sensor capabilities to the target variable, while also showing that reported classification performance and environmental measurements are specific to their study conditions.

Three practical distinctions emerge. First, habitat extent and ecological condition are not interchangeable monitoring products. Second, finer spatial resolution or additional spectral information does not automatically overcome environmental limitations. Third, multisensor integration is most useful when the combined observations address complementary information needs rather than merely increasing the number of datasets.

For example, combining optical and radar observations can improve the completeness of mangrove mapping under variable cloud conditions. Combining UAV and satellite imagery can connect localized seagrass cover measurements with broader spatial assessments. Combining reef habitat maps with environmental observations can distinguish the spatial distribution of reef environments from the pressures affecting them. These examples support a conditional approach to sensor selection in which the target variable, spatial scale, environmental constraints, and validation requirements determine the observation strategy.

The findings provide the empirical basis for the Sensor Selection Matrix developed in the following section. Rather than identifying a universally preferred sensor, the matrix should connect each monitoring objective with candidate technologies, the evidence supporting their application, and the conditions under which their outputs can be interpreted reliably.

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Practical Sensor Selection Framework

The cross-ecosystem synthesis indicates that remote-sensing sensor selection should be organized as a sequence of decisions rather than a comparison of technical specifications alone. The first decision concerns the monitoring product: habitat extent, percentage cover, vegetation structure, benthic composition, surface temperature, or another environmental variable. The second concerns the spatial and temporal scale at which that product is required. Environmental conditions, operational feasibility, and validation requirements should then be evaluated before a sensor or multisensor strategy is selected. This sequence is consistent with the distinction between habitat mapping and ecological assessment established in previous coral reef research (Hedley et al., 2016).

Defining the Monitoring Product

A clearly defined monitoring product provides the basis for determining the required observation characteristics. For example, mapping the extent of mangrove vegetation differs from estimating its canopy structure or leaf chlorophyll content, even though these applications concern the same ecosystem. Similarly, identifying seagrass distribution differs from estimating continuous percentage cover or discriminating seagrasses from macroalgae. Mapping reef substrate also differs from assessing benthic composition or thermal exposure.

Empirical studies illustrate these distinctions. Isdianto et al. (2026) used Landsat observations to examine mangrove loss, persistence, and regeneration on Lombok Island. Their application supports the use of a multitemporal satellite archive when the required product is a map of habitat transitions. In contrast, Carpenter et al. (2022) integrated field observations, UAV imagery, and Sentinel-2 data to estimate seagrass percentage cover. Zhao et al. (2019) investigated hyperspectral estimation of mangrove leaf chlorophyll content. These studies address different variables and therefore require different observation and validation strategies.

The monitoring objective should consequently be expressed as a measurable output before candidate sensors are identified. Broad terms such as mangrove health or reef condition should be translated into specific indicators rather than treated as variables that can be retrieved directly from any satellite image.

Matching Sensor Characteristics to Monitoring Scale

After defining the monitoring product, the required spatial detail and observation period should be established. Long-term assessments of habitat conversion benefit from consistent historical observations, whereas the delineation of small habitat patches or the discrimination of benthic components may require finer spatial resolution.

Hu et al. (2020) demonstrated the value of integrating Sentinel-1 radar and Sentinel-2 optical observations for mangrove mapping in China. Their combined approach achieved an F1-score of 0.94, compared with 0.88 and 0.895 for the individual radar and optical datasets, respectively. These values represent performance under the conditions of that study, not transferable accuracy guarantees for other coastlines.

For submerged habitats, Traganos et al. (2018) mapped approximately 2,510 km² of Posidonia oceanica using Sentinel-2 observations in the Aegean and Ionian Seas. Their reported overall accuracy of 72%, evaluated against independent field data, illustrates both the regional mapping potential of multispectral imagery and the need to retain classification uncertainty in subsequent interpretation.

Higher spatial resolution may be necessary for some objectives without being sufficient for all of them. Nieuwenhuis et al. (2022), for example, demonstrated the contribution of UAV-derived geomorphometric information to shallow-reef habitat classification. Conversely, Lachs et al. (2025) showed that finer nominal spatial resolution did not necessarily produce a better representation of local reef thermal conditions. The appropriate resolution therefore depends on the target variable, the spatial support of the observation, and the intended interpretation—not pixel size alone.

Evaluating Environmental and Operational Constraints

The feasibility of obtaining usable observations is a separate decision from nominal sensor capability. Optical monitoring of mangroves may be constrained by persistent cloud cover, while

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optical observations of seagrasses and coral reefs are additionally affected by water depth, turbidity, surface reflection, and substrate mixing. Radar can complement optical observations in some coastal environments, but radar backscatter cannot be interpreted as equivalent to optical reflectance.

Operational considerations also affect whether a monitoring strategy can be repeated. A satellite archive may support consistent observations over a broad region, while UAV surveys can provide detailed information within selected sites. Combining these observations requires attention to acquisition timing, spatial alignment, and the correspondence between measurements made at different scales.

Anggraini et al. (2026), in a study co-authored by Isdianto, examined UAV thermal observations alongside Landsat 8 TIRS land surface temperature estimates in northern Surabaya. The study is relevant to the decision to combine detailed local observations with broader satellite measurements. It does not establish that the two products are interchangeable, nor does it justify using land surface temperature as a direct measure of sea surface temperature.

For intertidal environments, tidal conditions constitute an additional operational constraint. Trinh et al. (2023), Jia et al. (2021), and Wen et al. (2024) illustrate different ways in which observation timing, multitemporal imagery, or tidal information can influence habitat mapping. Accordingly, nominal revisit frequency should be distinguished from the frequency of observations that are usable for the intended product.

Establishing Validation Requirements

Validation should be designed for the selected monitoring product rather than added after image processing. Habitat classification requires suitable reference observations for evaluating mapped classes. Percentage-cover estimation requires observations that represent the same variable and spatial support as the predicted product. Biochemical indicators require appropriate measurements of the target property, while temperature assessments require attention to measurement type, acquisition conditions, and spatial-resolution differences.

The empirical examples discussed above illustrate different validation needs. The Sentinel-2 seagrass map of Traganos et al. (2018) was evaluated against an independent field dataset, whereas the UAV–satellite workflow of Carpenter et al. (2022) connected field quadrats, UAV-derived observations, and satellite-scale estimates. Mills et al. (2024) linked detailed underwater spectral observations with ecological reference information. These applications demonstrate that reference-data quality and correspondence with the target variable are integral parts of monitoring design.

Validation should also reflect the intended interpretation of multisensor results. Dumpati (2026) found that incorporating satellite laser bathymetry improved the discrimination of selected benthic habitat classes without increasing overall classification accuracy. Consequently, aggregate accuracy alone may be insufficient when the monitoring objective concerns a particular habitat class. Class-specific performance and the ecological relevance of classification errors should also be considered.

Where independent field data are unavailable, the limitation should be stated explicitly. Reference imagery, previously published maps, and expert interpretation may provide useful supporting information, but they should not automatically be described as equivalent to field-based ecological validation.

Translating Evidence into a Sensor Selection Matrix

The preceding decisions can be consolidated into a practical Sensor Selection Matrix (Table 2). The matrix identifies candidate observation strategies according to the monitoring product and records the principal conditions that determine their suitability. It does not assign universal scores because the usefulness of a sensor depends on the question being investigated and the conditions of the study area.

The empirical studies also demonstrate that multisensor integration should be evaluated according to its contribution to the intended monitoring product. Combining radar and optical observations can address complementary information requirements in mangrove and intertidal mapping (Abdel-Hamid et al., 2018; Dong et al., 2026; Wang et al., 2025). However, adding another dataset does not necessarily improve every classification outcome, as illustrated by the class-specific

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contribution of satellite laser bathymetry in benthic habitat mapping (Dumpati, 2026). Similarly, finer nominal spatial resolution does not guarantee a better representation of reef thermal conditions (Lachs et al., 2025). The framework therefore treats multisensor integration as a conditional option that requires a defined purpose and appropriate validation.

Table 2. Practical Sensor Selection Matrix for coastal ecosystem monitoring

Monitoring objective	Candidate observation strategy	Principal selection consideration	Supporting empirical evidence
Historical mangrove extent and change	Landsat multispectral time series	Archive continuity, tidal conditions, and comparable classification procedures	Isdianto et al. (2026); Gao and Zhou (2023)
Fine-scale mangrove extent mapping	High-resolution optical imagery, optionally combined with SAR	Target size, tidal variability, and discrimination from adjacent vegetation	Sun et al. (2023); Abdel-Hamid et al. (2018)
Multitemporal mangrove mapping under variable cloud conditions	Sentinel-1 SAR and Sentinel-2 multispectral imagery	Optical data gaps, interannual consistency, and complementary radar information	Hu et al. (2020); Dong et al. (2026)
Mangrove leaf chlorophyll assessment	Hyperspectral observations with suitable reference measurements	Spectral sensitivity, measurement scale, and transferability	Zhao et al. (2019)
Regional seagrass distribution	Sentinel-2 multispectral time series	Water clarity, tidal stage, and independent reference observations	Traganos et al. (2018); Trinh et al. (2023)
Local seagrass cover and vegetation discrimination	UAV multispectral imagery and field observations	Spatial detail, spectral similarity, and validation	Carpenter et al. (2022); Elma et al. (2024); Oiry et al. (2024)
Intertidal seagrass mapping using complementary observations	Optical imagery with SAR	Tidal exposure, habitat discrimination, and measurement compatibility	Wang et al. (2025)
Broad reef geomorphic and benthic mapping	Multispectral and higher-resolution optical imagery	Water-column effects, thematic classes, and field reference data	Lyons et al. (2024); Harahap et al. (2026)
Shallow-reef habitat characterization	UAV imagery with elevation or geomorphometric information	Habitat structure, spatial heterogeneity, and class-specific performance	Nieuwenhuis et al. (2022)
Benthic classification with complementary bathymetry	Sentinel-2 and satellite laser bathymetry	Whether depth information improves the target classes	Dumpati (2026)
Detailed underwater benthic assessment	Underwater hyperspectral imaging and ecological surveys	Spectral discrimination, survey scale, and ecological validation	Mills et al. (2024)

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Monitoring objective	Candidate observation strategy	Principal selection consideration	Supporting empirical evidence
Coral reef thermal-environment assessment	Satellite sea surface temperature products	Representation of local thermal conditions and in situ validation	Lachs et al. (2025); Shabani et al. (2025)
Intertidal-flat distribution and change	Sentinel-2 or Landsat time series with tidal information	Tidal stage, observation frequency, and consistent habitat boundaries	Jia et al. (2021); Wen et al. (2024)
Coastal dissolved organic matter monitoring	Sentinel-2 multispectral observations and field measurements	Aquatic optical conditions and calibration–validation data	Ahmadi et al. (2025)
Coastal land surface temperature across observation scales	Landsat TIRS with complementary UAV thermal observations	Measurement type, acquisition timing, and spatial-resolution differences	Anggraini et al. (2026)

Source: Qualitative synthesis of the cited empirical studies. The matrix identifies candidate observation strategies and their principal constraints; it does not establish universal sensor rankings or transferable accuracy guarantees.

The matrix should be applied iteratively. When a candidate technology cannot provide usable observations under local environmental conditions, the monitoring design may need to incorporate complementary sensors, revise its spatial scale, or strengthen field measurements. Similarly, when the intended ecological variable cannot be inferred reliably from the available remote-sensing product, the output should be reported at the level actually supported by the observations.

The principal contribution of the framework is therefore a transparent connection between the management question, the measurable environmental variable, the observation strategy, and the evidence needed to interpret the resulting product. This connection is particularly important when remotely sensed maps are intended to inform coastal habitat inventories, change assessments, restoration planning, or the prioritization of field investigations.

4. CONCLUSION

Selecting remote-sensing sensors for coastal ecosystem monitoring requires a clear definition of the monitoring objective, the intended observation product, and the environmental conditions affecting data acquisition. Sensor suitability cannot be determined from spatial or spectral resolution alone. Temporal coverage, tidal stage, water clarity, cloud conditions, data accessibility, and the availability of reference observations also influence the feasibility and interpretation of monitoring results.

The reviewed studies indicate that observation strategies should be differentiated across monitoring tasks rather than assigned uniformly to ecosystem types. Multispectral satellite time series provide a basis for mapping habitat extent and change, while SAR, high-resolution optical imagery, UAV observations, and hyperspectral measurements can provide complementary information for specific objectives. For submerged habitats, water-column effects and field validation remain critical. Combining observation sources should therefore be justified by the information required and evaluated against the performance of simpler alternatives. Habitat extent, ecological condition, and environmental stress must also be distinguished as different monitoring products.

The proposed Sensor Selection Matrix consolidates these considerations into a practical, evidence-linked framework connecting monitoring objectives, candidate observation strategies, selection constraints, and supporting studies. It is intended to guide context-specific decisions rather

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than identify a universally superior sensor. Because the framework is based on a qualitative literature synthesis, it does not provide pooled accuracy estimates or guarantee performance across locations. Its principal contribution is a transparent basis for selecting observations, planning validation, and identifying when complementary data are necessary for coastal ecosystem monitoring and management.

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