Journal of Tourism, Hospitality and Environment Management
EISSN: 0128-178X
JTHEM

Volume 10 Issue 40 (June 2025) PP. 119-147
DOI 10/35631/JTHEM.1040009

JOURNAL OF TOURISM, HOSPITALITY AND ENVIRONMENT MANAGEMENT (JTHEM)
www.jthem.com

GLOBAL ACADEMIC EXCELLENCE

QUANTIFYING THE THREATS: A REVIEW OF MANGROVE VULNERABILITY ASSESSMENT

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Article Info:

Article history:
Received date: 27.03.2025
Revised date: 14.04.2025
Accepted date: 15.05.2025
Published date: 05.06.2025

To cite this document:

Hashim, S. S., Abd. Aziz, K. N., Mohd, F. A., Tajam, J., Kamaruddin, S. A., Abdul Maulud, K. A., Abd

Abstract:

Mangrove ecosystems are vital to preserve as they provide various crucial benefits and services not only to humans but also to other ecosystems and life. Yet, their distribution globally has been declining due to factors within nature itself and from humans. This establishes conservation awareness among researchers by assessing the vulnerability of mangroves and provides a clear picture for management and governance of the vulnerability status of the area. For such purposes, various vulnerability assessments have been developed but the degree of robustness of this assessment is not well assessed. Therefore, this review covers the development of mangrove vulnerability assessment methods along with the parameters incorporated for the assessment based on 20 years of research articles. The study found that remote sensing and Geographic

Journal of Tourism, Hospitality and Environment Management
EISSN: 0128-178X
Volume 10 Issue 40 (June 2025) PP. 119-147
DOI 10/35631/JTHEM.1040009

Latif, Z., Roslani, M. A., Ahamd, A., & Wan Mohd Azahary, W. A. H. (2025). Quantifying The Threats: A Review of Mangrove Vulnerability. *Journal of Tourism Hospitality and Environment Management, 10* (40), 119-147.

DOI: 10.35631/JTHEM.1040009.

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Information System (GIS) methods have gained prominence among researchers due to their accessibility to pertinent data. The evolving landscape of vulnerability assessment has witnessed the emergence of diverse methodologies, including multidisciplinary studies that enhance the comprehensiveness of the evaluations. Despite progress, there's still a significant gap in creating consistent ways to assess mangrove vulnerability. This review highlights the necessity for future studies to fill these gaps by establishing standards and parameters to evaluate mangrove ecosystem vulnerability more thoroughly. Ultimately, this determined effort will significantly contribute to these critical ecosystems' conservation and sustainable management, ensuring their continued resilience in the face of escalating threats.

Keywords:

Mangrove Ecosystem, Mangrove Vulnerability, Environmental Risk Assessment, Mangrove Vulnerability Parameters, Sustainable Management.

Introduction

Mangroves, situated globally in tropical and subtropical regions primarily between 25°N and 25°S latitude (Wang & Gu, 2021), thrive in challenging environments characterized by high salinity, oxygen-deficient waterlogged soil, turbulent sea waves, strong winds, and intense tidal pressures. Even with such extreme conditions, this marine ecosystem is known especially for its salt tolerance capability using ultrafiltration at their roots to remove salt (e.g.: *Rhizopora sp.*) or others that have special glands that actively secrete salt using their leaves (e.g.: *Avicennia sp.*) (Alappatt, 2008; Krishnamurthy et al., 2014; Natarajan et al., 2021; NOAA, 2022). Notably, their ability to endure harsh conditions is also evident in the intricate entanglement of root systems, forming a natural barrier that enables them to withstand waves. Conversely, from a biogeochemical perspective, mangroves serve as highly effective coastal carbon sinks, playing a vital role in the global blue carbon cycle where they trap and store carbon for extended periods in their carbon-rich and waterlogged soils (Smith, 2019; Castro & Silveira, 2020; Slamet et al., 2020; Chatting et al., 2022; Mulonga & Olago, 2024). The capabilities and functions provided by mangrove ecosystems have been recognized as major contributors to climate change mitigation as well as ecosystem support for coastal communities (Noor & Abdul Maulud, 2022; Boateng, 2018).

However, even with exceptional adaptations and functionality, mangrove trees can degrade for various reasons and their precedent habitat might be altered by open water or tidal flats (Lovelock et al., 2015), putting other mangrove-dependent ecosystems at risk and vulnerable. This can be seen in the past few decades, where the effect of climate change (e.g.: sea level changes, floods, storms, precipitation, temperature, atmospheric carbon dioxide (CO_2) concentrations, ocean circulation patterns) and human activities (e.g.: aquaculture, freshwater diversion, overfishing, urban expansion, and industrialization) have pressured mangrove forests around the globe making its coverage declining up to 3.4% over 24 years has impacting the ecosystem balance and causing erosion problems throughout the world (Gilman et al., 2008; Horstman et al., 2018; Rogers & Mumby, 2019; Merzdorf, 2020; Bunting et al., 2022). These issues have established an awareness among researchers to study the vulnerability of this unique and valuable marine environment for coastal protection (Hanggara et al., 2021), fish and mammalian habitats (Ermgassen et al., 2020), pollution filtration, and carbon sequestration (Tan & Siregar, 2021).

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JTHEM
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In evaluating the well-being and resilience of an ecosystem, researchers have been applying the vulnerability concept which includes exposure to hazards, adaptive capacity, and sensitivity. This concept plays a pivotal role in identifying resources that pose risks to an ecosystem's health, enhancing the ability of the mangrove ecosystem to adapt to stress, and promoting the sustainable use of resources while mitigating disasters. However, the robustness of vulnerability studies within mangrove ecosystems remains inadequately evaluated. Thus, this gap emphasizes the significance of this review, and three objectives have been constructed to fully understand the mangrove vulnerability assessment: (i) to evaluate the existing mangrove vulnerability assessment with a special focus on climate change and anthropogenic activity as stressors; (ii) to summarize a comprehensive assessment of mangrove vulnerability involving various parameters; (iii) to discuss selected parameters in the determination of mangroves vulnerability concerning the exposures.

Methodology
The literature searches were limited to topics, abstracts, titles, and author keywords in Google search and Google Scholar, covering from the year 2000 to 2024. The searches were limited to English language studies and searches were carried out in 2024. The search string used to identify related were the following: "mangrove vulnerability" and "assessment". It should be noted that the search string will not include all mangrove vulnerability assessment case studies as such studies have been described using variability of other terms including "resilient" or "sensitivity". However, it is believed this systematic approach produces data sets that show current trends in mangrove vulnerability assessments throughout the duration fixed. Overall, the main selection criteria to include research papers in the core analysis sample are as follows:

- Papers focusing on wider marine ecosystems such as wetlands and coastal areas or even non-mangrove biota within the mangroves, which generally do not mainly concentrate on mangrove areas are excluded from the results.
- Papers should address at least one of the following climatic and non-climatic related mangrove hazards: sea level rise, tsunamis, storm surge, hurricanes/cyclones/typhoons, waves, and human activities including deforestation, farming, and other activity within the mangrove area.
- Analysis should assess the vulnerability and/or risk to an ecosystem of at least one of the hazards as mentioned earlier.
- Studies focusing only on people/population/infrastructure or physical vulnerability were excluded.

The general literature workflow of this study is illustrated in Figure 1 in the stage of searching and screening. The selected articles (n = 54) have undergone a screening process that reviewed their connection to mangrove vulnerability assessment and sufficient information about the parameters for the respective study. For objectives (ii) and (iii), the selected works of literature are extracted based on the methods of assessment for mangrove vulnerability and the methods to examine all relevant parameters. The parameters are classified into the three dimensions of vulnerability as carried out by (Omer, 2019):

- Physical parameters: Known as parameters that can be observed without bringing a chemical change (abiotic)
- Chemical parameters: Parameters that can be observed or measured when a substance undergoes a chemical change (abiotic)

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- Biological parameters: Indicators which involving in living things (biotic)
- Social parameters: Parameters assessment involving community from all aspects, including ethnicity and finances.
- Mixed parameters: Indicators that have two or more other parameters pooled in a parameter (e.g., biochemical parameter)

After the screening process, only 25 articles (including review papers) were accepted for analysis and 4 articles were excluded as they provided insufficient information and did not meet the criteria mentioned earlier.

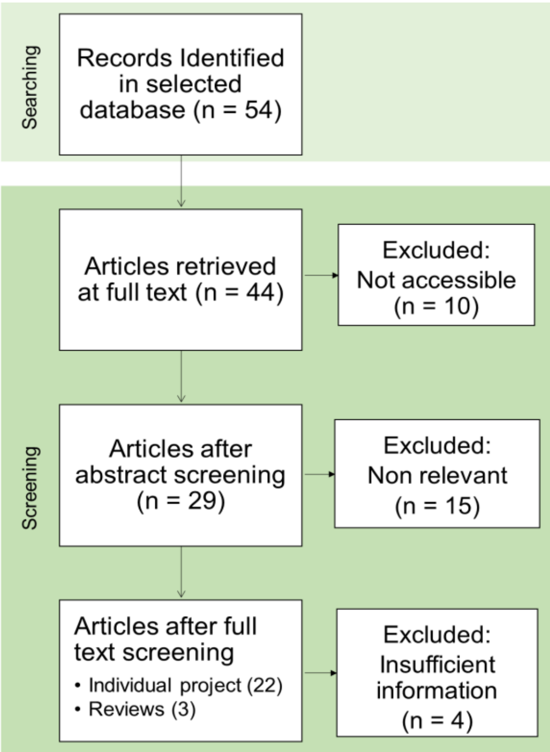

Figure 1: Literature Workflow for The Literature Materials Selection in Reviewing Mangrove Vulnerability Assessments

Vulnerability Concept

Environmental Vulnerability Concept

Vulnerability as a subject is not a new concept, yet the concept of vulnerability has evolved and has been broadened to encompass various scopes beyond its traditional understanding. Originally, vulnerability was often associated with physical or material susceptibility to harm or risk. However, contemporary perspectives recognize that vulnerability is a multi-approach, multi-structure, and multi-dimensional concept that extends beyond the physical realm and includes social, economic, environmental, and psychological features (Naudé et al., 2009; Wisner, 2016; Gibb, 2018; Chen et al., 2021; Kasperson et al., 2022) as shown in Figure 2. With such different definitions from different field perspectives, most vulnerability studies are only limited to the study of the exposure or stressors which is inadequate to provide a comprehensive understanding of impacts and responses on the affected system or its

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JTHEM
EISSN: 0128-178X
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components, where this can be seen in two typical environment risk assessment models that have informed vulnerability analysis: the risk-hazard (RH) and pressure-and-release (PAR) models, which only focus on the hazard and the social condition (Turner et al., 2003). Thus, it is important to address the ground for the vulnerability concept and its elements that are involved in developing comprehensive vulnerability assessments.

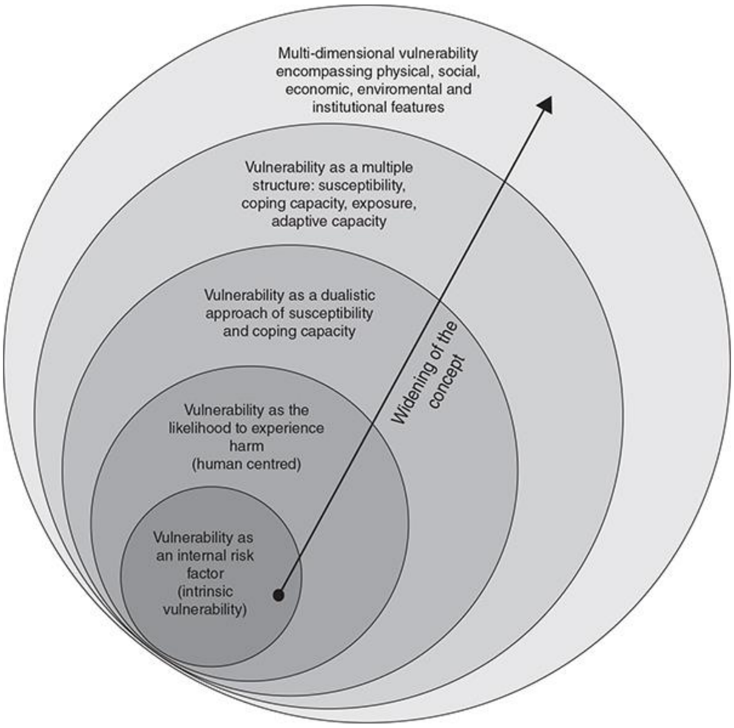

Figure 2: Vulnerability Concept Complexity Range Based on Different Focus on Vulnerability Definition

Source: (Birkmann, 2013)

This review paper outlines the basic description of the vulnerability dimensions which focus on comprehensive and improved environmental vulnerability. A key focus of sustainability science is understanding how to meet society's needs while also protecting the planet's life-support systems (human-environmental relationship). Generally, this vulnerability assessment is typically assessed through three dimensions of exposure, sensitivity, and adaptive capacity; answering the key questions for ecological vulnerability approaches: (i) how and why do systems change? (ii) what is the capacity to respond to the change? and, (iii) what are the underlying processes that control the ability to cope and adapt? (Turner et al., 2003; Adger, 2006; Polsky et al., 2007; Ellison, 2015; Wisner, 2016; Weißhuhn et al., 2018).

Dimension of Vulnerability

A comprehensive vulnerability assessment is considered comprehensive when it can understand the impact of the degree of exposure to the system that is influenced, by how sensitive the system is and its efforts to return into balance. Therefore, three dimensions of vulnerability have been classified into components or abstract features upon which to evaluate exposure, sensitivity, and adaptive capacity where these features can each be assessed using some measurements, which also are the evident characteristics of each of the element features (Polsky et al., 2007). The following sections briefly review the exposure, sensitivity, and

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Volume 10 Issue 40 (June 2025) PP. 119-147
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adaptive capacity vulnerability components for the mangrove ecosystem to identify comprehensive measurements of vulnerability.

Exposure

Exposure carries a meaning of extrinsic stresses such as the magnitude and rate of change that an ecosystem is likely to experience, where this can originate from nature, such as bioclimatic (climate change) and artificially from human intervention. Exposures bring negative consequences to mangroves, exposure such as warmer temperatures and direct exposure to CO_2 is significantly beneficial to mangrove forests, resulting in increased productivity and the latitudinal range of mangroves (Field, 1995; Alongi, 2008; Mulonga & Olago, 2024). The selected works of literature have identified relative sea level rise (an effect of climate change) as a major contributor to an ecosystem's vulnerability which damages the environment, particularly in the mangrove environment (Ellison, 2015). Another exposure such as changes in rainfall does increase the potential of sensitivity, particularly in freshwater supply and indirectly reduces mangrove production and habitat (Field, 1995). However, despite the negative value of exposure, it could be a turning point for positive changes, where awareness and responsible actions could have been carried out only by assessing the exposure experienced by the system. It is not advisable to combine different exposures into a single vulnerability assessment, especially if the interaction between the exposures is poorly understood (Weißhuhn et al., 2018). Consequently, acknowledgment of this dimension is crucial and should not be ignored in vulnerability assessment.

Sensitivity

Sensitivity is the distinctive characteristic of an ecosystem and considers the degree to which the ecosystem is affected by exposure (Ellison, 2015), this dimension closely shows how a characteristic of this ecosystem reacts to the identified exposures. The mangrove ecosystem is made up of various structures that define its characteristics, which can change in response to environmental conditions. Thus, understanding the sensitivity of mangroves helps us determine their vulnerability to changes and guides us in figuring out how to protect them (Zhang et al., 2021). However, it is hard to measure the mangrove sensitivity characteristics directly from the mangrove ecosystem indicators as it is composed of various species and forest structures, deriving many aspects of system sensitivity from inherent of species characteristics (Weißhuhn et al., 2018). For example, the retreat of mangroves towards the sea can be used as a measure of mangrove sensitivity, as it is associated with local relative sea level rise (Horstman et al., 2018) or human influences (Tran Thi et al., 2014). This difference in functionality indicates that different systems have varying levels of sensitivity and require different methods to assess them.

Adaptive Capacity

Adaptive capacity (AC) refers to an ecosystem's ability to adapt or cope with stressors which can be seen through the ecosystem response and also through human efforts that lessen the vulnerability level to any predictable changes. In simple terms, it is a continuous sum of flexibility, the response of biophysical ecosystem entities, and the ability of communities to learn in response to disturbances (Turner et al., 2003; Weißhuhn et al., 2018). Although this AC dimension shows the positive feedback of an ecosystem from being under pressure (Jurjonas et al., 2020), nonetheless different systems differ in their adaptation and it has been undervalued while evaluating the vulnerability of an ecosystem, which theoretically this idea could connect vulnerability and resilience research (Weißhuhn et al., 2018; Azcona et al.,

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2022). This shows how the incorporation of different AC dimensions is a critical component of analysis in human-environment systems, as it also repurposes vulnerability assessments to identify possible AC strategies. This, in turn, indirectly drives growing interest in management and policy, such as land use policy, focused on ecosystem conservation and rehabilitation (Jurjonas et al., 2020; Worthington et al., 2020).

Conversely, the AC also exists as a non-static dimension, where the ecosystem and the external adaptation such as human efforts change over time. Some authors differentiate between adaptive capacity with coping in vulnerability assessment, classifying them into the long and short-term capacities that lead to vulnerability (Birkmann et al., 2013; Pelling et al., 2015). Authors Pelling et al., (2015) and Birkmann et al., (2013) emphasize that adaptation involves actions aimed at making thoughtful changes in socio-ecological relationships to help systems under pressure maintain their stability. Some studies incorporate both short-term and long-term adaptive capacity in their vulnerability assessments, typically conducting the analysis in two distinct stages (Faraco et al., 2010). Therefore, term usage is crucial to define what kind of vulnerability adaptation that would be carried out.

Generally, limitations of adaptive capacity are often restricted by human factors, such as technological constraints, funding issues, and political challenges, all of which impact the ability to maintain desired systems in the face of hazards or exposures (Nagy et al., 2019). In mangroves, adaptive strategies include landward migration and vertical accretion of sediment, while communities and stakeholders contribute to adaptive capacity through effective management and supportive laws protecting mangrove forests from stressors (Gilman et al., 2008; Jennerjahn et al., 2017).

Mangrove Vulnerability

Mangrove Vulnerability Assessment Method

The application of vulnerability assessment in mangrove ecosystems may improve climate change adaptation plans by using an extensive variety of criteria for establishing a quantitative and qualitative understanding of the processes and consequences of vulnerability (Adger, 2006; Ellison, 2015; Castro & Silveira, 2020; Charrua et al., 2020, Moschetto et al., 2021). One of the well-known methods to assess changes in mangroves is through remote sensing and GIS (n=9), however, the computing and aggregation of features like vegetation density or settlement structures is complex, and comparison with ground truth is needed as found by Wisner (2016) that remote sensing data revealed some considerable inaccuracies. Nonetheless, in the general analysis remote sensing has shown that it can be a major help for rapid vulnerability assessment and hence most of the articles justify this method as it is time, energy, and cost-saving, with the high reliability to cover large mangrove area including areas that are hard to access due to safety.

Furthermore, open-source software and freely available satellite images are valuable tools for conducting vulnerability assessments. These cost-effective methods offer important information that can be easily accessed and frequently updated. However, despite the benefits of these methods, they are limited to parameters that can only be measured remotely. Additionally, the choice of procedure is crucial, highlighting the need to experiment with various algorithms, as demonstrated by Lee et al., (2018) and Vieira et al., (2018). Other mangrove vulnerability assessment methods are listed in Table 1.

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EISSN: 0128-178X
Volume 10 Issue 40 (June 2025) PP. 119-147
DOI 10/35631/JTHEM.1040009
Many previous studies used the vulnerability index because it corresponds to the three dimensions of vulnerability that have been mentioned previously. The vulnerability index method has also been used in various kinds of risk assessment especially in environmental studies because of its systematic approach. This assessment also indirectly requires capability from interdisciplinary fields as it requires a multitude of approaches from different research fields such as biological, chemical, and physical components within the mangrove ecosystems. This offers a finer and more detailed resolution in vulnerability assessment, enabling the identification of the specific parameters contributing to the vulnerability of the selected area. Consequently, it facilitates a clearer understanding of stakeholders and management (Yunus et al., 2018; Castro & Silveira, 2020; Hap sari et al., 2020).

Table 1: List of Mangrove Vulnerability Assessment Categorized Based on The Method of Assessment

Method	No. of articles	Authors
Remote sensing and GIS	9	Omo-Irabor et al., 2011; Dia Ibrahima, 2012; Wagner & Sallema-Mtui, 2016; Paul et al., 2017; Duncan et al., 2018; Lee et al., 2018; Vieira et al., 2018; Slamet et al., 2020; Ticman et al., 2021
Vulnerability Index	7	Omo-Irabor et al., 2011; Ellison, 2015; Ahmad & Fuad, 2018; Yunus et al., 2018; Castro & Silveira, 2020; Hapsari et al., 2020; Li et al., 2021
Direct field observation	4	Lovelock et al., 2015; Ward et al., 2016; Horstman et al., 2018
Others (Model, literature review)		
UPGMA (Unweighted Pair Group Method with Arithmetic Mean)	1	Weißhuhn et al., 2018
SES (Social-Ecological System)	1	Faraco et al., 2010
MaxEnt (Maximum Entropy Modelling)	1	Charrua et al., 2020
Literature review	3	Gilman et al., 2008; Pacifici et al., 2015; Boateng, 2018

Meanwhile, few studies are also using other indices as references to compute vulnerability such as exposure indicators (EI) which compromise human activity, sensitivity indicators (SI) which represent the conditions of the environment such as the digital elevation model (DEM) and resilience indicator (RI) to represent the resilience of the environment such as ecosystem services (Pacifici et al., 2015). Another example is the (Ahmad & Fuad, 2018) study, where

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the authors take the coastal vulnerability index to assess the mangrove vulnerability in Johor, Malaysia, and the index was initially developed for vulnerability assessment caused by climate change on the coast.

Alternative techniques such as modelling using MaxEnt by Charrua et al. (2020) also can be carried out to study the vulnerability of mangroves, where the model claimed has better performance than the other algorithm to predict mangrove species distribution based on the selected vulnerability indicator, where this data has become a reference for management and conservation in the area. Charrua et al. (2020) and a few other authors (e.g., Ahmad & Fuad, 2018), also show the importance of data availability from various sources to create a comprehensive assessment such as InVEST, an open-source tool developed by the Natural Capital Project (www.naturalcapitalproject.org), which includes a set of different ecosystem service models. Publicly accessible data such as this can assist in the development of more comprehensive assessments of environmental vulnerability.

Throughout the literature, there is a trend where the assessment is mainly conducted in a specific area with a moderate spatial scale. Vulnerability assessments that only cover the ecosystem level are hardly spatially explicit, despite their importance for prioritization and global-scale vulnerability assessments do exist but are unlikely to be accurate at a regional scale, or within specific ecosystems because there are extra elements that need to be taken into the assessment such as exposures or threats due to geographic location and data availability (Wisner, 2016; Lee et al., 2018). For example, mangroves ought to have different settings globally such as what (Horstman et al., 2018) conducted in New Zealand where the mangrove services differ from what tropical mangroves offer due to the limited height and complexity of the mangrove communities. Other than that, considering exposure such as sea level rise, this event will vary locally and have different impacts over the globe (Ward et al., 2018). Therefore, this proves the importance of scale and location of targeted assessment, to give better results of the vulnerability level in the specific area and be useful to manage locally.

It is advisable to include the community in the vulnerability assessment despite the method chosen, this includes the local community knowledge and inputs of the mangrove forest, to produce the finer scale of mangrove vulnerability (e.g., Ticman et al., 2021). This approach also ensures that the evaluation aligns with local needs, benefiting both mangrove forests and the surrounding communities. In addition to making the future assessment easier, the vulnerability scores of previous assessments such as coastal vulnerability assessment, can be improved in future detailed studies, which helps to save time and cost in assessing the vulnerability status of the desired location (Noor & Abdul Maulud, 2022).

It has been mentioned earlier that vulnerability does not solely involve quantitative approaches, but it also involves qualitative approaches, however, it is less commonly used and found in the reviewed literature. A study (Li et al., 2016) addressed that the qualitative approach is mainly used in assessing the vulnerability of society which includes the discussion in groups of the local community to develop practical tools. From the literature, it has been noticed that most of the studies are using the biocentric approach, which focuses exclusively on the fragility and susceptibility of ecosystems and environmental components, and some authors (Faraco et al., 2010) are focusing on the anthropocentric approach which analysed the interlinkages between environment or ecosystem services and human activities. Therefore, this shows how the vulnerability assessment has expanded and been recognized as equally important broadly.

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Mangrove Vulnerability Assessment Parameters

In the literature review, a pattern emerges where researchers consistently select certain parameters to assess mangrove vulnerability. Despite the various methods employed in different studies, the study will discuss parameters based on information gathered from selected articles that are deemed most suitable and should accurately represent the characteristics of mangrove areas (Viera et al., 2018). This trend occurs because there is no agreed or standardized method for parameter selection and aggregation (Birkman & Wisner, 2006). Furthermore, there are no greatest or perfect methods or parameters fit to assess all environments for their vulnerability. This study will further discuss the parameter selections based on the three dimensions of vulnerability used by the selected articles (n = 25).

The reviewed articles revealed that some similar parameters are classified under different vulnerability dimensions. For instance (Table 2), the parameter of human activities is majorly used in the exposure dimensions (e.g., Li et al., 2021), but other studies were using it in the sensitivity dimension (e.g., Ticman et al., 2021). This has shown the different understanding of each study towards vulnerability dimension and no standard parameters in each of the dimensions. Researchers need rigid opinions or schemes on the parameter assignation to vulnerability dimensions, to make the assessment standard and applicable to all.

Exposure Dimension Parameters

Sea Level Rise

A significant number of authors have included sea level rise (SLR) in the mangrove vulnerability assessment parameter as a natural exposure due to a direct relationship between mangrove vulnerability and inundation level, especially during the rainy and dry seasons (Bukvic et al., 2020). Without this parameter taken into assessment it would eliminate one of the main sources of exposure that cause the changes in the mangrove ecosystem, as has been highlighted by Ellison (2015). This parameter includes local factors such as long-term regional down-warping and sediment compaction that contribute to subsidence (Epinosa et al., 2001).

Human Activities

Exposure does not always come from nature it also can be sourced from humans itself. Human activities have been identified as one of the main problems of mangrove degradation worldwide (Yunus et al., 2018; Karlina & Johan, 2020; Goldberg et al., 2020). Human activities are diverse, most cities and public centres are close to water areas as this area is able to provide supplies and generate income for the local community. Therefore, those activities involve aquaculture, tourism, and fishing while these activities are not well managed, they will increase the vulnerability of mangrove areas to risk (Ivanova et al., 2022).

Wind

Wind can influence water level fluctuations, propagules distribution, and mangrove plant structure. Furthermore, different wind intensities produce different effects on mangrove forests, especially on the distribution pattern such as in the Charrua et al. (2020) study.

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Sensitivity Dimension Parameters

Tides/ Tidal range/ Tidal Inundation

Tides are taken into consideration for vulnerability assessment because of the linkage between flooding and the risk of sediment behaviour from the tidal range and velocity (e.g., Viera et al., 2018; Ahmad & Fuad, 2018). In most case studies involving SLR, intertidal sites are often more susceptible due to their tide-dominated systems. These sites typically found on beaches with a higher tidal range and active tidal currents, are vulnerable to changes in sediment supply, which can lead to erosion and increase mangrove susceptibility.

Elevation

Based on Hamilton (2013), the author has listed six sets of processes that are known to influence surface elevation change in mangroves which are sedimentation/resuspension; accretion/erosion; faunal processes (e.g., burrowing of crabs); growth/decomposition of roots; shrinkage/swelling of soils in the presence/absence of water; and compaction/compression/rebound of soils over time and under the weight of soil/water above. In the context of SLR, elevation data is required as it reflects the possibility of an area flooding, indicating insufficient such data would make it problematic to quantitatively assess the risk of flooding and rising sea levels (Charrua et al., 2020; Viera et al., 2018). In addition, elevation and slope impact hydrological processes by affecting flow direction and runoff velocity, which will influence erosion, inundation, soil moisture, local precipitation, and temperature. Moreover, the survival of mangrove species depends on their ability to keep pace with the SLR through the rates of slope and substratum elevation changes by building up vertically. Therefore, elevation can be used as a proxy for inundation vulnerability.

Ecosystem Health

Health can be an indicator of how the ecosystem is handled and most authors are evaluating the mangrove health from the historical data mainly from remote sensing data, to understand the trend of the mangrove structure along with the exposure Lee et al. (2018).

Mangrove Total Area and Types

Mangrove areas and types are important to know as they differ from one area to another, and each species has different vulnerability tolerances. Most studies rely on remote sensing for assessment because it provides historical data on mangrove forests. This data reveals detailed trends in mangrove cover and forest structure over the years, as demonstrated in the studies by Krishnamurthy et al., (2014) and Ellison (2015).

Distance to Coastline

The location of the desired area is influenced by the proximity to the interaction zone with the sea as the locations can have variations of physical and chemical parameters such as salinity and tidal range, respectively. Furthermore, locations dominated by rivers are more sensitive to changes in watershed flow, making them more sensitive to freshwater availability and sediment inflow, indirectly influencing the vulnerability of mangrove forests (Viera et al., 2018; McIvor et al., 2013).

Adjacent Ecosystem Health

Adjacent ecosystems like coral reefs and seagrass beds rely on mangroves for their water-purifying ability, which helps keep the water clear (Ellison, 2015; McKee, 2011). This

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parameter can serve as an indirect indicator of changes in mangroves. This also provides a broader understanding of how these ecosystems influence one another.

Adaptive Capacity Dimension Parameters

Ability to migrate/migrate areas

Mangrove trees possess the ability to migrate when dealing with exposure like SLR, where the distribution of the forest will either migrate landward as the water level rises or seaward as the water level decreases, and this process will often take time to occur (Ellison, 2015). However, the interaction between mangrove ecosystems with societies is interlinked, where the mangrove's ability to migrate is blocked or disturbed by humans by installation of sea walls on landward will be diminished, thus the mangrove area is exposed to vulnerability. This indirectly causes the community to be affected and vulnerable as it loses the services provided by the mangroves.

Land Use

Land cover is widely used to predict species distribution models as it is a crucial environmental variable to assess biodiversity patterns. The use of this parameter in the study (Faraco et al., 2010; Paul et al., 2017; Viera et al., 2018; Charrua et al., 2020) has provided the researcher with an understanding of the spaces and constraints on mangrove areas for their shifting behaviour.

Protection Status

Assessing the protection status of the mangrove area can contribute to lowering the vulnerability status from non-climate stressors, but as (Ellison, 2015) carried out, the author includes legislation review to see whether the government or agencies can effectively play their part in mangrove conservation.

Local Management

Ellison (2015) also takes local management into the vulnerability assessment as effective sustainable management encourages mangrove resilience, a perception linked with adaptive capacity as the ability to absorb and recuperate from the impacts of disturbance.

Stakeholder Involvement

Communication with stakeholders plays an important role in making the adaptation plan true and staying on the right path, indirectly improving the effectiveness of the management. Ellison (2015) again, includes such undervalued parameters in the assessment by assessing it through regional scale planning which aims to improve the policy and identification of management priorities. This parameter differs from the local management in the same study as it measures the involvement of the stakeholders in the adaptation plans carried out by the locals, through their participation in facilitating consultation, meetings, emails, and sharing their perspectives, knowledge, reports, and results.

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Table 2: Classified Mangrove Vulnerability Parameters Associated with Parameters Assessment Methods Carried Out by The Authors of Selected Works of Literature

Dimensions	Parameters	Parameters Assessment Methods	Qualitative	Quantitative	Source
Exposure	Relative sea level rise (RSLR)	DEM (Digital Elevation Model)		/	Faraco et al., 2010
		Secondary data		/	Lee et al., 2018
		Secondary data		/	Ticman et al., 2021
		Sea level records		/	Ellison, 2015
	Extreme climatic events	Secondary data from meteorology records		/	Faraco et al., 2010
	Wind	Secondary data from meteorology records		/	Lee et al., 2018
	Exposure frequency to climatic event	Secondary data from meteorology records		/	Lee et al., 2018
	Anthropogenic activities and degree	Secondary data		/	Li et al., 2021
	Overlap areas with human activities	Satellite image; Processed data		/	Li et al., 2021
	Waves	Secondary data		/	Ticman et al., 2021
	Storm surges	Secondary data		/	Ticman et al., 2021
	Sea surface temperature	Secondary data		/	Ticman et al., 2021
	Rainfall	Secondary data		/	Ticman et al., 2021
	Tidal range	Sea level records		/	Ellison, 2015
	Sediment Supply Type	Geomorphic setting and sources	/		Ellison, 2015

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	Climate	Climate models	/		Ellison, 2015
Sensitivity	Mangroves total area and types	Satellite images	/	/	Faraco et al., 2010
		GIS	/	/	Ellison, 2015
	Tides	Secondary data from tide forecast		/	Lee et al., 2018
	Ecosystem health	Satellite images; NDVI		/	Lee et al., 2018
	Mangrove elevation	Satellite image; Mangrove elevation		/	Lee et al., 2018
		Topographic survey		/	Ellison, 2015
	Mangrove distribution	Satellite image; Mangrove area		/	Lee et al., 2018
	Physical damage	Satellite image; Canopy height		/	Lee et al., 2018
	Mangrove area exposed	Satellite image; Mangrove area		/	Lee et al., 2018
	Lost mangrove area	Satellite image		/	Li et al., 2021
	Mangrove structure	Satellite image		/	Li et al., 2021
	Water quality	Field sampling		/	Ticman et al., 2021
	Anthropogenic activities	Field sampling		/	Ticman et al., 2021
	Habitat characteristics	Field sampling		/	Ticman et al., 2021
	Governance	Field sampling		/	Ticman et al., 2021
	Mangrove forest health	Forest Assessment	/		Ellison, 2015
	Seaward edge retreat	Remote sensing	/	/	Ellison, 2015
	Vertical accretion	Sediment rods		/	Ellison, 2015
	Adjacent ecosystem health	Ecosystem monitoring	/		Ellison, 2015
Adaptive capacity	Resources abundance	Field sampling		/	Faraco et al., 2010

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Mangrove migration	Satellite images, field survey		/	Faraco et al., 2010
Ability to migrate	Satellite image; Pixel identification	/		Lee et al., 2018
Species number	Secondary data		/	Li et al., 2021
Non-endangered species ratio	Secondary data		/	Li et al., 2021
Management involvement	Secondary data		/	Li et al., 2021
	Local community survey	/		Ellison, 2015
Ecological restoration	Secondary data		/	Li et al., 2021
Species type	Remote sensing		/	Ticman et al., 2021
Mangrove cover	Remote sensing		/	Ticman et al., 2021
Mangrove health	Remote sensing	/		Ticman et al., 2021
Governance and stakeholders' involvement	Field interviews	/		Ticman et al., 2021
	Local community survey	/		Ellison, 2015
Protection status	Survey and legislation review	/		Ellison, 2015
Migration areas	Topographic survey	/	/	Ellison, 2015

Table 3: Unclassified Parameters From The Mangrove Vulnerability Assessment Along with Assessment Methods From The Collective Literature

Parameters	Parameters Assessment Methods	Qualitative	Quantitative	Source
Elevation	Secondary data		/	Vieira et al., 2018
Geomorphology	Secondary data		/	
Land cover	Secondary data		/	

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Anthropogenic activities	Secondary data		/	
Distance to coastline	Secondary data		/	
Maximum tidal range	Secondary data		/	
Diurnal range	Secondary data		/	
Temperature	Secondary data		/	
Precipitation	Secondary data		/	
Land cover	Secondary data		/	Charrua et al., 2020
Slope, Land surface elevation	Secondary data		/	
Wind	Secondary data		/	
Salinity	Secondary data		/	
Mangrove density	Point Centered Quarter (PCQ) method		/	
Mangrove species	Field sampling		/	
Mangrove diameter	Field sampling		/	
Carbon biomass	analytical determination		/	Hapsari et al., 2020
Sediment texture	glass-tube settlement method	/		
Salinity	Syringe method		/	
Sediment organic material	Ignition method		/	
Population Pressure	Field sampling (Census)	/		
Deforestation	Remote sensing		/	
Civil Conflicts	Field sampling	/		
Poverty	Secondary data	/	/	
Corbon Dioxide	Secondary data		/	
Relative Humidity	N/A		/	Omo-Irabor et al., 2011
Temperature	N/A		/	
SLR	N/A		/	
Precipitation	N/A		/	
Alien Invasive Species	N/A	/	/	
Pollutant Input	N/A		/	
Erosion/ Accretion/ Abrasion	Remote sensing		/	

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Indigenous Knowledge	Interview	/		Wagner & Sallema-Mtui, 2016
Temperature	N/A		/	Dia Ibrahima, 2012
Humidity	N/A		/	
Wind	N/A		/	
Rainfall	N/A		/	
Mangrove health	Remote sensing		/	Paul et al., 2017
Land erosion	Remote sensing		/	
Sediment deposition	Remote sensing		/	
Storm effects	Remote sensing		/	
Land cover	Remote sensing	/	/	
Site morphology	Remote sensing		/	
Mangrove landward migration	Remote sensing		/	Duncan et al., 2018
Biomass changes	Remote sensing		/	
Topographic slope	Remote sensing		/	
Sediment availability	Remote sensing		/	
Coastal shoreline	Visual observation at site		/	Ahmad & Fuad, 2018
Salinity	Field sampling		/	
Tidal inundation	Secondary data from meteorology records		/	
Substrate	Grand size analysis test		/	

Legend

Biological	Physical
Chemical	Social
Mixed	

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Unclassified Parameters In The Vulnerability Dimension

There are some mangrove vulnerability assessments from the literature in which the respective authors did not follow the aforementioned three dimensions of the vulnerability concept. The selection of parameters from the previous study is based on factors like erosion and natural events (Dia Ibrahima, 2012; Vieira et al., 2018; Charrua et al., 2020). However, this does not imply that the assessment is less important or less accurate than other methods. It produces a similar result—a quantitative vulnerability value—that can effectively guide management in prioritizing conservation activities. Additionally, the initial and main objective of the vulnerability assessment is to provide sound suggestions to the management, and to create a more sustainable management plan, despite the concerns or issues. The sub-section will discuss comprehensively mangrove vulnerability with unclassified parameters based on the literature.

Erosion/Accretion

This parameter acts as an indicator for changes, especially in shoreline dynamics. Authors like Ellison (2015), Wagner & Sallema-Mtui, (2016), and Paul et al. (2017) highlighted their studies of erosion and accretion of mangroves based on the location of the occurrence of the phenomenon which often refers to landward and seaward, which this highlights the seaward mangrove area experience more erosion than accretion and some are the opposite. This dynamic parameter of erosion and accretion could cause changes in mangrove area coverage in the shoreline region.

Salinity

Sodium levels in soil have been measured as an indicator of saltwater exposure, a critical factor for the establishment, early development, and species migration of various mangrove types (e.g., Yunus et al., 2018). Salinity limits water uptake and photosynthetic rates of mangrove species.

Precipitation

Precipitation is an important driver of mangrove productivity, nutrient uptake, propagule movements, and species survival. Higher precipitation may imply increase run-off, decreased salinity, moderate acid sulphide soils, and increased mangrove forest expansion, richness, and productivity. Precipitation, temperature, and cyclone frequency greatly explain the global trends in mangrove canopy height. Since salt secretion by some mangrove species is a means to cope with "salt root", so does rainfall help to wash the salt off the leaves and keep them healthier (Omo-Irabor et al., 2011).

Temperature

Bioclimatic variables (precipitation and temperature) are commonly used to predict species distribution models including mangroves. Temperature has crucial effects on seedling establishment, survival, and mangrove species distribution as mangrove species usually occur where annual temperature is high, and temperature amplitude is small. Temperature varies significantly within mangrove forests as well as geographically across its distributional range. The effects of temperature (heat or cold tolerance in tropical and sub-regions) on early growth and physiology of mangrove species have been reported (Krauss et al., 2008; Mulonga & Olago, 2024). Moreover, higher temperature increases evaporation, resulting in higher salinity which in turn influences species distribution. The increasing mean air and ocean temperatures favour the expansion of mangrove forests.

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Sediment Types/ Substrate

Sediment types or substrates can influence the species of mangroves and other plants that can grow, affecting their growth rates and, consequently, the vulnerability of mangrove distribution in the area (Ahmad & Fuad, 2018; Krauss et al., 2008). Therefore, this parameter is important to consider especially when the selected sites are different in geological factors, such as mangroves in the coastal and salt marshes.

Sediment Redox Potential

Sediment redox potential is closely related to sediment types mentioned previously, where it can act as an environmental condition indicator, factors affecting this parameter are rainfall, tides, depth of sampling, sediment texture, and location, where the redox value decreases with the distance from coastal or estuary area (Hapsari et al., 2020).

Mangrove Roots

Mangrove roots are essential for anchoring trees in unstable muddy ground and enabling the uptake of nutrients by the tree. Besides, the combination of limited mineral deposits and low root mass accumulation can make the area more susceptible to relative SLR (Yunus et al., 2018).

Population Pressure

Omo-Irabor et al., (2011) included population pressure in the mangrove vulnerability study as it is known that human population pressure is a causative factor in the loss of mangroves globally. This parameter and geographical location are creating a challenge to mangrove's ability to adapt to environmental changes, therefore there is a need to measure this pressure on the desired mangrove area.

Deforestation

The deforestation of mangroves is largely attributed to changes in socioeconomic conditions, mainly linked to agriculture and aquaculture activities. This parameter needs to be accessed to understand the rate of deforestation impacting mangrove ecosystems like the (Omo-Irabor et al., 2011) study.

Civil Conflicts

Civil conflicts in the mangrove habitat can cause the area to become a hide-out for warring parties and the use of dangerous weapons due to the conflicts may negatively impact the fragile ecosystem native to such an environment (Omo-Irabor et al., 2011).

Poverty

According to (Duarte et al., 1998), poverty in local populations often arises from the destabilization of their community context, disrupting the provision of traditional resources and leading to increased environmental pressures. This can contribute to the mangrove vulnerability. Hence, the parameter is exclusively needed in assessment which focuses on the interaction of mangrove and community.

Carbon Dioxide

Mangrove is known to act as a buffer to sink excess carbon dioxide, storing this most produced greenhouse gas in the soils, roots, and branches. Increased carbon dioxide enhances its productivity, and yet this depends on other limiting factors such as salinity, humidity, and

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nutrients. This parameter can be supportive data for mangrove structure as it is closely related to the productivity of the mangrove (Chatting et al., 2022; Slamet et al., 2020).

Relative Humidity

The relative humidity is related to the saturation point, the amount of water vapor in the air divided by the capability of the air to hold the maximum amount of water at a given temperature. As air temperatures rise, it holds more water, and the saturation point of the air also increases. Mangroves require adequate humidity, which is essential for maintaining their ecological functions (Diop, 2003). Specific humidity refers to the actual amount of water vapor in the air. This shows the need to consider multiple concomitantly changing abiotic variables and their interactions with mangroves.

Precipitation

Some authors like (Devaney et al., 2021) suggest that alterations in rainfall can significantly influence both the growth and the geographical extent of the mangrove ecosystems. Specifically, areas with increased rainfall are expected to witness an expansion of mangrove coverage. This expansion may involve the colonization of previously non-vegetated land areas near the coast. Additionally, studies also anticipate a rise in the diversity of mangrove zones and an increase in growth rates because of these changing precipitation patterns (Ellison, 2015). Thus, there is an interconnected relationship between climate-driven precipitation changes and the dynamics of mangrove ecosystems, foreseeing both expansion and diversification under conditions of increased rainfall.

Alien/Invasive Species

A major anthropogenic factor contributing to the degradation and depletion of the mangroves is the invasion of the non-native Nypa palm (*Nypa fruticans*), this species unfortunately failed to play the role of erosion control. Other impacts caused by invasive species are general habitat conversion with attendant reduction in ecological degradation, poor navigation, loss of biodiversity, and fish catch (Omo-Irabor et al., 2011).

Pollutant Input

Pollutants comprise oil and solid waste, pathogens, nutrients, persistent organic pollutants, and heavy metals, this includes accidental oil spills from tankers, runoff from land and municipal and industrial wastes, exploration sites and pipelines, regular shipping, and exploration operations such as exchange of ballast water (McLeod & Salm, 2006). Such pollutants with heavy metals such as zinc, mercury, copper, cadmium, nickel, and lead, that are normally monitored are known to pose a threat to the survival of mangroves. For example, oils can coat the roots which act as breathing surfaces including the seedlings and this could lead to the death of mangroves. Even though a lighter oil spill does not cause mortality, it can cause initial defoliation (Wong et al., 2021).

Indigenous knowledge

Indigenous knowledge will greatly add to the extensiveness of the data obtained and it can be the source to cross-check and reinforce the other data such as natural sciences methods including remote sensing. This data is shown to be dependable and provides an oral history of changes that go back beyond in time than the natural science methods could, as the natural science methods sometimes could not cover the timeline due to technology factors (Wagner &

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Sallema-Mtui, 2016). This parameter also pointed to likely contributory factors of change in the area.

Mangrove Vulnerability Assessment Implications

In summary of the assignments of parameters assessment for the mangrove vulnerability study, it has been found the classified parameter of sea level rise (SLR) and sediment supply type parameters are being used frequently in the exposure dimension, while mangrove elevation and land cover parameters are the most assessed for sensitivity and adaptive capacity, respectively (Figure 3). This combination of parameters is important to assess the impact of the relative impact of sea level rise since sea level rise occurs differently throughout the globe (Durand et al., 2022). Meanwhile, parameters like indigenous knowledge and civil conflicts should be taken count into the vulnerability assessment for they have a close relation with the mangrove area (Omo-Irabor et al., 2011; Wagner & Sallema-Mtui, 2016). Other vulnerability parameters are seen to be used less frequently in mangrove vulnerability studies.

Meanwhile, mangrove vulnerability parameters of erosion, accretion, and abrasion are being used in most of the unclassified parameters by authors parameters in the mangrove vulnerability study (Figure 4). This shows this parameter is as much as important as the classified parameters earlier because mangrove ecosystems need stable erosion and accretion to maintain their territory (Nguyen et al., 2020). This also shows how authors need to identify the assignment of the parameters to carry out a comprehensive engagement in mangrove vulnerability studies.

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Figure 3: Overall Frequency of Classified Parameters Used in Mangrove Vulnerability Study in The Literature

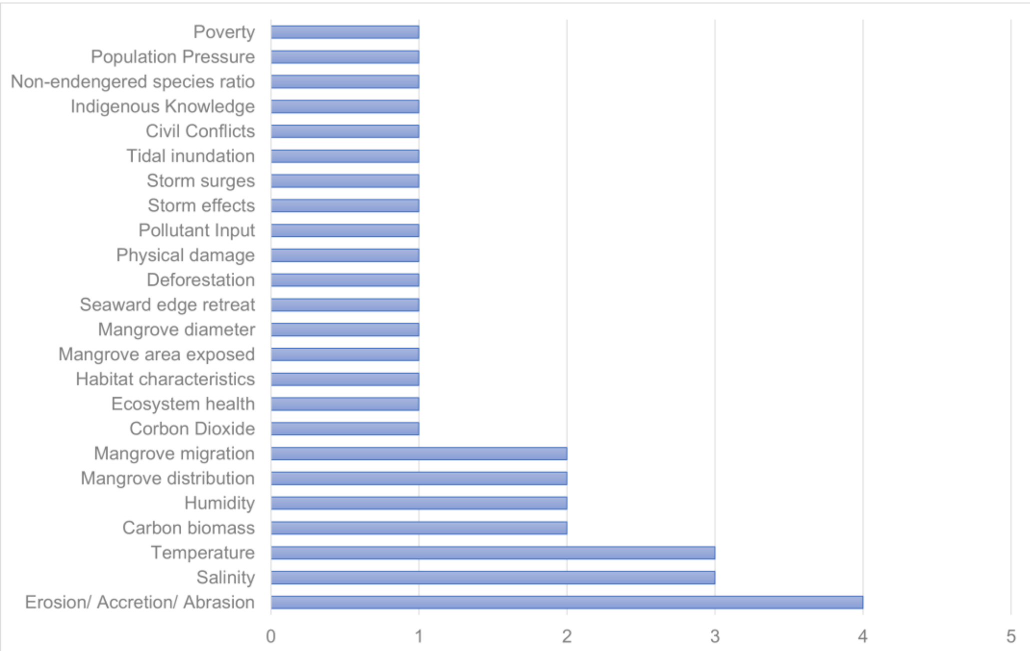

Figure 4: Unclassified Mangrove Vulnerability Parameters Frequency Used by Authors

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Conclusion

The significance of mangrove ecosystems cannot be overstated, yet their vulnerability to various exposures poses a serious threat to their health. Unplanned projects may inadvertently lead to a decline in biodiversity, disrupt natural functions, or overlook the complex stressors contributing to mangrove loss. Traditional restoration efforts are grappling with challenges, often resulting in misguided attempts due to a lack of understanding of vulnerability factors in specific areas. Consequently, it is imperative to acknowledge and address potential threats when evaluating mangrove ecosystem health.

Emphasizing the exposure dimension, sea level rise parameters are seen to be one of the concerning and well-adapted in mangrove vulnerability studies. Conversely, on sensitivity dimension and adaptive capacity, parameters like salinity and hydrology, and consideration of both natural and human intervention for the mangrove ecosystem adaptation emerge as essential factors for achieving and maintaining a healthy mangrove ecosystem, respectively. Therefore, a comprehensive approach that considers these parameters and acknowledges the intricate relationships within mangrove environments is essential for sustainable conservation and management practices. The vulnerability assessment could be seen to imply a better and more strategic method to support restoration and conservation activity, which will lead to a higher yield of success compared to the traditional method.

Sustainable mangrove management has been underrated and disregarded for decades; this finding identifies important parameters for assessing mangrove vulnerability from different dimensions of vulnerability concepts and will assuredly highlight areas of high relative vulnerability in the mangrove area. Thus, the information provides insights to build adaptation plans that may be most effective for a particular area since this vulnerability assessment will improve the interaction between science and decision-making.

For future study purposes, the vulnerability assessment could be implemented in biophysical modelling to provide a more comprehensive view of how the ecosystem, where mangroves in particular, works. In addition, future research in sustainability science can be made with suitable parameters to focus on the impact of climate change and human activity on mangrove vulnerability especially in mangrove areas that are actively being used to optimize the functionality of the mangrove ecosystem. It also recommended conducting more research on the method of assessment and standard parameters in assessing the mangrove vulnerability, especially from exposure to climate change and anthropogenic activities.

Acknowledgement

This research was supported by the Ministry of Higher Education (MoHE) of Malaysia through the Fundamental Research Grant Scheme (FRGS/1/2021/WAB05/UITM/03/2).

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EISSN: 0128-178X
Volume 10 Issue 40 (June 2025) PP. 119-147
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