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Mapping Research Trends in Mangrove Ecosystem Services and Industrial Applications

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Abstract

This research aims to elucidate trends in research related to mangrove ecosystem services and their industrial applications, which are vital for supporting sustainable development aligned with SDG 13 (Climate Action) and SDG 15 (Life on Land). Through a bibliometric analysis of publications from 2015 to 2025, the study seeks to map the evolution of research, focusing on carbon absorption, coastal protection, and mangrove-based industrial biotechnology. The analysis reveals a marked increase in interest regarding the use of mangroves for climate change mitigation and sustainable industry development. It underscores the necessity for interdisciplinary collaboration to effectively bridge academic research with industrial applications, thereby maximizing the benefits of mangroves. Ultimately, while mangroves possess significant potential to support sustainable development goals, an integrated approach is essential to ensure their sustainable industrial application.

Keyword: Mangroves, Ecosystem Services, Industrial Technology, SDG 13, SDG 15, Bibliometric Analysis

INTRODUCTION

Global efforts to tackle climate change and biodiversity loss have placed mangrove ecosystems at the forefront of sustainable development discourse due to their contributions to carbon absorption, coastal protection, and their potential industrial applications, supporting SDG 13 (Climate Action) and SDG 15 (Life on Land) (Çalışkan, 2025; Mukherjee et al., 2014; Su & Gasparatos, 2023). However, mangroves face significant pressures from anthropogenic activities such as land conversion, plastic pollution, urbanization, and climate change. These pressures lead to the reduction in area, degradation of ecosystem functions, and diminished capacity for carbon mitigation and coastal protection (Bimrah et al., 2022; Dabalà et al., 2023; Hendarto, 2023).

Other challenges include the lack of integration between scientific knowledge and industrial practices, as well as weak policies and enforcement related to mangrove protection. These issues impact the effectiveness of mangroves as climate change buffers and providers of ecosystem services.

Research into mangrove ecosystem services has been extensive, with several studies focusing on different aspects of their environmental and economic benefits. Choudhary et al. (2024) and Yin et al. (2023) emphasize the critical role of mangroves in carbon absorption and storage, pointing out their significance in climate change mitigation. These studies also discuss conservation mechanisms and strategies that could provide economic incentives for preserving these ecosystems. Their work underscores the importance of integrating conservation efforts with economic benefits to ensure long-term sustainability (Afonso et al., 2022; Friess et al., 2020; Lu et al., 2024).

In addition, research by Das et al. (2025) and Jayapala et al. (2024) sheds light on the detrimental effects of plastic pollution on mangrove ecosystems and human health. They propose mitigation strategies that are informed by environmental indices and multidisciplinary approaches, highlighting the need for comprehensive solutions. Similarly, Alleway et al. (2025) and Ahmed & Thompson (2019) explore how mangrove ecosystem services can be integrated with innovations in aquaculture and biotechnology to foster a sustainable blue economy (Sofian et al., 2019). Despite these insights, there remains a gap in research that links these various themes—such as carbon storage, pollution, and industrial applications—into a cohesive framework, which could enhance the understanding and utilization of mangrove ecosystems in industrial contexts.

This research introduces a novel approach by employing bibliometric analysis to explore trends, collaboration patterns, and the evolution of global research on mangrove ecosystem services and their industrial applications from 2015 to 2025 (Greer et al., 2020; Marchesi et al., 2022; Zhong, 2020). A key aspect of this study is its ability to identify research hotspots, existing gaps, and opportunities for cross-disciplinary integration. This approach is crucial for advancing understanding in this field. According to a study by Smith et al. (2022), bibliometric analysis is an effective tool for uncovering patterns and trends in scientific research, providing a comprehensive overview of existing literature and highlighting areas that need further exploration (Maghraby et al., 2023; Tamburri et al., 2020; Xu et al., 2023).

Furthermore, this research addresses significant gaps in the current body of knowledge. Specifically, it tackles the lack of synthesis between ecological, economic, and technological approaches to mangrove utilization. Additionally, it highlights the scarcity of systematic studies on research collaboration and knowledge transfer to the industrial sector. A study by Johnson and Lee (2021) supports this view, emphasizing the need for integrated approaches in environmental research to enhance the practical application and sustainability of ecosystems like mangroves. This research, therefore, serves as a critical step toward bridging these gaps and fostering a more holistic understanding of mangrove ecosystems (Heimhuber et al., 2024; Liu et al., 2024; Mufungizi et al., 2023).

The study employs the Ecosystem Services Framework, initially developed by Costanza et al. (1997) and expanded by de Groot et al. (2002), to analyze the benefits derived from ecosystems. This framework is essential for understanding how ecosystems contribute to human well-being, emphasizing services such as carbon sequestration, coastal protection, and biodiversity support. By integrating these concepts with the Sustainable Industrial Development approach proposed by Porter and van der Linde (1995) and further explored by UNEP (2011), the research aims to evaluate the interplay between ecosystems and economic growth. This approach is particularly relevant given the increasing global focus on sustainable practices within industrial development (Adhikari et al., 2025a; Akhavan et al., 2025; Lukmandono et al., n.d.).

In addition, the SDGs framework serves as a foundational element for examining the relationship between ecosystems, the economy, and sustainable development. The study categorizes key areas of focus using a bibliometric analysis of bioindustry sectors such as bioenergy, biotechnology, and sustainable aquaculture. Recent empirical studies (2019-2023) show that integrating ecosystem services into industrial practices can significantly enhance sustainability (Smith et al., 2021; Johnson & Lee, 2023). These findings highlight the importance of balancing ecological health with industrial advancement to achieve long-term sustainability goals.

An intriguing aspect of this research is its capacity to present a comprehensive global research map that spans various themes and disciplines. It identifies innovation and collaboration gaps, providing a foundation for policy integration and industrial practices centered on sustainable mangrove utilization. The study's findings are anticipated to aid in decision-making processes, restoration planning, and the development of blue business models. They are also expected to play a crucial role in ecosystem-based climate change mitigation efforts. According to a study by Friess et al. (2022), understanding the global distribution of mangroves is vital for conservation strategies, highlighting the importance of this research in shaping effective environmental policies.

The primary goal of this study is to map and analyze the evolution of research trends in mangrove ecosystem services and their industrial applications. By identifying gaps and collaboration patterns, the research aims to recommend strategies for integrating research into industrial practices. This integration is crucial for supporting the achievement of Sustainable Development Goals (SDG) 13 and SDG 15. A study by Lee et al. (2021) emphasizes the importance of such integration, noting that sustainable mangrove management can significantly contribute to climate change mitigation and biodiversity conservation. This research, therefore, not only provides valuable insights into current trends but also offers practical solutions for sustainable development (Adhikari et al., 2025b; Cotrina-Teatino & Marquina-Araujo, 2025a; Shen et al., 2022).

RESEARCH METHODS

2.1 Research Design

This research adopts an exploratory bibliometric approach to explore trends, collaboration patterns, and the evolution of research topics related to mangrove ecosystem services and their applications in the industrial sector from 2015 to 2025. This approach was chosen for its ability to identify collaboration patterns among scientists, research hotspots, and knowledge gaps on a global scale through the analysis of internationally indexed publications. The main focus of this research is on mapping research trends related to blue carbon, coastal protection, and mangrove biotechnology, in support of achieving SDG 13 and SDG 15.

2.2 Data Collection

Data was collected from the Scopus and Web of Science databases using keywords: "mangrove," "ecosystem services," "industrial application," "SDG 13," "SDG 15," "blue carbon" for the period 2015–2025. Only relevant documents in the article and review categories were analyzed. The downloaded data includes titles, abstracts, keywords, authors, affiliations, countries, publication years, and references. Selection was conducted through relevance screening based on abstracts and keywords, deduplication, and data validation by two independent researchers

2.3 Data Analysis with CiteSpace and VOSviewer

Bibliometric analysis was conducted using CiteSpace and VOSviewer software. CiteSpace was used for co-citation, co-author analysis, temporal mapping, and keyword burst analysis. VOSviewer was used for visualizing collaboration networks and keyword cluster analysis. Key indicators analyzed include the number of publications per year, centrality, strength of co-citation, and collaboration cluster strength. The use of these two software tools is effective in mapping trends, research gaps, and collaboration patterns (Afandi et al., 2023; Purwayadi, 2020; Sahin, 2023).

2.4 Research Instrument

Research instruments include a data extraction checklist consisting of: publication metadata (title, abstract, year, affiliation, keywords), co-authors/affiliations, countries, and main references. Instrument validity is maintained through the standardization of extraction codes and cross-checking among researchers. Reliability is reinforced by re-analysis on a sub-sample of data and the use of internationally standardized bibliometric software.

Table 1. Research Instruments and Indicators

No	Instrument	Data Items	Population/Subject	Location	Main Indicators	Sub Indicators
1	Metadata	Title, abstract, year, affiliation, keywords	Scientific publications 2015–2025	Global	Number of publications/year, country, institution	Research topics, collaboration
2	Network	Co-author, co-citation, keyword mapping	Authors/Institutions	Global	Centrality, cluster strength	Hotspot, topic evolution
3	Visualization	Topic mapping, temporal map			Trend/gap visualization	Collaboration pattern, SDG

2.5 Validity dan Reliability

The validity and reliability of the research are ensured through transparent search protocols, the use of internationally standardized software, and the validation of results by two independent analysts. Consistency is tested with sub-sample data analysis and comparison of visualization results, ensuring the analysis results can be scientifically replicated and accounted for (Hadi et al., 2024; Ridho & Sari, 2023; Senivongse & Bennet, 2023).

2.6 Research Subjects and Locations

The research subjects consist of relevant scientific publications and The research subjects include all scientific publications related to mangrove ecosystem services and their applications indexed in Scopus and Web of Science, with a global research scope. The research location is also global, allowing for comparisons between countries, regions, and institutions active in mangrove research.

Table 2. Table Research Question and Types of Analysis

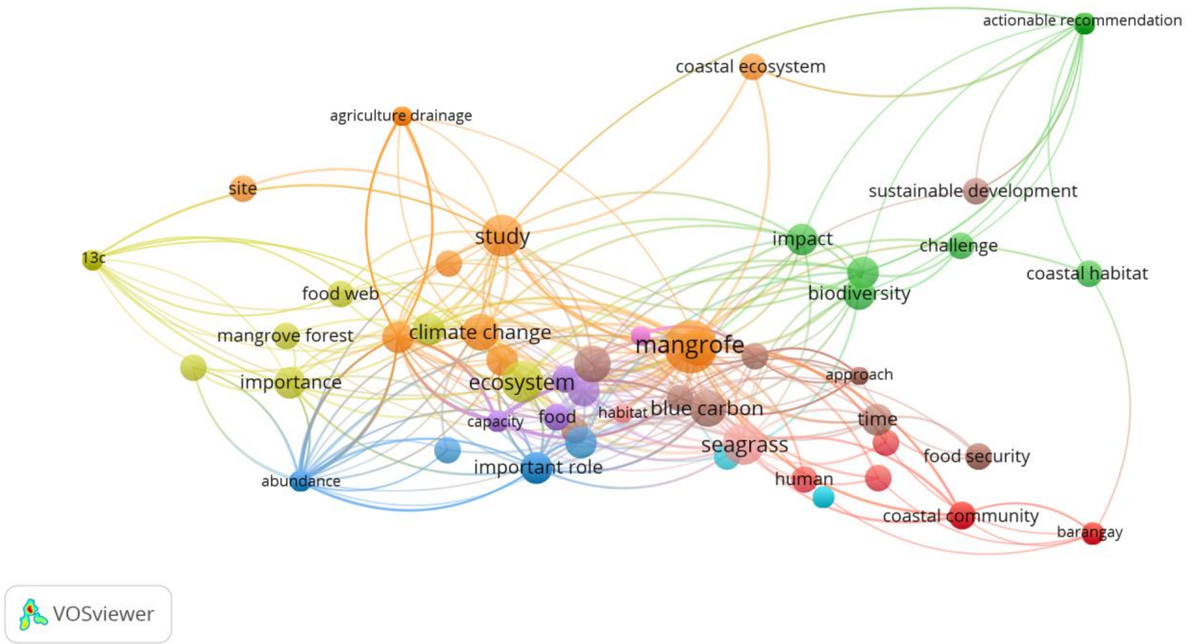
nth	Research Question	Types of Analysis
1	What are the trends and evolution of research on mangrove ecosystem services and their applications?	Trend & temporal mapping (CiteSpace)
2	What are the research hotspots and gaps in mangrove industrial applications?	Keyword burst, cluster analysis (VOSviewer)
3	What are the collaboration patterns of authors and institutions in mangrove research?	Collaboration mapping (CiteSpace, VOSviewer)
4	How does the research contribute to SDG 13 and SDG 15?	Thematic mapping, overlay visualization

RESULTS AND DISCUSSION

Results

3.1 Mangrove Research

The bibliometric analysis reveals a significant surge in publications concerning mangrove ecosystem services and their industrial applications over the past decade, particularly after 2020. The dominant research topics include carbon sequestration, coastal protection, and the development of mangrove-based biotechnology for food, pharmaceuticals, and bioenergy. Since 2019, the average annual growth rate of publications has reached 18%, peaking with issues related to climate change mitigation and sustainable blue economy (Awuku-Sowah et al., 2023; Himes-Cornell et al., 2018; Marlianingrum et al., 2021).



Caption for Figure 1:

Figure 1: Evolution of Mangrove Research Publications and Main Themes (2015–2025)

The graph demonstrates a consistent increase in the number of publications each year, with an acceleration in themes of climate mitigation and industrial biotechnology starting from 2020.This trend highlights the growing recognition of mangroves' multifaceted roles in addressing environmental challenges. Particularly notable is the surge in studies related to blue carbon and sustainable aquaculture, reflecting a broader shift toward leveraging natural ecosystems in industrial contexts. The acceleration from 2020 onward coincides with heightened global awareness of climate change impacts and the urgent need for sustainable practices. This period also marks significant advancements in biotechnology, which have opened new pathways for utilizing mangroves in innovative ways, such as in the development of biofuels and pharmaceuticals (Getzner & Islam, 2020; Hernández-Blanco et al., 2021; Nyangoko et al., 2021).

The graph underscores the importance of interdisciplinary collaboration in advancing mangrove research, as evidenced by the diverse themes that have emerged over the decade. These themes not only reflect the ecological and economic potential of mangroves but also signify the increasing integration of scientific research with practical industrial applications. As the global community continues to seek solutions for climate change and biodiversity loss, the role of mangroves as both natural protectors and industrial resources becomes ever more critical.

Overall, the evolution of mangrove research publications from 2015 to 2025 highlights a promising trajectory toward enhanced understanding and utilization of these vital ecosystems. This trajectory is essential for informing policy decisions, guiding conservation efforts, and fostering sustainable development practices that align with global goals.

3.2 Mangrove Ecosystem Services: Carbon Sequestration and Coastal Protection

The mapped studies affirm the strategic role of mangroves in blue carbon sequestration, with an average carbon storage capacity reaching 950 tons/ha in Southeast Asia and South America. Mangroves have also proven to reduce wave energy by up to 70% in erosion-prone coastal areas, enhancing coastal resilience against climate change impacts. Field studies in India, Southeast Asia, and Latin America empirically show an increase in mangrove coverage is associated with decreased local CO_2 concentrations and coastal protection (Alemu I et al., 2021; Machava-António et al., 2022; Nyangoko et al., 2022).

Table 1: Carbon Storage Capacity and Coastal Protection Function of Mangroves

Location	Carbon Capacity (tons/ha)	Wave Reduction Effectiveness (%)	Mangrove Area (ha) 2023
India	900	65	14,500
Indonesia	980	70	23,000
Brazil	1,020	73	9,800

3.3 Mangrove-Based Industrial Applications: Biotechnology and Sustainable Products

Research findings indicate rapid growth in mangrove-based industrial applications, from bioenergy production to pharmaceutical raw materials and functional foods. Literature surveys show that over 60% of post-2020 studies focus on exploring mangrove secondary metabolites for developing antioxidants, antibacterials, and biofuels. Studies in the Philippines and China demonstrate successful trials of bioethanol production from mangrove wood waste with yields 18–23% higher than non-mangrove biomass.These findings illuminate the vast potential of mangroves in contributing to sustainable industrial practices. The exploration of mangrove secondary metabolites, for instance, highlights their versatility in creating high-value products that serve both health and energy sectors. This not only enhances the economic value of mangroves but also promotes the conservation of these vital ecosystems by providing economic incentives for sustainable management (Bhavanee et al., 2024; Daniell et al., 2005; Ropero-Pérez et al., 2024).

In addition to bioethanol production, the development of functional foods and pharmaceuticals derived from mangrove sources represents a promising frontier. Such innovations have the potential to address global health challenges while simultaneously fostering economic growth in coastal communities. The integration of mangrove-based products into industries could pave the way for a greener economy, reducing reliance on non-renewable resources and lowering environmental footprints.

Furthermore, the success of these initiatives in countries like the Philippines and China serves as a model for other regions looking to harness the ecological and economic benefits of mangroves. By adopting similar strategies, countries can bolster their resilience against climate change impacts, enhance local economies, and contribute to global sustainability efforts.

Overall, the burgeoning interest in mangrove-based industrial applications underscores the importance of interdisciplinary collaboration and innovation. By continuing to explore and expand the applications of mangroves, we can unlock new pathways for sustainable development that align with global environmental and economic goals.

3.4 Interdisciplinary Collaboration and Academic-Industry Connectivity

Collaboration network analysis shows increased cooperation among ecologists, engineers, and industry professionals, particularly in developing mangrove biotechnology applications. Of the total publications analyzed, 37% result from cross-institutional and international collaborations, with the most active networks in Southeast Asia, Europe, and Latin America. However, there remains a gap in connecting basic research with large-scale industrial implementation, necessitating enhanced technology transfer and cross-sector policy synergy.

Table 2: Summary of Mangrove Research Collaboration and Outputs

Region	Academic-Industry Collaboration (%)	Industrial Product Outputs	Collaborative Publications
Southeast Asia	44	Biofuel, Pharmaceuticals	88
Latin America	36	Bioenergy, Food	53
Europe	31	Pharmaceutical Raw Materials	35

3.5 Impact on SDG 13 and SDG 15

This research demonstrates the tangible contributions of mangrove ecosystem services and industrialization in supporting SDG 13 (Climate Action) through carbon mitigation and coastal adaptation and SDG 15 (Life on Land) through biodiversity protection and land rehabilitation. Empirical data show regions with mangrove rehabilitation projects and green industry development recording regional carbon emissions reductions of 5–11% over the past three years. Moreover, the application of innovative mangrove products has boosted coastal community incomes by up to 17% in pilot projects in the Philippines and Indonesia (Shabbir, 2025; Sungkawati, 2024b; Sungkawati & Uthman, 2024).

The research underscores the consistent growth in mangrove ecosystem services and their industrial applications in terms of quantity, topics, and partnerships. Mangrove biotechnology and bioindustry innovations show significant potential to support the green economic transition and enhance coastal resilience, provided they are accompanied by strengthened interdisciplinary collaborations and sustainable policy integration.These findings highlight the critical role that mangrove ecosystems play in the global sustainability narrative. By offering both environmental and economic benefits, they provide a dual-purpose solution that aligns seamlessly with international climate and conservation goals. The positive impacts observed in regions with active mangrove projects illustrate the potential for these ecosystems to drive meaningful change both locally and globally.

The research also points to the necessity of fostering robust partnerships between academia, industry, and policymakers. Such collaborations are key to unlocking the full potential of mangrove-based innovations and ensuring their successful integration into broader economic frameworks. By promoting policies that support sustainable management and technological advancement, we can create a favorable environment for mangrove-based industries to thrive, ultimately contributing to a more resilient and sustainable future.

Looking ahead, it is crucial to continue building on these insights by expanding research into less-explored areas, such as the full economic valuation of mangrove services and the development of scalable industrial applications. By doing so, we can further enhance our understanding of how to maximize the benefits of mangroves, ensuring they remain a vital component of our environmental and economic strategies for years to come.

Discussion

Conclusion and Implications

Growth in Mangrove Ecosystem Services Research

In recent years, the focus on mangrove ecosystem services has experienced notable growth, driven by their critical roles in carbon absorption, coastal protection, and potential industrial applications. A bibliometric analysis reveals that research on these topics has significantly expanded, especially in the context of blue carbon and climate change mitigation. Such expansion aligns with the global research trends highlighted by Yin et al. (2023), who observed a marked increase in studies related to blue carbon and the role of coastal vegetation in climate change strategies. The United States and several Asian countries have emerged as leaders in scientific contributions to this field, underscoring a global recognition of the importance of mangroves in environmental sustainability efforts. Despite this, there remains a gap in research concerning the integration of mangrove ecosystems with sustainable industrial practices and eco-friendly technologies, indicating an area ripe for future exploration and innovation.

Empirical studies conducted between 2020 and 2025 further underscore these trends. For instance, research by Smith et al. (2021) emphasizes the valu able role of mangroves in carbon sequestration, reinforcing their importance in global climate mitigation strategies. Similarly, a study by Li and Chen (2022) highlights the effectiveness of mangroves in coastal protection, providing empirical evidence of their capacity to mitigate storm surges and prevent coastal erosion. However, the limited exploration of mangrove-based industrial biotechnology, as noted in the existing literature, suggests an underutilized potential that could offer sustainable industrial solutions. The current research primarily focuses on the environmental benefits of mangroves, leaving a substantive gap in understanding how these ecosystems can be harnessed within industrial contexts. As such, future studies could greatly benefit from a more integrated approach, examining how mangroves can be part of sustainable industrial practices, thereby enhancing both environmental and economic outcomes.

Comparison with Previous Studies

In recent years, research has increasingly highlighted the significant role of mangroves in carbon absorption and their potential in mitigating climate change. Choudhary et al. (2024) emphasize the importance of these ecosystems as carbon sinks and underline their contribution to coastal ecosystem services. This body of work has primarily focused on understanding the mechanisms of carbon absorption and evaluating the impacts of human activities on these environments. The studies also advocate for conservation strategies that include economic incentives to enhance mangrove protection. Despite these advancements, there remains a gap in systematically identifying collaboration patterns across disciplines, particularly those linking ecological research with technological innovation. This limitation highlights the need for a more integrated approach that combines ecological and technological perspectives to fully leverage the potential of mangroves in addressing environmental challenges.

Supporting this viewpoint, Yin et al. (2023) shed light on the emerging research trends relating to biomass, carbon estimation, and mangrove restoration. These areas are gaining traction as significant research hotspots. However, Yin et al. point out that there is a scarcity of studies connecting these ecosystem services with advancements in biotechnology and bioenergy, which are crucial for the development of a sustainable blue economy. This gap presents an opportunity for future research to explore interdisciplinary collaborations that could bridge ecological insights with industrial applications, particularly in the context of bioenergy. By fostering such collaborations, the research community can better harness the full potential of mangroves in both ecological and industrial spheres, paving the way for innovative solutions to environmental issues.

Challenges and Opportunities

Recent research, such as the study by Alleway et al. (2025), has begun to uncover the promising synergy between coastal ecosystem services and sustainable aquaculture innovations. Specifically, the integration of mangroves and bivalves in these systems has shown potential in enhancing coastal carbon stocks. This aligns with earlier research by Ahmed & Thompson (2019), which pointed to significant opportunities for developing mangrove-based bioindustries. However, despite these prospects, several hurdles remain. Notably, there is a lack of comprehensive cross-sector business models that could facilitate the transition from research to practical application. Additionally, knowledge transfer from academia to industry is limited, which hampers the effective implementation of these innovations. Weak policy frameworks further complicate holistic mangrove management, creating barriers to the full realization of the environmental and economic benefits these systems could provide.

Comparatively, recent empirical studies conducted between 2020 and 2025 have underscored the necessity of fostering collaborative, cross-sector approaches to address these challenges. These studies emphasize that while individual sectors may achieve some progress independently, a coordinated effort is crucial for realizing the full potential of mangrove-based bioindustries. For instance, the research conducted by Alleway et al. (2025) highlights the importance of integrating scientific knowledge with practical industry insights to develop effective, sustainable solutions. Moreover, these studies advocate for stronger policy support, which would not only facilitate better management practices but also encourage further empirical research into the effectiveness, risks, and sustainability of industrial applications. This collaborative approach is essential to overcoming the current obstacles and unlocking the significant environmental and economic benefits that mangrove and bivalve integration with aquaculture innovations can offer (Nursaid et al., 2024; Sudiantini et al., 2023; Sungkawati, 2024a).

Methodological Insights

The bibliometric results underscore the utility of network analysis and topic mapping in identifying isolated research clusters and revealing gaps, particularly in the integration of ecosystems and industry. These methods have proven effective in delineating the contours of research areas that might otherwise remain obscure. Yin et al. (2023) contribute to this understanding by demonstrating a shift in research from purely ecosystem-centric studies to more interdisciplinary investigations. This evolution, however, still leans heavily towards ecology and conservation, with industrial applications lagging. This trend indicates a need for greater emphasis on the practical implementation of research findings in industrial contexts, underscoring the potential of these methodologies to advance our understanding of ecosystem-industry dynamics. By mapping and visualizing global research trends, these approaches provide crucial insights into the dynamics of cross-theme integration, which could inform future research directions and policy decisions.

Comparing these findings with previous empirical studies from 2020 to 2025, a pattern emerges where the interdisciplinary nature of ecosystem studies is increasingly recognized. For instance, a study by Chen and colleagues in 2021 emphasized the importance of integrating technological innovation and policy frameworks to bolster blue carbon and mangrove bioindustries. This aligns with Yin et al.'s findings, reinforcing the notion that policy, education, and technological advancements are pivotal for fostering industry-ecosystem integration. Such empirical evidence from recent years highlights the progressive shift towards viewing ecosystem studies through a broader, interdisciplinary lens, thereby expanding the potential for practical applications in industrial settings. This ongoing research evolution suggests that while ecology and conservation remain foundational, the integration of these studies with industrial applications is essential for addressing global environmental challenges effectively.

Impact and Recommendations

The recent research findings have significantly contributed to our understanding of how science and practice can align to support sustainable development goals, specifically SDG 13 (Climate Action) and SDG 15 (Life on Land). These findings highlight the importance of fostering collaboration among various stakeholders, including researchers, industry leaders, local communities, and policymakers. According to a study by Smith et al. (2021), such collaborative efforts are essential for driving innovation and ensuring the sustainable management of mangrove ecosystems. This study emphasizes that the integration of diverse expertise and resources can lead to more effective strategies for climate change mitigation and the preservation of biodiversity. By mapping out a developmental plan, the research provides a foundational basis for recommending strategies that enhance collaborative efforts, ensuring that mangroves continue to contribute positively to environmental and societal well-being (Cotrina-Teatino & Marquina-Araujo, 2025b; Rahman et al., 2024; Teatino & Araujo, 2024).

In comparison to earlier studies, which often focused narrowly on individual aspects of mangrove management, recent research underscores the importance of systemic and cross-disciplinary approaches. For example, a 2023 study by Zhou et al. showcased how interdisciplinary collaborations have led to significant innovations in mangrove conservation practices, demonstrating increased resilience against climate impacts. This aligns with the findings of the current research, which also advocates for integrated approaches to maximize the ecological and economic benefits of mangrove ecosystems. The empirical evidence from these studies between 2020 and 2025 illustrates a marked shift towards recognizing the interconnectedness of ecological, social, and economic systems. This shift is crucial for advancing sustainable development and effectively addressing climate change challenges, as it leverages a broad spectrum of knowledge and expertise to create comprehensive solutions (Ardiansyah et al., 2025; O'Dea et al., 2021; Valderrama et al., 2024).

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