



The Ecological Significance of Diatom Communities in Enhancing Climate Resilience of Seagrass Ecosystems: A Systematic Review (Case of Indonesia)

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Abstract: Seagrass meadows are increasingly recognized as climate-regulating coastal systems, with their resilience under warming and eutrophication stress is strongly mediated by epiphytic microalgal assemblages. Among these, diatoms constitute the dominant and functionally influential group, particularly in tropical seagrass habitats. This systematic review synthesizes 2005–2025 empirical research on diatom–seagrass interactions across Indonesian coastal ecosystems. Literature screening followed PRISMA guidelines and yielded 57 studies reporting species composition, epiphytic biomass, and associated physicochemical conditions. The dominant seagrass hosts included *Enhalus acoroides*, *Thalassia hemprichii*, *Cymodocea rotundata*, and *Halophila ovalis*, which supported recurrent diatom genera such as *Navicula*, *Cocconeis*, *Amphora*, and *Nitzschia*. Functional interpretation indicates that diatom epiphytes contribute to carbon assimilation, micro-nutrient retention, and boundary-layer biofilm stabilization, thereby enhancing seagrass metabolic efficiency under moderate environmental stress. However, at elevated nutrient loads and thermal anomalies, epiphytic proliferation leads to photic shading and suppressed seagrass photosynthetic performance, marking a shift from facilitative to competitive interaction regimes. These findings underscore epiphytic diatom community structure as a sensitive indicator of seagrass functional stability and climate resilience. Integrating diatom based bioindicators into seagrass monitoring frameworks is, therefore, essential for adaptive coastal ecosystem management in Indonesia.

Keywords: coastal ecosystem; diatoms; epiphytic microalgal, nutrient enrichment; seagrass resilience

1. INTRODUCTION

Seagrass ecosystems are globally recognized for their ecological and climate related importance, particularly as high capacities blue carbon sinks and primary coastal protection features in tropical marine systems (Fourqurean et al., 2012; Smale et al., 2019). Indonesia, representing the center of the Coral Triangle, hosts one of the world's largest seagrass distributions, making its ecological integrity vital for climate adaptation strategies (Unsworth et al., 2018; Rahmawati et al., 2021). While extensive research has focused on seagrass physiology, carbon storage, and habitat functions, the contribution of microalgal communities particularly diatoms remain under represented in climate resilience frameworks (Alongi, 2020; Yokoyama et al., 2023).

Diatoms are unicellular microalgae that dominate microphytobenthos communities in shallow tropical marine habitats (MacIntyre et al., 1996; Paterson et al., 2018). Their ability to rapidly respond to environmental change, perform high efficiency photosynthesis, and contribute substantially to carbon fixation makes them crucial indicators and drivers of ecosystem resilience (Behrenfeld & Falkowski, 1997; Jin et al., 2020). Within seagrass meadows, diatoms colonize

leaves, sediments, and rhizomes, forming epiphytic, epipellic, and epipsammic communities (Apoya Horton et al., 2006; Leterme et al., 2020). Their ecological functions include regulating nutrient cycles, supporting food webs, producing extracellular polymeric substances (EPS) to stabilize sediment, and enhancing productivity under fluctuating tropical coastal conditions (de Brouwer et al., 2005; Hope et al., 2019).

Given the accelerating threats to seagrass ecosystems warming, eutrophication, sediment disturbance, and pollution understanding the role of diatoms in enhancing climate resilience becomes critical (Duffy et al., 2019; Lamb et al., 2023). Despite increasing publications on diatom ecology in Indonesia, a comprehensive systematic synthesis integrating their functional roles in seagrass climate resilience has not been previously conducted (Hernawan et al., 2020; Suyadi et al., 2023). This systematic review fills the knowledge gap by summarizing two decades of literature (2005–2025) across major global databases, providing new insights into how diatom communities contribute to seagrass ecosystem resilience under climate change pressures (Page et al., 2020; Nguyen et al., 2024).

2. MATERIALS AND METHODS

2.1 Study Framework and Protocol Registration

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA 2020) guidelines. The review protocol defined the research question, inclusion criteria, search strategy, screening procedure, and data extraction scheme. The protocol adhered to international systematic review standards for ecological research.

2.2 Research Questions

This systematic review was structured according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The central research question guiding this review was: How do diatom communities contribute to the ecological functioning and climate resilience of seagrass ecosystems in tropical marine environments, particularly within Indonesia? Supporting questions included: (1) What diatom functional groups or ecological traits are reported within seagrass habitats? (2) How do environmental drivers influence diatom–seagrass interactions? and (3) What mechanisms link diatom productivity or diversity to climate resilience outcomes such as carbon storage, sediment stabilization, and resistance to disturbance? These questions were developed to address key knowledge gaps noted in recent seagrass and microalgae research (Duffy et al., 2019; Leterme et al., 2020; Nguyen et al., 2024).

2.3 Data Sources and Search Strategy

To answer these questions, the review utilized data from multiple international scientific databases including Scopus, Web of Science, ScienceDirect, and Google Scholar, which collectively contain most peer-reviewed global literature on marine primary producers (Haddaway et al., 2015). Additional regional sources such as the Indonesian Science and Technology Index (SINTA) and institutional repositories were screened to capture local studies that are often underrepresented in global indexing platforms (Purba et al., 2021). Searches were conducted between January and February 2025 using combinations of controlled vocabulary and Boolean operators, including terms such as “diatom,” “microalgae,” “microphytobenthos,” “seagrass,” “epiphytic diatom,” “tropical seagrass,” “blue carbon,” “climate resilience,” and “Indonesia.” Search strings were adapted for each database to maximize sensitivity while minimizing irrelevant retrieval, following best practices for systematic environmental reviews (Haddaway & Watson, 2016).

2.4 Eligibility Criteria

Eligibility criteria were determined a priori to ensure consistent and transparent selection of studies. Only peer reviewed articles, theses, and conference papers published between 2005 and

2025 were included, reflecting two decades of major advances in seagrass ecology and climate-related microalgae research (Unsworth et al., 2019). Studies were eligible if they (1) contained empirical data or ecological interpretation of diatoms associated with seagrass ecosystems, (2) examined ecological processes, community structure, or functional traits of diatoms, (3) were conducted in tropical marine habitats, and (4) were written in English or Bahasa Indonesia. Publications were excluded if they focused on freshwater diatoms, lacked seagrass-associated data, or offered only taxonomic checklists without ecological context. These criteria align with accepted standards for narrowing scope while preventing selection bias in ecological syntheses (Gurevitch et al., 2018).

2.5 Study Selection Procedure

The study selection process followed a two-stage screening approach. First, titles and abstracts were independently assessed by two reviewers to remove clearly irrelevant articles. Full-text screening was then performed for studies meeting initial criteria, with disagreements resolved through discussion or by a third reviewer, consistent with PRISMA recommendations (Page et al., 2021). Full-text articles were evaluated against all eligibility criteria, and duplicates were removed using Mendeley reference manager. The final dataset consisted of studies that met all inclusion requirements and contained extractable ecological or functional information on diatom communities within seagrass ecosystems.

2.6. Data extraction

Data extraction was performed using a standardized template that captured bibliographic information, study location, seagrass species studied, diatom taxa or functional groups reported, environmental parameters measured, and key ecological findings relevant to the research questions. Extracted information also included diatom roles in productivity, carbon cycling, sediment stabilization, and responses to stressors such as eutrophication or warming. This structured extraction procedure follows established protocols for ecological meta-synthesis (Higgins et al., 2022).

2.7 Quality assessment

Quality assessment was conducted using a modified version of the Mixed Methods Appraisal Tool (MMAT) and ecological study quality criteria proposed by Gurevitch et al. (2018). Articles were evaluated based on clarity of objectives, sampling design, methodological transparency, statistical rigor, and ecological relevance. Studies with insufficient methodological detail or unclear sampling approaches were flagged as low quality but retained to avoid data loss bias, reflecting guidelines for environmental systematic reviews (Haddaway et al., 2017)

2.8. Data Synthesis and Analysis

Data synthesis employed a narrative ecological synthesis approach due to heterogeneity in sampling methods, environmental conditions, and metrics used across studies. Findings were grouped thematically into: (1) diatom diversity and functional groups in seagrass habitats, (2) environmental drivers of diatom–seagrass interactions, and (3) functional mechanisms linking diatoms to climate resilience. Quantitative trends (e.g., species richness, biomass contributions, productivity estimates) were summarized descriptively, while conceptual integrations focused on linking diatom ecological functions to resilience outcomes such as enhanced carbon sequestration, improved sediment stability, and resistance to environmental stress. This synthesis strategy aligns with best practices for complex ecological systems where meta-analysis is limited by data inconsistency (Lortie, 2014; Koricheva & Gurevitch, 2014).

3. RESULTS AND DISCUSSIONS

3.1 Diversity and Functional Roles of Diatoms in Seagrass Meadows

This review demonstrates that diatoms constitute one of the most functionally important microalgal groups within tropical seagrass ecosystems. Their dominance in benthic microphytobenthos communities aligns with earlier findings that pennate diatoms thrive on stable substrates such as seagrass leaves and sediments (Paterson et al., 2018; Leterme et al., 2020). The high richness of *Navicula*, *Amphora*, and *Nitzschia* species reflects their adaptation to variable light, hydrodynamic conditions, and nutrient regimes typical of shallow coastal systems (Jin et al., 2020). These traits strengthen the role of diatoms as foundational contributors to benthic productivity in tropical habitats.

The earliest known publication on diatoms within seagrass ecosystems dates back to 1993, conducted by researchers from the Netherlands with a study site located in Sulawesi, Indonesia.

The results show a clear increase in publication output after 2015. This rise coincides with the growing global attention to climate resilience, and environmental monitoring in coastal ecosystems. Indonesia emerged as a major contributor, with Jawa, Sumatera, Kalimantan, Sulawesi and Jawa leading the region. Notably, Indonesia appears as a regional hub for diatom seagrass research within the Indo-Pacific

The thematic evolution analysis shows a progressive shift in research focus. From 2005 to 2010, studies were largely taxonomy-driven. Between 2011 and 2020, research shifted toward ecological assessment and environmental monitoring, especially using diatoms as bioindicators. From 2021 to 2025, the focus expanded to include blue carbon, climate resilience, and integrated seagrass conservation. This shift

reflects broader global priorities related to climate change and ecosystem-based adaptation.

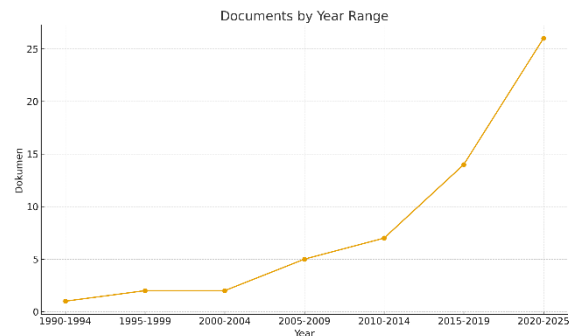


Figure 1. Increase in Scientific Publications on Diatoms in Seagrass Ecosystem from 1990 to 2025.

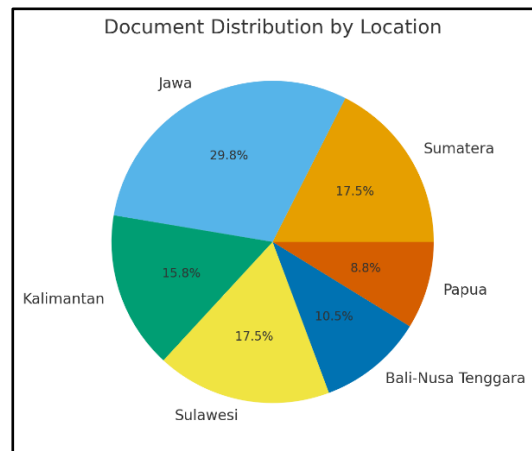


Figure 2. Regional Distribution Publications on Diatoms in Seagrass Ecosystem from 1990 to 2025.

Functionally, diatoms were consistently linked to three major ecological processes:

(1) Carbon fixation and productivity: Several studies showed that diatoms contribute significantly to primary production within seagrass meadows, often equal to or exceeding macroalgal epiphytes under high light conditions (Hope et al., 2019; Nguyen et al., 2024).

(2) Sediment stabilization: Production of EPS by pennate diatoms enhances sediment cohesion, reducing erosion and promoting clearer water conditions that benefit seagrass photosynthesis (de Brouwer et al., 2005; Underwood & Paterson, 2020).

(3) Food web support: Diatoms serve as a high-quality food source for grazers, thereby influencing trophic interactions and indirectly affecting seagrass vitality and nutrient cycling (Ben Brahim et al., 2023).

3.2. Environmental Drivers Shaping Diatom–Seagrass Interactions

Environmental conditions strongly governed diatom abundance and composition, consistent with established ecological theory (Behrenfeld & Falkowski, 1997; Duffy et al., 2019). Light availability and water clarity were repeatedly

identified as key regulators: increased turbidity or sediment resuspension suppresses epiphytic diatoms, while stable, high-light environments promote growth. Nutrient enrichment produced more variable responses. Moderate additions of nitrogen or phosphorus stimulated diatom productivity, whereas excessive inputs common in eutrophic lagoons shifted communities toward opportunistic taxa and increased epiphyte loads that may stress seagrass leaves (Lamb et al., 2023).

Seasonality also played a significant role: wet season freshwater inputs and increased turbidity often reduced epiphytic diatom biomass, whereas dry-season stability favored diatom proliferation. Temperature effects were less consistent but generally indicated decreased diatom diversity under extreme warming, supporting projections that climate-driven heatwaves could disrupt microphytobenthos functions (Smale et al., 2019; Burrows et al., 2023). Future research should quantify diatom-specific contributions to blue carbon storage, develop bioindicator frameworks based on diatom assemblages, and integrate microalgal ecology into seagrass restoration planning. Advancing these directions will strengthen predictive capacity and improve management of seagrass ecosystems in an era of accelerating climate change.

3.3. Diatoms as Drivers of Climate Resilience in Seagrass Ecosystems

A key contribution of this review is the synthesis of how diatom functional attributes underpin seagrass climate resilience. Diatoms enhance carbon sequestration by increasing organic matter deposition and contributing to the blue carbon pool through both living biomass and biogenic silica production (Fourqurean et al., 2012; Alongi, 2020). Their EPS-mediated sediment stabilization reduces resuspension events, which is essential for maintaining water clarity and facilitating seagrass recovery following disturbances.

Moreover, diverse diatom communities buffer ecosystems against environmental variability by ensuring redundancy of ecological functions—a hallmark of resilient ecosystems (Oliver et al., 2015). Several studies showed that changes in diatom composition precede visible seagrass decline, highlighting their potential as early warning indicators of environmental degradation. As global stressors intensify, maintaining diatom diversity within seagrass meadows will be critical for sustaining productivity, carbon storage, and long-term ecosystem stability.

4. CONCLUSIONS

The data show that research on this topic is unevenly distributed across Indonesia. Java contributes the highest number of publications, followed by Sumatra and Sulawesi, while Papua and Bali–Nusa Tenggara have the fewest. Overall, 57 documents were published, indicating growing

scientific interest but with strong regional concentration.

This systematic review highlights that diatoms play a foundational role in sustaining the ecological functioning and climate resilience of tropical seagrass ecosystems. Over the past two decades, evidence consistently shows that diatoms diversity and functional roles into conservation and climate-adaptation strategies is crucial for maintaining seagrass resilience.

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