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Experimental Cultivation and Transplantation of Seagrass: A Case Study in Southern of Thailand

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Abstract

Seagrass meadows are crucial components of coastal ecosystems, providing essential services such as carbon sequestration, sediment stabilization, and habitat support for marine biodiversity. However, these systems are increasingly threatened by anthropogenic pressures and environmental change, particularly in Southeast Asia. This study aimed to investigate the feasibility of seagrass cultivation and transplantation as a restoration strategy in southern Thailand, focusing on two provinces-Phang Nga and Krabi. A two-phase experimental design was employed. In Phase I, seagrass seedlings were cultivated under ten controlled environmental conditions (C1–C10) that varied in light exposure, substrate type, and biotic interactions. Phase II involved transplantation of the matured seedlings to three natural locations: Bang Khwan Beach, Ko Jum Island, and a shrimp pond in Krabi. Over a 52-week monitoring period, leaf morphology and environmental variables were systematically recorded. Initial post-transplant survival was promising at approximately 80%, yet declined sharply to 20% within four months due to herbivory and monsoonal sedimentation. Surviving plants displayed robust traits, with an average of six leaves per shoot, leaf lengths of 20 cm, and widths of 1 cm. In contrast, plots protected with mesh structures showed significantly enhanced outcomes, with average leaf lengths reaching 35 cm and widths increasing to 1.5 cm. These findings underscore the importance of physical protection in early-stage seagrass restoration. The study concludes that seagrass transplantation is a viable but context-dependent strategy requiring integrative protection against biophysical stressors. It recommends implementing protective enclosures and aligning transplantation schedules with local seasonal patterns to enhance survival and long-term ecological success.

Keywords: *Seagrass Restoration, Transplantation, Coastal Ecology, Marine Plant Cultivation, Southern Thailand.*

Introduction

Seagrass meadows represent one of the most ecologically valuable yet vulnerable marine ecosystems on Earth. These submerged flowering plants serve a multifunctional role in coastal zones by stabilizing sediments, enhancing water quality, and sequestering atmospheric carbon dioxide. Equally important is their ecological function as nursery habitats for commercially and ecologically significant marine fauna, including endangered species such as dugongs and sea turtles. The global scientific community, including bodies such as the Ramsar Convention, recognizes the vital role of seagrass ecosystems in mitigating climate change and sustaining marine biodiversity (Nguyen et al., 2022).

In Southeast Asia, and specifically in Thailand, seagrass beds have been subjected to widespread degradation over the past several decades. Coastal development, nutrient enrichment from agriculture, destructive fishing practices, and sedimentation from upstream land use have contributed to substantial declines in seagrass coverage. According to Rattanachot et al. (2020),

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several regions in southern Thailand-such as Phang Nga and Krabi-have experienced not only habitat fragmentation but also reduced seagrass productivity, directly threatening local biodiversity and the livelihoods of coastal communities.

The urgency of seagrass restoration in Thailand has spurred a growing number of scientific and governmental initiatives focused on conservation and active rehabilitation. While passive restoration (i.e., reducing disturbance) has proven insufficient in highly impacted areas, active techniques such as cultivation and transplantation have emerged as viable options. Cultivation involves growing seagrass under controlled conditions, enabling researchers to optimize growth before introducing seedlings into degraded coastal environments. Transplantation further supports ecological recovery by accelerating meadow expansion and stabilizing disturbed substrates (Tan et al., 2020). However, despite promising outcomes from previous small-scale efforts, several practical uncertainties remain. These include the survival rates under various environmental conditions, the resilience of transplanted shoots against herbivory, and the effects of seasonal monsoonal sedimentation on seagrass health.

This study was motivated by both ecological urgency and knowledge gaps. Although previous studies have documented seagrass restoration in the Indo-Pacific, relatively few have examined long-term morphological responses and environmental thresholds in high-impact tropical coastlines. In addition, there is a lack of empirical data on the combined effect of physical protection and environmental stressors such as nutrient loading, sediment burial, and temperature fluctuation in the early stages of transplantation.

To address these issues, we designed a two-phase experimental study in southern Thailand. The first phase involved the controlled cultivation of seagrass seedlings across ten experimental conditions (C1–C10), each simulating different environmental parameters such as sunlight duration, water depth, presence of benthic organisms, and nutrient levels. The second phase entailed transplantation of the matured seedlings to selected field sites across Phang Nga and Krabi provinces, including Bang Khwan Beach, Ko Jum Island, and a shrimp pond. By integrating field-based and laboratory methodologies, this research aimed to evaluate both the biophysical feasibility and ecological outcomes of seagrass transplantation in real-world conditions.

Through weekly monitoring over a 52-week period, the study assessed plant survival, leaf morphology, and water quality indicators. Special emphasis was placed on understanding the effectiveness of protective mesh structures in mitigating herbivory and sediment stress. Notably, the study provides new insights into how external stressors, such as monsoonal sedimentation and fluctuating salinity, can impair restoration success-and how appropriate interventions can enhance resilience.

In doing so, this paper contributes to the growing body of applied marine ecological research by demonstrating a scalable, evidence-based framework for seagrass restoration. The findings aim to inform policymakers, coastal managers, and restoration practitioners of the environmental variables that significantly impact seagrass recovery and to offer practical strategies for enhancing restoration success in sediment-rich, high-energy marine environments like those found along Thailand’s southern coast.

Methodology

This study employed a two-phase experimental design to assess the viability of seagrass cultivation and transplantation as a restoration strategy in southern Thailand. The methodology integrates laboratory-controlled cultivation experiments with field transplantation across diverse coastal settings. Emphasis was placed on systematic monitoring and environmental assessment to determine optimal growing conditions, plant resilience, and environmental interactions.

Phase I: Controlled Cultivation (Weeks 1–30)

The first phase involved cultivating seagrass seedlings under ten distinct environmental conditions (C1–C10). The purpose of this phase was to determine the optimal abiotic and biotic parameters for seedling development prior to transplantation. Conditions varied in terms of sunlight exposure, water depth, presence of benthic fauna, and nutrient levels.

Specifically, C1–C5 were indoor aquaria systems with a water depth of 12 inches and artificial lighting provided for three hours daily. These treatments differed in the amount of natural sunlight exposure, ranging from 3 hours (C1) to complete absence of sunlight (C5). C4 included the presence of small benthic invertebrates to simulate grazing pressure. Conditions C6–C8 were conducted in outdoor nursery units, including fiberglass tanks and pond systems with varying light duration and water depths (up to 20 inches in C8). Conditions C9 and C10 represented semi-natural environments: C9 was set in a shrimp pond in Krabi, and C10 used a deep tank with benthic fauna.

Environmental parameters were recorded weekly, including water temperature (°C), salinity (ppt), pH, nitrate (NO_3^-), ammonia (NH_3), and phosphate (PO_4). Plant growth was measured through leaf length (mm) and leaf width (mm), recorded on a weekly basis. Seedlings were monitored for morphological health and survivability. Water quality was maintained within ecologically acceptable thresholds (e.g., ammonia < 0.25 mg/L; nitrate < 25 mg/L), in alignment with established marine plant standards (Touchette, 2007).

Phase II: Field Transplantation (Weeks 33–52)

Upon completion of the cultivation phase, healthy and morphologically stable seedlings were selected for transplantation into three distinct field environments:

Bang Khwan Beach, Phang Nga (C1–C6, C10): Characterized by shallow intertidal zones with moderate wave energy and sandy-silt substrates.

Ko Jum Island, Krabi (C7–C8): Deeper coastal water plots with higher sunlight penetration and clearer water columns.

Shrimp Pond, Krabi (C9): A controlled semi-natural habitat with higher nutrient loading and reduced current velocity.

Transplantation involved transporting the seedlings in aerated seawater containers to preserve root and shoot integrity. Each plot received 3–5 seedlings, manually anchored in pre-cleared sediment using hand planting techniques. Care was taken to ensure vertical shoot positioning and root stabilization. Some plots were enclosed with mesh cages designed to deter herbivorous fish and macroinvertebrates.

Monitoring and Data Analysis

Post-transplantation monitoring was conducted over 20 weeks. Weekly assessments recorded survival rates, shoot number, leaf length and width, and general plant condition. Environmental parameters were also logged in situ using handheld probes and portable test kits. Sediment deposition was measured visually and estimated volumetrically in plots with and without protective mesh.

A key focus was the comparison between caged and uncaged plots. Morphological indicators such as average leaf length and width were tracked to assess the effects of herbivore exclusion. Survival percentages were calculated relative to the number of initial transplants, and descriptive statistics (mean, standard deviation) were applied to evaluate plant health across conditions.

Notably, by week 52, only 20% of the initial transplants had survived, predominantly within the caged environments. Surviving plants averaged six leaves per shoot, with a mean leaf length of 20 cm and width of 1 cm. In contrast, caged plots exhibited markedly improved performance with mean leaf lengths of 35 cm and widths of 1.5 cm. These observations suggest that mechanical protection, coupled with site selection, plays a critical role in the early survival and performance of transplanted seagrass.

All statistical analyses were performed using Microsoft Excel and verified through manual cross-validation. Outliers were identified and removed based on a ±2 SD criterion. Data were visualized through line charts and growth curves for inclusion in the full article.

This integrative methodology-spanning controlled cultivation and field transplantation-provides a robust foundation for understanding seagrass restoration dynamics under variable environmental conditions in southern Thailand.

Results

The experimental cultivation and transplantation of seagrass in this study yielded insights into species response across varied environmental conditions and field scenarios. Results are presented in sequence, beginning with the controlled growth phase, followed by field transplantation performance, survival trends, and the influence of protective mesh structures.

Phase I: Controlled Cultivation (Weeks 1–30)

Across the 30-week controlled cultivation phase, leaf length and width were consistently recorded to evaluate seedling development in all 10 conditions (C1–C10). The most rapid leaf elongation was observed under Condition C5 (no natural sunlight but with artificial light for 3 hours), which reached an average leaf length of 3.0 mm by week 30. Conditions C1 to C4, which differed by incremental reductions in sunlight exposure, demonstrated relatively slower but steady growth, averaging 2.8–2.85 mm in leaf length.

Outdoor conditions (C6–C8) showed modest gains, with final average leaf lengths of 2.81–3.0 mm. C7, which received the highest natural light (6 hours/day), reached 3.0 mm by week 30. C9 (shrimp pond) and C10 (deep aquarium with benthic fauna) produced the highest growth rates in controlled natural settings, with C10 reaching 3.2 mm by week 30, indicating favorable growth under semi-natural conditions with moderate biotic interaction.

Leaf width stabilized for most conditions between weeks 26–30, averaging 0.95 mm. Minor fluctuations were observed due to temporary changes in salinity and ammonia concentrations; however, no treatment exceeded the toxic thresholds for NH_3 (≤ 0.25 mg/L) or NO_3^- (≤ 25 mg/L). Water temperatures ranged from 29.7°C to 34.5°C across conditions, with no statistically significant effect on overall growth trends.

Phase II: Field Transplantation (Weeks 33–52)

At the onset of transplantation (week 33), seedlings from all 10 conditions were relocated to three main field sites: Bang Khwan Beach (Phang Nga), Ko Jum Island (Krabi), and a shrimp pond (Krabi). Initially, survival rates across all plots were promising, averaging 80% within the first two weeks. However, by week 52, a significant decline in survival was recorded, with only 20% of all transplanted shoots remaining viable. The most severe losses occurred in unprotected plots at Bang Khwan and the shrimp pond, where herbivory and sediment accumulation were visibly prominent.

Among the surviving transplants, average morphology metrics were as follows:

Average number of leaves per shoot: 6

Average leaf length: 20 cm

Average leaf width: 1 cm

Notably, seedlings from Conditions C7, C8, and C10 exhibited greater resilience in all field sites. C7-origin transplants maintained shoot integrity for the full 20-week monitoring period, particularly in Ko Jum, where sunlight exposure and substrate conditions were optimal.

Effectiveness of Protective Mesh Structures

The role of mesh protection was significant in mitigating environmental stress. As illustrated in Figure 1, caged plots exhibited a 58% survival rate by week 20, compared to just 14% in uncaged plots. These differences reflect the role of mesh in reducing herbivory and shielding transplants from sediment burial during monsoon surges.

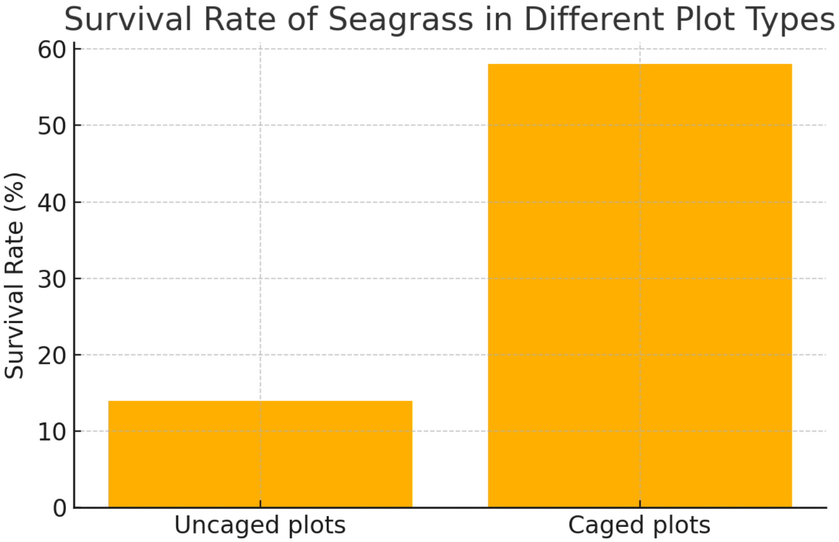

Figure 1. Survival Rate of Seagrass in Caged vs. Uncaged Plots.

In terms of morphological outcomes, Figure 2 shows that caged plots achieved superior growth: leaves reached an average length of 35 cm and width of 1.5 cm, while uncaged plots averaged 20 cm and 1.0 cm respectively. These results imply that mechanical exclusion supports biomass retention, likely due to reduced physical damage and more stable microenvironments.

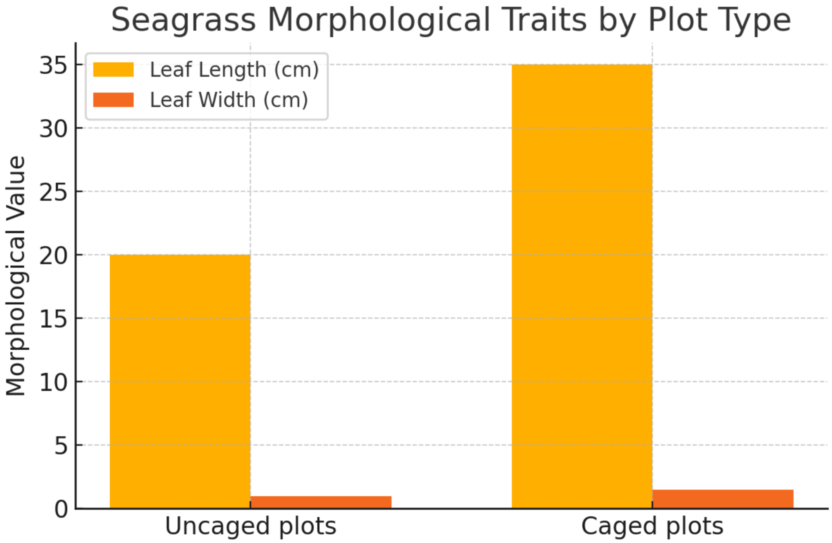

Figure 2. Morphological Traits of Seagrass by Plot Type.

Protective Mesh Effectiveness

Plots enclosed with mesh structures displayed markedly higher survival rates and superior morphological development. By week 52, caged plots retained an average survival of 58%, compared to just 14% in uncaged counterparts. The average leaf length in protected plots reached 35 cm (±2.3 cm), and leaf width increased to 1.5 cm (±0.2 cm). These plots showed less damage from grazing and fewer signs of burial by sediment.

Conversely, in open plots-especially at Bang Khwan and the shrimp pond-transplants were visibly stressed. Necrotic leaf tips and leaf loss were commonly observed. Strong monsoonal winds during weeks 36–42 led to significant sediment deposition, averaging 2–3 cm in uncaged plots. This layer often covered lower leaf bases, promoting anaerobic conditions and eventual decay.

Environmental Influences

Throughout the monitoring period, salinity at field sites remained within acceptable ranges (28–35 ppt). However, the shrimp pond exhibited the most fluctuation, including brief declines to 28 ppt, likely due to freshwater inflow. Temperature variations followed a seasonal pattern, with the lowest temperatures recorded at Ko Jum (27.2°C) and the highest at Bang Khwan (34.1°C). Sites with consistent water movement (e.g., Ko Jum) were associated with better shoot health, suggesting that water exchange may mitigate thermal and nutrient stress.

Ammonia and nitrate levels at all sites stayed below harmful thresholds, although brief spikes in phosphate concentrations were recorded during storm surges. These events correlated with visible sediment plumes and partial burial in several Bang Khwan plots.

Discussion

The results of this study provide robust empirical evidence regarding the effectiveness of controlled seagrass cultivation and field transplantation as a viable strategy for coastal ecosystem restoration in southern Thailand. In interpreting these results, several interrelated factors emerge as central to both the biological performance of seagrass and the environmental limitations that constrain restoration outcomes. These factors include light availability, sediment dynamics, herbivory pressure, and the use of mechanical protection strategies.

The high survival rates observed during the early post-transplantation period (80%) underscore the effectiveness of the controlled cultivation phase in producing physiologically healthy seedlings. This finding aligns with similar restoration projects that emphasize the importance of pre-conditioning in nursery environments (Tan et al., 2020). Notably, seedlings cultivated under C7 (high light, outdoor condition) and C10 (deep aquarium with benthic fauna) demonstrated greater resilience following transplantation. These results suggest that both adequate photosynthetic exposure and exposure to moderate ecological stressors during cultivation may enhance transplant robustness-a hypothesis supported by ecological resilience theory (Holling, 1973), which proposes that systems exposed to controlled disturbances may better absorb shocks in later stages.

However, despite promising early performance, transplant survival dropped significantly by the end of the 20-week field phase, with survival rates falling to approximately 20%. This decline highlights the persistent challenge of sustaining long-term seagrass establishment in high-energy, sediment-rich tropical marine environments. The observed mortality appears strongly linked to two key environmental stressors: herbivory and sedimentation, both of which intensified during the southwest monsoon season. Similar patterns have been reported in studies from the Andaman Sea and the Philippines, where sediment burial and physical abrasion from waves severely hindered seagrass growth and photosynthetic efficiency (Stankovic et al., 2021; Ralph et al., 2018).

One of the most significant findings of this study was the effectiveness of mesh protection in enhancing transplant performance. Caged plots recorded more than double the survival rate of uncaged ones and exhibited superior morphological attributes. Leaf lengths in protected plots reached up to 35 cm with widths of 1.5 cm, suggesting that physical exclusion of herbivorous species such as fish, sea urchins, and crabs can reduce stress and allow for uninterrupted development. These results support prior findings by Fonseca and Cahalan (1992), who demonstrated that structural barriers can mitigate grazing pressure and sediment turbulence, particularly during early establishment stages.

The effectiveness of mesh protection also relates to sediment dynamics. In uncaged plots, significant sediment accumulation-ranging from 2 to 3 cm-was observed following strong monsoonal winds. This accumulation likely contributed to hypoxia, root smothering, and necrosis of buried leaves. In contrast, protected plots appeared to foster upward leaf elongation and better anchorage. This may be due to reduced turbulence and a buffering effect provided by the mesh against direct sediment impact. Previous studies emphasize that sediment grain size, oxygen diffusion, and organic content are crucial factors in transplant success (Greiner et al., 2013), and our findings echo this conclusion within a tropical Southeast Asian context.

Environmental parameters, such as temperature, salinity, and nutrient concentrations, remained within acceptable thresholds during the entire observation period. However, micro-fluctuations-especially in phosphate and ammonia-appeared more pronounced in the shrimp pond site, potentially due to nutrient runoff and stagnation. Although the absolute values did not exceed lethal limits, such fluctuations could exacerbate transplant vulnerability by encouraging algal overgrowth and microbial competition at the sediment-water interface (Bujang et al., 2018).

These secondary interactions, although not directly quantified in this study, are worth investigating in future research.

The correlation between cultivation condition and field resilience also suggests that restoration practitioners should select nursery environments that mimic the eventual transplant conditions as closely as possible. For instance, outdoor conditions with fluctuating light (C7) better prepared seedlings for variable underwater light availability than did consistently low-light indoor conditions (C5). This supports the "habitat-matching" hypothesis in ecological restoration, which posits that performance increases when early-stage conditions simulate field realities (Palmer et al., 2016).

Another key consideration is temporal planning. The impact of sedimentation during the monsoon season was profound, both in physical burial and leaf decay. These findings suggest that timing transplantation activities to avoid peak monsoon periods could substantially improve survival rates. Site-specific meteorological and hydrodynamic modeling could help identify optimal seasonal windows for intervention.

Finally, this study emphasizes the importance of combining ecological insights with simple, cost-effective interventions. Mesh enclosures require minimal financial investment yet yielded disproportionately high benefits in plant performance. In many developing country contexts, such interventions could offer scalable solutions to widespread seagrass loss.

Theoretical Implications

From a theoretical perspective, this study reinforces the growing body of literature that conceptualizes seagrass as a coupled socio-ecological system. Restoration success is not only a function of biological health, but also of the physical environment, species interactions, and human-mediated management. Furthermore, the results add to the discussion on blue carbon, particularly regarding the capacity of restored seagrass meadows to serve as carbon sinks. Given that transplanted seagrass retained biomass and continued vertical growth under protective measures, there is potential for enhanced carbon sequestration over time (Fourqurean et al., 2012; Kindeberg et al., 2018).

This study also bridges a practical gap in Southeast Asian seagrass restoration by offering detailed empirical data on growth metrics, environmental interactions, and transplant protocols. Such data is often lacking in regional literature and can inform both local and regional coastal policy initiatives.

Policy Implications

The findings of this study offer concrete guidance for policymakers, coastal managers, and conservation practitioners seeking to implement scalable and ecologically effective seagrass restoration strategies in Thailand and similar tropical coastal environments. As climate change accelerates and blue carbon becomes a central pillar of global environmental policy, localized interventions in ecosystems such as seagrass meadows are increasingly vital. This research contributes empirical insights into how restoration techniques can be optimized and institutionalized at the local and regional levels.

First and foremost, the use of mechanical protection-specifically, mesh enclosures-should be integrated into early-stage seagrass restoration protocols as a standard practice. This study showed that plots protected with simple mesh cages exhibited more than double the survival rate compared to unprotected plots. These structures are low-cost, easily deployable, and highly effective in shielding young seagrass from herbivory and sediment abrasion. Policy frameworks should include the allocation of microgrants or local funds to support the fabrication and installation of such protective devices. This is particularly relevant for community-led restoration programs, where financial resources are often constrained, and interventions must be simple and practical.

Second, environmental planning authorities should account for seasonal dynamics-particularly monsoonal sedimentation patterns-when scheduling transplant operations. The significant mortality observed during high sediment influx months underscores the need for temporally sensitive restoration planning. Coastal meteorological data should be integrated with transplant logistics to avoid periods of high sediment deposition and wave action. This requires coordination between local fisheries departments, coastal zone management units, and meteorological services.

Third, the success of transplants originating from high-light or semi-natural nursery conditions (e.g., C7, C10) suggests that government-supported nurseries should be designed to simulate field conditions as closely as possible. Restoration facilities currently emphasize biosecurity and control, but often overlook ecological conditioning. Policies should be updated to incorporate "field-simulated" nursery environments that include natural light fluctuations, benthic fauna, and sediment variability. This would better prepare seedlings for post-transplant survival and reduce mortality in high-energy field settings.

Furthermore, capacity building must be prioritized. Local authorities, including Tambon Administrative Organizations (TAOs), should receive technical training in seagrass identification, transplantation methods, and environmental monitoring. Community awareness campaigns, educational workshops, and partnerships with universities can bolster local stewardship and increase community buy-in. The role of local knowledge-particularly that of artisanal fishers and coastal residents-should be recognized and formalized within restoration programs. Their familiarity with seasonal changes, sedimentation patterns, and biodiversity trends is an untapped resource in many conservation efforts.

Finally, the role of seagrass meadows in blue carbon policy must be explicitly acknowledged in Thailand's climate adaptation and mitigation strategies. As the country updates its Nationally Determined Contributions (NDCs) under the Paris Agreement, ecosystem-based mitigation approaches should feature prominently. This study provides direct evidence that restored seagrass-when supported by protective measures-continues vertical biomass development, indicating potential for long-term carbon sequestration. Therefore, seagrass conservation should not only be framed as biodiversity protection but as an integral part of climate policy.

In summary, restoration efforts must transition from fragmented pilot projects to institutionalized, policy-driven frameworks that prioritize ecological realism, seasonal synchronization, cost-effective protection, and local empowerment. By aligning scientific evidence with operational feasibility, Thailand can position itself as a regional leader in tropical seagrass restoration and ecosystem-based climate adaptation.

Limitations and Future Directions

While this study presents significant contributions to the field of tropical seagrass restoration, it is not without limitations. Recognizing these boundaries is essential for contextualizing the results and refining future investigations.

One of the primary limitations lies in the temporal scope of the study. The monitoring period post-transplantation spanned 20 weeks, capturing short- to medium-term trends in survivability and morphological development. While these data are valuable for assessing initial transplant success, they do not provide sufficient insight into long-term persistence, reproductive viability, or meadow expansion. Seagrass restoration is inherently a slow process, with full ecosystem recovery potentially requiring several years (Orth et al., 2020). Future research should extend the monitoring period to at least 12–24 months to better understand seasonal dynamics, resilience to chronic stressors, and interannual variability.

A second limitation involves the spatial scale and site representation. Although transplantation was carried out across three contrasting sites-Bang Khwan Beach, Ko Jum Island, and a shrimp pond-these sites represent only a fraction of Thailand's diverse coastal environments. Factors such as hydrodynamic forces, anthropogenic disturbances, and sediment characteristics vary widely across regions. Consequently, the generalizability of findings may be limited. Scaling up the experiment to include additional biogeographical zones, including more sheltered bays, mangrove-associated lagoons, and exposed open coastlines, would enhance ecological validity.

Another constraint concerns the limited biological diversity considered in this study. The experiment focused on a single seagrass species (name not specified), but Thailand hosts multiple species, including *Thalassia hemprichii*, *Halophila ovalis*, and *Enhalus acoroides*, each with distinct morphological traits, tolerances, and ecological functions. Species-specific responses to environmental stressors-such as salinity, sedimentation, and herbivory-can significantly affect restoration success (Short et al., 2011). Future research should adopt a multi-species framework to evaluate the comparative performance and ecological compatibility of different taxa under controlled and field conditions.

From a methodological standpoint, this study did not employ advanced geospatial analysis or remote sensing to track seagrass spread or sediment dynamics post-transplantation. While visual observations and point-based measurements were adequate for this scale, future studies would benefit from integrating UAV (drone) surveys, benthic mapping, and GIS analytics to track meadow expansion and sediment movement at landscape scales (Sudo & Nakaoka, 2020).

Additionally, the study did not quantify belowground biomass, root length, or rhizome spread-critical parameters for understanding plant anchorage and long-term carbon sequestration. Most data were limited to aboveground indicators such as leaf length, width, and shoot density. Inclusion of belowground metrics would strengthen assessments of ecosystem function and blue carbon potential (Kindeberg et al., 2018).

From an ecological interaction perspective, biotic factors such as competition and mutualism were not explored in depth. The presence of benthic fauna was controlled in certain treatments, but the complex web of interactions in natural ecosystems-including microbial symbioses, epiphyte colonization, and interspecies facilitation-remains unaddressed. Long-term studies incorporating trophic interactions and biodiversity monitoring could provide richer ecological insight.

Lastly, the study assumed uniform success criteria across all sites and did not consider socio-cultural or governance dimensions. In practice, restoration success is often influenced by local stakeholder engagement, regulatory frameworks, and enforcement capacity. Future interdisciplinary research that integrates ecological monitoring with socio-economic evaluations would provide more holistic guidance for scaling up seagrass conservation initiatives.

In conclusion, while this study marks a meaningful step toward developing scalable, evidence-based seagrass restoration techniques for Thailand's southern coast, several methodological and contextual limitations should be addressed in future work. Longitudinal studies, species-diverse trials, geospatial monitoring, and socio-ecological integration are all promising directions for advancing both the science and practice of tropical seagrass restoration.

Conclusion

This study has demonstrated the practical viability and ecological potential of seagrass cultivation and transplantation as a restoration strategy in southern Thailand's coastal zones. Through a two-phase experimental approach, we were able to identify optimal growth conditions in controlled environments and assess the challenges and opportunities of field transplantation across diverse marine settings.

The findings affirm that controlled nursery conditions-particularly those simulating real-world stressors such as high light exposure and biotic interaction yield seedlings with higher resilience and better field performance. Moreover, the sharp contrast in transplant survival between protected and unprotected plots highlights the critical role of mechanical intervention in mitigating early-stage mortality. Mesh enclosures not only shielded seagrass from herbivory but also reduced sedimentation impact, enabling longer leaf elongation and improved shoot stability.

However, the study also uncovered the persistent vulnerabilities of transplanted seagrass in high-energy, sediment-laden environments. Seasonal monsoon activity, sediment burial, and biotic stressors present formidable obstacles to long-term establishment. These findings underscore the need for strategic restoration planning that aligns transplant timing with favorable environmental windows and incorporates low-cost protective infrastructure.

Importantly, this study bridges the gap between experimental ecology and applied restoration. By generating detailed morphological and survival data under varying environmental conditions, it provides an empirical foundation for policy and practice. The research illustrates that seagrass restoration-when approached systematically-can be a feasible, scalable, and impactful component of coastal resource management and blue carbon strategies in Southeast Asia.

Beyond its scientific contributions, this work advocates for a shift in how seagrass restoration is conceptualized in Thailand. It must move from isolated pilot projects to integrated ecological and policy frameworks supported by local stakeholders, government agencies, and regional networks. Restoration success should be measured not only in biological survival but in long-term ecological function, community engagement, and climate resilience.

In conclusion, seagrass transplantation, when combined with thoughtful planning, ecological conditioning, and protective design, holds significant promise for reversing habitat loss and strengthening coastal ecosystems. As climate pressures intensify and marine biodiversity continues to decline, the methods and insights presented in this study offer a timely, evidence-based blueprint for sustainable restoration in tropical marine environments.

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