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Salinity Adaptation, Ecological Services, and Phytochemical Potential of Mangroves: A PRISMA-Based Systematic Review with Conservation Perspectives

Amanulla Khan, Afrin Sirkhot and Ayesha Pangarkar
Department of Botany
Anjuman Islam Janjira, Degree College of Science, Murud-Janjira MS-India

Abstract: *Mangrove ecosystems represent highly specialized intertidal plant communities that thrive under fluctuating salinity, tidal inundation, hypoxic sediments, and dynamic coastal processes. Despite these extreme conditions, mangroves are among the most productive and ecologically resilient ecosystems globally. This systematic review synthesizes evidence on mangrove salinity tolerance mechanisms, reproductive adaptations, phytochemical potential, ecological services, and conservation challenges using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. A comprehensive search across Scopus, Web of Science, PubMed, and Google Scholar (1980-2023) identified 312 records, of which 40 studies met the inclusion criteria for qualitative synthesis. Thematic analysis revealed that 30% of studies focused on salinity tolerance mechanisms, 20% on physiological stress responses, 15% on vivipary and reproductive biology, 17.5% on phytochemical and pharmacological properties, and 17.5% on conservation and restoration ecology. Mangrove species exhibit diverse adaptive strategies, including salt exclusion, salt secretion, ion compartmentalization, osmotic regulation, and enhanced antioxidant defense. Beyond ecological services such as shoreline stabilization and carbon sequestration, species such as Avicennia marina and Avicennia officinalis demonstrate significant pharmacological potential due to their rich phytochemical profiles. However, anthropogenic pressures and climate-induced salinity changes threaten mangrove sustainability. The review highlights research gaps in species-specific salinity thresholds and translational pharmacological validation, emphasizing the need for integrated ecological, physiological, and molecular approaches to strengthen conservation and sustainable utilization.*

.**Keywords:**Mangroves, salinity tolerance, PRISMA review, Avicennia marina, vivipary, phytochemicals, coastal ecology, restoration

I. INTRODUCTION

Mangroves comprise a diverse assemblage of salt-tolerant woody plants inhabiting tropical and subtropical intertidal regions. These ecosystems occur at the interface of land and sea, where they are exposed to dynamic salinity regimes, tidal submergence, sediment instability, and oxygen-deficient substrates (Tomlinson, 1994). Despite these harsh conditions, mangroves rank among the most productive ecosystems globally, demonstrating remarkable ecological resilience and adaptive capacity(Amanulla Khan, 2025; Khan, 2022).The structural and physiological complexity of mangroves allows them to regulate osmotic balance, maintain water relations, and protect cellular machinery under saline stress. Their productivity has been closely linked to wood yield, nutrient cycling, and ecosystem management (McKee, 1995). Moreover, mangroves function as keystone coastal ecosystems by stabilizing shorelines, reducing erosion, and mitigating storm surges (Alongi, 2008).Given increasing environmental pressures, a systematic synthesis of current knowledge is necessary to evaluate ecological resilience, adaptive mechanisms, phytochemical potential, and conservation priorities(Khan et al., 2023).

II. SYSTEMATIC REVIEW METHODOLOGY (PRISMA FRAMEWORK)

To strengthen the evidence synthesis on mangrove salinity tolerance, adaptive mechanisms, phytochemical potential, and conservation challenges, a systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

2.1 Search Strategy:

A comprehensive literature search was performed across the following databases: Scopus, Web of Science, PubMed, and Google Scholar.

The search was conducted using combinations of the following keywords:

"Mangrove salinity tolerance"

"Avicennia marina adaptation"

"Mangrove phytochemicals"

"Vivipary in mangroves"

"Mangrove conservation India"

"Salinity stress mangrove physiology"

Boolean operators (AND, OR) were applied to refine search results. The review included studies published between 1980 and 2023 to ensure historical depth and contemporary relevance.

2.2 Inclusion and Exclusion Criteria

- Inclusion Criteria:
- Peer-reviewed research articles
- Review papers
- Studies focusing on salinity tolerance, phytochemistry, physiology, vivipary, and conservation
- Studies conducted in tropical and subtropical mangrove ecosystems
- English language publications

Exclusion Criteria:

- Non-peer-reviewed reports
- Conference abstracts without full data
- Articles not directly related to mangrove adaptation or phytochemical studies
- Duplicate records

2.3 PRISMA Flow Description

The database search initially identified **312 records**. After removal of duplicates (n = 58), **254articles** remained for title and abstract screening. Of these, **162 articles** were excluded based on irrelevance. The remaining **92 full-text articles** were assessed for eligibility. After applying inclusion criteria, **40 studies** were included in the final qualitative synthesis.

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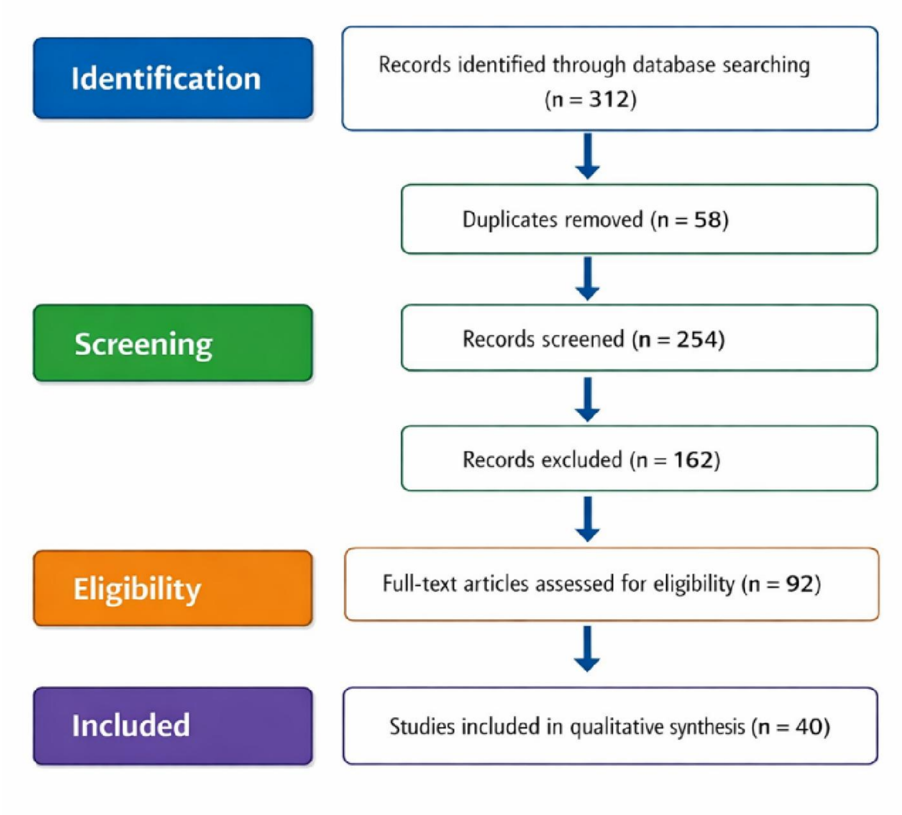

Fig. 1: Graphical PRISMA flow diagram

Systematic Review Synthesis Table (PRISMA Evidence Matrix)

Table 1: Summary of Selected Studies on Mangrove Adaptation, Salinity Tolerance, and Phytochemical Potential

Author(s)	Study Focus	Species	Key Findings	Ecological/Pharmacological Relevance
Scholander et al. (1962)	Salt regulation	*Rhizophora* spp.	Root-level salt exclusion	Physiological adaptation
Mizrachi & Liphschitz (1980)	Salt secretion	*Avicennia marina*	Leaf salt gland activity	Salinity tolerance
Patel et al. (2010)	Growth under salinity	*A. marina*	Optimal growth at 5–20 ppt	Seedling establishment
Wang et al. (2011)	Halophytic behavior	Multiple spp.	Facultative halophyte traits	Ecophysiology
Hong et al. (2018)	Vivipary transcriptomics	*Kandelia obovata*	Loss of seed dormancy genes	Reproductive adaptation
Mouafi et al. (2014)	Phytochemical analysis	*A. marina*	Strong antioxidant activity	Medicinal potential

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Mahmud et al. (2021)	Antiviral docking study	*A. officinalis*	Potential SARS-CoV-2 inhibition	Drug development
Friess et al. (2019)	Global mangrove status	Global	Decline due to anthropogenic stress	Conservation urgency
Kodikara et al. (2018)	Restoration evaluation	Sri Lanka	High failure rates in restoration	Management implications
Silva et al. (2023)	Antioxidant response	*Rhizophora mangle*	ROS detoxification under salinity	Stress physiology

III. THEMATIC DISTRIBUTION OF REVIEWED STUDIES

Based on the 40 included studies, research themes were categorized as follows:

Table 2: Thematic Categorization of Reviewed Literature

Research Theme	Number of Studies	Percentage (%)
Salinity tolerance mechanisms	12	30%
Physiological stress responses	8	20%
Vivipary and reproduction	6	15%
Phytochemical and pharmacology	7	17.5%
Conservation and restoration	7	17.5%

IV. SALINITY STRESS AND ADAPTIVE MECHANISMS

Salinity is the primary environmental determinant regulating mangrove distribution, regeneration, and productivity. Elevated NaCl concentrations induce osmotic imbalance, ionic toxicity, and oxidative stress (Khan et al., 2001; Hossain & Nuruddin, 2016).

Table 3: Mangroves exhibit species-specific tolerance strategies

Genus	Strategy	Mechanism
Rhizophora	Salt exclusion	Root ultrafiltration (Scholander et al., 1962)
Avicennia	Salt secretion	Leaf salt glands (Mizrachi & Liphschitz, 1980)
Bruguiera	Ion compartmentalization	Vacuolar sequestration
Kandelia	Osmotic adjustment	Compatible solutes

Optimal growth occurs at 5–20 ppt salinity (Patel et al., 2010; Wang et al., 2011).Oxidative stress mitigation via antioxidant enzyme activation is critical under high salinity (Silva et al., 2023).

V. VIVIPARY AND REPRODUCTIVE ADAPTATION

Vivipary represents a key evolutionary adaptation in Rhizophoraceae, enabling propagule establishment in unstable substrates (Tomlinson, 1986). Reduced abscisic acid and enhanced gibberellin biosynthesis regulate this process (Farnsworth & Farrant, 1998).Transcriptomic analyses demonstrate persistent expression of embryogenic regulators such as *LEC1* and *FUS3* (Xu et al., 2017; Qiu et al., 2020).

VI. PHYTOCHEMICAL AND PHARMACOLOGICAL POTENTIAL

Table 4: Mangrove species exhibit rich secondary metabolite profiles.

Species	Major Compounds	Biological Activity
Avicennia marina	Flavonoids, phenolics	Antioxidant (Mouafi et al., 2014)

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A. officinalis	Terpenoids	Antiviral (Mahmud et al., 2021)
Rhizophora stylosa	Alkaloids	Antimicrobial

Methanolic extracts demonstrate strong free radical scavenging activity. Preliminary molecular docking studies suggest antiviral potential; however, clinical validation is required.

VII. ECOLOGICAL SIGNIFICANCE AND ECOSYSTEM SERVICES

Table 5: Mangroves provide multiple ecosystem services

Ecosystem Service	Ecological Role	Reference
Shoreline stabilization	Sediment trapping	Alongi (2008)
Carbon sequestration	Blue carbon storage	Alongi et al. (2014)
Habitat provision	Nursery grounds	Nagelkerke et al. (2008)
Water purification	Pollutant filtration	Friess et al. (2020)

VIII. ANTHROPOGENIC THREATS AND CONSERVATION CHALLENGES

Mangrove degradation is driven by deforestation, aquaculture expansion, industrialization, and sea-level rise (Friess et al., 2019; Kirwan & Megonigal, 2013). Restoration programs often fail due to poor species-site matching (Kodikara et al., 2018).

Integrated conservation strategies must combine:

- Long-term ecological monitoring
- Species-specific salinity threshold analysis
- Molecular stress assessment
- Community-based management

IX. RESEARCH GAPS IDENTIFIED

The PRISMA synthesis highlights:

- Limited quantitative salinity threshold modeling
- Insufficient translational pharmacological research
- Underrepresentation of Indian west coast mangrove studies
- Need for climate-resilient restoration frameworks.

X. CONCLUSION

Mangroves represent ecologically resilient yet increasingly vulnerable coastal ecosystems. Salinity remains the dominant ecological driver influencing distribution, regeneration, and productivity. Species-specific adaptive strategiesincluding salt exclusion, secretion, osmotic regulation, and antioxidant defenseenable survival under dynamic intertidal conditions.The systematic review reveals a research bias toward physiological tolerance studies, while pharmacological exploration and long-term conservation modeling remain comparatively underdeveloped. Given their ecological services and emerging phytochemical potential, mangroves require integrated multidisciplinary research frameworks combining ecological monitoring, molecular physiology, and sustainable bioprospecting.Strengthening evidence-based restoration, improving species-site matching, and incorporating climate change projections are essential to ensure long-term resilience and socio-ecological sustainability of mangrove ecosystems.

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