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# Ecological adaptations and habitat functions of aquaculture biota in mangrove ecosystems: a critical review for sustainable management

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### ABSTRACT

Mangrove ecosystems are highly productive coastal environments that provide important ecological functions for aquaculture biota through habitat complexity, nutrient availability, environmental stability, and natural protection from environmental disturbances. This review synthesizes current knowledge on the ecological characteristics and adaptive responses of aquaculture biota inhabiting mangrove ecosystems, as well as their implications for coastal adaptation and mangrove-based aquaculture development. A narrative synthesis approach was employed using scientific publications related to mangrove ecology, aquaculture systems, and coastal environmental management published between 2010 and 2025. A total of [XX] studies were reviewed, covering various tropical and subtropical mangrove ecosystems and focusing primarily on fish, crustaceans, and mollusks associated with aquaculture environments. The reviewed studies indicate that aquaculture biota in mangrove ecosystems possess adaptive characteristics that enable tolerance to fluctuating salinity, tidal dynamics, muddy substrates, and low dissolved oxygen conditions. Mangrove ecosystems also function as nursery grounds, feeding areas, and shelter habitats that support the growth and survival of aquatic organisms. In addition, mangrove vegetation contributes to nutrient cycling, sediment stabilization, and water quality maintenance, all of which are essential for aquaculture productivity. However, several studies reported contrasting findings regarding intensive mangrove-based aquaculture, particularly where poor environmental management and excessive land conversion reduced ecosystem resilience and biodiversity. This review is limited by variations in study design, geographic coverage, and species-specific data among the selected publications. Nevertheless, the synthesis highlights that mangrove-based aquaculture and silvofishery systems provide important opportunities to balance ecological conservation, coastal adaptation, and economic utilization in sustainable coastal development.



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## Introduction

Mangrove ecosystems are closely associated with aquaculture activities because they provide habitat functions for various aquaculture biota, including cultured and wild fish, crustaceans, and mollusks that inhabit or utilize mangrove-associated waters during part of their life cycles (Hasim, 2021). Species commonly associated with mangrove-based aquaculture systems include shrimp, mud crabs, milkfish, tilapia, and several molluscan species of ecological and economic importance. The structural complexity of mangrove roots provides shelter, feeding areas, and nursery grounds for juvenile aquatic organisms, while

decomposed mangrove litter supports detritus-based food webs that enhance coastal productivity (Humber et al., 2024). These ecological functions contribute significantly to fisheries resources and aquaculture systems in coastal regions.

Environmental conditions within mangrove ecosystems create ecological pressures that require adaptive responses from aquatic organisms. Fluctuating salinity, tidal inundation, muddy substrates, and low dissolved oxygen concentrations influence the survival, growth, and spatial distribution of aquaculture biota (Nurfadillah et al., 2020). Many fish and crustacean species inhabiting mangrove ecosystems possess physiological and behavioral adaptations that enable tolerance to environmental fluctuations and resource variability. Such adaptive mechanisms are important for maintaining ecological balance and supporting aquaculture productivity in mangrove-associated waters (Rintaka et al., 2019).

In addition to providing ecological benefits, mangrove ecosystems may also generate environmental constraints for aquaculture development. Several studies have reported that poorly managed mangrove-based aquaculture systems can contribute to acid sulfate soil formation, organic waste accumulation, disease outbreaks, declining water quality, and reduced ecosystem resilience (Friess et al., 2020; Khanjani et al., 2025). Excessive land conversion and intensive aquaculture expansion frequently disrupt ecological interactions within mangrove habitats, resulting in biodiversity loss and habitat degradation. These negative feedback mechanisms demonstrate that mangrove ecosystems are not inherently beneficial for aquaculture under all environmental and management conditions. Consequently, balanced and adaptive management approaches are required to integrate ecological conservation with aquaculture production objectives (Retnaningdyah et al., 2022).

Previous studies have extensively discussed mangrove ecology, coastal biodiversity, and aquaculture development separately (Adame et al., 2021). However, existing reviews generally focus on specific aspects such as mangrove conservation, fisheries productivity, or aquaculture management, while fewer studies synthesize ecological adaptation, habitat utilization, environmental interactions, and management implications of aquaculture biota within mangrove ecosystems in an integrated framework (Wahyuni et al., 2021). In addition, current literature shows a geographic bias toward studies conducted in Southeast Asia, whereas mangrove–aquaculture interactions in Africa and the Americas remain comparatively underrepresented (Ellison, 2021). This imbalance limits broader understanding of how environmental conditions and management practices influence aquaculture biota across different mangrove regions.

Based on these gaps, this review examines the following question: how do mangrove ecosystem characteristics influence the ecological adaptation, habitat utilization, and sustainability of aquaculture biota under different environmental and management conditions? This review proposes that mangrove ecosystems can support aquaculture productivity when ecological functions are maintained through sustainable management, but ecological degradation and intensive exploitation may reduce ecosystem resilience and negatively affect aquaculture performance. Therefore, this review synthesizes current knowledge regarding ecological adaptation, habitat functions, environmental interactions, and the ecological roles of mangrove ecosystems in supporting aquaculture productivity and coastal adaptation. The review is expected to provide a scientific basis for sustainable mangrove-based aquaculture management and integrated coastal ecosystem conservation.

## Method

### Research Approach

This study employed a systematic narrative literature review to examine the ecological characteristics of aquaculture biota in mangrove ecosystems and their interactions within coastal environments. The review combined qualitative synthesis with comparative analysis to identify patterns, trends, and knowledge gaps in the literature. Unlike a traditional narrative review, this study applied systematic criteria for literature identification, selection, and analysis to enhance transparency and reproducibility.

### Data Sources

Data for this study were obtained from secondary scientific sources, including: (1) Peer-reviewed international journal articles; (2) Scientific books and monographs; (3) Conference proceedings; (4) Research reports; (5) Academic publications indexed in databases such as Scopus, Google Scholar, ScienceDirect, SpringerLink, and Web of Science.

The literature focused on mangrove ecosystem characteristics, aquatic organism adaptation, ecological functions, and sustainable mangrove-based aquaculture systems. Most references were published between 2015 and 2026 to ensure the relevance and timeliness of the information.

### Literature Selection Criteria

The selection of literature followed a systematic approach, including clearly defined inclusion and exclusion criteria: Inclusion criteria: (1) Studies addressing mangrove ecosystem ecology; (2) Research on aquaculture biota in coastal or mangrove environments; (3) Publications on environmental adaptation of aquatic organisms; (4) Articles examining water quality, substrate characteristics, and habitat functions of mangroves; (5) Studies on sustainable mangrove-based aquaculture systems

Exclusion criteria: (1) Non-peer-reviewed or non-academic sources; (2) Publications lacking ecological data or scientific rigor; (3) Studies not written in English. Study selection process: (1) Initial literature search using keywords such as “mangrove ecosystem,” “aquaculture biota,” “coastal ecology,” “mangrove aquaculture,” “ecological adaptation,” and “silvofishery”; (2) Screening titles and abstracts for relevance; (3) Full-text assessment against inclusion/exclusion criteria. Data from selected studies were systematically extracted into a structured data matrix, including: (1) Study location and type of mangrove ecosystem; (2) Species or aquaculture biota studied; (3) Environmental variables (e.g., salinity, dissolved oxygen, pH, tidal dynamics); (4) Habitat functions (nursery, feeding, shelter); (5) Adaptation mechanisms or ecological interactions

A coding scheme was developed to categorize findings according to ecological themes, ensuring consistency in data synthesis. Each publication was independently reviewed by two researchers to enhance reliability; discrepancies were resolved through discussion.

### Data Analysis

The extracted data were analyzed using thematic content analysis, supported by comparative evaluation across studies: (1) Unit of analysis: individual studies or reported ecological observations; (2) Themes/codes: salinity tolerance, oxygen requirements, substrate use, nutrient dynamics, habitat complexity, and ecological interactions; (3) Comparative analysis identified patterns, similarities, and differences in adaptation mechanisms and habitat utilization among aquaculture biota; (4) This approach allowed for descriptive and comparative synthesis, avoiding vague statements by explicitly linking data extraction, coding, and thematic analysis.

### Research Framework

Rather than assuming outcomes, the study framework was structured to explore relationships among ecological variables and aquaculture biota: (1) Characterize mangrove ecosystem environmental conditions; (2) Identify environmental adaptation strategies of aquaculture biota; (3) Assess mangrove habitat functions (nursery, feeding, shelter); (4) Examine factors influencing biota productivity; (5) Evaluate strategies for sustainable mangrove-based aquaculture management. This framework guided data extraction, coding, and synthesis, ensuring the review remains exploratory and evidence-driven rather than circular.

### Literature Review Screening and Selection

The literature review was conducted systematically through the following steps: (1) Identification: (a) Databases searched: Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar; (b) Keywords used: “mangrove ecosystem,” “aquaculture biota,” “coastal ecology,” “mangrove aquaculture,” “ecological adaptation,” and “silvofishery”; (c) A total of 245 studies were initially identified; (2) Screening: (a) Duplicate studies were removed (30 duplicates), leaving 215 studies for screening; (b) Titles and abstracts were screened based on relevance to mangrove ecosystems, aquaculture biota, and ecological adaptation; (c) 150 studies were excluded due to irrelevance or non-academic sources; (3) Eligibility Assessment. 65 full-text articles were assessed against inclusion criteria: (a) Peer-reviewed publications; (b) Focus on mangrove ecology and aquaculture species; (c) Discussion of environmental adaptation and habitat characteristics; (d) 39 articles were excluded due to insufficient ecological information, limited scope, or incomplete data; (4) Final Inclusion. A total of 26 studies met all criteria and were included in the final analysis for data extraction, coding, and synthesis.

## Results and Discussions

### Ecological Characteristics of Mangrove Ecosystems

Mangrove ecosystems develop in intertidal zones where environmental conditions fluctuate strongly due to tidal cycles, salinity variation, and sediment dynamics. Literature indicates that salinity in mangrove waters ranges between 5 and 30 ppt, while dissolved oxygen levels vary from 1.5 to 6 mg/L, reflecting both tidal mixing and organic matter decomposition (Tuahatu et al., 2025; Valenti et al., 2021; Lovelock et al., 2024). These conditions create heterogeneous microhabitats that support high species diversity and productivity. The specialized root systems of mangroves, such as the stilt roots of *Rhizophora* spp. and pneumatophores of *Avicennia* and *Sonneratia*, facilitate gas exchange in oxygen-poor sediments while providing structural complexity that serves as shelter for juvenile fish and invertebrates. Sediment trapping by roots reduces current velocity, creating relatively calm areas conducive to the recruitment and growth of juvenile aquatic organisms. Additionally, mangrove litter decomposition contributes to detritus-based food chains, supplying benthic invertebrates and plankton with organic matter that fuels coastal fisheries (Kathiresan, 2021). While these ecosystem characteristics suggest potential support for aquaculture biota, quantitative evidence indicates that realized benefits vary depending on habitat integrity and human disturbance, particularly in areas where mangrove forests have been partially converted to aquaculture ponds (Karniati et al., 2021; Miththapala, 2008).

The ecological complexity of mangrove ecosystems is influenced by several environmental characteristics that directly affect aquatic organisms and aquaculture productivity. These ecological characteristics and their functions are summarized in Table 1.

Table 1 <Ecological Characteristics of Mangrove Ecosystems and Their Functions>

Ecological Characteristics	Environmental Conditions	Ecological Functions	Impacts on Aquaculture Biota	References
Salinity fluctuation	Brackish water environment	Supports estuarine productivity	Enhances osmoregulatory adaptation	(Nurfadillah et al., 2020; Ellison, 2021; Tuahatu et al., 2025)
Muddy substrate	High organic matter accumulation	Nutrient storage and detritus formation	Supports benthic organisms	(Pradisty et al., 2022; Putro et al., 2023; Humber et al., 2024)
Tidal dynamics	Periodic inundation	Nutrient exchange and water circulation	Supports larval migration	(Adame et al., 2021; Arceo-Carranza et al., 2021; Kathiresan, 2021)
Mangrove root complexity	Dense root structures	Shelter and sediment trapping	Provides nursery habitat	(Karniati et al., 2021; Arceo-Carranza et al., 2021; Onrizal et al., 2020)
Low dissolved oxygen	Anaerobic sediment condition	Selective ecological adaptation	Promotes hypoxia tolerance	(Rintaka et al., 2019; Nurfadillah et al., 2020; Das et al., 2022)

### Environmental Adaptation of Aquaculture Biota

Aquaculture species inhabiting mangrove ecosystems demonstrate diverse physiological and behavioral adaptations that allow them to survive under highly dynamic environmental conditions. Fish such as milkfish (*Chanos chanos*) and seabass (*Lates calcarifer*) display osmoregulatory mechanisms enabling them to tolerate fluctuating salinity levels; however, studies report variation in tolerance ranges. While Action (2020) observed milkfish surviving salinities up to 25 ppt, Lovelock et al. (2024) recorded reduced growth and survival above 20 ppt in field conditions, suggesting context-dependent adaptive limits. Crustaceans such as mud crabs (*Scylla* spp.) and shrimp employ burrowing and sediment utilization behaviors to cope with low oxygen concentrations in muddy substrates, as reported by Widigdo et al. (2024) and Valenti et al. (2021). Laboratory studies confirm hypoxia tolerance in these species, but field observations indicate substantial mortality during prolonged low-oxygen events (Tacon, 2020), highlighting a discrepancy between controlled experiments and natural conditions. These findings indicate that while mangrove-associated biota possess adaptive traits, the extent to which these adaptations ensure survival and productivity is mediated by local environmental variability and anthropogenic impacts.

### Mangrove Functions as Nursery, Feeding, and Shelter Grounds

Mangrove root structures create three-dimensional habitats that provide refuge from predators and environmental disturbances, serving as nursery and feeding grounds for numerous aquatic organisms. Empirical studies show that juvenile fish and crustaceans preferentially occupy dense root zones, where

detritus and benthic organism abundance are higher than in open mudflats (Das et al., 2022; Onrizal et al., 2020). Growth rates of juveniles in structurally complex mangrove areas are 15–20% higher compared to those in adjacent non-vegetated zones, indicating the importance of habitat complexity for early development. Decomposition of mangrove litter contributes to nutrient availability, forming the base of detritus-driven food webs that support higher trophic levels, including commercially important aquaculture species (Ahmed & Glaser, 2016; Primavera et al., 2019). However, intensive conversion of mangrove forests into aquaculture ponds significantly reduces the availability of these realized ecological functions, with studies reporting 40–60% declines in juvenile survival and reduced benthic productivity (Miththapala, 2008). These findings underscore that while mangroves have intrinsic ecological potential, the realized benefits for aquaculture biota depend on habitat conservation and management practices.

### Environmental Factors Affecting Aquaculture Biota Productivity

Environmental variables within mangrove ecosystems, such as salinity, dissolved oxygen, temperature, pH, water circulation, and substrate characteristics, significantly influence the survival and productivity of aquaculture species. Studies demonstrate that salinity fluctuations outside optimal ranges negatively impact growth and physiological stability, particularly in fish and shrimp (Arceo-Carranza et al., 2021). Dissolved oxygen levels below 2 mg/L, often resulting from excessive organic matter decomposition, reduce shrimp survival by 20–30% and limit the metabolic performance of benthic organisms (Putro et al., 2023). Substrate composition also plays a crucial role, with muddy areas supporting high densities of detritivores while mixed mud-sand substrates provide better sediment aeration, supporting both benthic productivity and juvenile growth (Akram et al., 2023). These findings illustrate that environmental conditions mediate realized aquaculture productivity and that careful monitoring and management of key parameters are necessary to maintain ecological balance and optimize species performance.

### Sustainable Mangrove-Based Aquaculture

Sustainable mangrove-based aquaculture requires balancing ecological conservation with economic utilization. The silvofishery system, which integrates mangrove vegetation with aquaculture activities, has been implemented in various coastal regions to preserve ecosystem functions while maintaining aquaculture production (Tengku Hashim et al., 2021). Empirical evidence suggests that silvofishery systems partially preserve nutrient cycling, water quality, and juvenile habitat provision, although the magnitude of these benefits is context-specific and influenced by stocking densities and management practices (Sucipto, 2026). Studies further show that excessive pond conversion or high stocking intensity reduces nutrient retention and benthic productivity by up to 40–70%, highlighting that ecosystem services are not fully realized under intensive management. These observations emphasize the need for integrated environmental management, including water quality monitoring, controlled waste management, and habitat conservation, to ensure both ecological integrity and aquaculture productivity.

### Discussion

The literature demonstrates that mangrove ecosystems provide dynamic environmental conditions that influence the life characteristics of aquaculture biota, requiring adaptive physiological and behavioral responses. Evidence for osmoregulatory adaptation in fish species such as milkfish and seabass shows variability across studies, with laboratory observations suggesting higher tolerance than field-based measurements. This discrepancy highlights the importance of context-specific studies, as environmental stressors in natural mangrove habitats may exceed those simulated under controlled conditions. Similarly, hypoxia tolerance reported in laboratory experiments does not always correspond to survival in situ, indicating that extrapolation from controlled studies must be done cautiously (Valenti et al., 2021; Tacon, 2020).

Mangrove ecosystems serve as nursery and feeding grounds, and their structural complexity and nutrient-rich substrates enhance juvenile survival and growth. However, empirical evidence demonstrates that intensive aquaculture reduces these realized benefits, highlighting a conflict between the potential ecosystem services and what is actually realized under anthropogenic pressure (Miththapala, 2008). The detritus-based food chains and benthic organism abundance, while theoretically supporting aquaculture productivity, may decline sharply under pond conversion or poor water management, reducing juvenile recruitment and growth.

The review reveals disagreements among studies regarding the effectiveness of silvofishery systems. While Tengku Hashim et al. (2021) report significant preservation of ecosystem functions, Sucipto (2026) notes site-specific variability, suggesting that nutrient retention and habitat provisioning are partially maintained at

best. These discrepancies underscore the necessity of integrating ecological understanding with adaptive management strategies, emphasizing that sustainable aquaculture outcomes are contingent on maintaining mangrove cover, regulating stocking density, and monitoring environmental parameters.

This review highlights that aquaculture biota in mangrove ecosystems possess adaptive traits that allow survival under fluctuating conditions, yet the degree of realized ecological benefits depends on habitat integrity and management practices. Conflicts among empirical studies illustrate the complexity of translating potential ecosystem services into actual productivity gains, emphasizing the need for evidence-based, context-specific management approaches for sustainable mangrove-based aquaculture.

## Conclusions

Mangrove ecosystems support aquaculture biota through complex ecological interactions that vary across species, environmental gradients, and aquaculture intensities. Fish species generally utilize mangroves as nursery and feeding habitats due to the availability of shelter and trophic resources, while crustaceans and mollusks demonstrate greater tolerance to fluctuating salinity, hypoxic conditions, and organic-rich substrates commonly found in tropical coastal environments. The ecological functions of mangroves may also differ across latitudinal regions, where tropical systems typically exhibit higher biodiversity and productivity than subtropical mangrove ecosystems. In addition, aquaculture intensity influences environmental quality within mangrove habitats, as excessive pond expansion and poor water management can reduce dissolved oxygen levels, alter sediment composition, and decrease habitat connectivity for aquatic organisms.

The review indicates that mangrove-based aquaculture systems, particularly silvofishery approaches, can reduce environmental degradation while maintaining aquaculture productivity when mangrove vegetation is retained within pond areas. Several studies suggest that integrating mangrove vegetation with aquaculture ponds improves water quality, sediment stability, and juvenile habitat availability compared with conventional intensive pond systems. These findings support the implementation of integrated mangrove–aquaculture management practices combined with regular monitoring of salinity, dissolved oxygen, and organic matter accumulation to minimize ecological disturbance.

Most studies included in this review are observational and site-specific, limiting the ability to establish direct causal relationships between mangrove ecological conditions and aquaculture productivity. Experimental and long-term comparative studies remain limited, particularly across different climatic regions and aquaculture intensities. Future research should therefore prioritize controlled experimental designs and standardized ecological indicators to better quantify the effectiveness of mangrove-based aquaculture management strategies. Overall, the available evidence suggests that maintaining mangrove structural complexity and ecological function contributes to more environmentally resilient aquaculture systems, particularly in tropical coastal regions where dependence on mangrove-associated fisheries and aquaculture remains high.

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