



Ecological Importance of Mangroves Ecosystem: An Overview

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Mangroves are salt-tolerant woody trees and shrubs that inhabit intertidal coastal zones, forming a vital ecological link between terrestrial and marine environments through specialized adaptations. They are distributed along warm coastlines worldwide, predominantly between latitudes 25°N and 25°S. Global mangrove forests cover approximately 135,000–150,000 km², with the greatest species richness and structural complexity occurring in the Indo-West Pacific region compared with the Atlantic-East Pacific region (Girkin, 2026). Mangrove ecosystems are biodiversity hotspots because they support a diversity of species of flora, fauna, and microbes. Worldwide, there are about 50 to 70 species of mangroves, with about 3–6 species dominating each locality, of which four genera (*Rhizophora*, *Avicennia*, *Xylocarpus* and *Bruguiera*) are the most widespread. There are 71 species belonging to 19 families that are considered as true mangrove species, whereas other authors often listed over 80 mangrove species dominating tropical and subtropical coastlines. Mangrove vegetation comprises a unique group of shrubs and trees belonging to unrelated families, but they share several physiological and morphological adaptations that are characteristic of shallow intertidal wetlands (Ohimain et al., 2026).

In India, according to spatial mapping assessments, mangrove cover spans approximately 4,991.68 km², which accounts for 0.15 % of the country's total geographical area and nearly 3% of the global total. This is a decrease of 7.43 sq km compared to 2021. It is present in 12 States/UTs (9 States and 3 UTs). Except for Gujarat and A&N islands, Mangrove cover has increased in other States/Uts (ISFR, 2023). Indian mangroves are broadly categorized: East Coast Mangroves: Dominated by large deltaic formations like the Sundarbans (West Bengal), Mahanadi delta (Odisha), Godavari-Krishna deltas (Andhra Pradesh) and Pichavaram (Tamil Nadu). West Coast Mangroves: Characterized by estuarine, backwater and creek-based structures across Gujarat, Maharashtra, Goa, Karnataka and Kerala. Island Mangroves: Pristine, dense marine configurations situated in the Andaman and Nicobar Islands (India State of Forest Report (ISFR) 2023).

Morphological and Physiological Adaptations

Salinity Regulation

To dominate waterlogged, highly saline and anoxic coastal substrates, true mangroves exhibit advanced evolutionary specializations. The genus *Rhizophora* (red mangroves) relies on an ultrafiltration mechanism embedded within root epidermal and cortical cell membranes, utilizing negative hydrostatic pressure generated by transpiration to exclude up to 99% of ambient salt while drawing up freshwater (Reef and Lovelock, 2015). Conversely, the genus *Avicennia* (black mangroves) actively transports absorbed salt through the transpiration stream to specialize in foliar excretion via active-transport epidermal salt glands (Naidoo, 2025). Other

species leverage structural succulence, isolating toxic sodium and chloride ions within vacuoles of senescent leaves or bark prior to seasonal abscission (Cram et al., 2002).

Gas Exchange

Hydrophobic pores called lenticels populate specialized aerial root structures to facilitate gas exchange during low tide, replenishing internal oxygen stores (aerenchyma) to survive prolonged tidal inundation (Colmer & Flowers, 2008). These systems take various structural forms to balance respiration with physical support: the arched, branching prop and stilt roots of *Rhizophora* species, which maximize mechanical stability against wave action; the vertical, pencil-like pneumatophores of *Avicennia marina* and *Sonneratia alba* that project negatively geotropically above the mud and the flanged, looped knee roots of *Bruguiera* species (Tomlinson, 2016)

Reproductive Vivipary

To survive shifting, unstable muddy substrates, true viviparous mangroves bypass seed dormancy; embryos germinate while physically attached to the maternal plant, developing into elongated, weighted hypocotyls known as propagules (Tomlinson, 2016). Upon detaching, their specific gravity and density profile enable immediate vertical anchoring in the mud or prolonged horizontal dispersion via marine currents until they reach suitable shallow mudflats (Van der Stocken et al., 2019).

Structure and Functions of Mangrove Ecosystems

The mangrove ecosystem represents a tight coupling between its structural biotic community and physical abiotic constraints.

Table 1. Biotic and Abiotic Structural Typology of Intertidal Mangrove Ecosystems

Component Type	Ecological Factors
Abiotic Factors	Semi-diurnal or diurnal tidal regimes, ambient water temperatures (>20°C), fine-grained, depositional muddy sediments (silt and clay), fluctuating porewater salinity (5 PSU to >40 PSU), high solar radiation and highly negative soil redox potential (Alongi, 2014).
Biotic Flora	True mangroves (specialized, obligate halophytes restricted to the intertidal zone) and mangrove associates (facultative coastal plants like <i>Acrostichum aureum</i>) (Wang et al., 2011).
Biotic Fauna	Benthic macroinvertebrates (brachyuran crabs, gastropod molluscs), pelagic and transient estuarine fish, diverse avifauna and hyper-abundant sediment microbial communities (bacteria, archaea and fungi) (Holguin et al., 2001; Nagelkerken et al., 2008).

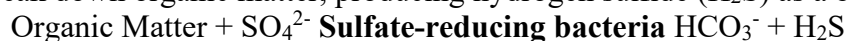
Trophic Structure and Food Web Dynamics

Mangrove food webs bypass traditional herbivorous grazing pathways, operating fundamentally via a detrital pathway (Selvam and Karunagaran, 2019). The primary production of the canopy enters the benthic system primarily as litterfall (leaves, twigs and reproductive structures). Freshly fallen senescent leaves are physically tough and possess high concentrations of secondary metabolites, such as tannins, rendering them unpalatable and virtually indigestible to most macrofauna. Benthic shredders predominantly sesarmid crabs (Family Sesamidae) act as ecological engineers by initiating mechanical breakdown. They drag the litter into their burrows, consuming and macerating it into fine particulate organic matter. This physical fragmentation exponentially increases the surface-area-to-volume ratio, facilitating colonization by marine fungi and bacteria (Maria & Sridhar, 2004). Through microbial enrichment, these colonization microflora metabolize the refractory carbon structure while simultaneously immobilizing dissolved inorganic nitrogen (such as ammonium and nitrate) from the water column (Holguin et al., 2001). This process transforms low-nutrient, carbon-heavy leaf fragments into a protein-rich detrital slurry. This microbial-detrital complex

supports a vast network of opportunistic detritivores, including amphipods, nematodes, and juvenile penaeid prawns, which subsequently sustain higher trophic levels, including zooplanktivorous and predatory fish, wading birds, and apex marine predators (Nagelkerken et al., 2008).

Nutrient Cycling and the Benthic Microbial Engine

Because mangrove sediments are highly compacted and waterlogged, oxygen diffusion is severely limited, rendering the substrate predominantly anoxic and highly stratified (Alongi, 2014). In the micro-oxic zone—a thin, millimeter-scale surface layer of the sediment aerobic heterotrophic bacteria rapidly decompose labile organic matter. Below this boundary, oxygen is completely depleted and anaerobic microorganisms dominate biogeochemical cycling. Given the high concentration of sulfate ions (SO_4^{2-}) supplied by daily seawater inundation, sulfate-reducing bacteria (SRB) become the primary drivers of organic carbon mineralization in deeper sediment layers (Kristensen et al., 2008). They utilize sulfate as a terminal electron acceptor to break down organic matter, producing hydrogen sulfide (H_2S) as a byproduct:



This metabolic pathway yields volatile sulfide compounds, giving mangrove mud its characteristic biogenic rotten-egg odor. Furthermore, deeper, highly reduced anoxic layers support methanogenesis. However, because sulfate reduction is thermodynamically favored over methanogenesis, methanogens are largely outcompeted for substrate (such as acetate and hydrogen) by SRBs in high-salinity zones, keeping overall methane (CH_4) fluxes significantly lower than those observed in freshwater wetlands (Bridgham et al., 2013; Rosentreter et al., 2021).

Ecological Importance and Ecosystem Services

Mangrove forests support high levels of biological diversity by functioning as critical biological corridors linking terrestrial, estuarine and marine realms (Alongi 2009; Srikanth et al. 2015). A distinct ecological division exists between true mangroves and associate species. True mangroves possess strict physiological and morphological adaptations to the intertidal zone, such as specialized aerial root systems, vivipary and salt-management mechanisms (e.g., *Rhizophora*, *Avicennia*, *Sonneratia*, *Bruguiera*) (Srikanth et al. 2015). Conversely, associate species lack these exclusive intertidal specializations and typically grow along the landward fringe where tidal inundation is occasional (Wang et al. 2011).

Avian and Macrofaunal Communities

These coastal marine zones harbor diverse bird assemblages, providing critical stopover feeding grounds for migratory species and nesting sites for resident shorebirds (Saenger 2002; Srikanth et al. 2015). Beneath the canopy, the dense, structural matrix of aerial roots serves as a high-density habitat for specialized macrofauna (Srikanth et al. 2015). This structural complexity hosts distinct assemblages, including specialized brachyuran crabs, mudskippers (*Periophthalmus* spp.) and essential structural bio-builders like oysters and barnacles (Ng and Sivasothi, 2001; Srikanth et al. 2015).

The Rhizosphere Microbiome: The subterranean root system acts as an exceptional habitat for structurally distinct microbial communities (Alongi 2005; Gomes et al. 2010). The continuous diffusion of oxygen out of the roots into the surrounding mud a mechanism known as radial oxygen loss (ROL) creates micro-oxygenated niches within otherwise anoxic sediments (Colmer and Pedersen, 2008). This localized oxygenation allows highly diverse aerobic and facultative taxonomic groups to thrive, including nitrogen-fixing endophytes and free-living bacteria (e.g., *Azotobacter*, *Rhizobium*, *Burkholderia*) that drive nutrient re-mineralization (Alongi 2005). Concurrently, outside these micro-oxic zones, the surrounding strictly anaerobic sediment matrix supports crucial anaerobic decomposers, such as sulfate-, iron and manganese-reducing bacteria (Srikanth et al. 2015).

Global Blue Carbon Sequestration

Mangroves are extraordinarily efficient carbon sinks, capturing and locking away atmospheric carbon dioxide (CO₂) at rates per unit area up to ten times greater than undisturbed terrestrial tropical rainforests. This coastal and marine carbon storage capacity is defined as Blue Carbon. Unlike terrestrial forests, which store the majority of their carbon in short-lived aboveground wood and canopy pools, mangroves sequester 70% to 90% of their total ecosystem carbon stock underground within their deep organic sediments (Donato et al., 2011)

High Belowground Allocation: Mangroves allocate large amounts of carbon to dense, complex root networks that continuously turn over.

Waterlogged Anoxia: The perpetual inundation of salt water seals the sediment from atmospheric oxygen, creating severe anaerobic conditions. Lacking oxygen, microbial decomposition slows down dramatically. Organic material is buried rather than respired back into the atmosphere as CO₂, locking carbon away for centuries or millennia (Donato et al., 2011)

Marine Fisheries and Nursery Grounds

Mangrove ecosystems provide essential structural and trophic support to coastal marine fisheries by serving as critical nursery habitats and breeding grounds for a diverse array of teleosts, elasmobranchs and macroinvertebrates (Igulu et al., 2014). The dense, interwoven physical matrices of specialized aerial root systems such as the submerged prop roots of *Rhizophora* and the vertical pneumatophores of *Avicennia* and *Sonneratia* act as a highly effective defensive hindrance against larger marine predators. This structural refuge markedly reduces predation vulnerability for post-larval and juvenile stages of high-value commercial species, including mullets, groupers, snappers, penaeid prawns, and the high-priced mud crab (*Scylla serrata*) (Rönnbäck, 1999). Additionally, the complex root architectures enhance water residence times, facilitating the retention and settling of planktonic larvae while concurrently trapping suspended particles and stabilizing adjacent soft sediments. Trophically, these habitats energetically subsidize adjacent marine environments through the export of organic matter, dissolved nutrients and living biomass, while the local breakdown of rich mangrove detritus provides a reliable food supply for developing organisms. Because capture fisheries production constitutes the major economic value derived from unexploited mangrove forests contributing significantly to municipal landings and global commercial catches the long-term productivity and species richness of offshore commercial fisheries remain intrinsically tied to the structural health and spatial footprint of adjacent coastal mangrove corridors (Igulu et al., 2014)

Threats, Vulnerabilities and Climate Dynamics

Globally and regionally, mangrove ecosystems face severe degradation driven by the synergistic effects of local human impacts and global climate shifts. The structural health, canopy connectivity, and overall ecological integrity of these coastal corridors are increasingly compromised by landscape fragmentation and persistent anthropogenic disturbances.

Anthropogenic Pressures

Aquaculture Conversion: The historical drivers of global mangrove loss stem from the clearing of coastal forests to install intensive aquaculture ponds, primarily for commercial shrimp and prawn farming. These destructive land-use conversions alter natural hydrology and frequently leave the remaining intertidal soils heavily salinized, acidic and toxic (Rachmansyah et al., 2025).

Urbanization and Infrastructure Expansion: Rapid real estate development, harbor construction, and linear coastal infrastructure have severely fragmented mangrove landscapes. The weak enforcement of environmental regulations and accelerating land-use developments have caused a continuous decline in total mangrove area across coastal megacities, disrupting the baseline function of these forests as natural urban infrastructure (Bhattacharjee et al., 2025)

Pollution and Effluents: Heavy metals, plastic waste, and untreated agricultural and municipal wastewater settle directly into mangrove sediments, overwhelming local filtration capacities

(Bazzi, 2014; Rahmila et al., 2026). Oil spills are exceptionally destructive to true mangrove species; crude oil coats aerial pneumatophores and lenticels, establishing a physical barrier that cuts off critical radial oxygen diffusion and suffocates subterranean root systems (Srikanth et al., 2015).

Climate Change Vulnerabilities

Sea-Level Rise (SLR) and Coastal Squeeze: As global sea levels rise, mangroves must adapt by migrating landward or by trapping enough water-borne silt and organic matter to build their sediment surface upward at a rate matching the rising water. If landward migration is blocked by human structures like seawalls, dikes, and roads a phenomenon known as coastal squeeze the forests end up permanently submerged, resulting in low relative root aeration, prolonged anoxia and eventual drowning (Gilman et al., 2008; Srikanth et al., 2015).

Temperature Anomaly Shifts: Rising global temperatures and a reduction in the frequency of extreme freeze events are prompting a poleward range expansion where tropical, cold-sensitive mangroves migrate into higher latitudes, progressively encroaching upon and replacing temperate salt marshes (Cavanaugh et al., 2014). However, these peripheral expanding populations remain highly vulnerable to extreme climate anomalies, particularly severe winter cold snaps. When localized physiological thresholds are breached by sudden freezing events, it can trigger widespread defoliation, canopy structural damage, and localized dieback along these new geographic frontiers (Enes Gramoso et al., 2026).

Conclusion

Mangrove ecosystems represent one of the planet's most ecologically sophisticated and biogeochemically vital coastal ecotones. Their specialized evolutionary adaptations ranging from complex root architectures to advanced salinity management and reproductive vivipary enable them to thrive within hostile intertidal environments. Beyond local ecological significance, mangroves function as global balancing engines for climate mitigation, anchoring a major portion of the world's coastal "Blue Carbon" by locking vast amounts of organic carbon within deep, anoxic sediments for millennia. Regionally, the deltaic and estuarine networks of India, particularly along the rapidly expanding urbanized coastlines of Maharashtra, highlight the delicate balance between ecological preservation and intense anthropogenic pressure. The persistence of localized fragmentation, coastal squeeze, and structural degradation caused by urbanization and aquaculture underscores the inadequacy of historical, passive preservation attempts. Ultimately, securing the future prospects and climate resilience of these vital marine forests demands a paradigm shift toward science-based Ecological Mangrove Restoration (EMR) which prioritizes the rehabilitation of natural tidal hydrology coupled with institutional enforcement and community-led co-management models. Integrating data-driven ecological science with localized socio-economic incentives remains paramount to safeguarding these invaluable marine ecosystems.

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