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Seagrass Restoration Review: Spatial Analysis of Potential Habitats, Innovative Restoration Methods, and Predictive Modeling for Monitoring

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Abstract

Seagrass ecosystems are vital for maintaining marine ecological balance, supporting the blue carbon cycle, offering habitat for marine organisms, and safeguarding coastal areas against erosion. Nevertheless, seagrass ecosystems worldwide are declining substantially due to human activities and climate change. This trend is also evident in Indonesia, where approximately 7% of seagrass coverage is lost annually. This research examines existing literature on seagrass restoration by focusing on three key approaches: spatial assessment of suitable habitats, advancements in physical restoration techniques, and the creation of predictive models for evaluating restoration outcomes. The goal is to offer comprehensive insights into the challenges and prospects for improving management and establishing more effective and sustainable restoration strategies in coastal environments. A Systematic Literature Review (SLR) combined with bibliometric analysis was conducted on 177 publications from the Scopus database spanning 2019 to 2024 to identify research trends, technological advancements, and existing challenges in seagrass restoration. The research emphasizes the necessity of a holistic approach to seagrass restoration, incorporating spatial analysis, developing flexible restoration techniques, and implementing predictive modeling and statistical assessments to enhance long-term planning and monitoring efforts. The case study in Jepara demonstrates the effectiveness of participatory approaches at the local scale, despite limitations in technology and long-term monitoring. Integrating spatial and digital technologies, strengthening local capacity, international collaboration, and multidisciplinary integration are key to improving the effectiveness and sustainability of seagrass restoration, while strengthening its contribution to coastal resilience and climate change mitigation.

Keywords: Seagrass, restoration, spatial analysis, innovative restoration methods, predictive models.

1. Introduction

Seagrass ecosystems in coastal regions play a vital role in sustaining marine ecological balance. They support the blue carbon cycle, offer habitats for diverse marine species, and contribute to shoreline protection against erosion (Fourqurean et al., 2012). Furthermore, seagrass meadows can capture atmospheric carbon dioxide and sequester it within their biomass and surrounding marine sediments, positioning them as key ecosystems in efforts to mitigate climate change (Fourqurean et al., 2012). Despite their ecological importance, seagrass ecosystems across the globe are being degraded due to human-induced activities, including land reclamation, pollution, and the impacts of climate change (Waycott et al., 2009). Around 29% of the world's seagrass habitats have disappeared since the early 20th century, with the rate of loss continuing to rise due to ongoing environmental pressures (Orth et al., 2006). In Indonesia, seagrass ecosystems include 15 species from 7 genera, with an area that has been studied reaching about 293,464 hectares, which is about 42%, with most of them categorized as unhealthy or poor based on the standards of Kepmen LH No. 200 Year 2004 (LCDI Indonesia, 2024). Seagrass areas in Indonesia are steadily declining, accounting for up to 7% of the global loss annually, primarily driven by human activities like coastal development and pollution, which are the leading factors contributing to the degradation of seagrass ecosystems in the country (Rahman et al., 2022).

Seagrass restoration is a key strategy for restoring degraded ecosystem functions (Lessy and Ramili, 2018). There are three main approaches in seagrass restoration research: the spatial approach, the physical restoration method, and the mathematical model for restoration success. The spatial approach includes the identification of seagrass presence using remote sensing data and spatial analysis to determine the optimal location for restoration activities (Agus et al., 2018; Ihsan et al., 2021). The utilization of satellite imagery and GIS technology has enabled higher accuracy seagrass mapping, which can be used to monitor ecosystem changes and identify areas with high potential for restoration (Sari and Lubis, 2017; Rosalina et al., 2022; Wattimury et al., 2024). Several studies have shown that remote sensing-based mapping techniques can identify changes in seagrass areas more quickly and efficiently than conventional field-based methods (Ginting and Anjarkusuma, 2022; Rosalina et al., 2022).

The physical restoration method is one of the solutions to overcome the decline in seagrass area, which can generally be done through transplantation or seeding (Van Katwijk and Hermus, 2000; Paling et al., 2009; Williams et al., 2017; Ambo-Rappe et al., 2019). Nevertheless, the effectiveness of seagrass transplantation techniques differs across various regions of the world. This variability may be affected by several factors, including physical conditions like current velocity (Van Katwijk and Hermus, 2000), wave activity (Bos and van Katwijk, 2007), water depth, and the characteristics of the substrate in the seagrass habitat (Alagna et al., 2015). The restoration method used (Paling et al., 2009). Various techniques have been developed, including seagrass fragments taken from natural populations, anchor transplantation, and non-anchor methods (Ferretto et al., 2023). Anchor methods, such as the grass and plug methods, involve removing mature seagrass plants from healthy areas and replanting them where they are degraded (Wulandari et al., 2013). In contrast, non-anchoring methods, such as seeding, are done by dispersing seeds directly into degraded seagrass meadow areas. Studies have shown that seagrass transplantation using anchoring methods can significantly increase seagrass growth and survival rates compared to other methods (Sumbayak et al., 2023).

In addition to physical and spatial approaches, a mathematical approach in mathematical models is used to evaluate the effectiveness of seagrass rehabilitation (Lessy and Ramili, 2018). The mathematical model includes an analysis of ecosystem sustainability based on various environmental parameters. Developing data-driven models enables more effective restoration planning and can be used as a predictive tool to anticipate future ecosystem changes. Data-driven models such as Generalized Additive Model (GAM), double-hurdle models, Generalized Linear Models (GLM), Generalized Linear Mixed Model (GLMM), and Generalized Additive Mixed Model (GAMM) can be used for ecosystem sustainability analysis based on various environmental parameters (Gagnon et al., 2021; Unsworth et al, 2024; Wong et al, 2021). In addition, machine learning algorithms can be applied for classification and forecasting in seagrass restoration efforts.

Understanding the three main aspects of seagrass restoration, namely spatial approaches, physical methods, and mathematical models, can help develop more effective and sustainable restoration strategies. This research seeks to analyze existing literature on these three aspects to offer a better understanding of the challenges and potential opportunities for seagrass restoration across different coastal ecosystems.

2. Materials and Methods

In the digital era and the rapid development of science, a systematic literature review (SLR) offers a thorough summary of the existing knowledge and developments within a specific research area (Carrera-Rivera et al., 2022). The Systematic Literature Review (SLR) approach is employed to methodically gather, assess, and integrate findings from prior studies, aiming to deliver a deeper and more comprehensive understanding of a particular field of research (Tranfield et al., 2003). The literature utilized in this research was primarily obtained from the Scopus database, which was selected as the main source due to its extensive and high-quality coverage of scholarly works (Mongeon and Paul-Hus, 2016). This approach is used in research to ensure that literature data is credible and relevant and can avoid subjective bias in literature selection (Boell and Cecez-Kecmanovic, 2015).

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework offers a systematic procedure for arranging, choosing, and evaluating literature within systematic reviews (Page et al., 2021). PRISMA and bibliometric methods are combined in this study so that it is expected to map the development of research and provide knowledge about research gaps and opportunities for studies that can be developed in the future (Zupic and Čater, 2015). The findings from this study are intended to serve as a resource for researchers and practitioners, helping them to comprehend the trajectory of scientific progress and the impact of research within related disciplines (Aria and Cuccurullo, 2017).

Literature data was obtained through a search on March 5, 2025, using the keywords TITLE-ABS-KEY (“seagrass” AND “restoration”). The search results amounted to 1,444 pieces of literature which were then given search limitations including publication years in the last 5 years, namely 2019-2024 to produce data and method updates, using English because it is a universal language used in research from all over the world, articles with open access to be checked by other researchers, and limited to subjects in Environmental Science, Earth and Planetary Science and Mathematics which will be a subject that is widely discussed in this study. So the full keywords in the Scopus search are TITLE-ABS-KEY ("seagrass" AND "restoration") AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (OA , "all")) AND (LIMIT-TO (EXACTKEYWORD , "Seagrass") OR LIMIT-TO (EXACTKEYWORD , "Restoration")) AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "EART") OR LIMIT-TO (SUBJAREA , "MATH")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) with a result of 1. 245 eliminated pieces of literature.

Analysis using the PRISMA method was used in the following selection, where the 199 pieces of literature obtained from the Scopus database were reviewed by scanning each abstract for relevance to seagrass restoration, and all were relevant. Although the database was restricted to open-access literature, 11 pieces of literature were still inaccessible. A deeper analysis was conducted on 188 kinds of literature, where 11 pieces did not fall under the spatial, mathematical, and physical subjects that will be the main discussion in this study. This resulted in 177 pieces of literature that could be analyzed (**Figure 1**). These 177 pieces of literature were then downloaded in BibTeX (.bib) format for input in the bibliometric analysis.

Literature extraction using the bibliometric method was performed in R software using the biblioshiny web-based RStudio platform. The formulas used were Install.packages(“bibliometrix”), library(bibliometrix), biblioshiny(), and Ctrl+A and Run. Extraction was done using the following steps: Data, Load Data, select “import raw file(s)” in Import or Load, select “Scopus” in Database, and select the file.bib, then click Start.

Apart from the 177 pieces of literature previously mentioned, 11 were added from Google Scholar to increase understanding of case studies in Indonesia. This is done to see how restoration methods are applied in an area in Indonesia and how successful they are, so that what can be developed can be seen.

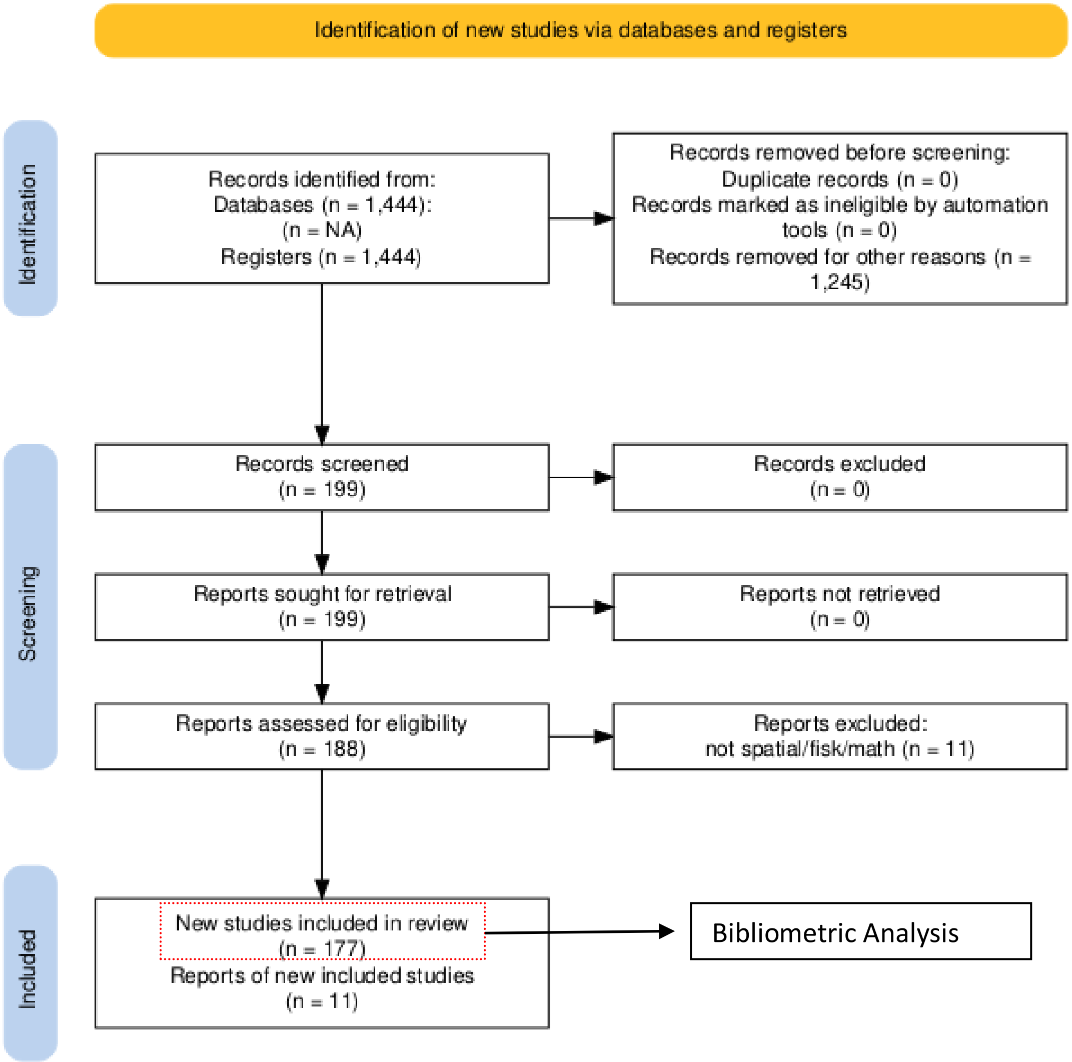

Figure 1. PRISMA flow diagram illustrating the systematic process of literature identification, screening, eligibility assessment, and inclusion. This process was applied in the Seagrass Restoration Review to support the analysis of potential habitats, innovative restoration methods, and predictive modeling for monitoring.

3. Results and Discussion

3.1. Bibliometric Analysis

Scientific publications from 177 literature in the 2019-2024 period were subjected to bibliometric analysis, and a co-occurrence network was generated showing the relationships between keywords that appeared in the search. **Figure 2** shows the close relationship between "seagrass" and "restoration ecology", one of the main themes in seagrass research. This relationship reflects the focus on restoring seagrass ecosystems that have been degraded by human activities, climate change, and other environmental factors. Large nodes such as "restoration ecology" and "ecosystem" indicate the importance of restoration in restoring seagrass ecosystem functions, including carbon sequestration and habitat for biodiversity. The red nodes, which are associated with global challenges like climate change mitigation, emphasize the importance of seagrasses in carbon sequestration and coastal protection. Meanwhile, blue nodes related to local biological aspects, such as "plants (botany)" and "ecosystems," show research on restoration techniques, such as shoot or seed transplantation. This network demonstrates that seagrass restoration holds significance beyond the local level, playing a crucial role globally, particularly in efforts to mitigate climate change and conserve marine ecosystems.

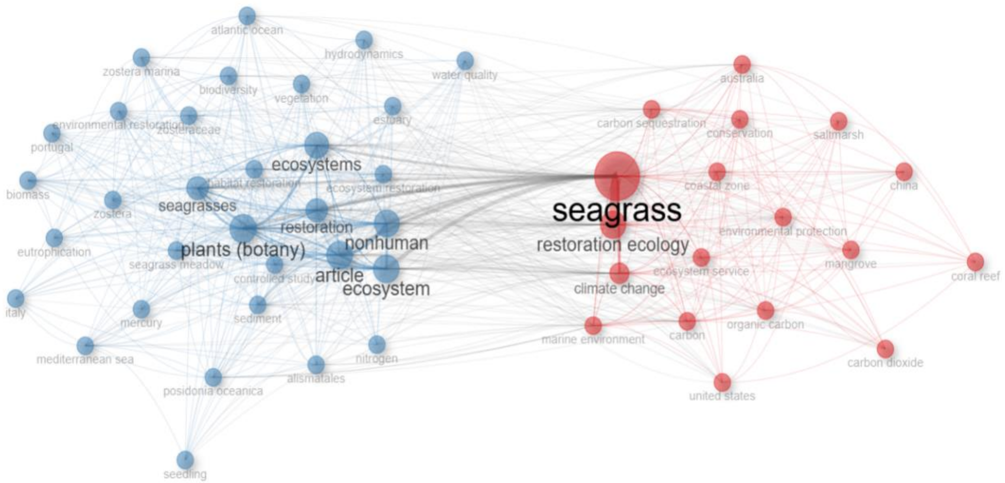

Figure 2. Co-occurrence network illustrating the close relationship between the keywords "seagrass" and "restoration ecology," highlighting one of the central themes in seagrass research.

Terms such as "carbon dioxide," "conservation of natural resources," and "blue carbon" have a high frequency, reflecting the focus on climate change mitigation through blue carbon. Research on "restoration ecology" and "climate change" shows increased attention to ecosystem restoration to address global environmental impacts. In addition, "*Zostera marina*" and "transplantation" indicate specific research activities related to seagrass restoration. This pattern aligns with studies like Lovelock et al. (2023), which emphasized the significance of blue carbon accounting models (BlueCAM) for forecasting greenhouse gas emissions resulting from coastal ecosystem restoration, as well as research by Tan et al. (2023), who evaluated the effectiveness of seed- and shoot-based restoration techniques for the seagrass *Zostera muelleri*. **Figure 3** illustrates the worldwide growth of research on coastal ecosystems as nature-based approaches for addressing climate change and conserving natural resources.

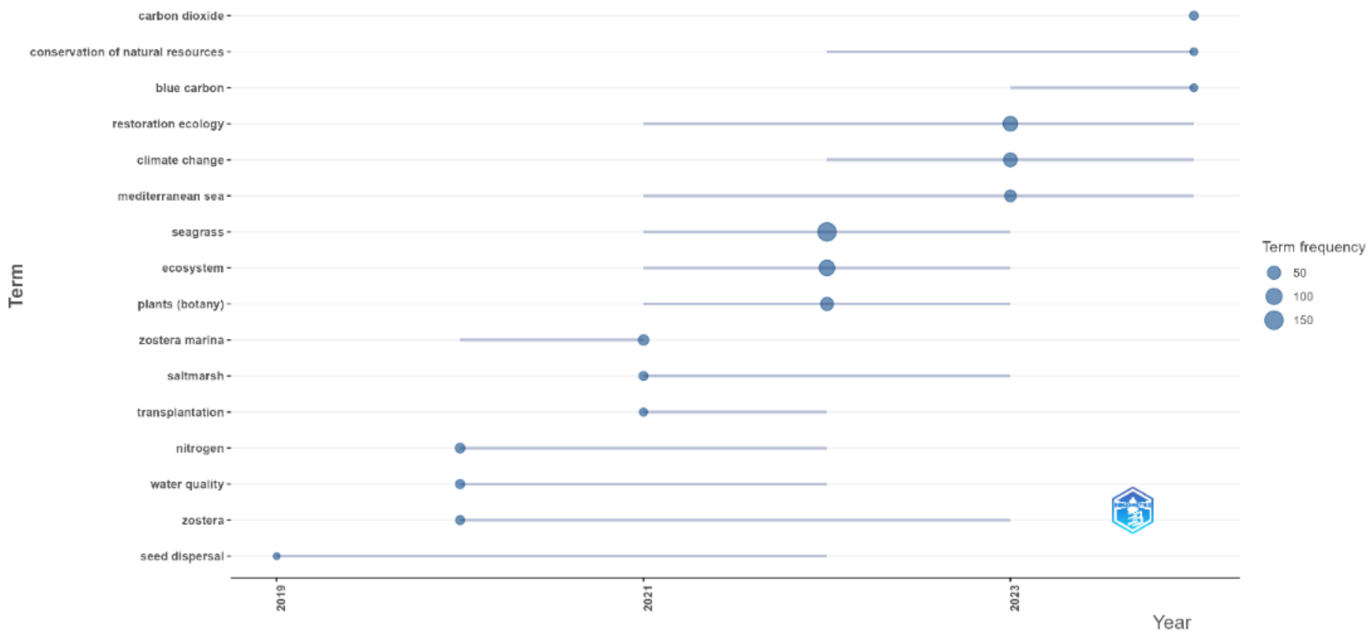

Figure 3. The global growth of research on coastal ecosystems focused on nature-based approaches. These studies emphasize the role of coastal ecosystems in addressing climate change challenges and conserving natural resources.

Publication trends relevant to ecosystem restoration include seagrass beds (**Figure 4**). Seagrass restoration, as an important part of marine ecosystem rehabilitation, is receiving increasing attention, reflected by the growth in publications, especially in journals such as Frontiers in Marine Science and Marine Environmental Research. This increase shows the focus of research on developing methods to restore seagrass meadows, which have an important role in climate change mitigation, providing habitat for marine biota, and shoreline protection. The graph in **Figure 4** indicates that seagrass restoration is becoming a priority in global scientific discussions related to marine environment sustainability.

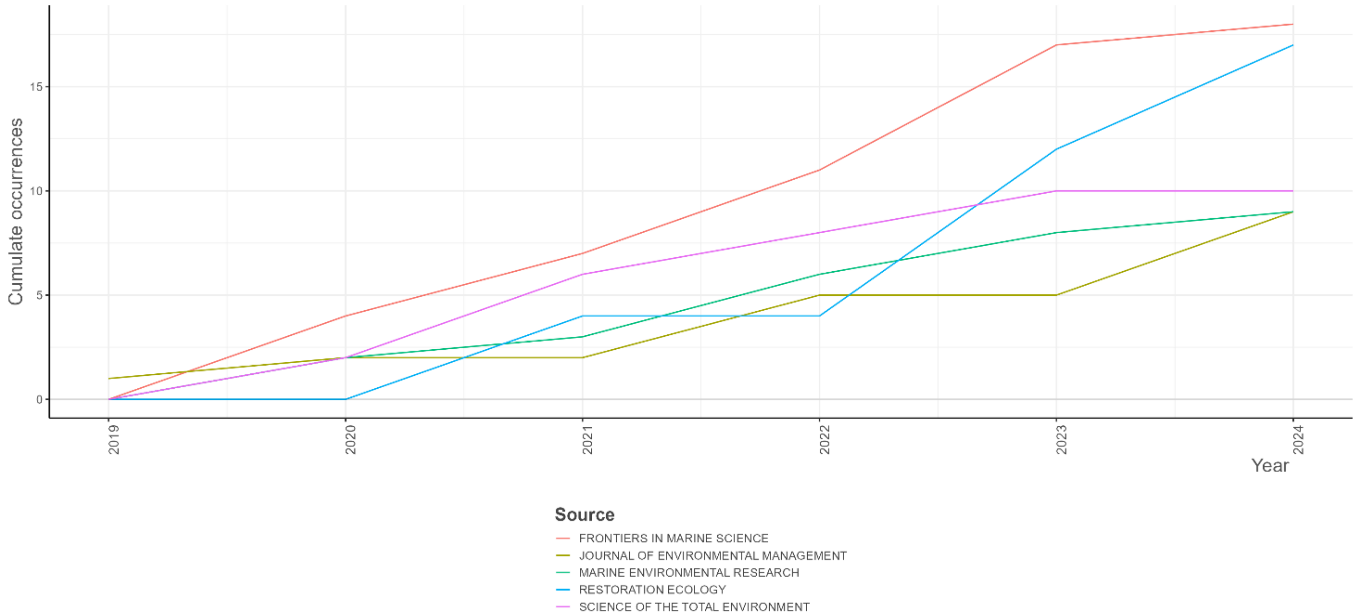

Figure 4. The increasing emphasis on seagrass restoration in global scientific research. This trend reflects its growing importance in discussions on marine environmental sustainability.

These seagrass studies show the important role of international collaboration in environmental conservation. The significant role of various institutions in publishing scientific research is evident, for example, through the University of Groningen's work on seed-based restoration in the Wadden Sea (Govers et al., 2022), the development of blue carbon methods by Deakin University and the study of salinity impacts on seagrasses by Radboud University (Van Katwijk et al., 2023). In addition, The University of Queensland focuses on climate change mitigation through blue carbon accumulation (Research Computing Centre, 2025), while The University of Western Australia integrates traditional knowledge in seagrass restoration (WA Parks Foundation, 2021).

Global collaboration patterns in research show that some countries are already active in international collaboration, and others focus on local research. This is depicted in **Figure 5**, which categorizes the number of research documents by corresponding author countries into two types of collaboration: Single Country Publications (SCP) and Multiple Country Publications (MCP). Australia has the highest number of documents, with a predominance of MCP publications, reflecting the strength of international collaboration. **Figure 6** is an international collaboration map highlighting Australia's collaborative relationships with countries worldwide. Australia is shown as the center of the network in dark blue, while other connected countries are represented in light blue. The connecting lines show the connections between countries, including cooperation in research, trade, education, or diplomacy. The network covers global regions, including North America, Europe, Asia, and Oceania, reflecting Australian collaboration's broad, transcontinental scope. The thickness of the lines or several connections can also indicate the intensity or level of interaction with a particular country. This map illustrates Australia's strategic position in global international relations. In contrast, countries such as Italy, the UK, and China are more heavily involved in the SCP, indicating a focus on domestic research. Indonesia is not included in the list of countries featured in the analysis of the number of research documents by collaboration type (SCP and MCP). This suggests that the contribution of research publications from Indonesia, particularly in international or domestic collaborations, is likely to be low compared to other countries.

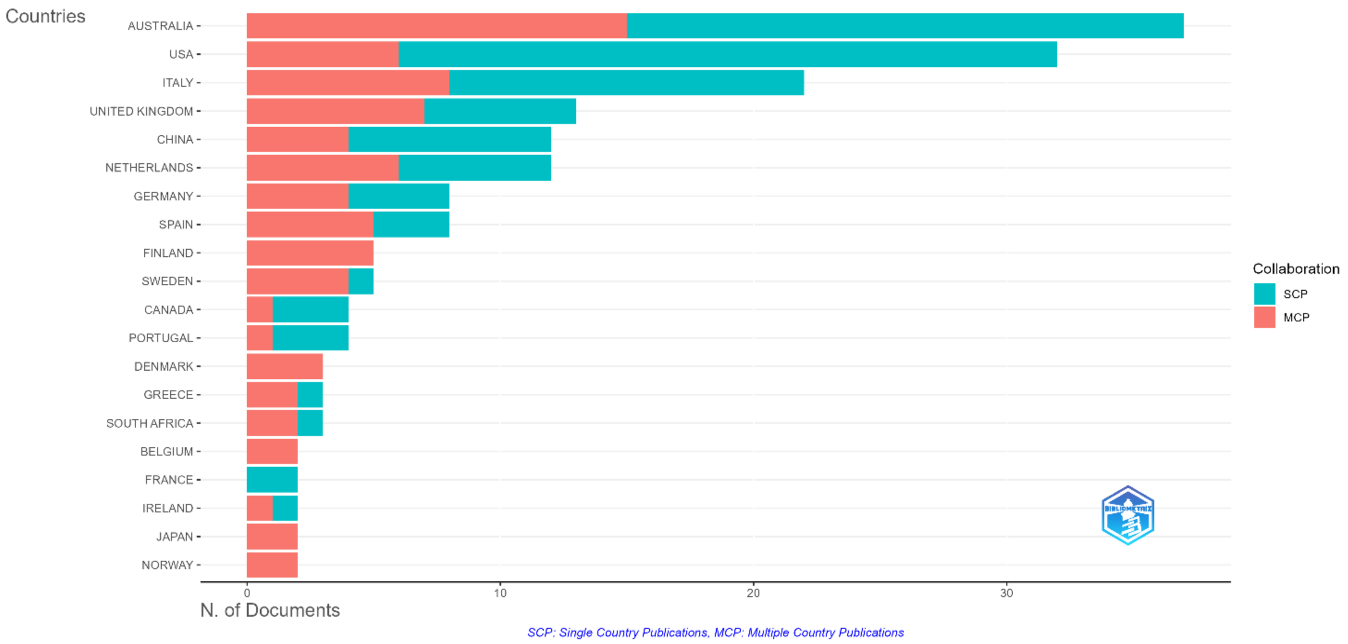

Figure 5. The figure categorizes research documents by corresponding author countries into Single Country Publications (SCP) and Multiple Country Publications (MCP). Australia records the highest number of publications, with MCP dominating, indicating strong international research collaboration.

To help understand the research priorities and development potential of the search keywords, the coastal ecosystem restoration research themes were analyzed based on relevance (centrality) and development (density), illustrated in a thematic map (**Figure 6**). Motor Themes such as seagrass, plants (botany), and ecosystems are at the center of innovation, with a focus on seagrass restoration and climate change mitigation through blue carbon, as shown in the research of Catherine E. Lovelock et al. (2023) using the BlueCAM model in Australia. Niche Themes, such as coastal zone and ecosystem services, highlighted in-depth studies of coastal ecosystem connectivity. For example, Stuart et al. (2023) found the importance of seascape connectivity for coral reef restoration. Basic Themes, such as restoration ecology and seagrass meadows, indicate the need for further development, such as Tan et al. (2023), who found shoot transplantation more effective than seed-based methods in Victoria, Australia. Meanwhile, Emerging or Declining Themes, such as the Mediterranean Sea and Posidonia Oceanica, highlight regional species conservation, for example, Comte et al. (2024), who developed the Bas-Carbone Label scheme for seagrass conservation in the Mediterranean as voluntary carbon credits. In conclusion, this map provides strategic guidance for prioritizing key research themes while identifying development opportunities in coastal ecosystem restoration.

Bibliometric analysis shows that seagrass restoration is a central theme of global research, focusing on climate change mitigation through blue carbon, shoreline protection, and provision of marine biota habitat. Seagrasses play an ecologically important role as carbon sinks, sediment stabilizers, and nursery areas for marine biota, and have significant economic benefits. Publication trends are increasing in journals such as Frontiers in Marine Science, reflecting attention to restoration techniques such as shoot transplantation. Australia is central to international collaboration in this research, while Indonesia has yet to contribute significantly. Key research themes include coastal ecosystem restoration innovations and regional species conservation, such as in the Mediterranean Sea. This highlights the vital role of seagrass restoration in promoting the sustainability of marine ecosystems at the local and global levels.

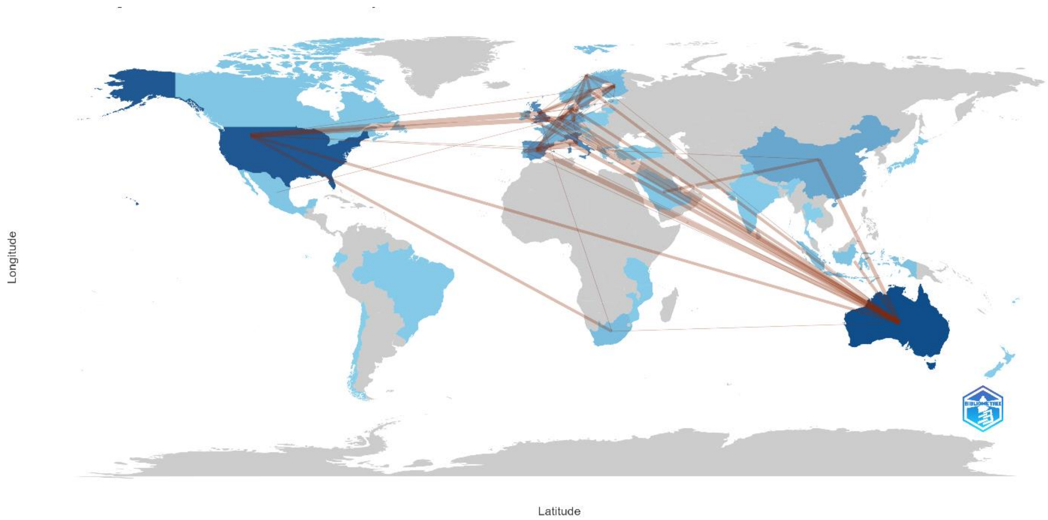

Figure 6. International collaboration network highlighting Australia's partnerships with countries worldwide. Australia appears as the central node, while the connecting lines represent collaborative links across research, education, trade, and diplomatic activities.

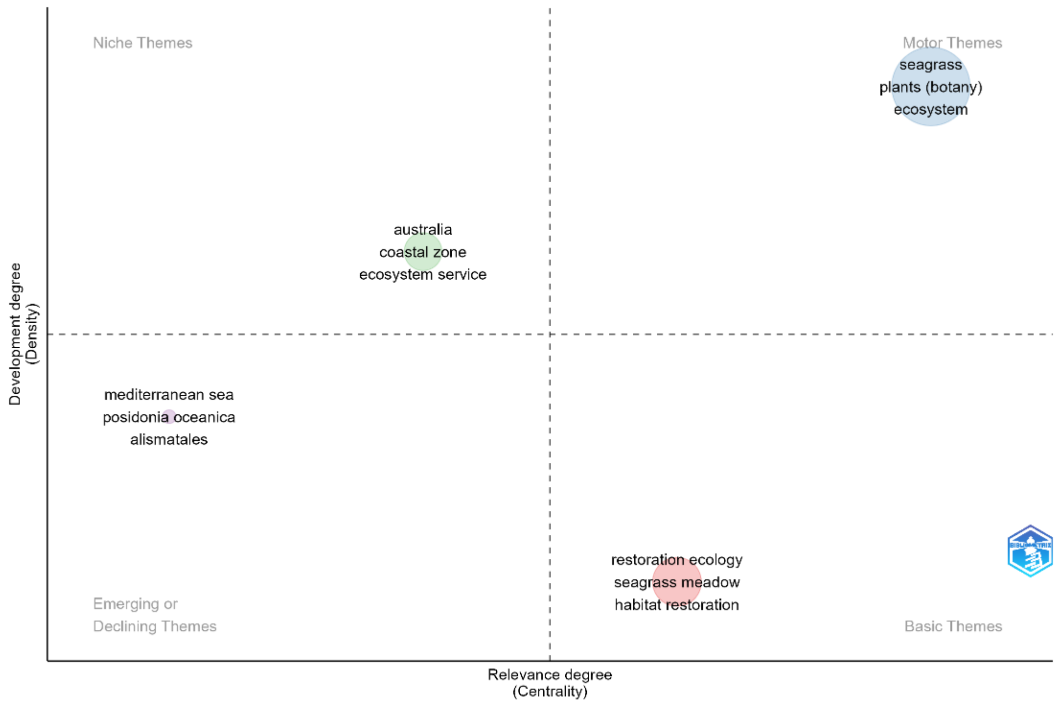

Figure 7. Thematic Map of Bibliometric Analysis.

3.2. Stages of Seagrass Meadow Restoration

Seagrass restoration is an effort to restore damaged seagrass ecosystems through replanting as a natural solution to climate change and biodiversity conservation. The restoration process consists of four main stages, namely: (1) feasibility study and site planning through literature review and field survey to determine the optimal location based on physical environmental conditions; (2) project design, which includes the selection of restoration methods and the development of a monitoring plan; (3) pre-restoration tasks such as seed or sprout collection from donor sites and method feasibility testing; and (4) implementation and monitoring, where restoration is carried out using seed-based or transplantation methods, followed by monitoring of ecological parameters and evaluation of success by comparing it to donor site conditions (Garmendia et al., 2023).

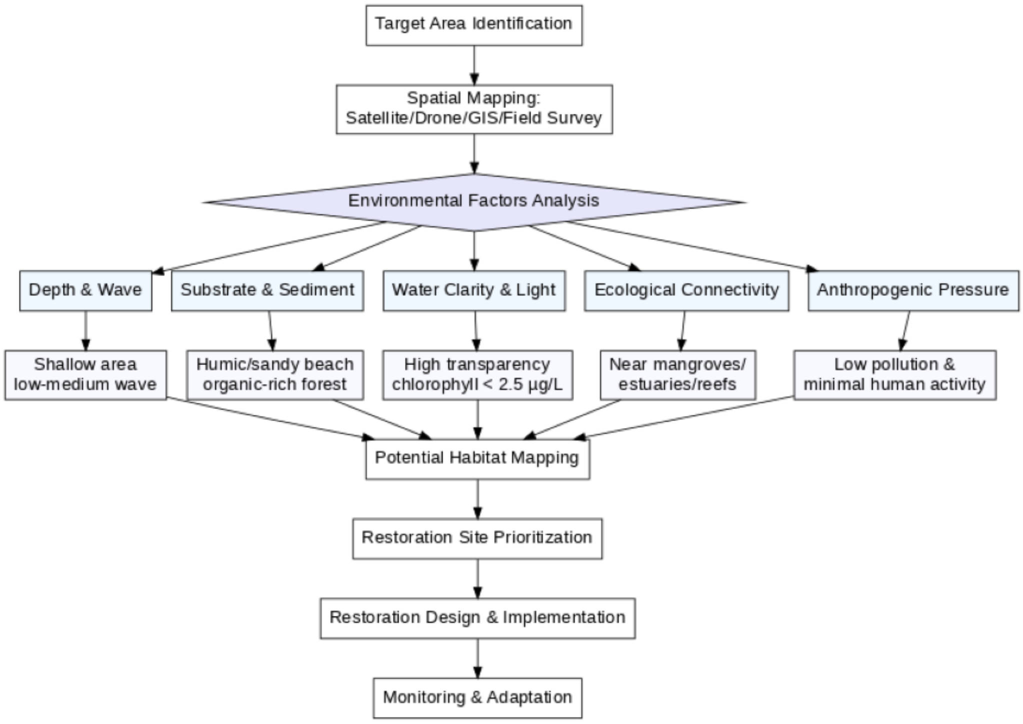

Figure 8. Stages of the Seagrass Restoration Method

3.3. Mapping Potential Habitats for Seagrass Restoration

Seagrass restoration represents a targeted approach to rehabilitating degraded coastal ecosystems due to human activities and environmental pressures. In the last two decades, the decline in the extent and quality of seagrass meadows has drawn global attention, mainly because of their vital function as providers of ecosystem services, including blue carbon sequestration, abrasion buffering, biodiversity support, as well as providers of biological resources for coastal communities. However, the success of seagrass restoration is primarily determined by proper site selection. This selection requires thoroughly mapping potential habitats, considering various ecological, biophysical, and spatial factors. With a systematic and data-driven approach, this mapping can direct restoration interventions to sites that are not only environmentally suitable but also have a high potential for sustainable recovery.

Spatial aspects play an important role in seagrass restoration as they identify optimal sites for intervention, analyze habitat connectivity, and monitor restoration success. Findings by Stuart et al. (2023) indicate that spatial graph modeling can identify the most effective nutrient flow routes among interconnected coastal ecosystems, such as mangroves, seagrasses, and coral reefs, thereby enhancing restoration efforts in areas with high habitat connectivity. In addition, Aiken et al. (2023) used spatial connectivity analysis to determine restoration sites that can support maximum seagrass population growth through propagule dynamics between patches. McHenry et al. (2023) also emphasized the importance of satellite data and GIS in identifying organic carbon distribution patterns in seagrass meadows, which supports restoration strategies based on carbon storage capacity. Thus, spatial aspects become an essential tool in seagrass restoration to ensure ecological and functional sustainability of the ecosystem.

In the literature, various kinds of spatial data support mapping, distribution analysis, and evaluation of seagrass ecosystems. The spatial data consists of optical, sonar, RADAR, and field measurements. Optical data is obtained from visible and infrared light-based remote sensing through satellite imagery, drones, or underwater cameras. Sonar data is obtained through acoustic technologies such as multibeam sonar and echosounder to map the seafloor and underwater vegetation. RADAR data is obtained from active sensor-type remote sensing, such as SRTM and InSAR. **Table 1** shows the spatial data used in the literature, where combining these data is key to sustainable seagrass restoration and conservation (Rende et al., 2022; Xu et al., 2021).

Table 1. The spatial data sources reported in the literature, highlighting the importance of integrating multiple data types to support sustainable seagrass restoration and conservation.

Data	Sensor/Field Data	Usage	Advantages	Disadvantages
Landsat	optical	Long-term seagrass cover	Suitable for mapping large areas	Dependent on water brightness and depth, less effective in turbid waters
Sentinel-2	optical	Large-scale mapping		
WorldView-3	optical	Seagrass Identification		
SPOT-6	optical	Seagrass Identification		
High-resolution Aerial Photos	optical	Monitoring seagrass transplants (Rende et al., 2022; Ventura et al., 2022)	Temporal change detection	Water column correction required to improve accuracy in shallow waters
Orthophoto Mosaic	optical	Orthophoto mosaic for seagrass cover change detection (Ventura et al., 2022)	Analysis of vegetation health through spectral indices	
SGI	optical	Automatic classification of seagrass		
Multibeam Sonar	Sonar / Acoustics	Mapping seafloor topography and seagrass distribution (Calvo et al., 2021)	Effective in turbid or deep waters, able to detect subsurface structures (Calvo et al., 2021; Rende et al., 2022)	High cost and complexity of data analysis (Xu et al., 2021)
		Side Scan Sonar (SSS) for seagrass structure identification (Rende et al., 2022)		
Echosounder	Sonar / Acoustics	BioSonics MX for satellite data validation and seagrass biomass estimation (Xu et al., 2021)		
		High frequency (200 kHz) acoustic technology for measuring seagrass density (Unsworth et al., 2019)		
SRTM	RADAR	Analysis of shoreline elevation and hydrodynamics in estuaries (Barcelona et al., 2021)	Not affected by weather or darkness, suitable for topographic mapping	Lower spatial resolution compared to optical data (Le Fur et al., 2019)
InSAR	RADAR	Potential for monitoring sediment elevation changes in the tidal zone, though not yet widely applied in seagrass studies (Le Fur et al., 2019)		
GNSS survey (GPS	Field Survey	Spatial data validation and accuracy (Donaher	High accuracy and location specific	Time and human resource costs

Data	Sensor/Field Data	Usage	Advantages	Disadvantages
Geodetik, RTK)		et al., 2021; Muench et al., 2019)		
Direct sampling	Field Survey	Measurement of biomass, shoot density, and sediment chemistry parameters (Aoki et al., 2021; Lapointe et al., 2020) Post-transplant seagrass rhizosphere microbial community analysis (Wong et al., 2021)		

Notes: SGI: Seagrass Index, GNSS: Global Navigation Satellite System, GPS: Global Positionong System, InSAR: Interferometric Synthetic Aperture Radar, RADAR: Radio Detection and Ranging, RTK: Real-Time Kinematic, SRTM: Shuttle Radar Topography Mission

Conceptually, mapping potential habitats for seagrass restoration aims to identify coastal areas that have characteristics that support seagrass growth and regeneration. This approach is based on the understanding that seagrass beds only grow in certain environmental conditions, such as shallow waters with sufficient light penetration, stable seabed substrate, and good water quality. Therefore, water depth, clarity, currents and waves, and substrate type are key considerations in site suitability analysis. Ferretto et al. (2023) showed that *Posidonia australis* seagrass transplantation in Shoal Bay, Australia, was only successful in sites with soft sand substrates, optimal depths between two and four meters, and high illumination levels. Sites exposed to strong currents and waves showed a higher failure rate as the plants could not establish stable roots.

A spatial approach is essential to support the mapping process. Remote sensing and GIS technologies facilitate the comprehensive and effective integration and analysis of diverse environmental variables across large areas. Bathymetry data, for example, is instrumental in identifying suitable depth zones for seagrass growth. The ideal water depth depends on the seagrass species, but generally ranges from one to five meters, where light can still penetrate the seafloor. Bathymetry data sources can come from multibeam sonar surveys, bathymetry LIDAR mapping, or global databases such as GEBCO. Seafloor substrate type, which affects the ability of seagrasses to take root and grow stably, can be obtained from side-scan sonar images or marine sediment maps. Sandy or muddy substrates tend to be more favorable to seagrasses than rocky or too soft substrates such as fine mud.

Another key element influencing seagrass photosynthesis is water quality. Optical satellite data from platforms like Sentinel-2 or Landsat 8 can evaluate water transparency by measuring the light attenuation coefficient (Kd) and turbidity. These satellite images also make it possible to track changes in coastal environmental conditions over time, supporting monitoring seagrass habitat decline and recovery. Integration of oceanographic data, such as ocean currents and waves, is also important, as seagrass plants in the early stages of transplantation are vulnerable to physical disturbances. Numerical models such as MIKE21 or observational data from buoys can help map the dynamics of currents and wave exposure in coastal areas, enabling site selection with sufficient hydrodynamic stability.

In addition to biophysical factors, ecosystem connectivity approaches are beginning to be applied in seagrass restoration planning. Stuart et al. (2023) demonstrated that restoration areas within networks of connected habitats, such as those linking seagrass beds, coral reefs, and mangroves, are more likely to enhance biodiversity and support ecological functions across multiple ecosystems. Using a graph-based spatial model, the study mapped spatial relationships between coastal habitats and identified strategic nodes worth prioritizing for restoration. This connectivity is important because it supports the movement of organisms and the natural dispersal of seagrass seeds, and it maintains important ecological processes at the seascape scale.

Conversely, identifying potential habitats has become increasingly important for climate change mitigation efforts. Seagrass meadows act as efficient long-term carbon sinks and are therefore included in blue carbon accounting schemes. Lovelock et al. (2023) showed that using the Blue Carbon Accounting Model (BlueCAM), seagrass restoration areas can be identified based on potential carbon storage in sediment and biomass. The model integrates data on carbon stocks, land use change, and environmental pressures to create a map of restoration priorities based on carbon mitigation capacity. This approach makes mapping restoration habitats ecological and strategic in supporting national and international climate policies.

All data is processed through a GIS system with a multi-criteria analysis approach. Methods such as the Analytical Hierarchy Process (AHP) or weighted overlay allow for incorporating various parameters with specific weights tailored to the local context and conservation needs. Platforms such as QGIS and Google Earth Engine (GEE) make it easier to conduct this analysis quickly and accurately. Furthermore, engaging local communities and decision-makers in the mapping process can enhance restoration initiatives' acceptance and long-term success, particularly when these efforts are integrated with coastal zoning and marine spatial planning.

Mapping potential habitats for seagrass meadow restoration is thus an important multidimensional and interdisciplinary step. This approach considers ecological suitability and integrates spatial dynamics, ecosystem function, and the urgency of climate change. Utilizing accurate spatial data and thorough analysis is crucial for ensuring the lasting effectiveness of restoration efforts and enhancing seagrasses' contribution to coastal resilience against diverse environmental challenges.

3.4. Physical Parameters in Seagrass Restoration

Besides spatial considerations, physical parameters are also crucial in seagrass restoration because they help identify the most suitable locations for seagrass survival and optimal ecosystem functioning. After establishing the coordinates of the study area, the suitability of environmental parameters for seagrass transplantation was evaluated using the Preliminary Transplant Suitability Index (PTSI) described by Short and Coles (2001).

Table 2. Physical Environmental Parameters

Parameter	Description
Light	Light has a minimum intensity for photosynthesis of 85 µE-2s-1, and a maximum intensity of 485 µE-2s-1 (Orth et al., 2006).
Depth	Seagrasses can grow naturally at depths < 2 m and with additional modifications at depths of 2-4 m (Flindt et al., 2022).
Sediment	Seagrasses have higher stability in fine sediments than in coarse sediments (Nugraha et al., 2022).
pH	pH values below 8 cause chlorophyll concentrations and photosynthetic rates to be lower than normal pH (Nugraha et al., 2021).
Temperature	Low temperatures (<20°C) can inhibit seagrass growth by reducing the rate of photosynthesis. Meanwhile, high temperatures (>30°C) can cause thermal stress that can trigger cell death (Orth et al., 2006).
Salinity	Low salinity causes stress in seagrasses that can inhibit photosynthesis (Koch et al., 2007). High salinity causes a decrease in seagrass reproduction (Touchette, 2007).
Wave	High current waves can wash away seagrass seeds (Rustam et al., 2014). Planting with the transplantation method is more resistant to currents (Harnianti et al., 2016).
Nutrient	Delicate substrates are richer in nutrients that support faster leaf growth, while coarse substrates are lower in nutrients, so seagrass leaf growth is smaller (Sahertian et al., 2017).

In 177 literature reviews, several parameters are most influential in seagrass restoration, including hydrodynamics that affect sedimentation stability, and depth that affects the level of light availability for seagrasses for photosynthesis. In Ambo-Rappe (2022) study using a seed-based approach, it was shown that variations in sediment and hydrodynamic exposure (wave current strength) determine seed survival rates and seagrass seedling establishment. Fine sand sediments with moderate wave exposure showed 64% of seeds survived to become seedlings. Whereas coarse sand substrate with high wave exposure causes <2% of seeds to survive due to seeds being easily washed away before the formation of roots on the substrate, additional techniques are needed using physical barriers such as nets or planting developed seedlings.

Furthermore, a study by S. Yue et al. (2020) utilizing transplantation methods found that light availability is the primary factor influencing seagrass's depth range, growth, and spatial distribution. Transplanted shoots positioned at depths of 2 meters or less can survive throughout their annual growth period. Meanwhile, shoots transplanted at a depth of >2 meters will continue to decrease in density and even experience death along with the increase in depth, which causes an increase in the level of light deprivation. Therefore, determining the optimal depth and monitoring water quality are important to ensure light availability. Therefore, physical parameters are key to seagrass restoration and maintaining sustainable ecosystem functions.

3.5. Innovative Methods in Seagrass Restoration

In the 177 literature reviews, researchers have tested various restoration techniques, achieving differing degrees of success. Widely adopted restoration world-wide fall into two principal categories: transplantation and seed-based strategies. The shoot transplantation method is the most widely used because it can establish new habitats quickly, although the success rate varies depending on environmental conditions (Orth and Heck, 2023). In contrast, seed-based approaches offer greater genetic diversity than transplantation, but they present more difficulties during the initial phases of restoration (Maulidiyah et al., 2024). Combining both methods is recommended (Cronau et al., 2023). Table 3 presents some of the results of seagrass restoration research using different combined methods to show reasonable success rates.

Table 3. Innovative Methods for Seagrass Restoration

Author	Location	Method	Description	Result
Scapin et al. (2019)	Venice lagoon, North Adriatic Sea, Italy	Sods Transplantation	Sods containing *Zostera marina* and *Zostera noltei*, their substrates, and rhizomes, were relocated from donor areas to the designated transplant sites.	Recovery of seagrass vegetation and nekton communities at some sites within 2-3 years.
Oliveira et al (2023)	Laranjo Bay, Ria de Aveiro, Portugal	Sods Transplantation	Sods consisting of *Zostera noltei* seagrass and their substrate, along with rhizomes, were moved from donor locations to the intended transplant sites.	Reduction of mercury concentration by 40% in the upper sediment layer. Recovery of transplant sites within 3 months.
Crespo et al (2023)	Vanesia Lagoon, Goro Lagoon, and Fattibello Pool, Italy	Sods Transplantation	Sods containing *Zostera noltei* seagrass and their substrate, along with rhizomes, were relocated from donor sites to nearby transplant locations, which were situated close to each other.	After one year, the transplanted seagrass area connected with the naturally occurring meadow.
Sfriso et al (2023)	Vanesia Lagoon, Goro Lagoon, and Fattibello	Sods Transplantation	Sods, which include seagrass plants and their substrate, along	Establishment of a new habitat after 1 year with up to 95%

Author	Location	Method	Description	Result
	Pool, Italy		with rhizomes, were relocated from donor to target transplant sites, and the seagrass species selected for planting varied by season: *Zostera marina* was transplanted in autumn, *Cymodocea nodosa* in late spring, and *Ruppia cirrhosa* in summer.	survival rate. Choosing the right transplantation site and season increases restoration success.
Beheshti et al (2022)	Elkhorn Slough, California	Plot Transplantation	Directly transplanted seagrass *Zostera Marina* in 117 small plots (2,340 shoots) measuring 0.25 m^2.	Seagrass area increased by ~8,500% (from 29 m^2 to 2,513 m^2). Ecosystem structure and function improved rapidly, approaching natural seagrass meadow conditions within three years.
Mourato et al. (2023)	Professor Luiz Saldanha Marine Park, Arrábida Natural Park, Portugal.	Checkers Transplantation	Transplanting seagrass *Zostera Marina* and *Zostera Noltei* in a checkerboard pattern.	Increase seagrass density and cover within 6 months.
Boulenger et al (2024)	Calvi Bay, West Corsica, France	Natural Fragment-Based Transplantation	Transplanting *Posidonia oceanica* seagrass shoots from natural fragments dislodged by storms and from natural erosion areas.	Seagrass survival rate reaches 90% within one year.
Lange et al. (2022)	Horsens Fjord, Denmark	Modular Transplantation	Transplanting seagrass *Zostera marina* in a checkerboard pattern with two planting methods (V-stake and weighted shoots) and protection using nets and crab traps.	After two years, seagrass density increased by 70 times, the vegetated area expanded by 30%, and sediment carbon and nutrient levels rose significantly.
Ventura et al. (2022)	Giglio Island, Central Tyrrhenian Sea, Italy	Grid Transplantation	*Posidonia oceanica* seagrass fragments were transplanted using iron pegs on the marine substrate with a 5x5 meter grid area to facilitate data management.	Seagrass cover increased from 10%. Changes in seafloor elevation up to +20 cm showed fragment growth. Seafloor morphological

Author	Location	Method	Description	Result
				complexity increased (VRM from 0.23 to 0.42).
Piazzi et al. (2021)	Capo Carbonara Marine Protected Area (MPA), Southern Sardinia, Italy Elba Island, Tuscan Islands, Italy	Biodegradable Structure	Biodegradable mats made of coconut fibers with steel mesh were used to stabilize *Posidonia oceanica* seagrass shoots on the substrate as well as trap drifting natural shoots.	92.5% of the transplant plots survived after three years. The shoot survival rate reached 60%.
Robello et al (2023)	Ligurian Sea, Italy	Biodegradable Structure	Biodegradable mats made of coconut fibers with steel mesh were used to stabilize *Posidonia oceanica* seagrass shoots on the substrate as well as trap drifting natural shoots.	Seagrass survival rate reaches 90%.
Pansini et al (2024)	Western Mediterranean Sea (Italy and France)	Biodegradable Structure	The biodegradable mat was installed on the dead matte substrate (rhizoma and root residues from dead seagrasses) using iron stakes, then planted with *Posidonia Oceanica* seagrass shoots.	Seagrass growth rate reached the same level as natural seagrass after 4 years.
van der Heide et al. (2021)	Finland, Sweden, England, and United State (Puget Sound).	Biodegradable Structure	Using biodegradable structures to mimic natural ecosystem characteristics in seagrass *Zostera Marina.*	Underground structures mimicking dense roots improve seagrass survival and growth in sites with high hydrodynamics.
Flindt et al. (2022)	Odense Fjord, Denmark	Sand-capping	Cover muddy sediments using a 10 cm thick layer of sand to increase sediment stability and reduce resuspension in *Zostera marina* seagrass.	Increased erosion resistance by 300%. Resuspension significantly reduced by 96%. Benthic light conditions improved by 22% at 2 m depth, supporting seagrass habitat recovery.
Sullivan et al. (2022)	Port Phillip Bay, Victoria, Australia.	Chemical Seed Priming	Treatment of seagrass Heterozostera Nigricaulis seeds with copper sulfate solution (0 ppm, 0.2	Copper sulfate concentration of 2.0 ppm increased germination by 17.2%. A total of 15% of the

Author	Location	Method	Description	Result
			ppm, 2.0 ppm) to improve germination and seedling growth.	germinated seeds developed into seedlings with photosynthetic tissues.
Pazzaglia et al. (2022)	Marsala (West Sicilia), Spanyol (Murcia), and laboratory facilities at Torretta Granitola.	Thermo-priming Seeding	Seagrass *Posidonia Oceanica* seedlings were pretreated (30.5°C) before facing extreme temperatures (32°C) to improve heat tolerance.	Seedlings had higher heat tolerance, with better photosynthesis rates, maintained carbon balance, faster growth, and higher expression of stress and epigenetic genes.
Villanueva et al. (2022)	Ludwig-Franzius Institute, Leibniz Universität Hannover, Germany	Artificial Seagrass	The use of artificial seagrass (ASG) to create protection from currents increases the chances of successful natural seagrass restoration.	Artificial seagrasses can reduce current velocities by up to 70% and create a protection zone up to 10 times the height of the seagrass canopy.
Gräfnings et al. (2023)	Wadden Sea, Netherlands	Dispenser Injection Seeding (DIS)	Seagrass *Zostera Marin*a seeds were injected into the sediment to prevent seed drift and increase direct contact with the substrate to enhance germination.	Efficiency was 11.4% at 4 m depth, compared to surface seeding with an efficiency of 0.2%. After one season 57 plants/m² were recorded.
Liu et al. (2023)	Rongcheng City, Shandong Province, northern China	Stone Anchored Seeding	*Zostera Marina* seagrass shoots are tied to a rock using biodegradable rope to remain in the water column until the seeds mature and fall naturally to the seafloor.	Each shoot releases about 50 seeds with a germination rate of 25-30%, which is equivalent to natural seagrass beds.
Unsworth et al. (2019)	Coastal waters in Wales, UK, including Porthdinllaen, Helford River, Dale, Longoar, and Freshwater East	Bags of Seagrass Seeds Line (BoSSLine)	Hessian cloth bags containing 100 *Zostera Marina* seagrass seeds were tied to ropes anchored to the seabed, allowing the seeds to be naturally submerged and protected from predation.	A total of 94% of the bags produced shoots. About 2.37 shoots grew per bag after 10 months, with a shoot length of 206 -293 mm.
Unsworth et al (2024)	Wales, England	Planting Seeds in Hessian Bags	Planting seagrass *Zostera Marina* seeds using hessian bags with two variations:	Shoot density increased by 7-13 times. Seeds in buried

Author	Location	Method	Description	Result
			- Hessian bags are buried in the sediment. - Hessian bags are placed on the sediment surface. Control: Seeds were planted directly in the sediment furrow without bags.	bags had the highest shoot emergence rate (32%) compared to the control (3%).
Alvarez, A. (2019)	Theoretical study	Sediment-Integrated Seeding	Seagrass seeds of *Zostera marina* and *Posidonia oceanica* were mixed with fine sediments to improve seed retention in areas with high current strength or unstable substrate.	Seed retention on the substrate increased up to 45%.
Le Fur et al. (2019)	Mediterranean coastal lagoons in France, including the Gulf of Lion and the eastern coast of Corsica	Buoy Deployed Seeding	Seagrass *Zostera marina* seeds were planted in PVC pots and suspended using a floating raft at 1-6 m depth to control seed germination according to light requirements.	At depths of ≤2 m, 40% of the seeds germinated, but this percentage decreased significantly at depths >2 m due to light limitation.
Balestri et al. (2019)	Italy	Bio-container Seedling	Using bio-containers made from seagrass fibers and biodegradable polymers as planting containers, compared to conventional plastic containers, to compare the growth of seagrass *Zostera Noltei*.	Seagrass growth using Bio-containers was better than plastic containers, with 80% of seagrass successfully growing after 6 months in the field.
Zhang et al. (2021)	Outer Banks, North Carolina, United States	Bio-encapsulated Seeding	Planting seagrass *Zostera marina* seeds with and without adding mussels to assess their effect on seagrass growth and biomass.	Adding mussels enhanced seagrass growth from seed, with a 5-fold increase in patch area and a 10-fold increase in seagrass underground biomass compared to no mussels.
Ambo-Rappe (2022)	Indonesia (Coastal Waters)	Seed-Based Restoration	Seeds of *Enhalus acoroides* were planted in various substrate types and hydrodynamic conditions to assess germination, growth,	Restoration success was highly dependent on substrate suitability and moderate currents, leading to greater

Author	Location	Method	Description	Result
			and survival rates.	establishment and survival of seagrass.
Ambo-Rappe (2019)	Indonesia (Marine Waters)	Generative & Vegetative Combo	Seeds of *Enhalus acoroides* were germinated and planted with varying adult plant densities for protection in high-energy environments.	High-density co-planting with adult transplants led to higher six-month survival rates for seedlings.
Nugraha et al. (2021)	Indonesia (Field Sites)	Bamboo Box Seed Protection	*E. acoroides* seeds were planted inside bamboo boxes in the field to shield them from hydrodynamic forces and predation and to monitor seedling growth.	Bamboo boxes increased survival rates and were effective for protecting seeds in generative restoration.
Nugraha et al. (2022)	Bintan Island, Indonesia	Seed-Based Restoration	Preliminary study using Enhalus acoroides seedlings transplanted into Bintan Island's tropical seagrass ecosystem, monitoring survival and growth.	Around 20% seedling survival; environmental factors affected restoration outcome.

3.6. Mathematical Approach to Seagrass Restoration

In addition to spatial aspects and physical parameters, mathematical approaches, in this case, statistical models and machine learning algorithms, play an important role in seagrass restoration because they can be used to evaluate the success of seagrass restoration. Statistical models, such as Species Distribution Models (SDMs), can be used to forecast optimal seagrass restoration sites. After seagrass restoration, they can also be used as an evaluation tool to analyze relationships between factors that affect seagrass growth. The predicted results can inform the evaluation of seagrass restoration success (Orth et al., 2020). Machine learning algorithms can classify seagrass species and predict the percentage of seagrass cover based on features obtained from spatial data. However, machine learning algorithms cannot analyze relationships between variables or features. Several machine learning algorithms, such as Support Vector Machine and Random Forest, are used in the reviewed literature. In the 177 literature reviews, several statistical models and analyses are used to analyze the success of seagrass restoration. Table 4 presents some of the statistical models used in the literature.

Table 4. Statistical Models

Statistical Model	Purpose	Advantages	Disadvantages
Double-Hurdle Model	Predict whether seagrasses grow successfully or not. Then, if it grows, how much growth or area (Unsworth et al., 2024).	1. Able to handle null data. 2. The factors that affect seagrass's initial emergence and growth after emergence can be seen separately.	1. Assumes factors affecting 2 stages separately, when often the stages are not separate. 2. A large amount of data is required for both stages to be adequately estimated.
Generalized Linear Model	To test, explain, and predict relationships between	1. Suitable for binary data.	1. Does not accommodate

Statistical Model	Purpose	Advantages	Disadvantages
(GLM)	ecological variables and restoration outcomes	2. GLM supports many distributions, not just normal. 3. This model can predict the likelihood of transplant success.	random effects. 2. The model may become unstable if there is a strong relationship between environmental variables. 3. GLM assumes a linear relationship, which is not always realistic in complex ecology.
Generalized Linear Mixed Model (GLMM)	Analyze how various environmental factors and biological interactions affect ecosystem restoration success, while accounting for natural variability between sites or experimental units that cannot be directly controlled.	1. Accommodates Natural Variability (Random Effects). 2. Suitable for Complex Field Data. 3. Able to model treatment and interaction effects.	1. Fixed GLMM assumes a linear relationship between fixed covariates and response. 2. Random effects often have no direct biological interpretation. 3. Requires large enough data.
Generalized Additive Model (GAM)	Analyzing non-linear relationships of various indicators of seagrass restoration success (Zhang et al., 2021)	1. Capturing Non-linear relationships. 2. GAM does not require the relationship between predictor and response to be a straight line. 3. No need for explicit specification of function shape. 4. Suitable for independent data (no clustering or repetition of measurements) 5. Suitable for complex ecological data.	1. GAM results are in the form of smoothing curves, not producing regression coefficients that are easy to interpret. 2. Risk of overfitting 3. GAM requires more intensive numerical calculations, especially if used in large data or with many predictors.
Generalized Additive Mixed Model (GAMM)	Analyzing the non-linear relationship of various indicators of seagrass restoration success by accounting for random effects (Wong et al., 2021).	1. Captures non-linear relationships. 2. Used when data has a hierarchical structure such as repeated measurements in the same tank (Wong et al., 2021) 3. Suitable for Complex Ecological Data.	1. Large data requirements and risk of overfitting 2. Complexity of Interpretation. 3. GAMM still assumes a certain distribution for the response variable. If the assumptions are not met, the results may be

Statistical Model	Purpose	Advantages	Disadvantages
			biased.

In the literature review, research conducted by Ucko et al (2024) used General Additive Models (GAMs) to understand how the combination of depth, latitude, and season affects seagrass distribution. The model was used to analyze the probability of seagrass presence based on a combination of influencing factors. Wang et al (2021) used the Generalized Additive Mixed Model (GAMM) to examine the effects of light disturbance on seagrass density (shoot density, biomass, leaf sheath length, and rhizoma carbohydrate content). Research conducted by Unsworth et al (2024) used a double-hurdle model to predict the success of germination and growth. In this study, the dependent variable is seagrass germination and growth, while the independent variable is the seed restoration method using hessian bags and compares it with conventional restoration methods.

Gagnon et al (2021) used Generalized Linear Models (GLM) to analyze the effects of nutrient addition and predator exclusion on seagrass biomass. Research by Maulidiyah et al (2024) used the Generalized Linear Mixed Model to analyze seagrass growth based on leaf and root length between treatments. This study evaluated three seed-based restoration techniques: surface sowing, transplanting seedlings, and using hessian bags for planting. Then, Rifai et al (2023) predicted seagrass percent cover and biomass using a machine learning random forest algorithm based on satellite imagery and in situ data.

3.7. A Case Study of Seagrass Restoration in Indonesia: Long Island, Jepara

Panjang Island, located in Jepara Regency, is known to have a relatively extensive and healthy seagrass ecosystem. About 76.75% of its water area is covered by seagrasses, with the dominance of *Enhalus acoroides* species. The high seagrass diversity and favorable environmental conditions make it a potential location for seagrass restoration activities (Pradhana et al., 2021). However, most seagrass areas on Jepara island are degraded due to environmental factors (Ritniasih and Endrawati., 2013). Wulandari et al. (2013) have conducted restoration using the anchor method to transplant seagrass in Jepara waters. The results showed that this method was quite effective in Jepara waters.

3.7.1 Mapping Potential Habitats

Identifying suitable locations for seagrass restoration is a key step in advancing coastal ecosystem conservation, given the essential function of seagrasses in preserving marine environmental stability. One effective method for site mapping is the use of remote sensing data. A study by Huda et al. (2024) demonstrated that Sentinel-2 satellite imagery can be used to map the distribution of seagrass beds around Panjang Island, Jepara, with the supervised classification method achieving an overall accuracy of 70% and a kappa value of 0.4. These results show that satellite image technology has excellent potential in mapping existing seagrass areas and identifying open land suitable for restoration.

Besides spatial considerations, evaluating the physical environmental suitability is also a critical factor in selecting sites for seagrass restoration. Riniatsih et al. (2013) analyzed land suitability in Ujung Piring Beach and Blebak Beach, Jepara, by considering parameters such as depth, water brightness, substrate type, and water current. The results showed that most of the area fell into the "moderately suitable" to "suitable" category for seagrass transplantation activities. Thus, spatial data should be integrated with habitat suitability assessment to find the optimal restoration sites.

The type of substrate is also a crucial factor that influences the success of seagrass restoration efforts. Research by Nugraha et al. (2022) compared the growth of seagrass seedlings *Enhalus acoroides* on various types of substrates, such as coarse sand, mud, and sand-mud mixture. The results showed that mud and sand-mud substrates gave better root and leaf growth than coarse sand substrates. This shows the importance of considering the characteristics of the water bottom in mapping seagrass restoration.

Nutrient availability and supporting biota communities are other ecological factors that contribute to restoration success. The study by Silvi et al. (2022) found that sediment nutrients, particularly nitrate and phosphate, contribute to seagrass growth, especially in areas with high seagrass density, such as Awur Bay and Panjang Island. Sites with balanced nutrient conditions tend to have healthier ecosystems favorable for post-restoration seagrass growth. Thus, mapping potential sites for seagrass restoration should ideally combine spatial approaches, analysis of habitat suitability, substrate conditions, and ecological and chemical parameters of the marine environment.

3.7.2 Restoration Method

Sumbayak et al. (2023) carried out seagrass restoration research using two techniques: the anchor method and the seedling method. The anchor method involves a vegetative technique by relocating mature seagrass shoots from a donor location to the transplantation site. The seedlings are tied to bamboo pegs using mattress twine, then planted on the substrate (Short and Coles, 2001). The seedling method uses a generative approach that uses seeds collected from mature seagrass plants from the donor site. Seedlings were cultivated in the laboratory for five weeks, and seeds were placed into polybags filled with substrate and kept in seawater containers. Seagrass growth was measured, and the quality of seagrass seedlings was maintained until they were ready to be transplanted at the site (Thorhaug, 1974).

Transplantation involved establishing three plots of 50 x 50 cm for each technique: the anchor method, the seedling method, and natural vegetation, which served as the control. Each plot was bordered with a net to protect the plants from physical disturbance (Sumbayak et al., 2023). The prepared seedlings were tied with bamboo pegs using mattress twine. The seedling method was used to prevent the seedlings from being washed away by the current. Planting holes are made using a crowbar or drill, then the seedlings are planted according to the predetermined position (Grech et al., 2012). Numbering is done on each transplant unit for observation purposes (Sumbayak et al., 2023).

3.7.3 Monitoring

Restoration success was evaluated through two leading indicators: growth and seagrass survival rates. The ANOVA technique was applied to assess whether there were significant differences among the various restoration methods. Observations were carried out every two weeks over three months (Sumbayak et al., 2023). Seagrass growth rate showed variation among the three treatments. The highest growth rate was recorded in natural vegetation, about 0.31 cm per day. The anchor method produced an average growth of 0.25 cm per day, while the seedling method recorded 0.18 cm per day (Sumbayak et al., 2023). Generally, seagrass survival rates declined in the second and fourth weeks, except for natural vegetation, which maintained a 100% survival rate as it did not undergo an adaptation phase. In contrast, survival rates in the anchor and seedling methods dropped to 96% and 84%, respectively (Sumbayak et al., 2023). This difference is because seagrasses that grow naturally need not adjust to new environmental conditions. In contrast, transplanted seagrasses require adaptation before growing optimally in their new environment (Thangaradjou and Kannan, 2008). Statistically, the growth rate and survival rate between methods have significant differences, meaning that the restoration method affects the survival rate of seagrasses (Sumbayak et al., 2023).

4. Conclusions

Restoration of seagrass ecosystems demands a comprehensive approach that integrates spatial analysis, innovative physical restoration methods, and predictive modeling for effective long-term monitoring. Strategic site selection, supported by high-resolution spatial data and GIS tools, ensures that restoration projects target areas with optimal environmental conditions for seagrass establishment and survival. In addition, the combination of generative and vegetative techniques, as well as adaptive restoration strategies like the use of protective structures, improves the resilience and success rate of seedling growth and transplantation. Utilizing predictive models based on field and satellite data offers timely insights for managers, facilitates adaptive management, and strengthens the scientific foundation of restoration efforts.

Furthermore, fostering collaborations among local communities, government, academia, and stakeholders is vital for program sustainability and capacity building. Supporting restoration with long-term policies, sufficient funding, and international partnerships further amplifies positive outcomes, enabling restoration programs to respond effectively to climate change and anthropogenic pressures. Continued research, technological innovation, and data-driven monitoring will help seagrass ecosystems not only recover but also contribute significantly to coastal resilience, biodiversity conservation, and global climate goals through enhanced blue carbon stocks.

Conflicts of Interest

There are no conflicts to declare.

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