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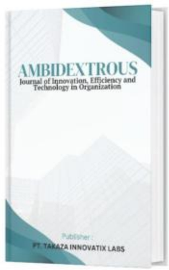

Standardization of Seagrass Biophysical Parameterization for Wave Attenuation in Nature-Based Coastal Protection: A Systematic Review Based on PRISMA

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Abstract: *Nature-based coastal protection has increasingly gained attention as an alternative or complementary approach to conventional coastal infrastructure, with seagrass meadows providing important functions in wave attenuation and sediment stabilization. However, the biophysical characteristics of seagrass used in hydrodynamic and morphodynamic models remain heterogeneous in terms of definitions, measurement methods, and parameterization. This study aims to systematically synthesize the biophysical parameters used to characterize seagrass for wave attenuation and to evaluate how these parameters are incorporated into hydrodynamic and morphodynamic models for nature-based coastal protection. A systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. Relevant studies were identified from major scientific databases and screened according to predefined inclusion and exclusion criteria, resulting in 30 studies included in the final synthesis. Data were extracted using a structured protocol covering study characteristics, seagrass species, biophysical parameters, modeling approaches, hydrodynamic responses, and coastal protection outcomes. The synthesis indicates that shoot or stand density, canopy height, blade dimensions, blade stiffness, and biomass are the most frequently reported parameters for representing vegetation effects on wave attenuation. However, substantial differences remain in parameter definitions, measurement procedures, and conversion into model parameters such as frontal area and drag coefficient. The findings highlight the need for harmonized measurement protocols and multiscale parameterization frameworks that connect field observations, laboratory experiments, and numerical models. Such standardization can improve the consistency, transferability, and reliability of seagrass-based nature-based coastal protection assessments.,*

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Introduction

Coastal zones globally are increasingly exposed to a combination of sea-level rise, shoreline erosion, and increased frequency of storms and coastal flooding driven by climate change and intensified human activities. Conventional coastal protection approaches based on gray infrastructure such as seawalls, breakwaters, and revetments have long been implemented, but they are often expensive in the long run, contribute to coastal ecosystem degradation, and can even displace erosion problems to other coastline segments instead of addressing them.(Hejnowicz et al., 2015;O'Hogain and McCarton, 2018)Nature-Based Solutions (NBS) that utilize the protective capacity of natural ecosystems are increasingly seen as a more sustainable, adaptive, and multifunctional coastal engineering approach.(Pillai et al., 2022;Unguendoli et al., 2023;Amone-Mabuto et al., 2023;Huynh et al., 2024;El Rahi et al., 2024)Seagrass meadows stand out among the various types of coastal ecosystems proposed as NBS because they simultaneously provide ecological benefits and coastal protection services, making them relevant for integration into long-term coastal adaptation strategies.(Barbier et al., 2008;Wissler et al., 2009;Charanachitta and Chukaew, 2025).

Seagrass beds are a highly valuable but highly vulnerable marine ecosystem.(Charanachitta & Chukaew, 2025)Seagrass acts as an ecosystem engineer that influences the flow patterns and transport of coastal sediment because it is a flowering plant that lives completely submerged.(Wissler et al., 2009;Hendriks et al., 2008;Vieira et al., 2019)This ecosystem provides important services in the form of nutrient cycling, food sources, biodiversity habitat, water quality improvement, carbon sequestration, and coastal protection.(Wissler et al., 2009;Dewi et al., 2020;O'Hogain and McCarton, 2018;Sudo et al., 2021).. The global economic value of seagrass is estimated to reach USD 6.4 trillion(United Nations Environment Programme, 2020), and as a blue carbon ecosystem, seagrass is able to store carbon in sediments for hundreds to thousands of years(Tanaya et al., 2018)This ecosystem continues to face a global crisis of up to 7% annual area loss due to coastal development, eutrophication, and sedimentation, which weakens its capacity for coastal protection.(Serra et al., 2020;Le Pevedic et al., 2025;Charanachitta and Chukaew, 2025).

Seagrass beds are seen as effective NBS for coastal protection because they are able to dampen wave and current energy and stabilize the substrate.(O'Hogain and McCarton, 2018;Windira, 2022;Lee, 2023). The canopy acts as a physical barrier that results in energy dissipation through drag, so that wave height decreases significantly when passing through vegetated areas.(John et al., 2015a;Pillai et al., 2022)Field evidence and modeling suggest that seagrass meadows can reduce significant wave heights by up to 50% or more, particularly in shallow waters and high wave conditions.(Infantes et al., 2012;Pillai et al., 2022;Unguendoli et al., 2023)This damping creates calmer hydrodynamic conditions, increases sediment deposition, and reduces the risk of coastal erosion. (Hejnowicz et al., 2015;Windira, 2022;Astudillo et al., 2022;Twomey et al., 2022). Thus, the ability of seagrass to dampen waves makes it an important element in coastal risk adaptation and mitigation strategies amidst sea level rise and extreme events.(Pillai et al., 2022;Unguendoli et al., 2023;Amone-Mabuto et al., 2023).

Seagrass meadows not only dampen waves but also alter local hydrodynamics by reducing current velocity and turbulence, particularly in the bottom boundary layer. This baffling effect can reduce flow velocity by up to 60% in highly flexible species, although the extent depends on local conditions.(Hendriks et al., 2008;Fonseca et al., 2019;Pillai et al., 2022)These changes in flow strengthen the function of seagrass as a sediment trapper and stabilizer through a network of roots and rhizomes that increase resistance to erosion and resuspension.(Infantes et al., 2012;Pillai et al., 2022;Twomey et al., 2022)Experiments show that the loss of canopy biomass can trigger significant erosion, with a decrease in the sediment surface of 8–120 mm/year and the release of previously stored

SOC.(Dahl et al., 2021)This sediment retention mechanism is important for the accumulation of blue carbon, both through trapping suspended organic matter and the input of underground detritus.(Tanaya et al., 2018). Therefore, sediment stabilization by seagrass plays a dual role in coastal morphodynamics and preventing the release of carbon into the atmosphere.(United Nations Environment Programme, 2020).

The effectiveness of seagrass meadows in dampening waves is largely determined by their biophysical characteristics, particularly shoot density, canopy height, biomass distribution, and mechanical properties such as elastic modulus that regulate the plant's response to waves and currents.(Infantes et al., 2012;John et al., 2015b;Familkhalili and Tahvildari, 2021;AlYousif et al., 2025;Chen et al., 2024)Flexibility is a key factor because flexible plants tend to reconfigure, reducing the frontal area and drag coefficient, which ultimately weakens the wave damping capacity.(van Veelen et al., 2021;Markov and Stolle, 2023). Stiffer vegetation can produce up to 70% greater attenuation than flexible vegetation, while in highly flexible species such as Zostera marina, increasing density does not necessarily increase flow attenuation due to the compression effect of the canopy.(Fonseca et al., 2019)Seasonal variations in biomass also affect attenuation, with the highest attenuation in the growing season, while belowground biomass remains the main support for sediment stability throughout the year.(Koch et al., 2009;Reidenbach and Thomas, 2018). Therefore, consistent biophysical characterization is very important in the design of coastal NBS.(Barbier et al., 2008;Manousakas et al., 2022;Kamperdicks et al., 2025).

To predict and optimize the role of seagrass in coastal protection, various numerical models are used, ranging from WW3, SWAN, and SHYFEM in a digital twin approach to XBeach and Delft3D with vegetation modules.(Pillai et al., 2022;Manousakas et al., 2022;Unguendoli et al., 2023). Representation of seagrass effects is generally through drag coefficient, bottom roughness, or canopy energy dissipation terms.(Reidenbach and Thomas, 2018;Yin et al., 2021), enabling simulation of wave attenuation, reduction of bottom shear stress, and stability of coastal morphology, including in the hybrid green–grey scenario.(Huynh et al., 2024;El Rahi et al., 2024;Shirinov et al., 2025)However, these models are still limited by the assumption of canopy uniformity and simplification of plant mechanical properties, so that the estimation of coastal protection benefits is not yet fully comprehensive.(Pillai et al., 2022;Kamperdicks et al., 2025).

Despite various advances, the biophysical characterization of seagrass for wave attenuation purposes remains fragmented and inconsistent across studies, due to differences in definitions, measurement methods, and reporting formats that make it difficult to compare and transfer parameters between locations and models.(Barbier et al., 2008;Manousakas et al., 2022;Twomey et al., 2022;El Rahi et al., 2024). Many coastal engineering studies simplify vegetation properties into one or two aggregate parameters that do not reflect the complexity of the natural canopy, seasonal variability, and differences between species.(Yin et al., 2021;Shirinov et al., 2025). In addition, global databases are still biased towards temperate species, while tropical and subtropical seagrass meadows remain underrepresented despite being located in highly vulnerable coastal areas.(Tanaya et al., 2018;Serra et al., 2020;Charanachitta and Chukaew, 2025). Ecological and engineering perspectives often operate separately, so that structural descriptions are not always connected to hydrodynamic performance, and engineering parameters are often not based on adequate empirical data.(O'Hogain and McCarton, 2018;El Rahi et al., 2024).

This situation highlights a knowledge gap at the interface between ecology and coastal engineering. To date, there has been no integrated review that systematically synthesizes how the biophysical characteristics of seagrasses are measured, quantified, and translated into parameters for modeling wave attenuation and coastal protection.(Pillai et al., 2022;Unguendoli et al., 2023;Kamperdicks et al., 2025)Therefore, this study aims to compile a comprehensive review of seagrass biophysical characterization methods in field studies, experiments, and modeling, and analyze their application in coastal hydrodynamic and morphodynamic process simulations. Furthermore, it will identify key gaps and uncertainties in parameter standardization to improve the integration of seagrass biophysical data in nature-based coastal protection design. With this approach, this study provides a structured reference for future researchers in developing seagrass-based coastal protection solutions.

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Research methods

Review Design and Search Strategy

This review adopted a structured process aligned with the PRISMA principles to ensure transparency in the identification, screening, and selection of studies. A conceptual framework linking three main components—biophysical characterization methods, implementation of seagrass properties in hydrodynamic and morphodynamic models, and coastal protection outcomes—was used to guide the formulation of the search strategy, eligibility criteria, and data extraction. This approach was chosen to ensure the resulting synthesis was not only descriptive but also explicitly linked biophysical aspects to coastal engineering performance.

A systematic search was conducted in the Scopus, Web of Science, ScienceDirect, and SpringerLink databases, with Google Scholar used to identify additional relevant publications. Search terms combined keywords related to seagrass, biophysical attributes, and coastal hydrodynamics or morphodynamics, using database-specific adaptations of the following term groups: (1) "seagrass" AND ("wave attenuation" OR "wave dissipation"); (2) "seagrass" AND ("vegetation parameters" OR "biophysical" OR "canopy height" OR "shoot density"); (3) "seagrass" AND ("coastal protection" OR "coastal defense" OR "nature-based solutions"); and (4) "seagrass" AND ("XBeach" OR "SWAN" OR "Delft3D" OR "hydrodynamic model" OR "morphodynamic model"). The search was limited to English-language publications and focused primarily on the last two decades, coinciding with the rise in research on coastal vegetation modeling and nature-based coastal protection.

Study Eligibility and Selection Criteria

Eligibility criteria were established a priori to ensure the review focused on seagrasses in the context of coastal engineering. Studies were included if they assessed seagrasses through field observations, laboratory experiments, or numerical modeling; reported relevant biophysical parameters such as canopy height, shoot density, leaf dimensions, flexibility or stiffness, or drag/roughness coefficient; and investigated interactions between seagrasses and hydrodynamic or sedimentary processes. Only publications with sufficient methodological detail were considered for inclusion. Studies were excluded if they focused solely on ecological aspects without wave, current, or sediment analysis; used generic submerged vegetation without specifying seagrass species; lacked quantitative biophysical data; or provided inadequate methodological information.

All retrieved records were deduplicated and screened based on title and abstract to exclude articles that were clearly irrelevant. The remaining articles were then fully assessed against the eligibility criteria. Studies were excluded at this stage if they did not report the required biophysical parameters or did not have a hydrodynamic or sedimentary component. The number of studies at each selection stage, along with the main exclusion reasons, is summarized in a PRISMA-style flow diagram (Figure 1).

Data from each selected study were extracted using a standard template that included: (i) bibliographic and geographic details (author, year, journal, study location); (ii) ecological context, including seagrass species, habitat type, and depth range; (iii) study design and scale (field, laboratory, modeling, or combined approach); (iv) biophysical characterization methods and parameters (e.g., canopy height, shoot density, leaf properties, flexibility, drag or roughness coefficient, and subsurface properties); (v) vegetation representation in hydrodynamic or morphodynamic models, including parameterization, coupling schemes, and calibration/validation; (vi) environmental boundary conditions such as waves, currents, sediment, and initial bathymetry; and (vii) response indicators, including wave attenuation, current reduction, shear stress changes, sediment transport, and bed elevation dynamics.

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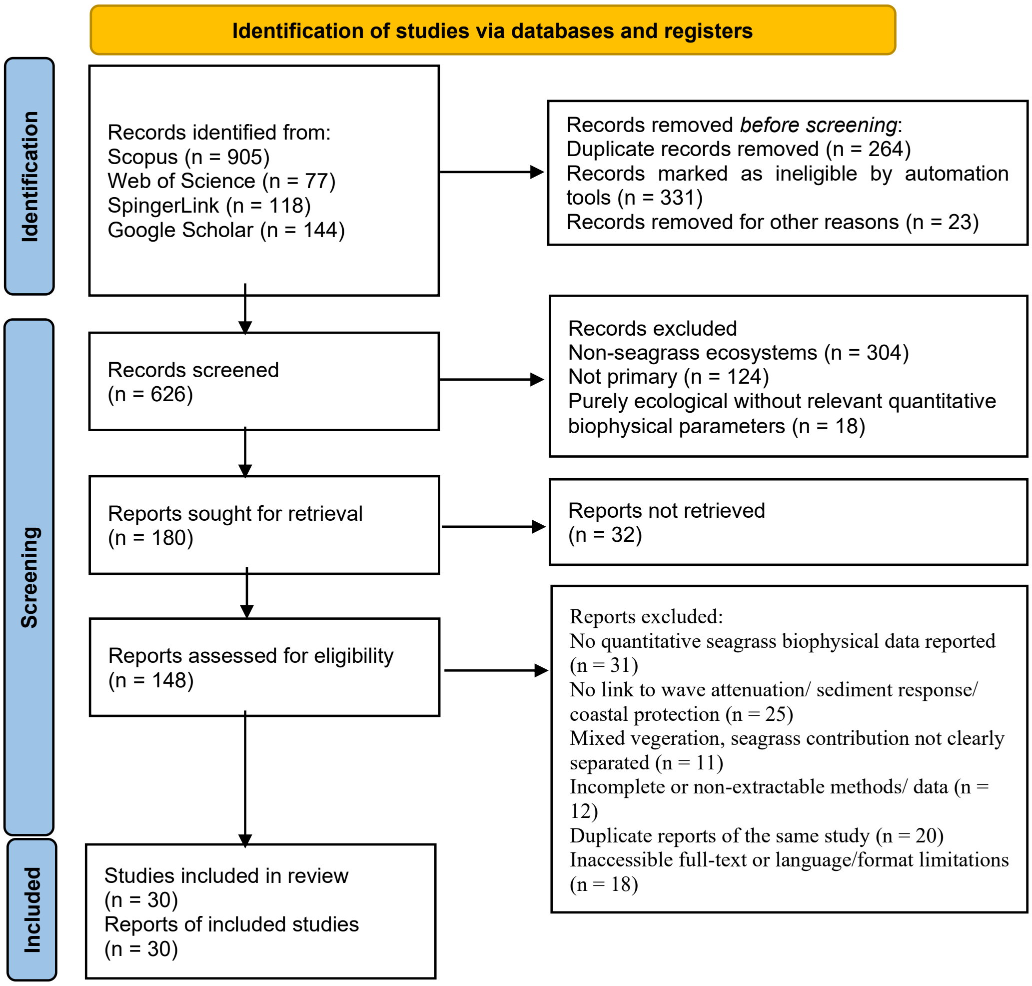

Figure 1. PRISMA flowchart of the literature search and study selection process.

Results and Discussion

General Characteristics of the Reviewed Studies

A total of 30 studies were reviewed, as summarized in Appendix 1, with a relatively balanced distribution of methods. Approximately 30% of the studies involved numerical modeling, 30% field studies (including in situ flumes), and the remainder were divided between laboratory flume experiments, hybrid studies, and reviews/meta-analyses (±13–15%). This diversity of approaches confirms that understanding of the role of seagrass in wave attenuation and coastal protection stems from a combination of observational, experimental, and modeling approaches.

Numerical modeling studies use two-dimensional and three-dimensional schemes to simulate the interaction of waves, currents, and seagrass canopies, and evaluate the contribution of seagrass to storm wave attenuation, wave force reduction, and coastal energy redistribution.(Donatelli et al., 2019;Dinu et al., 2023;van de Vijsel et al., 2023;Sierra et al., 2023). Various parameters such as density, height, blade stiffness, depth, and bottom slope are tested to assess response sensitivity, allowing exploration of extreme scenarios that are difficult to observe directly.

Field studies provide empirical evidence through measurements of significant wave heights, current velocities, bottom shear stress, and morphological changes compared between seagrass and non-seagrass areas.(Christianen et al., 2013;Reidenbach and Thomas, 2018;James et al., 2019;James et al., 2020;Infantes et al., 2022)Observations were conducted using sensors along the transects to accurately document hydrodynamic-sediment dynamics in a real-world environment, including the effects of tides, seasons, and storms. Laboratory flume experiments isolated key factors such as wave shape, depth, canopy density, and blade mechanical properties to study wave decay, turbulence, and flow patterns in

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a controlled manner.(Schaefer and Nepf, 2022;Gong et al., 2024;Xu and Salauddin, 2025). The findings from these experiments provide fundamental parameters, such as Cd or the turbulence scale, which strengthen the formulation of numerical models.

Hybrid field-model studies and synthesis studies (reviews/meta-analyses) expand the scope of analysis beyond these two approaches. Hybrid studies utilize field data for calibration and validation before running long-term scenarios, such as sea level rise or seagrass degradation. Synthesis across studies produces key parameter estimates and transfer functions for application to large-scale coastal risk modeling.(Barbier et al., 2008;Pinsky et al., 2013;Twomey et al., 2020;Contti Neto et al., 2022;Contti Neto et al., 2025).

Species Distribution and Hydrodynamic Context

Taxonomically, almost half of the studies focused on the genus Zostera (±47%) and about 20% on Posidonia, while the remainder examined Thalassia, Enhalus, Halodule, Cymodocea, as well as multi-species studies or artificial vegetation.(Chen et al., 2007;Christiansen et al., 2013;Reidenbach and Thomas, 2018;James et al., 2019; Muna, 2020)The dominance of Zostera and Posidonia reflects a geographic focus on temperate regions such as the Mediterranean, Adriatic, and the European–North American coast.(Donatelli et al., 2019;Pillai et al., 2022;Dinu et al., 2023;Sierra et al., 2023). Conversely, tropical species are still underrepresented, so that typical tropical biophysical parameters—for example, wider or more flexible leaves—have not been fully characterized for modeling and planning applications in nature-based solutions.(Christianen et al., 2013;James et al., 2019;Muna, 2020). This condition indicates the need for local calibration when latitude-based species results are applied to tropical systems.

This taxonomic bias is compounded by the wide variety of hydrodynamic contexts in the literature, ranging from large storms with wave heights exceeding 4 m to low-energy environments such as lagoons, sheltered bays, and estuaries. Several studies have modeled historical storm events or climate scenarios to assess the effectiveness of seagrass in reducing wave height, run-up, and coastal flooding risk under high-energy conditions.(Pillai et al., 2022;Unguendoli et al., 2023;Shirinov et al., 2025). Studies under low to moderate energy conditions have instead highlighted the accumulative role of seagrass in damping small waves, modifying local circulation, and gradually increasing sediment stability.

Laboratory and flume experiments serve to clarify the sensitivity of damping mechanisms to variations in biophysical parameters in this relationship, because conditions can be tightly controlled through manipulation of leaf density, height, and stiffness, as well as waveform.(Schaefer and Nepf, 2022;Gong et al., 2024;Xu and Salauddin, 2025)The experimental results yielded quantitative relationships between canopy structure and hydrodynamic parameters such as damping or drag coefficients, which were then integrated into field-scale modeling.

The combination of taxonomic bias, geographic distribution, and overall variation in hydrodynamic regimes suggests that the effectiveness of seagrass as a coastal protection component is determined by two main factors, namely the biophysical properties of the dominant species and the character of local wave energy, ranging from calm lagoons to extreme storms Chen et al., 2007;Christiansen et al., 2013; Reidenbach and Thomas, 2018; James et al., 2019;Muna, 2020;Pillai et al., 2022;Unguendoli et al., 2023;Shirinov et al., 2025;Schaefer and Nepf, 2022;Gong et al., 2024;Xu and Salauddin, 2025). These findings emphasize the importance of integrating species type, local conditions, and wave intensity in assessing the capacity of seagrass as an ecosystem-based coastal protection solution.

Characterized Biophysical Parameters of Seagrass

The literature consistently uses a set of biophysical parameters to describe the structure and function of seagrass stands in the context of wave attenuation. These parameters include the canopy component above the sediment surface, belowground biomass, and derived parameters commonly adopted in statistical modeling and analysis. Stand density (Nv) is the most common parameter because it determines the frontal canopy area and plays a direct role in the formulation of drag forces.(Chen et al., 2007; Twomey et al., 2020;Schaefer and Nepf, 2022;Dinu et al., 2023). The higher the Nv, the greater the interaction of leaves and stems with the flow, thus increasing energy attenuation. This density value

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is then reduced to other parameters such as frontal area per water volume in modeling.(Chen et al., 2007;Twomey et al., 2020).

Canopy height and blade length (Hv, Lv) complement the density function by determining how much of the plant is exposed to wave energy. Many studies calculate the effective leaf length (le) to represent the structural changes due to deflection by currents.(Pillai et al., 2022;Shirinov et al., 2025). The model can capture the effect of canopy reconfiguration on wave attenuation variations by including Hv, Lv, and le simultaneously.

Blade geometry and biomechanical parameters, such as diameter and stiffness (EI), play a role in explaining differences in species' responses to flow. Flexible seagrasses tend to follow the flow direction, reducing drag per element, while stiff seagrasses produce different turbulence patterns.(Beth Schaefer and Nepf, 2022;Gong et al., 2024). The EI parameter is therefore key in explaining differences in damping efficiency between species.

Below-ground biomass (BGB), particularly rhizomes and roots, influences sediment stability by binding grains and increasing bed elevation beyond the above-ground component.(Christianen et al., 2013;James et al., 2019;Astudillo-Gutierrez et al., 2024). The role of BGB remains crucial for understanding the long-term capacity of seagrasses to maintain shorelines and store carbon, although this parameter is rarely characterized quantitatively.

These basic parameters in modeling and meta-analysis are often converted into derived parameters such as LAI, frontal area per volume (a), and effective drag coefficient (Cd), which are obtained through calibration against observational data.(Twomey et al., 2020;Contti Neto et al., 2022;Contti Neto et al., 2025). This conversion allows for simplification of the formulation without losing consistency with the underlying physical dynamics.

Density (Nv), canopy height or length (Hv, Lv/le), and stiffness (EI) as a whole appear as the most decisive minimum parameter package in quantifying wave attenuation, while subsurface biomass and derived parameters strengthen the understanding of the stabilization function of sediments.(Chen et al., 2007;Twomey et al., 2020;Schaefer and Nepf, 2022;Beth Schaefer and Nepf, 2022;Pillai et al., 2022;Dinu et al., 2023;Gong et al., 2024;Shirinov et al., 2025). This combination of parameters can be used as a basis for standardizing seagrass biophysical measurements and modeling in the development of coastal NBS.

Representation of Seagrass in Hydrodynamic Models

Seagrass representations in hydrodynamic and wave models exhibit key patterns ranging from simple roughness-based schemes to process-based representations that link biophysical parameters to drag and energy decay. Understanding these differences in approach is crucial for assessing the extent to which models capture the coastal protection function of seagrasses and how the results can be applied to coastal coastal protection systems.

The drag coefficient formulation (±30%) is the most widely used approach, with seagrass stands represented as volumetric drag through Cd values calibrated against changes in wave height or current speed.(Chen et al., 2007;Twomey et al., 2020;Schaefer & Nepf, 2022;Dinu et al., 2023)This scheme is simple and easy to implement, although the details of the canopy structure are often absorbed into the effective Cd value. Some other studies use a cylindrical representation (±23%), which replaces the seagrass leaves or blades with rigid stems to facilitate drag and turbulence analysis.(Beth Schaefer & Nepf, 2022;Gong et al., 2024). This representation is useful for understanding the basic mechanisms, but tends to produce greater drag than a flexible canopy in the field.

Flexible vegetation approaches (±13%) are increasingly used as model capacity increases. Methods such as effective length calculate the portion of the blade that remains upright and contributes to drag as a function of flow conditions and stiffness.(Shirinov et al., 2025)This approach also appears in the vegetation modules of spectral models such as SWAN or WAVEWATCH III, which incorporate biophysical parameters directly into the wave energy source/loss terms. A small number of other studies (≈ 3–7%) rely on hydraulic roughness or empirical attenuation coefficient approaches, deriving parameters such as Chezy, Manning, or αw from differences between vegetated and unvegetated conditions (Barbier et al., 2008; Pinsky et al., 2013). These approaches are practical, but they lack the ability to explicitly link changes in plant parameters to physical responses.

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A number of other studies have evaluated the role of seagrass without an explicit parameterization scheme, primarily to assess erosion, retention, or sediment stock directly.(Christianen et al., 2013;James et al., 2019;James et al., 2020)This empirical approach does not produce a drag formulation, but provides strong evidence of the ecological benefits of seagrass and forms the basis for the development of further parameterizations.

The overall spectrum of approaches demonstrates a trade-off between simplicity, data requirements, and the fidelity of the processes represented. Drag and rigid cylinder approaches are effective for initial needs, while flexible vegetation models and custom modules offer more realistic representations with higher data demands.(Chen et al., 2007; Luhar et al., 2017;Twomey et al., 2020;Pillai et al., 2022;Schaefer & Nepf, 2022;Beth Schaefer & Nepf, 2022;Dinu et al., 2023;Gong et al., 2024;Shirinov et al., 2025). Roughness and direct measurement approaches, on the other hand, strengthen empirical evidence but lack a generic predictive framework. This synthesis helps map the modeling landscape used to capture the biophysical role of seagrass in wave attenuation and coastal protection.

Hydrodynamic Model and Experimental Setup

This study shows that SWAN and its variants, including the coupled configuration with Delft3D-FLOW, are the most commonly used modeling frameworks for analyzing wave attenuation by seagrass at bay to regional scales.(Donatelli et al., 2019;Dinu et al., 2023;van de Vijsel et al., 2023;Sierra et al., 2023)As a spectral wave model, SWAN is able to capture the transformation of waves from the open sea to the coast and their interaction with vegetation, and when integrated with Delft3D-FLOW, enables integrated simulation of waves and currents so that the feedback dynamics between attenuation, current patterns, and energy distribution can be comprehensively analyzed along the coast.(Donatelli et al., 2019;Dinu et al., 2023)This approach is particularly relevant for coasts with extensive and heterogeneous seagrass beds, including lagoons and semi-enclosed bays.

Nearshore and morphodynamic models such as XBeach and COAWST are used to evaluate the response of coastal morphology to storms and sea level rise.(Unguendoli et al., 2023;Astudillo-Gutierrez et al., 2024;Forrester et al., 2024)XBeach is widely used for short-term storm dynamics, run-up, overtopping, and beach profile changes. COAWST as an integrated wave-current-sediment system allows for long-term analysis, including the combination of recurring storms and sea-level rise trends on the stability of seagrass beaches.

This large-scale model framework is strengthened by flume experiments, both in the laboratory and using portable flumes in situ. Laboratory experiments allow for tight control of hydrodynamic variables and canopy characteristics, allowing for systematic field testing of the sensitivity of responses to biophysical parameters.(Schaefer and Nepf, 2022;Beth Schaefer and Nepf, 2022;Schaefer and Nepf, 2022;Gong et al., 2024;Xu and Salauddin, 2025)The collected data includes changes in wave height, velocity profiles, turbulent kinetic energy (TKE), and bed shear stress. In situ portable flumes provide a more realistic representation of field conditions, including the influence of sediment, tides, and biotic communities, making them essential for validating laboratory results and calibrating numerical models.

The combination of bay-regional scale wave-morphodynamic models (SWAN, Delft3D-FLOW, XBeach, COAWST) and laboratory and in situ flume experiments collectively yields a dataset spanning microscales to coastal landscape scales.(Donatelli et al., 2019;Schaefer and Nepf, 2022;Beth Schaefer and Nepf, 2022;Gong et al., 2024;;Infantes et al., 2022;Dinu et al., 2023;van de Vijsel et al., 2023;Sierra et al., 2023;Unguendoli et al., 2023;Astudillo-Gutierrez et al., 2024;Forrester et al., 2024;Xu and Salauddin, 2025)This integration ensures that the representation of seagrass function in wave attenuation is not only theoretically based, but also tested through observations at various spatial and temporal scales, making it more reliable to support the evaluation and design of nature-based solutions in coastal areas.

Wave Attenuation and Coastal Protection Performance

Wave attenuation by seagrass meadows quantitatively varies across locations and configurations, but follows a consistent pattern. Significant wave height reductions are generally in the range of 20–50% under conditions of canopy representation, moderate depth, high density, and realistic canopy thickness, and can increase to over 80% in shallow waters with the canopy occupying a large portion of

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the water column, particularly in nearshore zones or lagoons where waves have experienced shoaling.(Chen et al., 2007;Muna, 2020;Schaefer & Nepf, 2022;Xu & Salauddin, 2025)This finding confirms the ability of seagrass to act as an effective wave energy buffer, particularly in shallow coastal systems.

Modeling and observations at the coastal landscape scale indicate that the presence of seagrass can reduce the wave height reaching the shoreline by around 30–50% in NBS configurations, including those combined with coastal engineering structures.(Pillai et al., 2022;Unguendoli et al., 2023;Astudillo-Gutierrez et al., 2024)This effect translates into a 30–55% reduction in shoreline erosion, indicating that seagrass functions not only to absorb energy in the water column but also to modify the energy patterns that control sediment transport. Seagrass meadows thus provide significant quantitative protective benefits when integrated into NBS designs.

Seagrasses have been shown to reduce bed shear stress, increase sediment retention, and slow bottom erosion by reducing near-bed flow velocities and breaking down turbulence structures from a sediment perspective.(Christianen et al., 2013;James et al., 2019;James et al., 2020;Infantes et al., 2022;Forrester et al., 2024)The magnitude of this effect depends on the canopy thickness relative to depth and wave height. Canopy-wave interactions are more intense and sediment stabilization stronger in shallow waters, while the canopy's contribution to bottom dynamics decreases in deeper waters.

The overall consistency of the results from the model, experiments, and observations indicates that parameterizations based on realistic biophysical characteristics, such as stand density, canopy height, blade stiffness, and biomass, are able to reproduce the measured wave attenuation and sediment response patterns.(Chen et al., 2007;Christiansen et al., 2013;James et al., 2019;James et al., 2020;Muna, 2020;Infantes et al., 2022;Schaefer & Nepf, 2022;Pillai et al., 2022;Unguendoli et al., 2023;Astudillo-Gutierrez et al., 2024;Forrester et al., 2024;Xu & Salauddin, 2025). Seagrass management and restoration are therefore essential elements in an adaptive and sustainable ecosystem-based coastal protection strategy.

Discussion

A literature synthesis shows that most studies adopt a basic set of biophysical parameters—density, height, diameter, and canopy stiffness—as a minimal representation of seagrass structure for drag and energy attenuation analyses across various approaches, from flumes to numerical modeling. The depth of this characterization does not always commensurate with the complexity of the physical processes being studied. Studies targeting turbulence dynamics and wave-current interactions typically add more detailed biomechanical parameters and spatial information, such as EI, blade deformation profiles, and vertical-horizontal density distributions, to more accurately capture velocity and energy decay patterns.(Schaefer & Nepf, 2022)Bay-scale or regional studies, on the other hand, often simplify canopy properties to effective parameters such as Cd and mean height to facilitate integration into coastal engineering models.(Donatelli et al., 2019;Pillai et al., 2022;Dinu et al., 2023;van de Vijsel et al., 2023)This approach is adequate for estimating wave attenuation and shoreline change, but has the potential to obscure the model's sensitivity to more subtle changes in canopy structure.

The limitations of this representation are further evident in wave attenuation analyses. Most models still use a constant-drag or rigid-cylinder approach, even though flume experiments have shown that blade deformation and reconfiguration mechanisms can significantly reduce effective drag, making Cd dependent on both the hydrodynamic conditions and the biomechanical properties of the blade.(Schaefer & Nepf, 2022;Gong et al., 2024). The use of constant Cd can result in biased damping estimates in the context of extreme events, for example during storms when the blades experience partial collapse.(Twomey et al., 2020;Pillai et al., 2022;Contti Neto et al., 2022;Contti Neto et al., 2025;Shirinov et al., 2025). Empirical or semi-analytical relationships linking canopy parameters (Nv, Hv, EI) to dynamic Cd are therefore necessary for the vegetation module in SWAN, XBeach, or COAWST to describe a more realistic drag response.

The relevance of these limitations becomes even more apparent when seagrass beds are positioned as a component of NBS in a hybrid configuration alongside hard structures. Various studies have shown that seagrass meadows can reduce wave height reaching the shore, reduce wave loads on structures, and increase sediment retention.(Pillai et al., 2022;Unguendoli et al., 2023;Astudillo-Gutierrez et al.,

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2024);Forrester et al., 2024). This effectiveness is highly dependent on the accuracy of biophysical parameterization, while some studies still use generic values or do not take into account the seasonal dynamics of biomass and canopy health.(Sierra et al., 2023;Shirinov et al., 2025). The reliability of model-based risk analysis can decrease without parameter updates based on field monitoring, especially for long-term projects, so periodic measurements of Nv, Hv, health conditions, and post-storm dynamics need to be integrated into the management scheme so that model parameters continue to reflect system conditions throughout the project's service life.

Several general limitations at a more strategic level explain the challenges of implementing seagrass-based NBS, particularly in tropical regions like Indonesia. The empirical database is still dominated by temperate species, while high-canopy tropical species such as Enhalus acoroides or Thalassia testudinum are relatively underrepresented, making parameterizations from non-tropical regions impractical without local calibration.(Christianen et al., 2013;James et al., 2019;Muna, 2020). Integration of belowground components in the form of roots and rhizomes, as well as long-term morphological responses, is still limited, even though both are important for assessing sediment stability in multi-year horizons.(Christianen et al., 2013;James et al., 2019;James et al., 2020). Limited spatial resolution in large-scale models also makes it difficult to represent seagrass patchiness, so that the relationship between small-scale detailed processes and regional dynamics is often not explicitly connected. (Chen et al., 2007;Donatelli et al., 2019;Dinu et al., 2023)..

The current characterization and modeling approaches have generally demonstrated the significant potential of seagrass beds as NBS. Improving tropical databases, integrating subsurface processes, and developing a multiscale framework that connects flume results with regional models are key priorities for more accurate and applicable NBS performance estimates in the Indonesian coastal context.(Chen et al., 2007;Christiansen et al., 2013;Donatelli et al., 2019;James et al., 2019;James et al., 2020;Muna, 2020;Dinu et al., 2023).

Conclusion

This study demonstrates that the biophysical characterization of seagrasses through field studies, laboratory experiments, and modeling has evolved toward a relatively consistent set of parameters, thus addressing the first objective of this study regarding seagrass biophysical characterization methods. Stand or shoot density, canopy height, blade dimensions and stiffness, and aboveground biomass are the main variables commonly measured and then converted to derived quantities such as frontal area, leaf area index, drag coefficient (Cd), and wave attenuation coefficient. These parameters, when integrated into hydrodynamic and morphodynamic models, have been shown to represent the role of seagrasses in reducing wave height, lowering bottom shear stress, increasing sediment retention, and controlling coastal erosion, as confirmed by a cross-case meta-analysis.

This conceptual consistency has not been fully implemented in standardized practices, thus addressing the second objective of this study regarding the gap in parameter standardization. Differences in definitions and measurement methods, ranging from effective canopy height and blade stiffness approaches to parameter conversion to Cd, still result in significant variation between studies and add uncertainty to model calibration. Geographic bias and the dominance of temperate species, particularly in studies on Zostera and Posidonia, limit generalizability to high-canopy tropical ecosystems such as Indonesia. The contribution of belowground components and long-term responses to repeated disturbances are also underexplored, even though both play a role in sediment stability and erosion thresholds.

These findings collectively emphasize the need for harmonized methodologies and multiscale approaches to minimize uncertainty in the biophysical characterization of seagrass. Future priorities include standardizing measurement protocols, establishing functional relationships between morphological-biomechanical properties and Cd and condition-based attenuation coefficients, and integrating detailed process experiments with numerical modeling and long-term monitoring, particularly in tropical regions (Xu and Salauddin, 2025). These efforts provide the foundation for biophysical characterization to support the planning and design of nature-based coastal protection solutions that are applicable to practitioners and policymakers, while also addressing the study's ultimate goal of serving as a structured reference for the development of seagrass-based coastal protection solutions.

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