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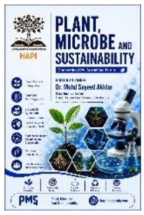

Type of the Paper – Review Article

Crustaceans in Mangroves: Bioindicator Potential for Ecosystem Health Assessment – Review

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Abstract:

Mangrove ecosystems, renowned for their exceptional productivity, play a pivotal role in sequestering carbon in tropical coastal regions, while simultaneously offering a spectrum of socio-economic advantages. They are considered among the most significant coastal environments. Paradoxically, mangrove forests are dwindling at an accelerated pace, surpassing the rate of decline witnessed in coral reefs and rainforests, with annual estimates ranging from one to two percent. The phenomenon of mangrove loss transcends geographical boundaries, affecting both urbanized locales and areas focused on tourism. Given the profound importance of mangrove ecosystems, there is an imperative need to establish robust indices for the comprehensive assessment of their ecological health. A variety of indices have been developed for this purpose, the Mangrove Quality Index being a pertinent example. These indices are substantially informed by the utilization of bioindicators that inhabit mangrove ecosystems, notably the decapod crustaceans known as crabs. Crabs, particularly those belonging to the infraorder Brachyura, have garnered recognition as preeminent bioindicators of mangrove forest health. Their eminent status as bioindicators is attributed to their distinctive ability to convey information regarding pollution within their specific substrates, their role as a dietary resource for a diverse array of predators, and their propensity to consume litter from the mangrove forests. These intrinsic attributes position them as exceptional candidates for appraising the well-being of these invaluable ecosystems. In the context of this review, we undertake a comprehensive exploration of the intricate relationship between brachyuran crabs and mangrove ecosystems. This investigation delves deeply into the ramifications of crab feeding preferences and their ecological lifestyle on the dynamics of mangrove ecosystems. The ensuing analysis is poised to provide an intricate understanding of the pivotal role that crabs play in the assessment and preservation of mangrove ecosystem wellness.

Keywords: Crabs, Mangrove Quality Index, Ecosystem, Bioindicator, Ecosystem health

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1. Introduction

Mangrove ecosystems stand out as the most productive and biologically diverse ecological systems on our planet. Within tropical coastal regions, they play a crucial role in sequestering carbon. These unique ecosystems consist of intertidal forests populated by halophytic plants specially adapted to their environment. Globally, 70 distinct mangrove species have been identified, of which 11 species are added to the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (Polidoro et al., 2010). These ecosystems host a diverse array of terrestrial and aquatic organisms. The significance of mangrove ecosystems lies in their pivotal role as vital coastal environments, offering a myriad of social and economic benefits. Moreover, the intricate and extensive structure of mangrove forests significantly contributes to the stability of coastal areas (Bosire et al., 2003).

The loss of mangrove forests is not confined to natural ecosystems but also significantly affects urban and tourist regions, exacerbating ecological challenges. One of the most effective strategies for mitigating this decline is the establishment and management of Protected Areas (PAs). These areas play a pivotal role in conserving biodiversity and fostering ecosystem restoration through mechanisms such as financial backing and stringent conservation policies. Research indicates that PAs can create robust safeguards for mangroves by minimizing external disturbances, encouraging biodiversity, and enhancing ecosystem services (McGowan et al., 2020; Liu et al., 2022). Despite their benefits, only 6.9% of global mangrove ecosystems are currently under PA management (Giri et al., 2011), leaving a significant proportion vulnerable to degradation. This stark underrepresentation necessitates urgent efforts to expand PA coverage and efficacy. The post-2020 Global Biodiversity Framework (GBF) under the Convention on Biological Diversity (CBD) calls for the inclusion of at least 30% of marine areas, including mangroves, in protected networks by 2030 (Johnson et al., 2021). This ambitious target emphasizes the global priority of mangrove conservation, highlighting the need for integrated policies that combine local, regional, and global efforts to ensure ecosystem resilience. By integrating PAs more effectively into mangrove conservation strategies, we can address multifaceted challenges such as habitat destruction, species decline, and climate change impacts. Enhanced indicators like the Mangrove Quality Index (MQI) can provide critical insights into PA effectiveness, linking tree biomass, soil health, and species diversity, including bioindicators like mangrove crabs, to the broader goals of ecosystem sustainability (Harshana & Gunathilaka, 2023; Ibrahim et al., 2019). A notable distinction of mangrove crabs is their adaptability to environmental stressors, which underscores their potential as sentinel species. Studies consistently demonstrate their utility in reflecting habitat quality and anthropogenic impacts through measurable changes in population density and substrate preferences. E.g., crab populations in well-maintained PAs show higher densities and species richness, offering tangible evidence of the success of conservation measures.

Primarily, they contribute significantly to energy cycling within the forest by excavating and utilizing leaf litter as a source of nourishment (Tomascik, 1997). Furthermore, these crabs exhibit remarkable adaptability, altering their physical behavior by burrowing into the soil to withstand high tides and even climbing trees to evade predators for self-protection (Semeniuk & Cresswell, 2018). It is noteworthy that among crustaceans, only Hermit and Mangrove crabs possess the ability to ascend trees for defensive purposes (Kricher, 2015). Moreover, their excreta play a vital role in initiating the coprophagous food chain, thereby contributing to the secondary productivity of mangrove ecosystems (Lee & Kwok, 2002). Importantly, crab larvae serve as a primary food source for juvenile fish in nearby waterways, underscoring the role of crabs in supporting coastal fisheries. Adult crabs, in turn, are preyed upon by crab-eating fish, such as *Lutjanus argentimaculatus* (Mangrove Red Snapper), and other endangered species, including the Mangrove Kingfisher and Varanus indicus (Mangrove Monitor Lizard), which rely on crabs as a significant part of their diet (Tiralongo et al., 2019).

Furthermore, the burrowing activities of mangrove crabs play a crucial role in enhancing sediment aeration through changes in topography and grain size within the mangrove ecosystem (Ridd, 1996). The burrowing activities of mangrove crabs play a crucial role in ecosystem engineering by enhancing sediment aeration, nutrient cycling, and water exchange, which directly support mangrove regeneration and growth. These activities mitigate harmful concentrations of sulfide and ammonium in sediment, fostering plant productivity and ecosystem resilience (Andreetta et al., 2014; Kristensen, 2008). Protected Areas (PAs) are critical for safeguarding such ecological processes by providing controlled environments that minimize external pressures, such as pollution and habitat destruction. Studies have demonstrated that mangrove crab populations thrive within PAs, as reduced anthropogenic disturbances enhance their capacity to perform ecosystem services essential for mangrove health. The synergistic relationship between crab activity and mangrove productivity underscores the importance of PAs in maintaining the ecological integrity of these forests, which are key biodiversity hotspots and carbon sinks (Bhagarathi & DaSilva, 2024; Salleh-Mukri & Shuhaida, 2021).

These areas, as supported by various studies (McGowan et al., 2020; Myers et al., 2000; Strassburg et al., 2020), offer clear geographic boundaries to guide decision-makers in prioritizing conservation efforts, enhancing biodiversity, and minimizing external disturbances (Eklund et al., 2019; Jia et al., 2016; Liu et al., 2022). Within these PAs, mangroves can be safeguarded and restored through financial backing and other methods, as suggested by research (Atkinson et al., 2016; Maretti et al., 2019; Valderrama et al., 2020). Consequently, PA-based strategies play a vital role in safeguarding mangroves globally. The Food and Agriculture Organization of the United Nations (FAO) has advocated for the protection of at least 30% of marine areas, including mangrove ecosystems, by 2030, as outlined in the post-2020 Global Biodiversity Framework (GBF) of the Convention on Biological Diversity (CBD) (*Conversation on Biological Diversity*, GBF, 2021). Tracking and assessing the harmful effects on aquatic ecosystems are vital. Various sources emphasize this importance (Banaee et al., 2022; Impellitteri et al., 2022; Maharajan et al., 2016; Oulmi et al., 1995; Pagano et al., 2022; Uğurlu et al., 2019; Vali et al., 2022). When organisms are exposed to toxins for an extended period, it doesn't necessarily lead to immediate death. Instead, it can harm their essential organs, putting the entire population at risk. Analysing the species and examining the tissues of these organs can often reveal how living beings respond to unfavorable conditions, using various biomarkers (Restrepo et al., 2020). This study aims to investigate the potential of crabs as biological indicators for assessing mangrove quality. The MQI is introduced as a data-driven tool for evaluating ecosystem health by examining the interrelationship between tree biomass, soil characteristics, and crab abundance. Specifically, this research addresses the question of how the dietary preferences and lifestyle of crabs influence the dynamics of the mangrove ecosystem.

2. Bioindicators In Ecosystem Assessment: Nature's Pulse Readers

Bioindicator organisms are employed to evaluate environmental conditions and changes over time by scrutinizing biological processes, communities, or species. Over the years, scientists have developed an extensive array of bioindicators tailored to investigate diverse ecological settings. It is crucial to note that bioindicators are not confined to single species with low environmental tolerance. On the contrary, researchers often utilize entire ecological communities as bioindicators, providing a multifaceted perspective for assessing environmental conditions through biotic indices or a holistic approach (Holt & Miller, 2010).

The presence of diverse environmental variability should be reduced to promote the growth and survival of bioindicators under certain climate conditions. Such unpredictability can disrupt the reproductive and behavioral patterns of species, potentially impacting their population dynamics (Hellawell, 1986; Pandey & Dhuria, 2023).

Microorganisms prove highly convenient as bioindicators, particularly for their ability to serve as indicators of environmental toxins. Certain microorganisms respond to specific contaminants by producing stress proteins. The assessment of stress protein intensity and quantity offers insights into the extent of pollution within the environment. To qualify as a bioindicator, organisms must meet several criteria, including considerations of geographical and temporal duration, sampling efficiency, and the scale of biological responses (Phillips & Rainbow, 2013). E.g., Sesarmidae crabs (*Selatium* sp) are known for their climbing behaviors in mangrove trees such as *Avicennia marina*. They thrive in mangrove ecosystems where they process organic matter and enhance soil aeration through their burrowing activities. E.g., *Selatium brockii* has been observed to display fidelity to specific mangrove trees, indicating the health and regeneration status of mangrove ecosystems. This specificity in habitat choice makes them reliable indicators of localized environmental conditions, especially after disturbances like typhoons (Matillano et al., 2020). Studies on *M. frontalis* populations in mangroves reveal their potential as indicators of sediment quality and their sensitivity to variations in sediment and pollution levels impacted by anthropogenic activities. (Retnaningdyah et al., 2022). Another e.g., fiddler crabs, i.e., *Uca crassipes,* known for their reliance on specific intertidal zones and their responsiveness to substrate changes. The density and behavioral patterns of *Uca spp*. make it a prime candidate for assessing ecosystem responses to mangrove deforestation (Roni et al., 2019).

3. Brachyura Crabs: A Brief Overview

Crabs are crustaceans with a short tail hidden beneath their thorax. They are equipped with a pair of pincers and are distributed across various aquatic environments, including oceans and freshwater bodies, as well as terrestrial habitats. The crab taxon encompasses a wide array of species, falling into different orders and infraorders. Among these, the infraorder Brachyura stands out as one of the most diverse groups within the realm of crustaceans, with over 7,000 classified species organized into 98 families, populating marine, freshwater, and land-based ecosystems (Tsang et al., 2014).

The suborder Brachyura, as shown in Figure 1 of crabs, is part of the larger Reptantia category, which belongs to the extensive Decapoda order (Wolfe et al., 2019). Brachyura crabs predominantly inhabit various habitats, totalling sixteen major types, with a strong emphasis on benthic marine environments. Owing to their adaptability to diverse ecosystems and distinctive lifestyles, Brachyura crabs have emerged as valuable indicators or sensors for monitoring ecological systems. These crabs play a pivotal role in supporting ecosystem functions, with a notable impact on mangrove ecosystems. The forthcoming sections of this manuscript delve into the discussion of the role of these crabs as bioindicators.

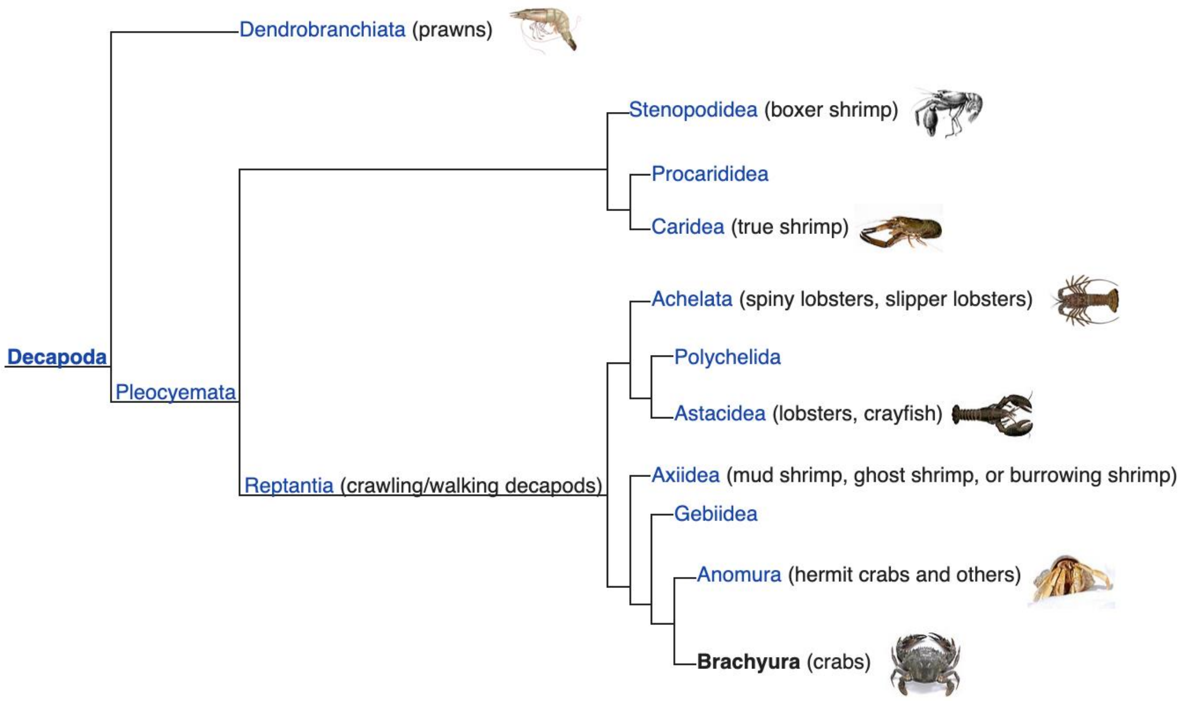

Figure 1. A general diagram for the demonstration of the placement of Brachyura crabs in their phylogenetic tree (Taha, 2023).

4. Crabs As Bioindicators

Crabs assume a pivotal role in preserving, altering, and maintaining equilibrium within ecosystems by regulating both abiotic and biotic components. They occupy various trophic levels within the ecosystem, being both predators and prey, and are characterized by their abundance (Siddon & Witman, 2004). Macroinvertebrates serve as valuable indicators for studying natural marine environments across a broad spectrum of research. Studies have consistently demonstrated that brachyuran crabs are particularly effective indicators of changes in both abiotic and biotic factors. For instance, researcher (Pestana et al., 2017) found that *Ucides cordatus*, plays a crucial role in indicating variations in sediment quality and the impacts of human-induced pollution in mangrove ecosystems, indicating sediment quality and pollution levels in mangrove environments, underlining the sensitivity of brachyuran crabs to environmental disturbances (Pinheiro et al., 2013). As such, research efforts have been directed towards examining the impact of various variables on crab populations. Their ecological significance within food webs spanning multiple trophic levels is noteworthy. They function as prey for numerous invertebrates and vertebrates while also competing with other small herbivores, small fish, prawns, and invertebrates for plant matter. Crabs exhibit a remarkable adaptability, enabling them to withstand a wide range of environmental fluctuations (Scalici et al., 2008).

When comparing brachyuran crabs to other biological taxa serving as bioindicators, they offer several advantages. Initially, crabs exhibit a distinct preference for specific habitats, and any alterations in environmental conditions, such as pollution, can directly impact crab populations. Consequently, assessing the health of an ecosystem can be particularly effective when examining species such as crabs, where their activities significantly influence ecological processes in environments such as mangrove and intertidal ecosystems (Elwin et al., 2024). Moreover, the substrate preferences of crabs can serve as an indicator of the condition of those substrates. Changes in crab populations can reveal issues with the substrates, particularly in the context of mangrove forests. Brachyuran crabs serve as vital bioindicators of human-induced impacts on benthic communities, reflecting environmental features such as salinity, sediment types and content, and their response to anthropogenic factors encompassing both abiotic and biotic components. This multifaceted attribute renders them indispensable as bioindicators of human-induced effects on benthic environments (Bartolini et al., 2009).

5. Crabs As Prime Ecological Indicators In Mangrove Ecosystems

The suitability of habitat quality for crabs is recognized as a promising indicator (Pagliosa & Barbosa, 2006). Within intertidal mangrove environments, both mangrove and Grapsid crabs are notable organisms with potential as bioindicators (Amaral et al., 2009; Hogarth, 2015). Nonetheless, there exists limited knowledge concerning the physiological condition of mangrove crabs, which could serve as a means to assess habitat quality and the influence of seasonal variations and pollution. Studies have identified various crustaceans, including *Amphipoda quadrata* (Brachyura), *Atlantorchestoidea brasiliensis* (Amphipoda), *Emerita brasiliensis*, and *Excirolan brasiliensis* (Isopoda), as essential ecosystem engineers (Suciu et al., 2018).

Among crustaceans, crabs stand out as the most effective indicators, primarily due to their distinctive attributes as ecosystem engineers. Their foremost characteristic is their capacity to effect physical changes, notably through burrow formation. The processes of burrowing and maintenance result in alterations to the physical structure of their habitat, as shown in **Figure 2.** The second attribute pertains to physical transport, encompassing the movement of materials, fluids, and gases. Crabs facilitate the redistribution of materials within the sediment, as well as the pumping of fluid or gas through their burrows, thereby modifying the transport dynamics. Passive transport mechanisms without the direct input of energy, in crab burrows, are mediated by their physical structures, such as burrow collapses, which facilitate the movement of materials and gases, as well as the diffusive movement of gases through the sediment. The third property is associated with changes in substance chemistry, primarily concerning degradability. In essence, crabs actively manage or assimilate potential food sources (substances), leading to transformations in the substance state as shown in Figure 2. They modify these substances to render them accessible to other organisms, including detritivores and decomposers. Physical transport processes may also influence substances by removing toxic metabolites and modulating factors such as redox conditions to increase oxygen penetration depth in sediments (Amaral et al., 2009).

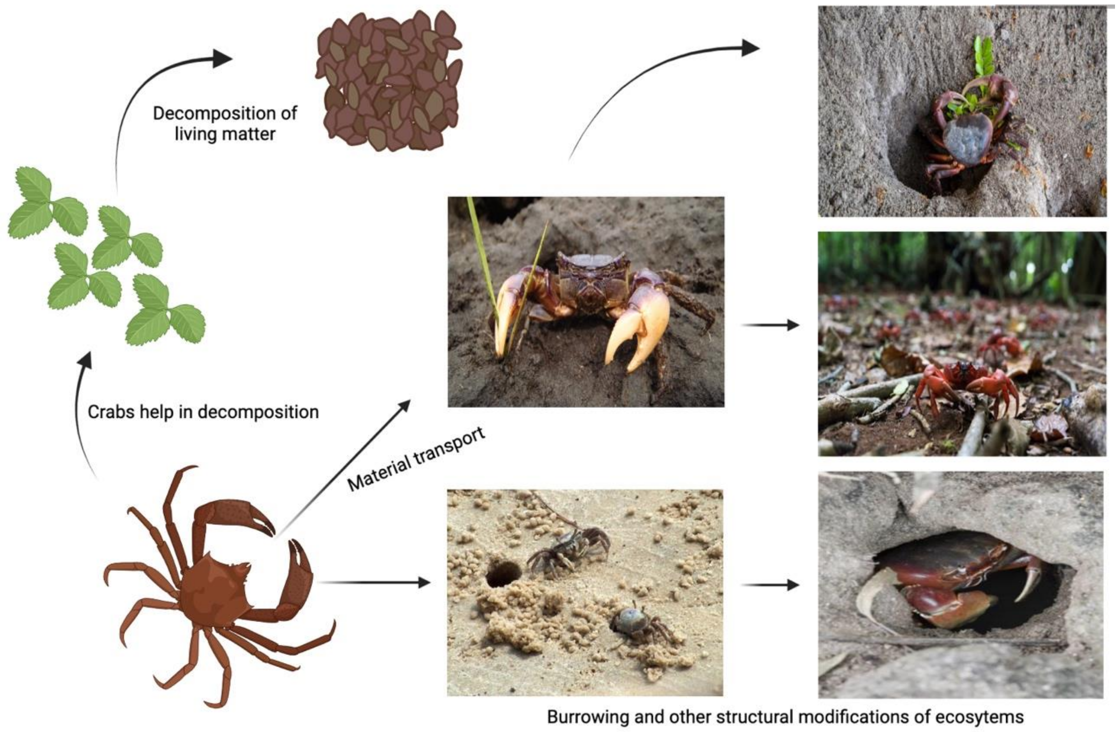

Figure 2. Demonstration of how Crabs could serve as the best bioindicators in Mangrove ecosystems

6. Mangrove Crabs: Allogenic Engineers Shaping Ecosystem Dynamics

Mangrove crabs are regarded as allogeneic engineers due to their capacity to induce environmental changes through mechanical and other processes, leading to the transformation of organic matter from one state to another. Their active contribution of leaf litter plays a critical role in sustaining the productivity of mangrove ecosystems (Nicholson, 2009). From a biogeochemical perspective, this input of leaves maintains sediment diversity and richness. Through maceration and burrowing activities, crabs expedite the microbial decomposition of leaves. Subsequently, the faecal matter generated from their ingestion promotes the growth of bacterial and algal communities (Nicholson, 2009). The burrows they create also exert a significant influence on both the topography and chemical composition of the sediment, facilitating nutrient exchange and increasing soil aeration (Amaral et al., 2009).

Crab-induced bioturbation plays a substantial role in reducing ammonium and sulfide concentrations within mangrove soils, thereby benefiting the overall productivity of the mangrove ecosystem (Nordhaus & Wolff, 2007). The burrows enable the mixing of groundwater and excess water, facilitating the removal of salt from the root zone and enhancing nutrient exchange within the soil. Due to their comprehensive engagement with the ecosystem, burrowing crabs constitute a vital component of mangrove forests within the Western Indian Ocean (WIO) (Nicholson, 2009).

7. Crabs And The Mangrove Environment

7.1. The Significance of Crabs in Mangrove Ecosystems

Although the absence of crabs would not necessarily lead to the complete elimination of a mangrove ecosystem, it would entail the loss of a substantial portion of its overall biological diversity. In many Indo-Pacific ecosystems, the biomass of crabs is likely the most critical component of benthic animal biomass. Crabs are particularly vulnerable to habitat destruction, as the landward belt of mangroves, which they inhabit, is typically larger and, in most cases, more susceptible to reclamation. An illustrative e.g., comes from the Hong Kong Mai Po Marsh, where the destruction of this mangrove belt would result in an unacceptably significant loss of crab fauna (Lee, 1999).

Marine invertebrates exhibit habitat preferences and thus serve as excellent indicators of environmental quality. The diversity, abundance, rhythms, and behaviors of invertebrates are all influenced by the quality of the aquatic environment in which they reside. In the marine context, macroinvertebrates assume vital roles within various community dynamics. Consequently, community stresses can manifest in indicators such as diversity, groupings, behaviours, abundance, reproduction, larval populations, and changes in macroinvertebrate communities (Arya et al., 2014).

Numerous studies have highlighted the pivotal role of fiddler crabs in nutrient cycling and tidal marsh ecosystem efficiency, as demonstrated by researchers (Bertness, 1985). An increasing body of evidence underscores the mutually influential relationship between mangroves and crabs. The actions of one can potentially impact the performance and even the survival of the other.

Furthermore, grapsid crabs have been observed to modify the structure of mangrove communities through their dietary habits. Research on Indo-Pacific mangroves has confirmed the essential role of grapsid crabs in shaping benthic ecosystems and objectives. A substantial portion of organic matter, including leaves, is recycled within the forest during the feeding process of crabs. This processed organic matter can form the basis of a coprophagic food supply, including small invertebrate microparticles that are subsequently redistributed. This distinct feeding behavior of crabs also influences the composition of mangrove communities by reducing the relative abundance of species with preferred propagules. The bioturbation activities of crabs further alter surface topography, particle size distribution, and aeration. Consequently, the concentration of phytotoxins in the substrate changes. Such alterations can exert a notable impact on the growth and productivity of mangroves. However, species associated with mangroves could, in turn, influence the reproduction and growth of crabs, primarily through the provision of food resources.

7.2 Ecosystem Engineering Effects of Mangrove Crabs

For instance, in New South Wales mangroves, the surface topography underwent significant modifications, and the abundance of coarse sediment particles notably increased in areas inhabited by compound crabs (Warren & Underwood, 1986). Bioturbation of this nature has the capacity to relocate organic matter from deeper layers of the soil to surface layers, simultaneously affecting other members of the mangrove biota. Smith conducted a series of field investigations to examine and elucidate the role of grapsid crabs in the mangrove ecosystems of northeastern Australia, identifying them as key propagule consumers (Smith III, 1987b, 1992). These observations, initially proposed by Macnae (MacNae, 1969), have been further extended by Smith. Moreover, Smith identified a consistent negative correlation between the dominance of conspecific canopy vegetation and the intensity of crab predation. It is essential to acknowledge that these findings hold significance across a wide range of forest crab assemblages. Such nuances in this context imply that herbivorous crabs can modulate the establishment of mangrove seedlings in species-specific ways, thereby influencing the composition of the mangrove forest.

Typically, benthic communities in mangrove forests are dominated by sedge sesarmids and fiddler crabs (Ocypodidae). These groups predominantly engage in burrowing activities within the sediment, seeking refuge from predators and environmental fluctuations. The behaviors of these abundant organisms, which significantly influence biogeochemical processes and microbial diversity, align perfectly with the concept of ecosystem engineering. Ecosystem engineers are typically classified into two categories, based on the mechanisms they employ to modify their environment (Jones et al., 1994). Rising temperatures affect crab physiology, influencing their metabolism and reproductive cycles. For instance, higher temperatures may reduce the viability of crab larvae, as they are sensitive to thermal stress during early developmental stages (e.g., *Perisesarma eumolpe*). A study on sediment salinity during the dry season showed that crab burrowing activities reduced sediment salinity, enhancing mangrove health. However, the study also noted that areas with dense pollution showed reduced burrowing activity, emphasizing the sensitivity of these processes to environmental stress. Sea level rise threatens mangrove ecosystems by inundating habitats, altering sediment composition, and reducing available space for burrowing crabs like *Ucides cordatus*. This loss of habitat affects sediment aeration and nutrient cycling, critical functions facilitated by crabs. Species like *Neoepisesarma versicolor* to migrate, leading to reduced ecosystem engineering activities in their native habitats and potentially destabilizing the mangrove structure (Vianna et al., 2020).

7.3 Behavioural Ecology of Mangroves Crabs

The active incorporation of leaf litter by crabs plays a vital role in ensuring the sustained efficiency of mangrove ecosystems. This practice helps in preserving the diverse and nutrient-rich sediment in a biogeochemically favorable state. Within the mangrove ecosystem, crab burrowing activities enhance soil porosity, subsequently promoting the regeneration of mangrove seeds (Khan et al., 2005). Macerating and burrowing crabs expedite the microbial decomposition of leaf litter. In fact, crab burrows exert substantial influence over both the chemical composition and physical topography of sediments. They also facilitate the mixing of groundwater with excess water, thereby facilitating salt removal from the root zone and enabling the exchange of soil nutrients. Consequently, burrowing crabs emerge as a foundational and indispensable component of mangrove forests, contributing significantly to the functioning of these ecosystems.

The morphology of fiddler crab burrows across various species is relatively straightforward and typically comprises somewhat permanent vertical shafts extending to depths of 10 to 40 cm within the sediment. These burrows often exhibit a distinctive J- or L-shape, culminating in a chamber (Koretsky et al., 2002). However, sesame crab burrows can vary significantly in morphology. Some species have also been observed not to create burrows; instead, they take advantage of established and abandoned burrows of other species (Gillikin & Kamanu, 2005). An e.g., of the Neoepisesarma Versicolor cave in Thailand shows differences from very simple caves, containing only a few branches and having some labyrinthine structures with several openings (Thongtham & Kristensen, 2003). The morphology of crab burrows, such as age, sediment characteristics, and the type and diversity of a particular fauna, depends on many different factors. E.g., sesame crab burrows are usually durable, and the deeper the sections, the longer they last. However, it is noteworthy that the morphology of burrows created by sesarmid crabs can exhibit significant variations. The characteristics of crab burrows, including their age, sediment properties, and the specific fauna present, are influenced by various factors. Sesarmid crab burrows, for instance, tend to be quite durable, with deeper sections expected to persist for extended periods. However, the complex structure of deeper burrow regions may also result from the cumulative construction efforts of multiple generations (Micheli et al., 1991).

Furthermore, while the population density of sesarmid crabs is lower compared to fiddler crabs (1-5 individuals per square meter), they are significantly larger and can burrow a comparable volume of sediment. Consequently, their impact on the composition of organic matter on the sediment surface is essentially equivalent. Another distinction lies in the tendency of sesarmid crabs to bury leaf litter and debris during the construction and maintenance of their burrows. This behavior leads to the direct incorporation of litter into the burrows (Robertson, 1986).

In addition to the relatively infrequent presence of sesarmid crabs, neither of the two crab types directly stimulates microbial activity by secreting reactive mucus along the walls of their burrows (Kristensen & Kostka, 2005). Nonetheless, the burrowing process still enhances biological and chemical interactions, thereby promoting sediment-water or air exchanges. Field research conducted by Robertson (Robertson, 1986) in northeast Australia revealed that *Sesarma messa* crabs contributed to the removal of approximately 28 percent of mangrove leaf litter in a mixed Rhizophora forest. This reduction in leaf litter was achieved through either direct consumption or relocation, signifying a pivotal finding for mangrove functioning. These findings indicate a direct association between organic matter depletion and this recent discovery. Previous studies on mass balances primarily focused on the assumption that export was simply the difference between production and the biomass remaining on the forest floor after the high tide period (Boto & Bunt, 1981).

Subsequent studies conducted in the Indo-Pacific region following Robertson's work have demonstrated varied, often significant, levels of litter consumption on mangrove leaves. This data collection underscores the highly influential role of crabs in eastern mangroves, which had not been previously recognized in the dominant paradigm of organic exports, particularly in Caribbean systems with substantially lower crab diversity and abundance (HEALD, 1971; Odum & Heald, 1975). Additionally, laboratory experiments have confirmed that *Sesarma erythodactyla* is capable of consuming substantial quantities of mangrove detritus, with tests highlighting the pivotal role of mangrove crab consumption in the energy dynamics of the mangrove ecosystem (Camilleri, 1989).

Furthermore, a cross-continental comparison by Smith, spanning North America, Asia, and Australia, assessed the extent of crab seed consumption in mangroves (Clarke & Kerrigan, 2002). His analysis revealed significant variations in consumption patterns, generally declining in the east and west directions within the Indo-Pacific region. These findings align with the broader trend observed in mangrove and grapsid crab diversity. These shifts are believed to be more likely attributed to differences in crab fauna identification and actual crab abundance rather than inherent variations in crab behavior. Some crab species often spend several weeks on the shoreline before migrating to the mangroves for their adult lives. Currently, there exists no definitive explanation for this type of biotic biomass movement, serving as an intermediary exchange between mangroves and connected ecosystems. Nonetheless, it has become increasingly evident that the preservation of abundant large crab species, particularly in the Indo-Pacific region, holds paramount ecological significance. Any alteration or depletion of grapsid crab biota in any form could result in significant changes to the structure and function of the mangrove ecosystem. This would undoubtedly lead to a considerable reduction in the overall biodiversity of mangroves, with the possibility of the entire mangrove ecosystem's viability coming into question. Among crab species, Ocypodidae and Grapsidae are likely the most environmentally influential, particularly within the mangrove crab fauna (Lee, 1998).

7.4 Feeding Habits and Ecological Impact of Mangrove Crabs

Both types of crabs are burrowing species that primarily rely on shredded, ground, or fine sediment for their sustenance. They are classified as semi-terrestrial since they utilize atmospheric oxygen for respiration (Lee, 1995). An investigation conducted in a polluted mangrove-fringed river in Hong Kong revealed that the majority of macrobenthos were adversely affected by pollution, but interestingly, fiddler crabs appeared to benefit from the pollution (Lee, 2008). The activities of benthic macrofauna that bioturbated the sediment in intertidal ecosystems include burrowing, sediment reworking and grazing, sediment transport and deposition of faecal material (Allard et al., 2020; Sunish, 2024). Consequently, it can be inferred that grapsid crabs exhibit greater vulnerability to organic pollution in general, which could facilitate their survival in habitats proximate to human activities.

The feeding behaviors of sesarmid crabs significantly alter the structural and chemical composition of intertidal sediments. Their consumption and incorporation of mangrove leaf litter lead to a transformation of the sediment environment. By consuming litter, crabs create new habitats for other organisms, thus providing an additional source of food. Moreover, the addition of leaves, both through consumption and burrowing, impacts nutrient retention, decomposition processes, soil chemistry, mangrove colonization, and overall dietary dynamics (Krauss et al., 2008; Robertson & Daniel, 1989; Smith III et al., 1991; Woitchik et al., 1997).

While certain species meticulously feed on leaves attached to trees, the majority of herbivores rely on mangrove litter. Crabs either directly consume this litter or transport it to their burrows for future use. Crabs predominantly utilize their chelipeds to grasp and tear off leaves at approximately <1 mm, repeatedly alternating this motion. Food preferences are also influenced by territorial behavior, where dominance typically prevails, with larger individuals asserting superiority. Smaller crabs tend to retreat in encounters with larger counterparts, while some crabs simply transport leaves to their burrows to avoid confrontation.

Mangrove crabs predominantly rely on leaf litter as their primary food source. However, due to the exceedingly high carbon-to-nitrogen (C:N) ratio of mangrove leaves, their nutritional value is relatively low, a fact that has been consistently demonstrated in numerous studies. Consequently, crabs do not solely depend on litter as a food source but also spend a significant amount of time foraging for particulate matter in the sediment (Nicholson, 2009). Furthermore, scientific investigations have revealed that crabs fulfil their nitrogen and other nutritional requirements by consuming microfauna present in the sediment. Microalgae, epifauna, sediment-scraping animals, and bacteria are all considered supplementary sources of nitrogen for mangrove crabs (Lee, 1998). Additionally, studies have demonstrated that faecal pellets, rich in microbial communities, are a significant feeding material for crabs. Crabs process this material to meet their nutritional needs, further emphasizing their role in nutrient cycling within mangrove ecosystems (Bui & Lee, 2015a, 2015b).

7.5 Ecological Significance of Crabs in Mangrove Ecosystems

Early observations have highlighted the vital ecological role that crabs play in mangrove ecosystems. Their significance is underscored by the discovery, through stomach content analysis, of the substantial presence of mangrove detritus in the diets of various crab species in the Indo-Pacific region. This finding underscores the role these crabs play in the primary turnover of mangrove productivity. Notably, laboratory experiments have provided direct evidence of the substantial capacity of *Sesarma erythodactyla* to convert substantial quantities of mangrove leaf litter, marking a pivotal link between mangrove crabs and the energy flow within these ecosystems.

Field and laboratory investigations conducted in the Indo-Pacific region by Robertson (Robertson, 1986) have unveiled a diverse range of interactions between grapsid crabs and mangrove litter, often demonstrating their significant role. The actual rate of litter removal is influenced by factors such as the type of mangrove forest and its tidal position (Robertson et al., 1992). These findings challenge the conventional paradigm of organic mangrove material exports, primarily based on Caribbean systems (Tomlinson, 2016), and suggest an important trophic role for crabs in the "eastern mangroves."

This discovery raises intriguing questions for future research in mangrove ecology and emphasizes potential functional distinctions between Eastern and Western mangroves. Understanding the interactive behaviors, including material export levels, and long-term dynamics between mangrove trees and dominant macrofauna, such as crab speciation in relation to mangrove diversity, becomes pivotal.

While it is undeniable that grapsid crabs play a substantial role in the consumption of mangrove exports in the Indo-Pacific marine environment (Lee, 1995), the precise trophic functions of crabs remain enigmatic. A significant challenge in assessing the true importance of crabs lies in the lack of a reliable method for estimating field crab densities, introducing an element of uncertainty. Current density estimation methods rely on burrow counts and pitfall traps (Micheli et al., 1991), providing relative abundance data but not precise abundance figures. Some Sesarmid species have multiple burrow openings, and certain individuals may evade pitfall traps, rendering them less accurate for quantifying crab abundance. Therefore, until less invasive and more precise methods are developed, interpretations of crab population sizes should be approached with caution.

Additionally, the fate of mangrove organic matter ingested by grapsid crabs further underscores their trophic significance. Previous studies failed to account for the typical levels of total leaf litter production (Lee, 1989). While these consumption estimates support the role of crabs as processors of mangrove materials, they offer an incomplete perspective of crab trophic importance. Camilleri documented that approximately 20% of the material processed by crabs was lost through slot feeding, 68% was eliminated as faeces, and 12% was converted into crab biomass (Camilleri, 1989).

Lee conducted a comprehensive investigation into the dietary habits of *Sesarma messa*, a mangrove crab species found in north-eastern Australia (Lee, 1997). The study evaluated the consumption of mangrove leaf material, specifically from *Rhizophora stylosa*, and assessed the corresponding production of faecal matter. The estimated daily production of dry faecal material by *S. messa* was approximately 0.36 grams per square meter, equivalent to 25% of the ingested Rhizophora leaf litter. The significance of this faecal material was highlighted in a laboratory experiment involving the amphipod *Parhyallela* sp. Amphipods fed on *S. messa* faecal matter exhibited a notably higher frequency of molting and lower mortality rates compared to those fed pure mangrove litter. Furthermore, Lee proposed that faecal material could be resuspended and transported, potentially supporting nearshore pelagic organisms like copepods, while establishing a coprophagic food chain within the mangrove benthos (Lee, 1997).

In a mangrove forest located in New South Wales, a comparative assessment of surface topography and the composition of particulate sediment particles was conducted within enclosures that either contained or lacked the burrowing activities of the crab *Heloecius cordiformis*, an ocypod (Warren & Underwood, 1986). This study revealed substantial alterations in these parameters due to crab burrowing.

Smith et al. delved into the ecological ramifications of grapsid crab bioturbation (Smith III et al., 1991). Enclosures with caged crabs exhibited significant increases in soil sulphide and ammonium concentrations compared to plots devoid of crab presence, attributed to enhanced aeration resulting from crab burrowing activity. Concurrent assessments of forest productivity, based on stipule and propagule production, demonstrated heightened mangrove productivity in areas inhabited by these crabs. While the long-term effects of crabs in growth experiments are yet to be fully elucidated, these findings forged a novel link between mangrove forest production and crab activities, leading to the designation of Grapsid crabs as "keystones" in these ecosystems.

In temperate saltmarsh ecosystems, Taylor and Allanson reported on the beneficial role of fiddler crabs in productivity and nutrient flow. This mutualistic relationship between grapsid crabs and mangroves has garnered substantial empirical support, with each entity exerting a profound influence on the performance and, in some instances, the survival of the other (Taylor & Allanson, 1993). Crabs subjected to varying *Ceriops* diets exhibited varying lifespans. A 10-week laboratory study was conducted (Lee, 1999) and found that *Ceriops tagal* litter remained unchanged, but crabs provided with ad libitum food had a higher frequency of ovigerous females and molting events compared to those with limited food availability. Survival rates did not differ significantly when different litter species were provided, but variations in molting frequency were observed. Furthermore, Kwok and Lee established a leaf litter hierarchy through a 10-month laboratory rearing experiment, resulting in significant survival differences among individuals of Parasesarma plicata and *Perisesarma bidens* (Kwok & Lee, 1995), This mutualistic interplay may have contributed to the conspicuous correlation between mangrove and crab diversity across different biogeographic regions over time. However, the validation of this hypothesis awaits additional data on the distribution and role of grapsid crabs in a broader range of geographical locations and environments (Lee, 1999).

7.6 Crab-Induced Transformations in Mangrove Ecosystems

Crabs have the capacity to exert an influence on the mangrove community structure through their feeding activities. Their preference for mangrove propagules has been demonstrated, although they do not exhibit a specific preference for litter from particular mangrove species (Micheli, 1993). Field experiments conducted by Smith (Smith III, 1987a, 1987b; Smith, 1988), in Northeast Australia substantiated the significant role of grapsid crabs as major consumers of mangrove propagules. Propagules from various mangrove species were observed to experience high mortality rates. Smith's research also unveiled variability in consumption within forests dominated by distinct mangrove species (Smith III, 1987a, 1987b; Smith, 1988). A noteworthy finding was the general inverse relationship between the dominance of conspecific canopy and the severity of crab attacks. If this selectivity holds across various forest-crab pairings, it suggests that herbivorous crabs can impact forest zoning by altering the recruitment of mangrove seedlings. Contrary to expectations, researchers failed to find empirical support for the dominance-predation dynamics hypothesis, suggesting that alternative mechanisms may be driving the observed patterns (McGuinness, 1997; McKee, 1995).

The extent of crab seed consumption in mangroves, predominantly in the Indo-Pacific, exhibited a declining trend both eastward and westward, aligning with the patterns of mangrove and grapsid crab diversity (Smith, 1988). Twilley et al. highlighted significant leaf removal by the ocypodid *Ucides occidentalis* within high-energy mangrove forests in Ecuador (Twilley et al., 1997). Crabs play a substantial role in regions where their abundance does not match that of Australia's east coast, where *Heloecius cordiformis* is prevalent. An often-overlooked facet of crab ecology is their contribution to the movement of animal biomass between mangroves and adjacent offshore systems (Lee, 1995).

Most mangrove crabs follow a reproductive pattern in which they incubate their eggs and release developed larvae into the water, guided by environmental cues such as *A. pisonii*. These pelagic larvae typically spend several weeks in near-shore waters before returning to adult mangroves. The significance of this flow of animal biomass as part of the material exchange between mangroves and neighboring ecosystems is still under investigation. Dittel and Epifanio found that although there was no significant trend for all taxa examined, certain groups, like crab zoeae, exhibited net export of biomass (Dittel & Epifanio, 1990). Given the prevalence of crabs in mangroves, it would be intriguing to quantify the potential contribution of this organic matter source to the consumers within adjacent ecosystems (Lee, 1999). Broader ecological consequences of crab activities contribute to the resilience of mangrove ecosystems against environmental stressors. Ocypodid species, e.g., *Ucides occidentalis*, play a critical role in leaf litter removal and nutrient redistribution in high-energy mangrove forests, while *U. cordatus* fulfils various ecological functions, serving as a primary consumer of neotropical litter and *Rhizophora* propagules, while also contributing significantly to bioturbation, burrowing activities, and the regulation of soil microbiota (Ferreira et al., 2024). By maintaining soil aeration and nutrient cycles, crabs enhance the ecosystem's capacity to recover from disturbances, such as storms or anthropogenic impacts. Additionally, *Uca pugnax* burrowing on sediment biogeochemistry in Georgia's salt marshes highlights their influence on sulfur and iron cycling, carbon oxidation, and nutrient turnover (Gribsholt et al., 2003; Thomas & Blum, 2010). This reinforces the ecological role of fiddler crabs in enhancing sediment aeration and nutrient dynamics. Interdependence between mangrove vegetation and crab populations underscores their role in maintaining ecosystem stability and biodiversity.

8. Evaluating Mangrove Ecosystems Using The Mangrove Quality Index And The Significance Of Crabs As Bioindicators

As evident from the discussion, mangroves are immensely valuable as versatile ecosystems offering resource provisioning and a spectrum of ecosystem services. Therefore, having a tool capable of assessing the quality of mangroves and the ecosystems they constitute proves to be highly advantageous (Ávila-Flores et al., 2020). The MQI emerges as such a tool, designed to evaluate five critical factors reflective of the mangrove ecosystem: biotic integrity, hydrology, socio-economic aspects, soil quality, and marine-mangrove interactions. The parameters considered in the Mangrove biotic integrity index encompass aboveground biomass, basal area, crab abundance, tree height, and tree volume. The MQI employs these parameters to gauge the mangrove ecosystem's quality (Hanum et al., 2019). According to Ibrahim et al. (Ibrahim et al., 2019), MQI represents a comprehensive, integrative ecological and socio-economic index, providing a more holistic perspective on the health of the mangrove ecosystem. A noteworthy feature of MQI is its comprehensive development process, undertaken in a stepwise manner (MQISi). The methodology involved in constructing this MQI encompassed five primary steps: classification of disturbance levels utilizing GIS and remote sensing; identification of socio-ecological variables characterizing the mangrove ecosystem through principal component analysis; formulation of sub-indices (MQISi) and overall MQI; aggregation of the MQI; and ultimately, the validation of the methodology (Ibrahim et al., 2019). The study supporting the highlights of using MQI can be reflected through the growing use of Geographic Information Systems and Remote Sensing for sustainable mangrove management, focusing on Sri Lanka's eastern coast. It assessed geospatial methods, including spectral indices and classification techniques, using Landsat 8 satellite data from 2018 and 2021. Vegetation indices helped detect degraded mangroves, and spatial data was processed with ArcGIS software. Overestimation and misclassification challenges were addressed using the MQI, which categorized mangroves into three degradation levels, offering insights into their overall health and conservation needs (Harshana & Gunathilaka, 2023).

In another study, Ibrahim et al. scrutinized 43 variables categorized into biotic integrity, mangrove hydrology, mangrove socioeconomics, mangrove soil quality, and marine mangrove aspects (Hanum et al., 2019). These variables were monitored over the course of a year to capture seasonal fluctuations in mangrove forest conditions, spanning pristine, moderately disturbed, and significantly disturbed mangrove ecosystems. Principal component analysis, a key component of the MQI tool, identified ten pivotal variables critical to the final MQI determination. The categorization involved designating the index as MQIS 1-5 for each category (Hanum et al., 2019).

The PCA analysis across all tested variables unveiled that the highest variance score was attributed to aboveground biomass and crab abundance. When compared to the traditional practice of manually assessing timber stock volume data as an indicator of mangrove health, the adoption of MQI promises efficiency gains in terms of time, labour, and cost in mangrove ecosystem monitoring. Furthermore, MQI has the potential to serve as the foundation for an intelligent automated monitoring system leveraging modern technologies such as artificial intelligence. This would ensure the long-term sustainability of mangrove ecosystems and the services they provide for both present and future generations. However, challenges associated with MQI in implementing its potential may include biases in crab population studies, which may be influenced by various factors, such as habitat characteristics, water quality, and human activities, which can lead to biased results. Additionally, data variability in crab populations can exhibit high spatial and temporal variability, making it challenging to obtain reliable and consistent data. Taking into account the logistical constraints while conducting crab surveys and collecting data can be time-consuming, labour-intensive, and costly, particularly in remote or inaccessible areas. Two more key challenges that can be taken into account are its reliance on a limited number of crab species, which may not adequately represent the full diversity of mangrove ecosystems, and its limited scalability to larger or more complex ecosystems. Addressing these limitations requires further research to broaden the taxonomic scope and adapt the index for application across diverse spatial scales and ecosystem complexities, ensuring its utility in varied environmental contexts.

8.1 Effectiveness of crabs as bioindicators

Goessens et al.(2014) conducted a study that revealed higher crab population density in less disturbed mangrove ecosystems compared to moderately disturbed ones (Goessens et al., 2014). Another study demonstrated the utility of crabs as bioindicators through their study of crab populations across mangrove forests of varying ages (Aminah et al., 2020). Their findings revealed that younger mangrove stands with abundant fresh leaf litter supported higher crab abundance, while older forests with reduced canopy cover and decomposed stems hosted fewer crabs. These results highlight the sensitivity of crab populations to changes in forest structure and resource availability, reinforcing their role as indicators of ecosystem health.

Mangrove forest ecosystems are subject to various influential factors, including salinity. Burrowing crabs, which are prevalent in mangrove forests globally, play a role in sediment water fluxes and reducing salinity in mangrove sediments. Pestana et al. (Pestana et al., 2017) investigated the interaction between crab burrow density and secondary fine root biomass in driving sediment salinity during the dry season in a northern Brazilian mangrove forest. They compared the density of *Rhizophora mangle* prop roots with that in areas without such roots. The study identified the crab species *Ucides cordatus* as contributors to sediment desalination beneath mangrove trees. However, in areas with dense prop and fine roots, there was no correlation between burrow density and sediment salinity. Thus, the efficacy of crabs in reducing sediment salinity appears to be context-dependent, with salt-excluding mangrove species like R. mangle, characterized by high root density, counteracting the crabs' effects. These findings underscore the year-round influence of crabs, which should be considered when assessing their overall ecological impact within mangrove ecosystems (Pestana et al., 2017).

Similarly, according to Andreetta et al. (2014), sesarmid burrowing crabs exhibited a preference for densely vegetated habitats, where their burrowing activities enabled them to act as ecosystem engineers by modifying the sediment structure and surrounding environment. The presence of a dense canopy cover in these areas created a cooler environment on the forest floor, facilitating foraging and burrow construction by the crabs (Van Nedervelde et al., 2015).

The sesarmid crab species *Perisesarma eumolpe* plays a crucial role in the trophic dynamics of mangrove forests, contributing to their overall health and ecosystem functioning. Within the mangrove ecosystem, this crab is recognized as a keystone species. The preference of specific mangrove species as a food source among these crabs is an important aspect to consider (Salleh-Mukri & Shuhaida, 2021). Researchers

Aminuddin & Arai explored the feeding ecology of *Perisesarma eumolpe* using leaves from three mangrove species (*Avicennia lanata*, *Bruguiera gymnorrhiza*, and *Ceriops decandra*) (Aminuddin & Arai, 2017). Their findings demonstrated that crabs exhibit preferences influenced by the nutritional quality and moisture content of the leaves. For instance, fresh *C. decandra* leaves, with a low C/N ratio and high moisture content, were highly preferred, suggesting that leaf traits significantly impact crab feeding behaviour. This highlights the role of sesarmid crabs in nutrient cycling and sediment enrichment, as their selective feeding and subsequent decomposition activities contribute to sediment organic matter diversity and microbial activity. These results underscore the importance of understanding crab feeding preferences to assess their ecological impact on mangrove productivity.

9. Future Research And Its Prospects

Future research needs to focus on verified, location-specific monitoring techniques that link crab responses to sedimentation, water quality, and restoration outcomes, rather than making general assumptions about crabs being good bioindicators. A multi-site, season-specific investigation that compares crab density, population form, and biomarker responses to environmental variables like metallic compounds, salinity, organic matter, and other disruption gradients would be an excellent next step. Studies should also include various endpoints, like fertility, histological analysis, oxidative and genetic damage, and tissue loads, rather than depending on one indicator, since integrated metrics are more likely to detect ecosystem disruption. Monitoring should be standardized through both dry and wet seasons, with baseline, damaged, and recovered sites included, to increase consistency and monitor whether biotic restoration accompanies physical or chemical progress following mangrove regeneration. These crab parameters can subsequently be integrated into larger mangrove health frameworks, such as composite indices, to enable more rigorous and management-specific ecological evaluations. Future research should broaden the phylogenetic scope beyond a few dominating crab species by creating multiple species bioindicator frameworks that better depict the ecological range of mangrove habitats. Therefore, developing standardized measurement procedures and threshold criteria for crab-based ecological indicators would make cross-regional comparisons easier and would promote the implementation of crab bioindicators into national and international mangrove preservation, rehabilitation, and environmental management initiatives.

Conclusion

Based on a comprehensive analysis of multiple studies, it is evident that crabs represent highly reliable indicators for evaluating the overall health of mangrove ecosystems. The activities of crabs offer valuable insights into crucial ecological parameters, such as tree height, tree basal area, biomass, and the presence of various other species within the ecosystem. Substantial evidence within mangrove ecosystems indicates that a greater abundance of mangrove biomass is associated with an increased density of crab populations. While studies have indicated a correlation between the parameters of crab populations and mangrove trees, the precise mechanisms underlying this linkage remain inadequately explored. Current correlations, primarily semantic or numeric, lack a robust logistic basis to fully elucidate the interactions between these two gradients. Recent research underscores the importance of examining crab composition and distribution across diverse mangrove sites, as these patterns can reveal critical ecological interdependencies. Specifically, the role of crabs in bioturbation, nutrient cycling, and propagule predation is hypothesized to influence mangrove tree health and diversity. However, detailed mechanistic studies are essential to confirm and quantify these relationships in varying environmental and geographic contexts. To enhance conservation and ecosystem management efforts, future investigations must examine mangrove crabs' responses to environmental stressors, particularly in regions with distinct climatic seasons, to harness their potential as sentinel species in these initiatives.

Author Contribution

HM: Conceptualization, Data curation, Formal Analysis, Writing - Original Draft, Writing - Review & Editing. FHI: Supervision, Proofreading, Formal Analysis. HK: Supervision, Proofreading, Formal Analysis.

Declaration of competing interests

Conflict of interest - The author herewith declares that there is no conflict of interest regarding the publication of this research article.

Funding

We are thankful to Tawaran Skim Geran Penyelidikan Fundamental FRGS FASA 1/2019 Universiti Putra Malaysia (Vote No – 5540232).

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