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Mangrove ecosystems in climate change mitigation: A sociological and ecological approach

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ABSTRACT
Background: Mangroves have been identified as an effective strategy for climate change mitigation, due to their capacity to absorb carbon dioxide (CO_2) and safeguard coastal ecosystems. This study examines the role of mangrove ecosystems in climate change mitigation through the lens of both social and ecological approaches. Mangroves are acknowledged as efficacious carbon sinks and natural protectors for coastal communities, thereby making their contribution to climate resilience considerable. The objective of this research is to enhance awareness of the significance of mangrove ecosystems and to facilitate enhanced collaboration between diverse stakeholders in addressing climate change challenges. **Methods**: This study employs a bibliometric analysis methodology to examine pertinent literature, discerning research trends, patterns of collaboration between stakeholders, and the social impacts of mangrove ecosystem management. The data collected from scientific publications will provide a comprehensive picture of the intertwining of ecological and social aspects in climate change mitigation efforts. **Findings:** This study reveal a sharp increase in global research on mangrove ecosystems and climate change mitigation, alongside clear thematic clusters emphasizing carbon sequestration, ecosystem services, and conservation priorities. The analysis also shows that despite their vital role as major carbon sinks, mangroves remain threatened by deforestation, underscoring the need for strengthened conservation and restoration efforts. **Conclusion**: It is anticipated that the findings of this study will facilitate a more profound comprehension of the part played by mangroves in adaptation and mitigation strategies, thereby stimulating the formulation of more efficacious policies for the conservation and management of coastal resources. **Novelty/Originality of this article:** This article uniquely integrates ecological and social dimensions through a bibliometric analysis to reveal collaborative patterns and social impacts in mangrove-based climate change mitigation efforts.

KEYWORDS: bibliometric analysis; climate change mitigation; ecological approach; mangrove ecosystem; social approach.

1. Introduction

The problems of global warming and climate change are global challenges that are primarily driven by the emission of greenhouse gases, particularly carbon dioxide (CO_2) (IPCC, 2023). Greenhouse gas emissions encompass a range of substances, including carbon dioxide, methane, nitrogen dioxide, fluorinated gases, and other gases (IPCC, 2023). The primary sources of emissions can be attributed to the utilization of fossil energy, industrial activities, transportation, construction, waste management, agricultural practices, forestry, and other land uses. In 2022, global GHG emissions reached 57.4 $GtCO_2e$, representing a 1.2% increase compared to the previous year. The unrelenting surge in CO_2 emissions

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represents a significant threat to the sustainability of the planet, as it elevates temperatures and intensifies weather anomalies across all regions, resulting in phenomena such as heat waves, floods, droughts, and tropical cyclones (Clarke et al., 2022). Given that carbon dioxide emissions are primarily the result of the combustion of fossil fuels, it can be reasonably concluded that energy consumption represents a significant driving force behind climate change (Xue et al., 2021).

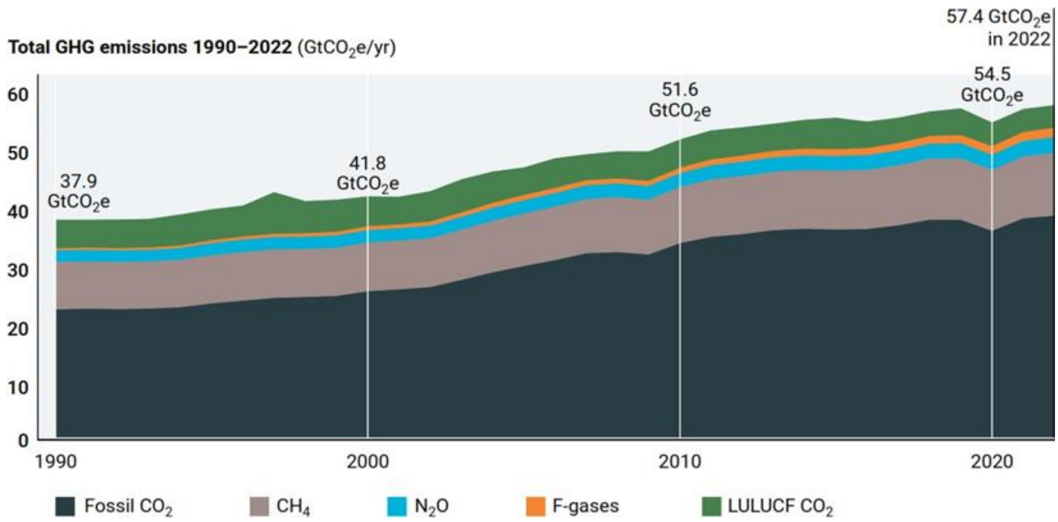

Fig. 1. Global greenhouse gas emissions for the period 1990-2022 (UNEP, 2024)

Global emissions reached their peak value in 2022, with an estimated 37.49 billion tons of CO_2 emitted annually (Sheehy et al., 2024). Land use change alone accounts for up to 20% of global carbon emissions (IPCC, 2007). It can be argued that the most effective way to mitigate and adapt to climate change through nature-based solutions is through land use, land use change, and forestry, particularly in the context of "blue carbon" (Sheehy et al., 2024). The term "blue carbon" was first proposed in 2009 by Nellemann & Corcoran (2009) to describe carbon captured by marine living organisms. Vegetated coastal habitats, particularly mangroves and seagrass beds, are exemplars of blue carbon ecosystems, wherein substantial quantities of carbon are captured in vegetation and sediments (McLeod et al., 2011). Despite occupying less than 0.4% of the Earth's surface, vegetated blue carbon ecosystems play a significant role in terrestrial carbon sequestration, accounting for approximately 1.3% of this process (Friess et al., 2016; Taillardat et al., 2020). Furthermore, vegetated blue carbon ecosystems comprise less than 2% of the seafloor but are responsible for up to 10% of the ocean's net primary production, representing approximately half of the global ocean carbon sinks (Duarte et al., 2017). It is therefore proposed that blue carbon sequestration represents a cost-effective solution to climate change, potentially reducing global carbon emissions by up to 3% by 2030 (Macreadie et al., 2021).

Mangrove forests serve as highly effective coastal carbon sinks, offering a potentially valuable means of mitigating climate change (Bernardino et al., 2024). Mangrove forests are among the most carbon-intensive coastal wetlands on Earth (Ouyang & Lee, 2014), despite occupying less than 0.1% of the Earth's total land area (Atwood et al., 2017). In the absence of disturbance, mangroves are capable of long-term carbon sequestration, with over two-thirds of the total stored carbon located underground (Alongi, 2023). Their soils have the capacity to store significant quantities of carbon over extended periods, with a high potential for long-term burial (Xiong et al., 2018). The global organic carbon stock in mangrove soils has been estimated to reach 10.2 Pg C (Kauffman et al., 2020), representing approximately 3% of the total carbon sequestration in tropical forests worldwide (Alongi, 2012). Prior research has indicated that soil carbon stocks constitute a significant portion of the total carbon pool in mangrove forests, with estimates ranging from 49 to 98% (Xiong et al., 2018). Moreover, soil organic carbon is a vital component of soil ecosystem services, including improved soil structure, water retention capacity, nutrient cycling, and cation exchange.

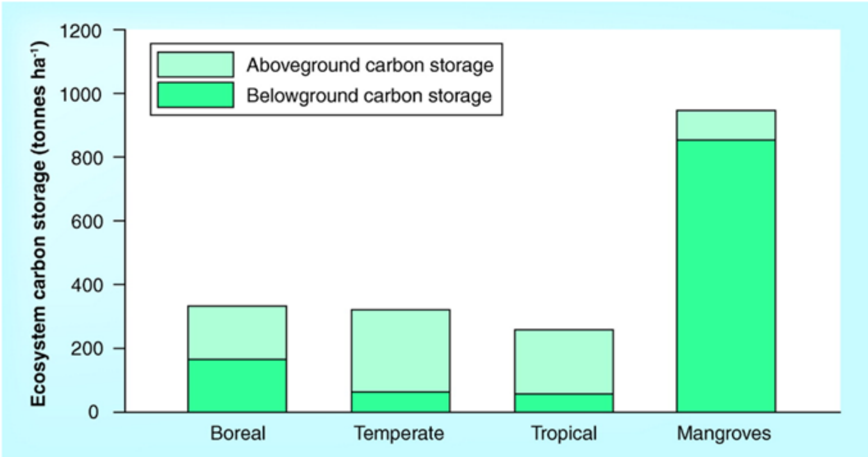

Fig. 2. The distribution of carbon stocks across ecosystems
(Nature Geoscience, 2022)

Research by Wang et al. (2009) demonstrates, the role of mangroves in providing ecological and social goods and services to local. These services include the stabilisation of coastlines and the mitigation of the adverse impacts of tropical storms and hurricanes. This is achieved by the effective reduction of storm surge, the minimisation of inundated areas and the maintenance of inland wetlands (Kraus et al., 2009). Additionally, mangroves exhibit some resistance to tsunamis and promote sediment deposition, thereby preventing coastal erosion and enhancing the safety of communities situated in coastal areas (Guannel, 2016). Moreover, mangroves demonstrate considerable potential for carbon sequestration, which can contribute to the mitigation of global warming (Li, 2023). The establishment of mangrove coastal ecosystems is economically advantageous in comparison to conventional coastal engineering practices (Rebecca, 2020). Additionally, mangroves provide a variety of resources, including food, medicine, fuel, and building materials, as well as opportunities for aquaculture (Thanne et al., 2024). Mangrove ecosystems serve an important function in the context of climate change mitigation and adaptation (Macreadie et al., 2021). In addition to acting as carbon sinks, these ecosystems provide a number of other benefits, including improvements in water quality (Adame et al., 2021), buffering against flooding and extreme events (Menéndez et al., 2020), serving as nurseries for fishery species (Jones et al., 2020), and coastal erosion prevention (Kazemi et al., 2021).

Fig. 3. Mangove ecosystem services
(Tussadiah et al., 2022)

The Indo-Pacific region is home to the largest and most diverse mangrove forests and seagrass beds in the world. The region is habitat to 37% of the world's mangrove forests and approximately 23% of the world's seagrass meadows, which encompass 42 and 21 species, respectively (McKenzie et al., 2020). These ecosystems provide a habitat for a variety of ecological communities, which enhance food security, improve livelihoods, and underpin the well-being of coastal populations (Friess et al., 2020a; Nordlund et al., 2017. The global mangrove forest area is estimated to be approximately 16,530,000 hectares, with Indonesia accounting for 3,490,000 hectares, representing 21% of the world's mangroves.

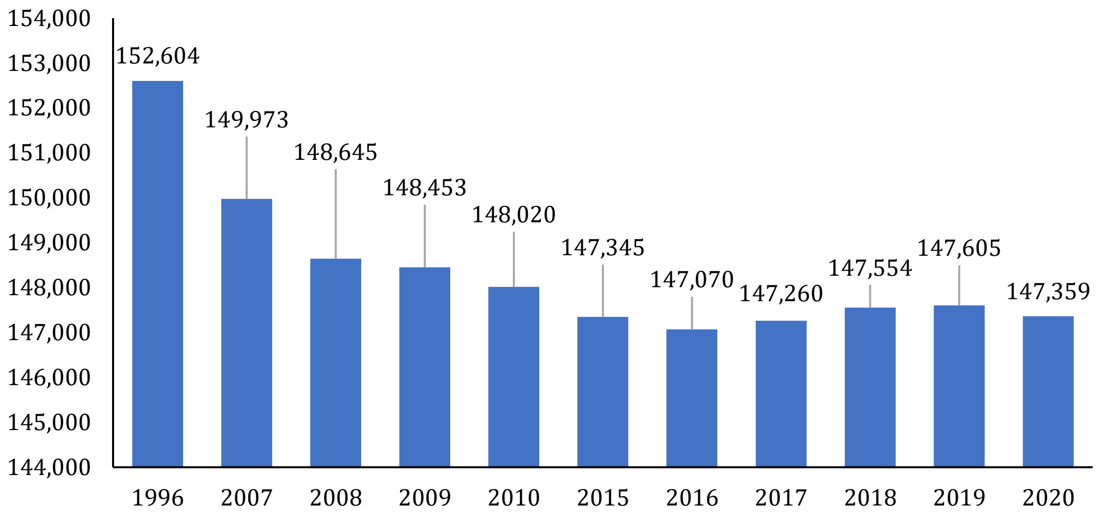

Fig. 4. Mangrove forest area in the world 1996-2020

The region has been identified as a global hotspot of mangrove deforestation due to anthropogenic activities, including aquaculture, agriculture, and urbanization (Bunting et al., 2022). From 1996 to 2020, a loss of 3329 km^2 (equivalent to 4.3% of the total mangrove area) was reported in the Asia-Pacific region (Bunting et al., 2022). This loss occurred mainly in Indonesia, Myanmar, Malaysia, the Philippines, Thailand, and Vietnam (Roy et al., 2024).

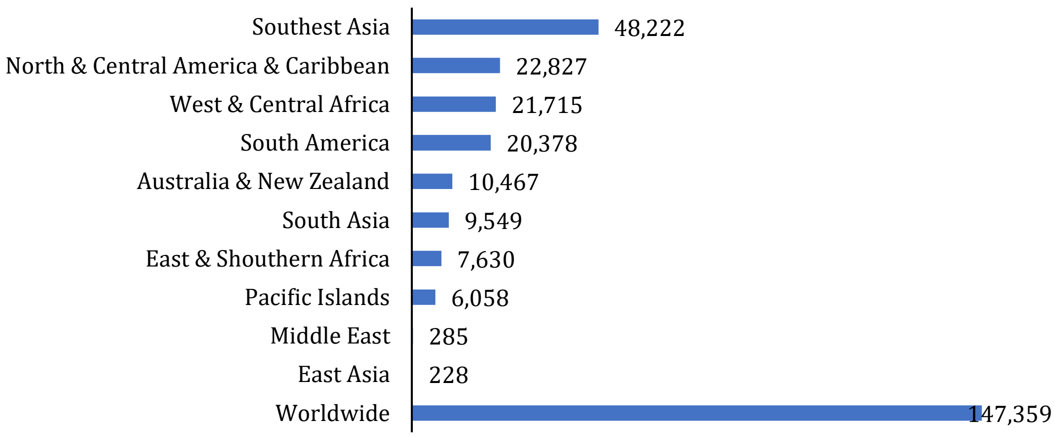

Fig. 5. Global mangrove cover by region

Despite this, the mapping results of the Ministry of Marine Affairs and Fisheries indicate that Indonesia has experienced a reduction in its mangrove area. In 2020, the area of mangroves was 3,311,208 hectares. This indicates that mangrove ecosystems have undergone degradation, particularly in Indonesia. The degradation of the mangrove ecosystem can be attributed to a number of factors. The primary factor contributing to mangrove degradation is unregulated human exploitation, including the extensive harvesting of mangrove vegetation (Mulyadi et al., 2018). Global emissions reached their peak value in 2022, with an estimated 37.49 billion tons of CO_2 emitted annually (Sheehy et al., 2024). Land use change alone accounts for up to 20% of global carbon emissions (IPCC, 2007). It is estimated that the use of mangrove land releases 0.15 to 1.02 billion tons of CO_2 annually (Pendleton et al., 2012). This figure represents 0.4-2.7% of the total global emissions in 2022 (Sheehy et al., 2024).

The estimated annual release of CO_2 from mangrove land use is 0.15-1.02 billion tons (Pendleton et al., 2012). This represents 0.4-2.7% of the total global emissions in 2022 (Sheehy et al., 2024). It can be argued that the most effective means of mitigating and adapting to climate change through nature-based solutions is through mangrove restoration, as part of the broader land use, land use change, and forestry sector (Sheehy et al., 2024). Mangrove restoration projects have emerged as a means of reducing carbon emissions (Lovelock & Duarte, 2019). Through collaboration between the private sector, government, and communities, mangrove restoration can serve as an integral component of climate change mitigation strategies (Alongi, 2014).

2. Methods

This research employs quantitative analysis techniques to examine the existing literature on the role of mangrove ecosystems in climate change mitigation, adopting a social and ecological perspective. The analysis is based on data drawn from Scopus. The quantitative method employed in this research is bibliometric analysis, which is a technique utilized to quantify and examine the literature pertinent to a specific subject matter. The bibliometric analysis of mangrove ecosystems, a quantitative method applied in this study, is an invaluable tool for elucidating trends and patterns in studies pertaining to the role of mangroves as climate change mitigation. The application of bibliometric analysis techniques enables researchers to identify key publications, prominent authors, and collaborative networks among researchers engaged in this field of study. Furthermore, this analysis can also provide insights into methodological developments, dominant research themes, and gaps in the existing literature. The information thus obtained enables stakeholders to devise more efficacious strategies for the conservation of mangroves and to enhance awareness of the significance of these ecosystems in the context of climate change mitigation. The present study employed bibliometric analysis to ascertain the nature of the information presented in publications pertaining to the disclosure of mangrove ecosystems in climate change mitigation in Asia.

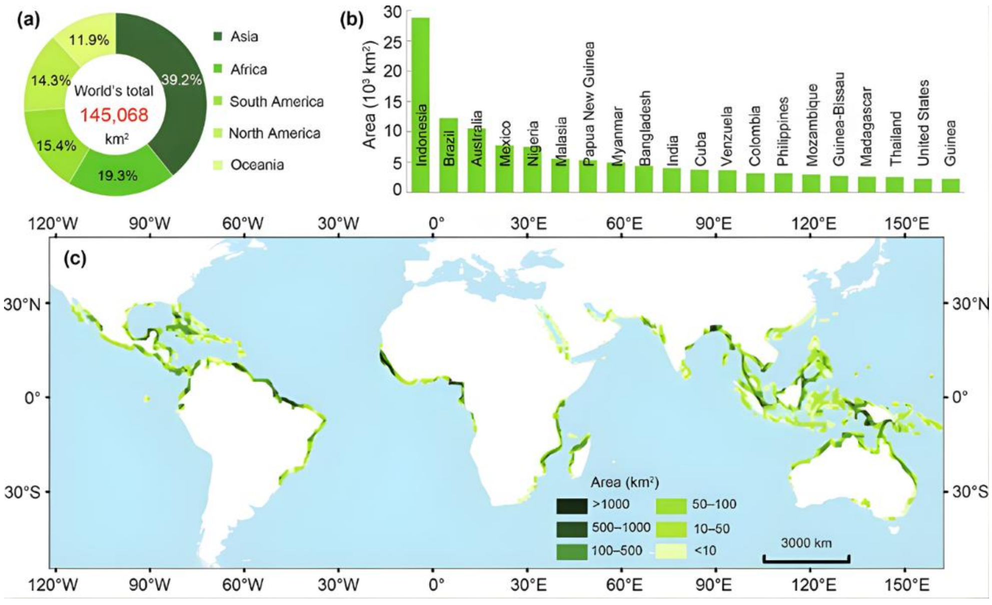

Fig. 6. The global extent of mangrove forests in 2020
(Jia et al., 2023)

The application of quantitative methods in this study offers a more comprehensive understanding of mangrove ecosystems, facilitating the identification of opportunities for conservation, climate change mitigation, and carbon sequestration. The combination of these two methods exhibits the evolution of scientific knowledge in a field through the application of quantitative bibliometric tools and a systematic qualitative review, which enables the determination of in-depth topic content. The method must be clear with description of the materials used in the study, the population and sample or key informant, research variables, data sources, the general procedures and techniques, the data collection technique, the analysis method, and data presentation. For research using experiments, the method should also include the design or the setup of the research. For article review, the author should also describe the theoretical components. For a qualitative method, the author may include the methods in data condensation (for example, coding system), data display (how the data is presented which allow for drawing conclusion), and conclusion drawing. For quantitative methods, the author may include the methods in sampling, data collection, and data analysis.

This research involved an online search of the academic literature for the period 2019 to 2024. The use of updated article data (2019-2024) will ensure greater relevance in the context of the current research, as mangrove ecosystems in climate change mitigation with social and ecological approaches continue to evolve and change over time. The inclusion of more recent information will facilitate the generation of a more accurate picture of current trends and challenges. The Scopus database, developed by Elsevier, was utilized for this study. This study employed the following combination of search queries to explore article titles, abstracts, and keywords in the Scopus database using the TITLE-ABS-KEY operator (mangrove AND ecosystem AND climate AND change AND mitigation) AND PUBYEAR > 2019 AND PUBYEAR < 2024 AND (LIMIT-TO (SUBJAREA, "ENVI")). Furthermore, the search was limited to articles with the document type "ar." Furthermore, the search was limited to articles written in the English language. The search yielded a total of 152 documents.

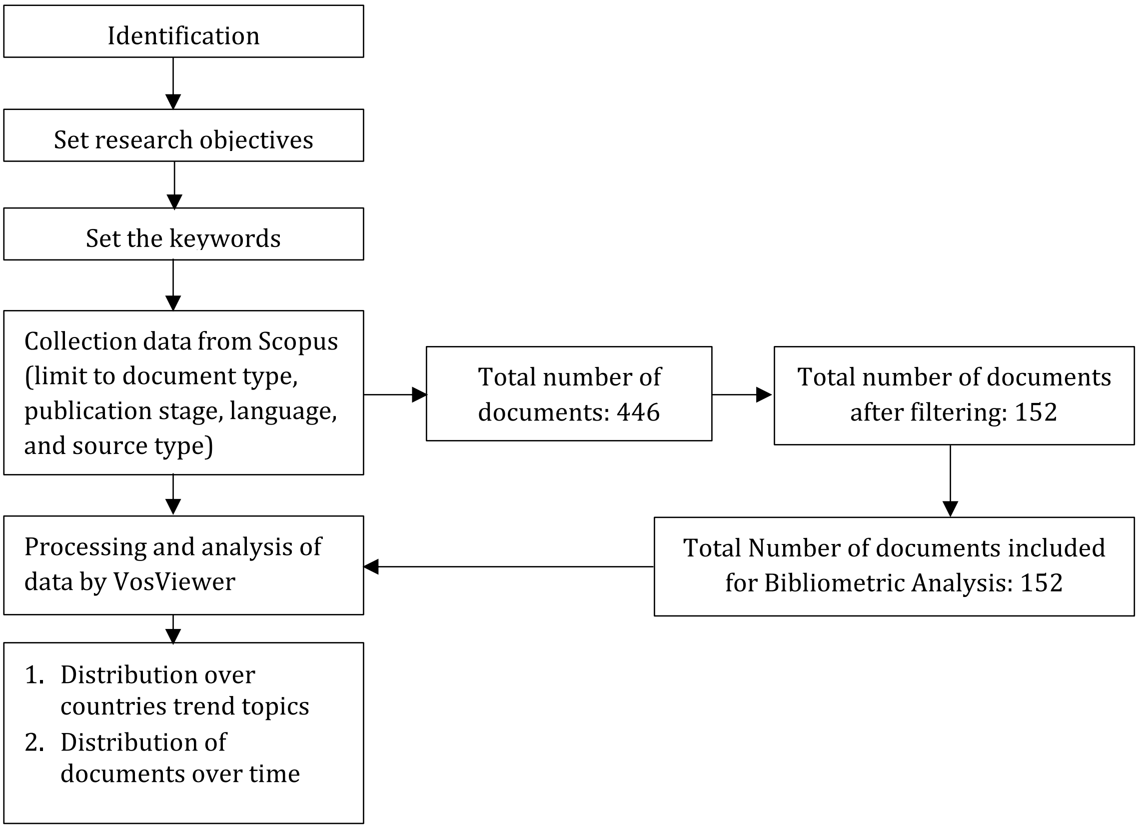

Fig. 7. Flow diagram of the research design

3. Results and Discussion

3.1 Descriptive analysis

Descriptive analysis indicators are presented in this section to directly address the first research question regarding how trends in scientific publications related to mangrove ecosystems and climate change mitigation have evolved over the past decade. The intersection of mangrove ecosystems and climate change mitigation has emerged as a significant area of research, given the important role mangroves play in addressing increasingly pressing environmental challenges. This article presents a bibliometric analysis of research on this topic, aiming to map the evolving landscape and identify key trends and insights. Figure 88 illustrates publication trends on mangrove ecosystems in the context of climate change mitigation from 2019 to 2024. The early stages of 2019 showed an emerging awareness of the importance of mangroves in climate change mitigation, with only 14 publications identified. However, over time, research interest increased rapidly, reflecting greater global attention to the need to conserve these ecosystems for environmental sustainability. These limited results likely reflect the still-evolving attention to mangrove ecosystems in the context of climate change mitigation since 2019 (Geraldi et al., 2019).

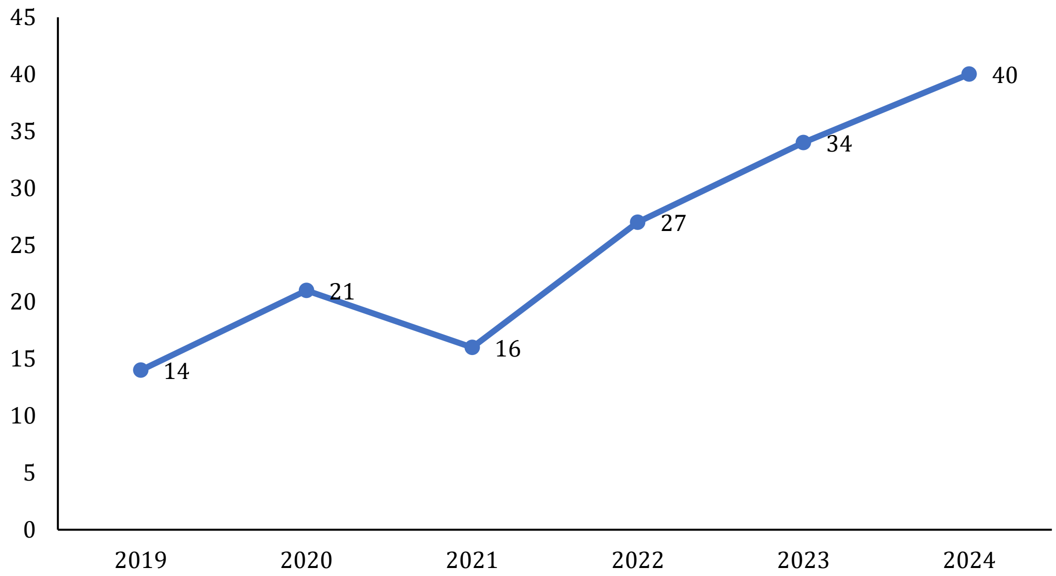

Fig. 8. The following is a list of publications from 2019 to 2024–scopus database

A significant increase in research activity on mangrove ecosystems in climate change mitigation has been seen in recent years. Publications peaked in 2024 with 40 articles, indicating increasing recognition of the crucial role of these ecosystems in climate change mitigation strategies. This surge in research is likely influenced by several factors, such as (1) increased awareness of the importance of mangrove conservation–as the challenge of climate change becomes more pressing, researchers are focusing on the potential of mangroves as effective carbon sinks, (2) growing empirical evidence–early research showing the link between mangrove management and greenhouse gas emission reductions attracted the attention of more researchers, (3) increased support from governments and international organizations–global initiatives to protect coastal ecosystems are driving the allocation of funds and resources to further research in this area.

Figure 9 presents a concise overview of the geographical distribution of research activities on mangrove ecosystems and their role in climate change mitigation. Despite the global scope of the field, some countries exhibit a notable degree of involvement in mangrove-related policy development (Tan & Fogarty, 2019), reflecting the pivotal role these ecosystems play in carbon sequestration and environmental protection (McLeod et al., 2011). The majority of article publications are the result of contributions from a number of countries, including the United States, Australia, Indonesia, China, and India.

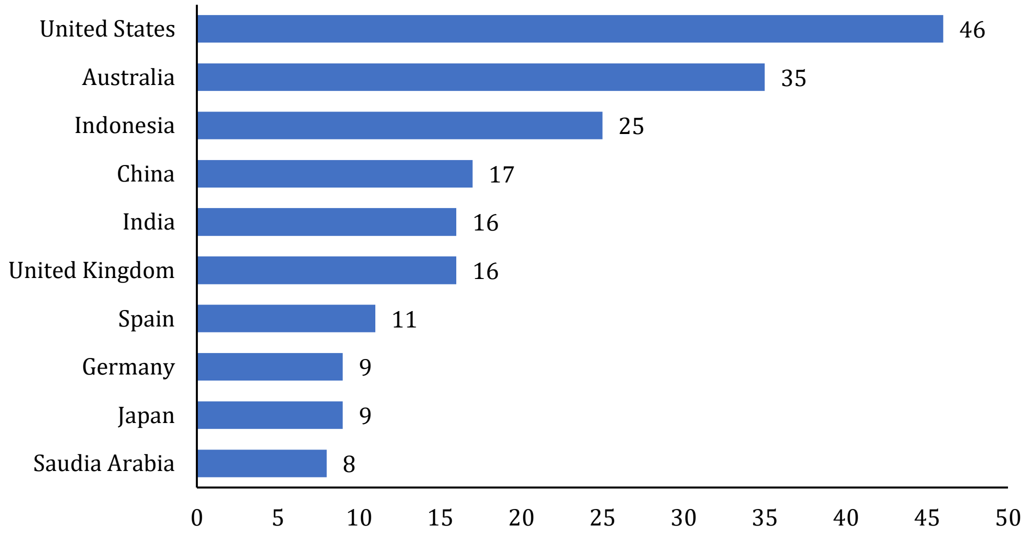

Fig. 9. Document statistics by country or region–scopus database

The United States has emerged as a pioneer in mangrove ecosystem research and climate change mitigation, with 46 publications to its name. This reflects the country's strong academic tradition and commitment to addressing pressing environmental issues. Australia, with 35 publications, evinces a pronounced interest in investigating the social and ecological consequences of mangrove management. Indonesia, with 25 publications, evinces a noteworthy commitment to the conservation of mangrove ecosystems, which are vital to the sustainability of the environment and the well-being of coastal communities. China, with 17 publications, has been engaged in investigating the interconnections between mangrove conservation and climate change mitigation strategies. India, with 16 publications, demonstrates a growing interest in utilizing mangrove ecosystems to address environmental and social challenges. These research activities reflect a growing global awareness of the importance of mangrove ecosystems in the context of climate change. Furthermore, international collaboration is crucial for developing more comprehensive solutions. The knowledge and experience from different countries can be utilized to complement one another, thereby enhancing the overall effectiveness of the solution. Consequently, the preponderance of publications from these countries reflects the global endeavor to comprehend and safeguard mangrove ecosystems as a means of effectively mitigating climate change.

This study was able to reveal the main thematic clusters in mangrove ecosystems and climate change mitigation by analyzing the occurrence of keywords in academic publications. The VosViewer application was employed to identify five principal groups based on the occurrence of frequently occurring keywords, which are illustrated in Figure 10. The mapping illustrates a comprehensive range of research interests within this field, encompassing topics such as climate change, mangroves, carbon sequestration, conservation, restoration, mitigation, and carbon emissions, as well as ecosystem services. These thematic clusters reflect the intricate interconnections between ecological and social factors in mangrove ecosystem management, underscoring the necessity for a multidisciplinary approach in future research.

The primary focus of this research is the role of mangrove ecosystems in climate change mitigation, specifically the vital function such ecosystems perform in carbon sequestration and environmental protection. In addition to its role as an effective carbon sink, the mangrove ecosystem plays a crucial part in disaster mitigation, reducing the risk of tidal disasters and abrasion (Horchard et al., 2019). Furthermore, it serves as a nursery and feeding ground for aquatic organisms (Carrasquilla-Henao et al., 2019). This research examines the potential for sustainable management and community or stakeholder participation to enhance mangroves' capacity to adapt to climate change (Spalding & Parrett, 2019). Accordingly, an examination of the nexus between mangrove ecosystems and climate change mitigation is of particular significance in the broader context of global initiatives aimed at curbing the adverse effects of climate change and fostering environmental sustainability.

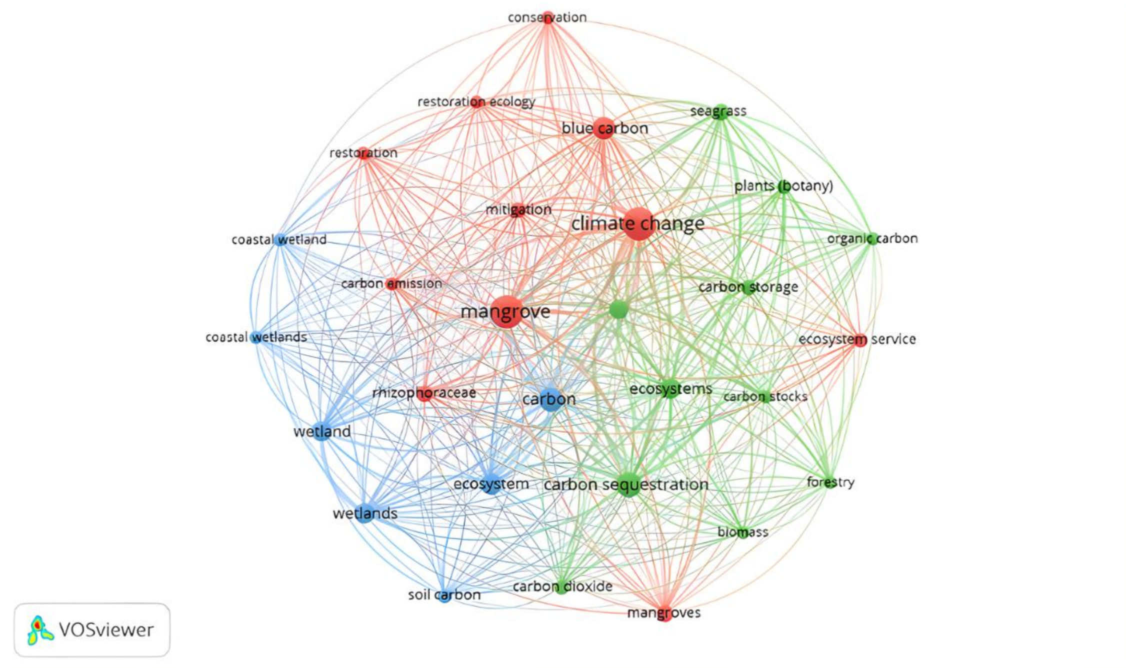

Fig. 10. The network of mangrove ecosystem involvement in climate change mitigation presented here was created using VOSviewer.

A bibliometric analysis of keywords by publication year offers profound insight into the evolution of topics and research focus within the field of mangrove ecosystems. By monitoring the evolution of keywords over time, researchers can identify emerging trends, such as an increased focus on issues related to climate change, disaster risk mitigation (Adame et al., 2018), and the role of mangroves as habitats for biodiversity (Carrasquilla-Henao et al., 2019). The data is a valuable resource, as it indicates significant shifts in the focus of research as global environmental issues and societal needs evolve. Furthermore, the analysis facilitates the mapping of relationships between keywords, reflecting the integration of multiple disciplines, including ecology and social sciences. An appreciation of the evolution of keywords over time enables researchers to identify deficiencies in the existing literature and areas that require further investigation. In this way, bibliometric analysis not only facilitates the development of more targeted and relevant research strategies, but also contributes to a more nuanced understanding of the role of mangrove ecosystems in the context of climate change and overall environmental sustainability. The bibliometric analysis indicates that in 2024, the primary focus of research is on issues related to mitigation, carbon storage, and ecosystem services. Meanwhile, the majority of studies on mangroves, climate change, and carbon sequestration were conducted between the years 2022 and 2023. This suggests that although research has recently concentrated on issues such as climate change, carbon storage, and mitigation, there is still scope to enhance comprehension of the significance of mangrove ecosystems in climate change mitigation.

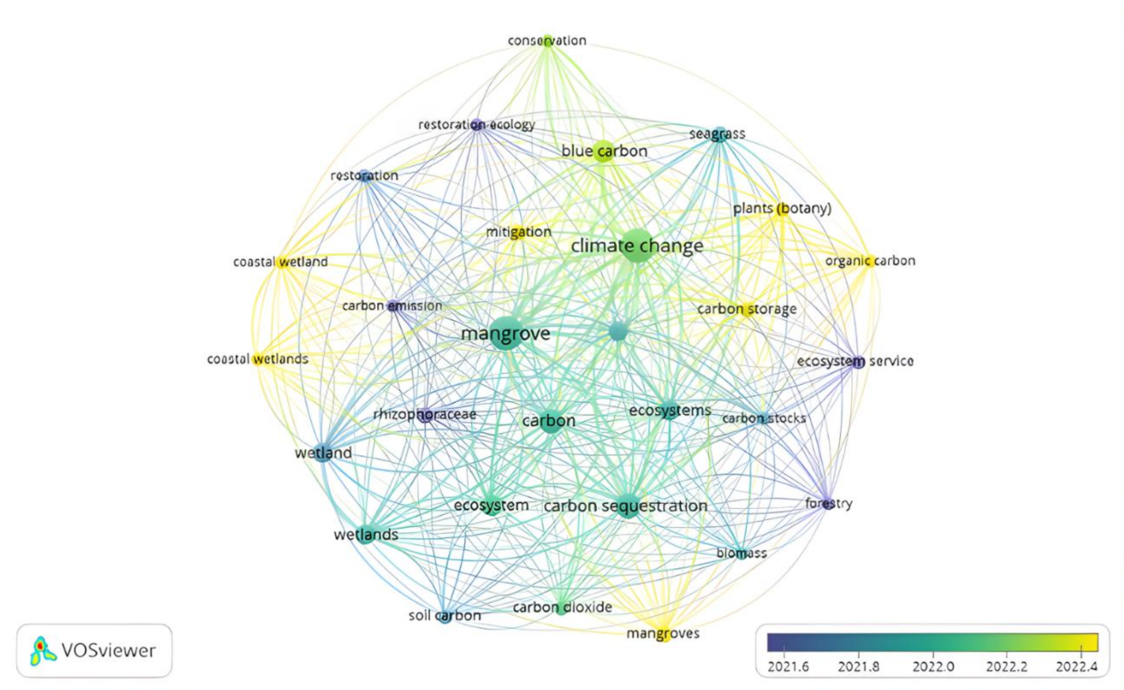

Fig. 11. The analysis of documents by year of novelty was created using VOSviewer

3.2 In-depth analaysis of selected content

In the range of 2019-2024, focusing on the keyword mangrove ecosystem in climate change mitigation, only thirteen articles were found. Selected articles that have a strong relationship with these keywords will be discussed further.

Table 1. Review of studies on mangrove restoration, conservation, and their contribution to climate change mitigation

Title	Authors	Findings
Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia	Arifanti et al. (2022)	This article focuses on highlighting the importance of conserving and restoring existing mangroves as a more effective strategy for reducing carbon emissions and achieving Indonesia's NDC targets, compared to large-scale reforestation projects with limited contribution.
Optimal mangrove restoration through community engagement on coastal lands facing climatic risks: The case of Sundarbans region in India	Ranjan (2019)	This article focuses on evaluating the effectiveness of community-led mangrove restoration in India's Sundarbans, focusing on the role of carbon credits in improving local livelihoods and accelerating the restoration of mangroves threatened by extreme cyclones, while highlighting the importance of financial incentives comparable to traditional incomes to ensure long-term commitment.
Importance of mangrove plantations for climate change mitigation in Bangladesh	Uddin et al. (2023)	This article focuses on evaluating the contribution of mangrove plantations to blue carbon sequestration and climate change mitigation in Bangladesh,

		considering the role of natural mangroves in coastal protection and cyclone impact reduction.
Carbon storage potential of mangrove forests from Northeastern Vietnam	Nguyen et al. (2020)	This article focuses on highlighting the importance of mangrove ecosystems, particularly in Vietnam's Dong Rui Mangrove Forest (DRM), as a significant carbon store with a large capacity to capture and sequester carbon in sediment layers, contributing to global climate change mitigation.
The impacts of degradation, deforestation and restoration on mangrove ecosystem carbon stocks across Cambodia	Sharma et al. (2020)	This article focuses on assessing the impact of conversion of mangrove forests to aquaculture, oil palm plantations and other developments on carbon stock loss and the effectiveness of a mangrove restoration project using the monospecific plant Rhizophora sp. in restoring mangrove carbon storage capacity.
Stakeholder preferences for payments for ecosystem services (PES) versus other environmental management approaches for mangrove forests	Thompson & Friess (2019)	This article focuses on the importance of incorporating local knowledge into mangrove conservation approaches, and explores the potential application of Payments for Ecosystem Services (PES) as a more socially acceptable and effective alternative to conventional conservation approaches.
Mangrove wetland recovery enhances soil carbon sequestration capacity of soil aggregates and microbial network stability in southeastern China	Ning et al. (2024)	The article focuses on highlighting that although mangrove wetlands provide a range of important ecosystem services, intensive aquaculture expansion and coastal land reclamation since the beginning of the 21st century has led to the loss of 62% of the world's mangroves, with 80% of the loss concentrated in Southeast Asia, mainly due to the development of shrimp and fish farms.

This study highlights the importance of mangrove ecosystems as a significant carbon store and a critical component of climate change mitigation. However, mangrove deforestation is one of the major threats hindering the potential of these ecosystems to mitigate climate change. The loss of mangroves to activities such as aquaculture, land reclamation and development has led to significant land degradation and reduced the carbon storage capacity of these ecosystems (Ning et al., 2024). Mangrove deforestation not only results in the release of carbon stored in biomass and sediment to the atmosphere, but also removes important ecosystem services such as coastal protection and biodiversity conservation (Ning et al., 2024).

Region	Year	Extent (km²)	Compared to 1996 Net change (km²)	Compared to 1996 Net change (%)
Africa	1996	29,993	0	-
	2020	29,345	-648	-2.2
Americas	1996	44,465	0	-
	2020	43,205	-1,260	-2.8
Asia-Pacific	1996	78,146	0	-
	2020	74,809	-3,338	-4.3
Global	1996	152,604	0	-
	2020	147,359	-5,245	-3.4

Fig. 12. Mangrove change between 1996 and 2020
(UNEP, 2024)

Recent estimates of mangrove deforestation range from 0.16% to 0.39% per year at regional and global scales. However, the baseline datasets used do not capture dynamic changes due to natural processes and human disturbance, or local-scale variability in canopy structure and vegetation biomass (Hamilton & Friess, 2018). Mangrove loss in the 20th century was largely driven by forest clearance and exploitation for timber and raw material production, as well as rapid coastal population growth and urban expansion (Richards & Friess, 2016; Thomas et al., 2017). Mangrove loss in the 20th century has been largely driven by forest clearing and exploitation for timber and raw material production, as well as rapid population growth and urban expansion in coastal areas (Richards & Friess, 2016; Thomas et al., 2017). Mangrove loss due to exploitation and urbanization puts pressure for more sustainable resource management, making forest growth and reforestation rates critical information to support sustainable forest management practices and data-driven decision processes in conservation and restoration projects (Díaz-Balteiro & Romero, 2008). Conservation of existing mangroves is more effective than large-scale reforestation, which contributes little to carbon emission reductions (Arifanti et al., 2022).

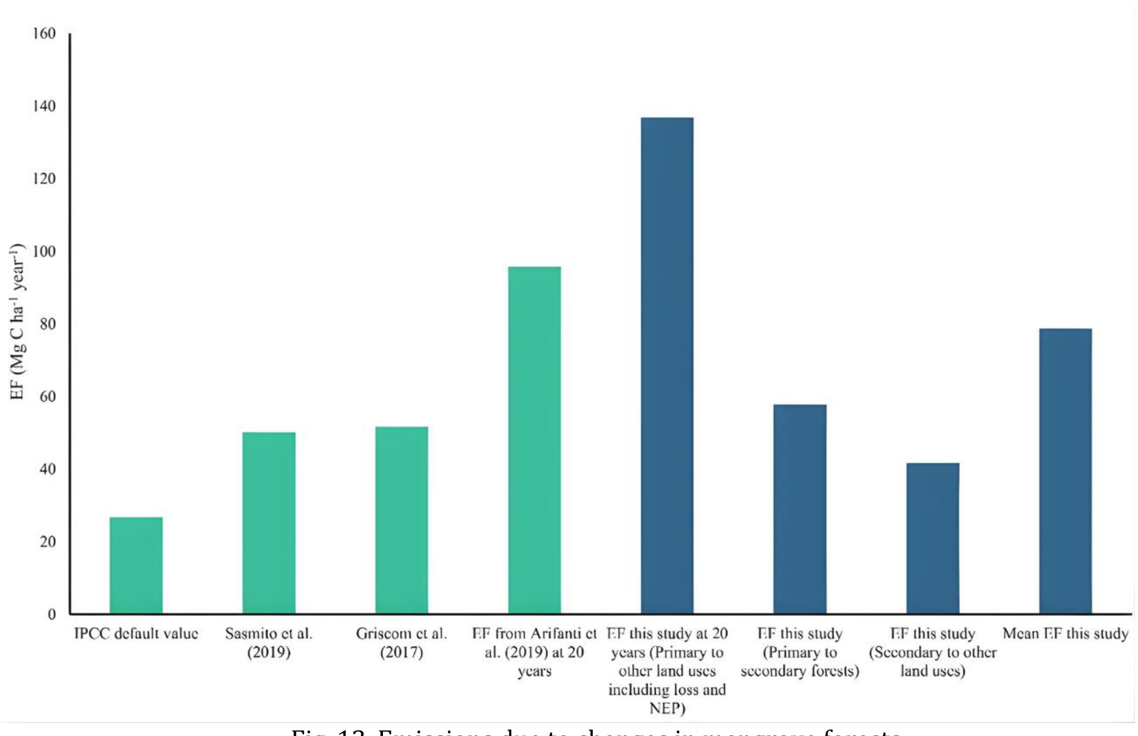

Fig. 13. Emissions due to changes in mangrove forests
(Arifanti et al., 2022)

Protection of remaining mangroves, combined with restoration of degraded areas, can optimize the potential of mangroves as a net carbon sink and support Indonesia's Nationally Determined Contribution (NDC) targets (Arifanti et al., 2022). Under a business-as-usual (BAU) scenario, mangrove loss could result in global emissions of up to 2,391 Tg CO_2 eq by the end of the century (2010-2100). If the loss of soil carbon sequestration potential due to deforestation is taken into account, this figure could increase to 3,392 Tg CO_2 eq. Previous estimates of emissions from mangroves over the same period show significant variation, ranging from 630 to 40,230 Tg CO_2 eq (Friess et al., 2020b). In Indonesia, the conversion of mangroves to aquaculture ponds accounts for nearly 15% of total national carbon emissions, demonstrating the sector's significant impact on climate change (Murdiyarso et al., 2015). In Myanmar, mangrove deforestation is largely driven by national policies that prioritize rice production intensification as a strategy to improve food security at the expense of mangrove ecosystem sustainability (Webb et al., 2014). The main drivers of mangrove deforestation are urban development, aquaculture, mining, and overexploitation of timber, fish, crustaceans, and shellfish (Alongi, 2014).

These deforestation rates represent a potential loss of 2.0-7.5 million tons C yr-1 from mangrove soils, which is equivalent to ~7.3-27.5 million tons of CO_2 emissions annually (Atwood et al., 2017). Global emissions from soil carbon loss are based on a stock change approach. Carbon loss from mangrove soils is equivalent to 0.6% of annual global CO_2 emissions from deforestation (Atwood et al., 2017), taking into account that 43% of C stocks up to 1 m in the soil are remineralized after mangrove deforestation and immediately released to the atmosphere as CO_2 (Atwood et al., 2017). Another study estimated that mangrove conversion could release 84-159 million tons of CO_2 into the atmosphere, assuming that between 27.25% and 90% of the carbon stored in the soil is lost after deforestation (Siikamäki et al., 2012).

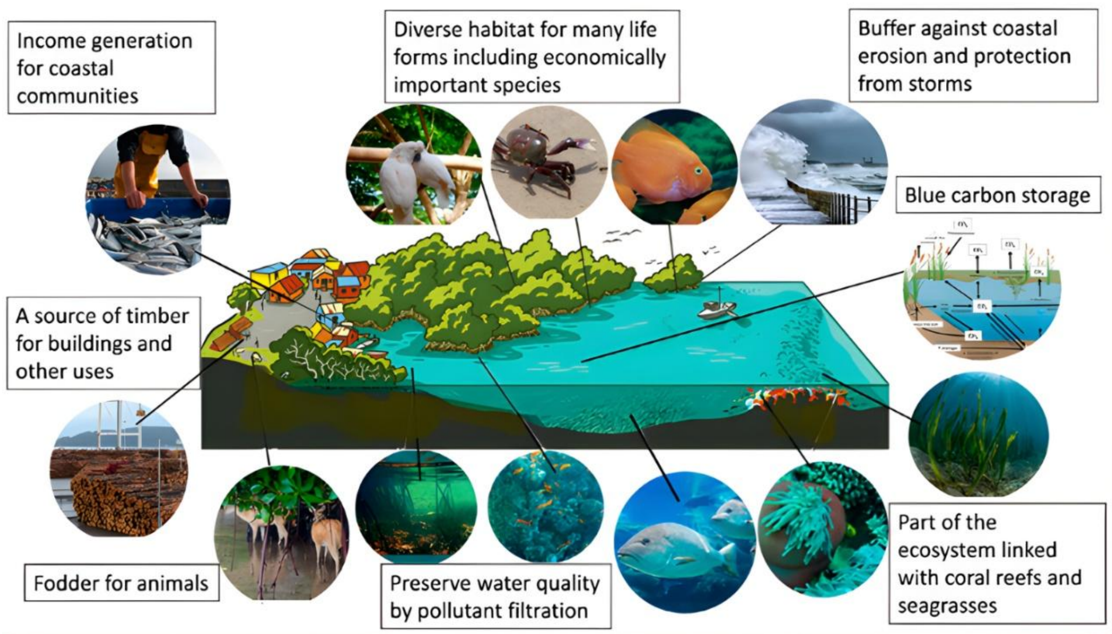

Fig. 14. Functions and services of an intact mangrove ecosystem (Akram et al., 2024)

Mangroves provide a range of ecosystem services essential for environmental sustainability and human well-being, in addition to acting as a significant carbon sink. Mangroves provide a wide range of benefits known as ecosystem services (Millennium Ecosystem Assessment, 2005), making them invaluable to human populations in many parts of the world (Barbier et al., 2011). Coastal communities in particular have long utilized the provisioning services of mangroves, such as extracting construction materials and firewood for daily needs (Chow, 2018) and catching shellfish and finfish as primary food sources (Carrasquilla-Henao et al., 2019). In addition, mangroves also provide cultural ecosystem services, including recreational, aesthetic, and spiritual values that contribute to the emotional and social well-being of coastal communities (Spalding & Parrett, 2019).

In addition, mangroves play an important role in providing valuable regulating services, such as coastal protection from erosion and natural disasters (Ranjan, 2019), assimilation of pollutants to maintain environmental quality (Horchard et al., 2019), and climate regulation through carbon storage and sequestration (Adame et al., 2018). These regulating services range from local scales, such as directly protecting coastal communities from the threat of storm surges and storms, to global scales, such as mitigating climate change through climate regulation. With benefits that span multiple ecological, social, and economic dimensions, mangroves are irreplaceable environmental assets, making them a central focus of sustainable conservation and restoration strategies.

4. Conclusion

Mangrove ecosystems contribute significantly to the mitigation of climate change due to their capacity to sequester carbon dioxide and safeguard coastal ecosystems. The present study demonstrates, through bibliometric analysis and a systematic literature review, that mangroves serve not only as effective carbon sinks, but also as a source of a range of ecosystem services that support the resilience of coastal communities. The findings underscore the necessity for interdisciplinary collaboration among stakeholders to enhance sustainable mangrove management practices. The analysis additionally indicates a trend of increasing global attention to mangrove research in the context of climate change mitigation. The year-on-year increase in the number of publications is indicative of a growing awareness of the importance of conserving these ecosystems. The countries engaged in this research demonstrate a commitment to the protection and utilisation of mangroves, which is aligned with global efforts to reduce greenhouse gas emissions. From this comparative analysis, it can be concluded that the most effective approach to climate change mitigation through mangrove ecosystems is an integrated approach focusing on both social and ecological aspects. The involvement of local communities in mangrove management and restoration, coupled with the reinforcement of conservation-oriented policies, offers a viable strategy for fostering more efficacious synergies that can effectively address the multifaceted challenges posed by climate change. Additional research is required to identify optimal practices and enhance understanding of the significance of mangrove ecosystems in the context of environmental sustainability.

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Author Contribution

The author solely contributed to the study's conception, design, data collection, analysis, and manuscript preparation. The author was responsible for drafting, reviewing, and approving the final version of the manuscript for publication.

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References
Adame, M. F., Connolly, R. M., Turschwell, M. P., Lovelock, C. E., Fatoyinbo, T., Lagomasino, D., Goldberg, L. A., Holdorf, J., Friess, D. A., Sasmito, S. D., Sanderman, J., Sievers, M., Buelow, C., Kauffman, J. B., Bryan-Brown, D., & Brown, C. J. (2021). Future carbon emissions from global mangrove forest loss. *Global change biology*, *27*(12), 2856–2866. https://doi.org/10.1111/gcb.15571

Adame, M. F., Najera, E., Lovelock, C. E., & Brown, C. J. (2018). Avoided emissions and conservation of scrub mangroves: Potential for a Blue Carbon project in the Gulf of California, Mexico. *Biology letters*, *14*(12), 20180400. https://doi.org/10.1098/rsbl.2018.0400

Akram, H., Hussain, S., Mazumdar, P., Chua, K. O., Butt, T. E., & Harikrishna, J. A. (2023). Mangrove Health: A Review of Functions, Threats, and Challenges Associated with Mangrove Management Practices. *Forests*, *14*(9), 1698. https://doi.org/10.3390/f14091698

Alongi D. M. (2014). Carbon cycling and storage in mangrove forests. *Annual review of marine science*, *6*, 195–219. https://doi.org/10.1146/annurev-marine-010213-135020

Alongi, D. M. (2012). Carbon sequestration in mangrove forests. *Carbon Management*, *3*(3), 313–322. https://doi.org/10.4155/cmt.12.20

Alongi, D.M. (2023). Current status and emerging perspectives of coastal blue carbon ecosystems. *Carbon Footprints*. http://dx.doi.org/10.20517/cf.2023.04

Arifanti, V. B., Kauffman, J. B., Subarno, Ilman, M., Tosiani, A., & Novita, N. (2022). Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia. *Global Change Biology*, *28*(15), 4523-4538. https://doi.org/10.1111/gcb.16216

Atwood, T. B., Connolly, R. M., Almahasheer, H., Carnell, P. E., Duarte, C. M., Ewers Lewis, C. J., Irigoien, X., Kelleway, J. J., Lavery, P. S., Macreadie, P. I., Serrano, O., Sanders, C. J., Santos, I., Steven, A. D. L., & Lovelock, C. E. (2017). Global patterns in mangrove soil carbon stocks and losses. *Nature Climate Change, 7*, 523–528. https://doi.org/10.1038/nclimate3326

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs, 81*(2), 169–193. https://doi.org/10.1890/10-1510.1

Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R. M., Thomas, N., Tadono, T., Worthington, T. A., Spalding, M., Murray, N. J., & Rebelo, L.-M. (2022). Global Mangrove Extent Change

1996–2020: Global Mangrove Watch Version 3.0. *Remote Sensing*, *14*(15), 3657. https://doi.org/10.3390/rs14153657

Carrasquilla-Henao, M., Ban, N., Rueda, M., & Juanes, F. (2019). The mangrove-fishery relationship: A local ecological knowledge perspective. *Marine Policy, 108*, 103656. https://doi.org/10.1016/j.marpol.2019.103656

Chow, J. (2018). Determinants of household fuelwood collection from mangrove plantations in coastal Bangladesh. *Forest Policy and Economics, 96*, 83–92. https://doi.org/10.1016/j.forpol.2018.08.007

Clarke, B., Otto, F.E., Stuart-Smith, R.F., & Harrington, L.J. (2022). Extreme weather impacts of climate change: an attribution perspective. *Environmental Research: Climate, 1*. https://doi.org/10.1088/2752-5295/ac6e7d

Díaz-Balteiro, L., & Romero, C. (2008). Making forestry decisions with multiple criteria: A review and an assessment. *Forest Ecology and Management, 255*(8-9), 3222–3241. https://doi.org/10.1016/j.foreco.2008.01.038

Duarte, C. M., Wu, J., Xiao, X., Bruhn, A., & Krause-Jensen, D. (2017). Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers in Marine Science, 4*, 100. https://doi.org/10.3389/fmars.2017.00100

Friess, A. D., Yando, E. S., Abuchahla, G. M. O., Adams, J. B., Cannicci, S., Canty, S. W. J., Cavanaugh, K. C., Connolly, R. M., Cormier, N., Dahdouh-Guebas, F., Diele, K., Feller, I. C., Fratini, S., Jennerjahn, T. C., Lee, S. Y., Ogurcak, D. E., Ouyang, X., Rogers, K., Rowntree, J. K., Sharma, S., Sloey, T. M., & Wee, A. K. S. (2020a). Mangroves give cause for conservation optimism, for now. *Current Biology, 30*(4), R153–R154. https://doi.org/10.1016/j.cub.2019.12.054

Friess, D. A., Thompson, B. S., Brown, B., Amir, A. A., Cameron, C., Koldewey, H. J., & Sidik, F. (2016). Policy challenges and approaches for the conservation of mangrove forests in Southeast Asia. *Conservation Biology, 30*(5), 933–949. https://doi.org/10.1111/cobi.12784

Friess, D., Krauss, K. W., Taillardat, P., Adame, M., Yando, E. S., Cameron, C., Sasmito, S., & Meriadec, S. (2020b). Mangrove blue carbon in the face of deforestation, climate change, and restoration. *Annual Plant Reviews, 3*. https://doi.org/10.1002/9781119312994.apr0752

Geraldi, N. R., Ortega, A., Serrano, O., Macreadie, P. I., Lovelock, C. E., Krause-Jensen, D., Kennedy, H., Lavery, P. S., Pace, M. L., Kaal, J., & Duarte, C. M. (2019). Fingerprinting blue carbon: Rationale and tools to determine the source of organic carbon in marine depositional environments. *Frontiers in Marine Science, 6*, 263. https://doi.org/10.3389/fmars.2019.00263

Guannel, G., Arkema, K., Ruggiero, P., & Verutes, G. (2016). The power of three: Coral reefs, seagrasses, and mangroves protect coastal regions and increase their resilience. *PLOS ONE, 11*(7), e0158094. https://doi.org/10.1371/journal.pone.0158094

Hamilton, S. E., & Friess, D. A. (2018). Global carbon stocks and potential emissions due to mangrove deforestation from 2000 to 2012. *Nature Climate Change, 8*(3), 240–244. https://doi.org/10.1038/s41558-018-0090-4

Horchard, J. P., Hamilton, S., & Barbier, E. B. (2019). Mangroves shelter coastal economic activity from cyclones. *Proceedings of the National Academy of Sciences of the United States of America, 116*(24), 12232–12237. https://doi.org/10.1073/pnas.1820067116

IPCC. (2007). *Climate change 2007: Impacts, adaptation and vulnerability. Working Group II contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.2134/jeq2008.0015br

IPCC. (2023). *Climate change 2022 – Mitigation of climate change: Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157926

Jia, M., Wang, Z., Mao, D., Ren, C., Song, K., Zhao, C., ... & Wang, Y. (2023). Mapping global distribution of mangrove forests at 10-m resolution. *Science Bulletin*, *68*(12), 1306-1316. https://doi.org/10.1016/j.scib.2023.05.004

Jones, H. P., Nickel, B., Srebotnjak, T., Turner, W., Gonzalez-Roglich, M., & others. (2020). Global hotspots for coastal ecosystem-based adaptation. *PLOS ONE, 15*(5), e0233005. https://doi.org/10.1371/journal.pone.0233005

Kauffman, J. B., M. F. Adame, V. B. Arifanti, L. M. Schile-Beers, A. F. Bernardino, R. K. Bhomia, D. C. Donato, I. C. Feller, T. O. Ferreira, M. C. Jesus Garcia, R. A. MacKenzie, J. P. Megonigal, D. Murdiyarso, L. Simpson, and H. Hernández Trejo. (2020). Total ecosystem carbon stocks of mangroves across broad global environmental and physical gradients. *Ecological Monographs, 90*(2), e01405. https://doi.org/10.1002/ecm.1405

Kazemi, A., Azimian, J., Mafi, M., Allen, K.-A., & Motalebi, S. A. (2021). Caregiver burden and coping strategies in caregivers of older patients with stroke. *BMC Psychology, 9*, 51. https://doi.org/10.1186/s40359-021-00556-z

Lovelock, C. E., & Duarte, C. M. (2019). Dimensions of blue carbon and emerging perspectives. *Biology Letters, 15*(1), 20180781. http://dx.doi.org/10.1098/rsbl.2018.0781

Macreadie, P. I., Costa, M. D. P., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., Lovelock, C. E., Serrano, O., & Duarte, C. M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment, 2*, 826–839. https://doi.org/10.1038/s43017-021-00224-1

McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment, 9(10)*, 552–560. https://doi.org/10.1890/110004

Menéndez, P., Losada, I. J., Torres-Ortega, S., & Others. (2020). The global flood protection benefits of mangroves. *Scientific Reports, 10*, 4404. https://doi.org/10.1038/s41598-020-61136-6

Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Synthesis.* Island Press.

Mulyadi, A., Efriyeldi, & Ilham, I. (2018). Analisis deforestasi hutan mangrove di Kota Dumai, Riau. *Prosiding Seminar Nasional Pelestarian Lingkungan (SENPLING) 2018*, 124–129.

Murdiyarso, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., Donato, D. C., Manuri, S., Krisnawati, H., Taberima, S., & Kurnianto, S. (2015). The potential of Indonesian mangrove forests for global climate change mitigation. *Nature Climate Change, 5*, 1089–1092. https://doi.org/10.1038/nclimate2734

Nellemann, C., & Corcoran, E. (Eds.). (2009). *Blue carbon: The role of healthy oceans in binding carbon: A rapid response assessment.* UNEP/Earthprint.

Nguyen, T. T., Nguyen, D. T., & Mai, T. N. (2020). Carbon storage potential of mangrove forests from Northeastern Vietnam. *Regional Studies in Marine Science, 40*, 101516. https://doi.org/10.1016/j.rsma.2020.101516

Ning, H., Yang, X., Wang, W., Sardans, J., Yin, X., Jiang, F., Song, Z., Li, Z., Tian, J., Ding, X., Zhou, J., Tariq, A., & Peñuelas, J. (2024). Mangrove wetland recovery enhances soil carbon sequestration capacity of soil aggregates and microbial network stability in southeastern China. *Science of The Total Environment, 951*, 175586. https://doi.org/10.1016/j.scitotenv.2024.175586

Nordlund, L. M., Koch, E. W., Barbier, E. B., & Creed, J. C. (2017). Correction: Seagrass ecosystem services and their variability across genera and geographical regions. *PLOS ONE, 12(1)*, e0169942. https://doi.org/10.1371/journal.pone.0169942

Ouyang, X., & Lee, S. Y. (2014). Updated estimates of carbon accumulation rates in coastal marsh sediments. *Biogeosciences, 11*, 5057–5071. https://doi.org/10.5194/bg-11-5057-2014

Pendleton, L., Donato, D. C., Murray, B. C., Crooks, S., Jenkins, W. A., et al. (2012). Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PLOS ONE, 7(9)*, e43542. https://doi.org/10.1371/journal.pone.0043542

Ranjan, R. (2019). Optimal mangrove restoration through community engagement on coastal lands facing climatic risks: The case of Sundarbans region in India. *Land Use*

Policy, 81, 736–749. https://doi.org/10.1016/j.landusepol.2018.11.047

Richards, D. R., & Friess, D. A. (2016). Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences of the United States of America, 113(2)*, 344–349. https://doi.org/10.1073/pnas.1510272113

Roy, A. D., Arachchige, P. S. P., Watt, M. S., Kale, A., Davies, M., Heng, J. E., ... & Mohan, M. (2024). Remote sensing-based mangrove blue carbon assessment in the Asia-Pacific: A systematic review. *Science of the Total Environment*, *938*, 173270. https://doi.org/10.1016/j.scitotenv.2024.173270

Sharma, S., MacKenzie, R. A., Tieng, T., Soben, K., Tulyasuwan, N., Resanond, A., Blate, G., & Litton, C. M. (2020). The impacts of degradation, deforestation and restoration on mangrove ecosystem carbon stocks across Cambodia. *Science of The Total Environment, 706*, 135416. https://doi.org/10.1016/j.scitotenv.2019.135416

Sheehy, J., Porter, J., Bell, M., & Kerr, S. (2024). Redefining blue carbon with adaptive valuation for global policy. *Science of the Total Environment*, *908*, 168253. https://doi.org/10.1016/j.scitotenv.2023.168253

Siikamäki, J. V., Sanchirico, J. N., Jardine, S., McLaughlin, D., & Morris, D. F. (2012). *Blue carbon: Global options for reducing emissions from the degradation and development of coastal ecosystems.* Resources for the Future.

Spalding, M., & Parrett, C. L. (2019). Global patterns in mangrove recreation and tourism. *Marine Policy, 110*, 103540. https://doi.org/10.1016/j.marpol.2019.103540

Taillardat, P., Thompson, B. S., Garneau, M., Trottier, K., & Friess, D. A. (2020). Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. *Interface Focus, 10(5)*, 20190129. https://doi.org/10.1098/rsfs.2019.0129

Thomas, N., Lucas, R., Bunting, P., Hardy, A., Rosenqvist, A., & Simard, M. (2017). Distribution and drivers of global mangrove forest change, 1996–2010. *PLOS ONE, 12(6)*, e0179302. https://doi.org/10.1371/journal.pone.0179302

Thompson, B. S., & Friess, D. A. (2019). Stakeholder preferences for payments for ecosystem services (PES) versus other environmental management approaches for mangrove forests. *Journal of environmental management*, *233*, 636-648. https://doi.org/10.1016/j.jenvman.2018.12.032

Tussadiah, A., Ervita, K., & Makhas, K. A. (2022). *The Role of Economic Valuation for Regulating Service of Mangrove Ecosystem.* WRI Indonesia. https://wri-indonesia.org/en/insights/role-economic-valuation-regulating-service-mangrove-ecosystem

Uddin, M. M., Abdul Aziz, A., & Lovelock, C. E. (2023). Importance of mangrove plantations for climate change mitigation in Bangladesh. *Global Change Biology, 29*, 3331–3346. https://doi.org/10.1111/gcb.16674

UNEP. (2024). *Emissions Gap Report 2024.* United Nations Environment Programme. https://www.unep.org/resources/emissions-gap-report-2024

Wang, J., Mendelsohn, R., Dinar, A., Huang, J., Rozelle, S., & Zhang, L. (2009). The impact of climate change on China's agriculture. *Agricultural Economics, 40*, 323–337. https://doi.org/10.1111/j.1574-0862.2009.00379.x

Webb, E. L., Jachowski, N. R. A., Phelps, J., Friess, D. A., Than, M. M., & Ziegler, A. D. (2014). Deforestation in the Ayeyarwady Delta and the conservation implications of an internationally-engaged Myanmar. *Global Environmental Change, 24(1)*, 321–333. https://doi.org/10.1016/j.gloenvcha.2013.10.007

Xiong, Y., Liao, B., & Wang, F. (2018). Mangrove vegetation enhances soil carbon storage primarily through in situ inputs rather than increasing allochthonous sediments. *Marine Pollution Bulletin, 131*, 378–385. https://doi.org/10.1016/j.marpolbul.2018.04.043

Xue, K., Hossain, M. U., Liu, M., Ma, M., Zhang, Y., Hu, M., ... & Cao, G. (2021). BIM integrated LCA for promoting circular economy towards sustainable construction: an analytical review. *Sustainability*, *13*(3), 1310. https://doi.org/10.3390/su13031310

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