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Review Article

Pharmacological Potential of Halophytic Mangroves from the Indus River Delta: A Review on Novel Metabolites, Phytochemicals, Challenges and Future Prospects

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ABSTRACT

Indus River Delta-Arabian Sea mangroves are among the most diverse and large mangrove ecoregions of the world situated on the coast of Sindh Province, Pakistan. The Indus River forms a massive alluvial fan in this region consisting of mud flats interspersed with channels and fringed with mangrove forests. Indus river delta is a saltier estuary than usual due to salt brought by river from Thar Desert. Only a few biochemically distinct plant species may survive in hostile environments caused by high salt concentrations. A wide range of natural compounds with distinct bioactivity are produced by these salt-tolerant plants. They include active metabolites that belong to several families of chemical compounds, such as steroids, terpenoids, tannins, alkaloids, phenol, etc., and have some unique biochemical structures. Recent research on the pharmacological bioactivities of phytochemicals originating from these halophytic mangrove species is included in this review. The current paper also sheds light on mangroves as a source of several active substances, unique medicines, and agrochemicals.

Keywords: Delta-Arabian Sea, Diversity, Halophytes, Mangroves, Metabolites, Pharmacological activities, Phytochemicals.



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INTRODUCTION

Mangroves are primarily found in the world's tropical and subtropical intertidal zones. About 25% of the world's coastline is covered with these salt-tolerant forest habitats (Spalding *et al.*, 2010) (Figure 1). These forests, which are among the most productive environments, are growing luxuriantly along the shore as a muddy bedrock with varying consistency and depth. There are around 84 mangrove plant species worldwide, of which 70 are real mangroves and 14 are semi-mangroves (Wu *et al.*, 2008). In Pakistan mangroves forests are spread in about 60,000 hectares on Indus delta (Sindh Forest Department, 1990). The Indus Delta contained 17 major streams, several minor streams, and widespread mudflat zones. Approximately 95 percent of Indus Delta mangroves forest is dominated by species *Avicennia marina*. A relatively small population of *Ceriops roxburghiana* (Rhizophoraceae) and *Aegiceras corniculatum* (Myrsinaceae) occurs near the mouth of the Indus River at Ketu Bunder. In addition to these naturally occurring stands, species such as *Rhizophora mucronata* and *Ceriops tagal*, both belonging to the Rhizophoraceae family, have also been introduced into the area through replantation initiatives. These restoration efforts aim to enhance species diversity and strengthen the ecological resilience of mangrove forests in the Indus Delta (Figure 2). These salt tolerant species are utilized in indigenous system of medicine as insecticides and pesticides. These plant species represent an excellent source for the identification of novel secondary metabolites that can reveal information on a variety of phytochemicals found in nature as well as their functions as antioxidants, antimicrobials, anticancer agents, and other agents (Patra *et al.*, 2009).

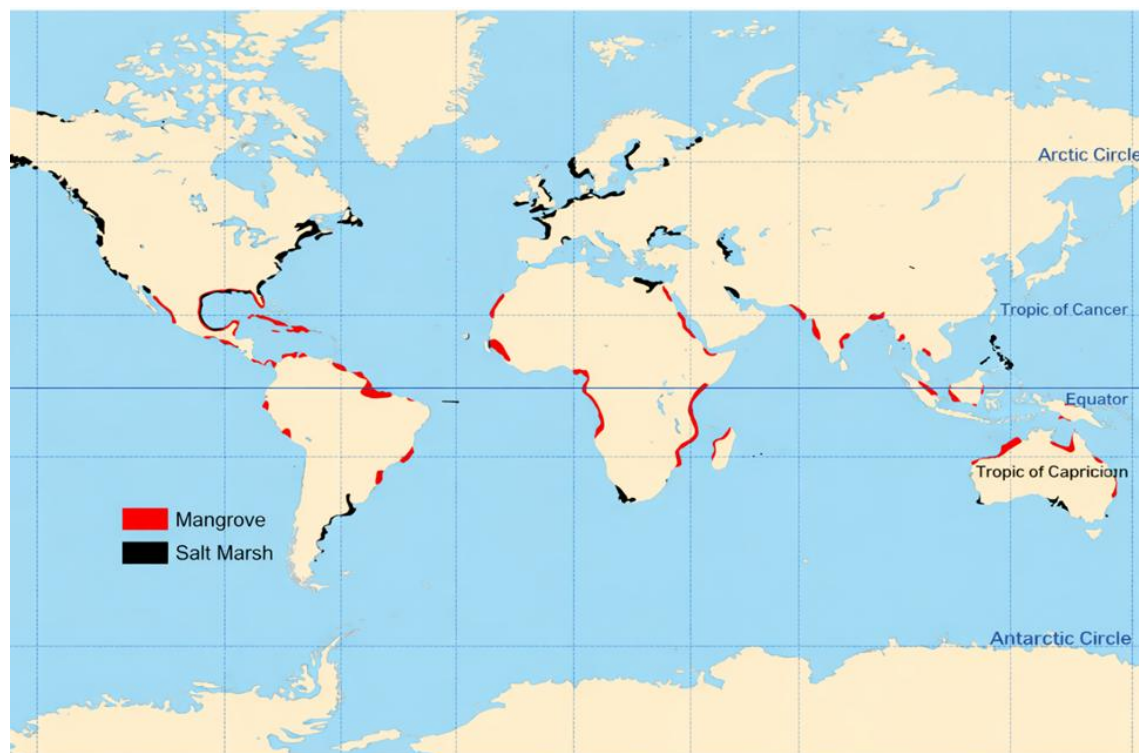


Figure 1. World distribution of mangroves and salt marshes.

This information may also lead to production of novel therapeutically beneficial constituents as against few diseases. Conversely, the systematic evidence about the active substances and biological properties of mangrove are poorly documented. The current review aims to summarize the information about biological activities and chemical composition of mangrove species and their usage in pharmaceutical production.

MANGROVE SYSTEM – EXTENT AND DISTRIBUTION

Pakistan's coastline is roughly 885 kilometres long. Mangrove forests can be found between latitudes 24° 10' and 25° 37' north and longitudes 61° 38' and 68° 10' east. The Indus Deltaic marshes along the Arabian Sea coast are where they congregate most frequently. Mangroves cover the entire coastline of the province of Sindh, (Figure-3). Previously various surveys has been conducted on mangroves of Pakistan, Khan (Rafique, 2018) estimated that 249,486 ha in the Indus Delta is occupied by mangrove and ranked fifth in the world. Mirza (Qureshi, 1993) revealed that mangroves cover 0.64 million hectares, or 44%, in the Korangi-Phitti Creek region of the Indus delta. According to a study by an IUCN-Pakistan team, mangrove forests cover 86,727 hectares of Pakistan's coastline.

ANATOMIC AND PHYSIOLOGICAL CHARACTERISTICS

About 0% to 4% salinity is recorded in the upstream region, 1% to 17% in intermediates and 27% to 28% in the downstream. Salinity effects the plant's growth rates, due to high percentage of Na⁺ in soil hinder nitrate uptake and impairs the uptake of K⁺, Mg²⁺, and Ca²⁺ (N.Duke *et al.*, 1998) Due to ionic imbalance processes like CO₂ exchange, hydraulic conductivity, protein synthesis and conduction of stomata are also affected. Plants adjust themselves in this salt rich environment in numerous means i.e. Exclusion of salt from roots (Scholander, 1968), making their environment more hypertonic by accumulating organic acids as osmotica, Ion accumulation in leaf cells, Leaf succulence and salt recreation via glands (Popp, 1995). Studies showed that Mangrove species often display growth stimulus at low salinity (25% seawater) and then a sudden drop in growth with additional rise in salinity (Ahmed *et al.*, 2023). Although in the Indus delta the most commonly distributed species, *Avicennia marina*, is well studied and is proved to respond as osmoregulator, the other species of Indus delta have received slight attention (Hibino *et al.*, 2001).

Compatible metabolites produced during salt stress

Under salt stress mangroves species specifically produced different metabolites as osmolytes to maintain their homeostatic environment. (Hibino *et al.*, 2001) reported the presence of pinitol as compatible solute exclusively in *B. gymnorhiza* whereas Mannitol is found in *Sonneratia caseolaris* as a compatible solute under salinity. Compounds of

methylated quaternary ammonium are reported in *Avicennia marina* as dominant osmoregulatory compounds (Popp, 1995). *A. mariana* is also reported to contain Glycinebetaine as protector of photosynthetic machinery (Fukushima, Sasamoto, Baba, & Ashihara, 1997). Compatible solutes of *B. gymnorhiza* and *Rhizophora stylosa* are O-methylmucoinositol (Ashihara *et al.*, 2003). Species like e.g. *Sonneratia alba*, *A. marina* are also reported to accumulate inorganic ions as osmolytes whereas *B. gymnorhiza* Salt tolerance may be due to accumulation of high concentration of Na and Cl (Miyama & Tada, 2008). Under salt stress Na and Cl are used by mangroves species in order to maintain K.

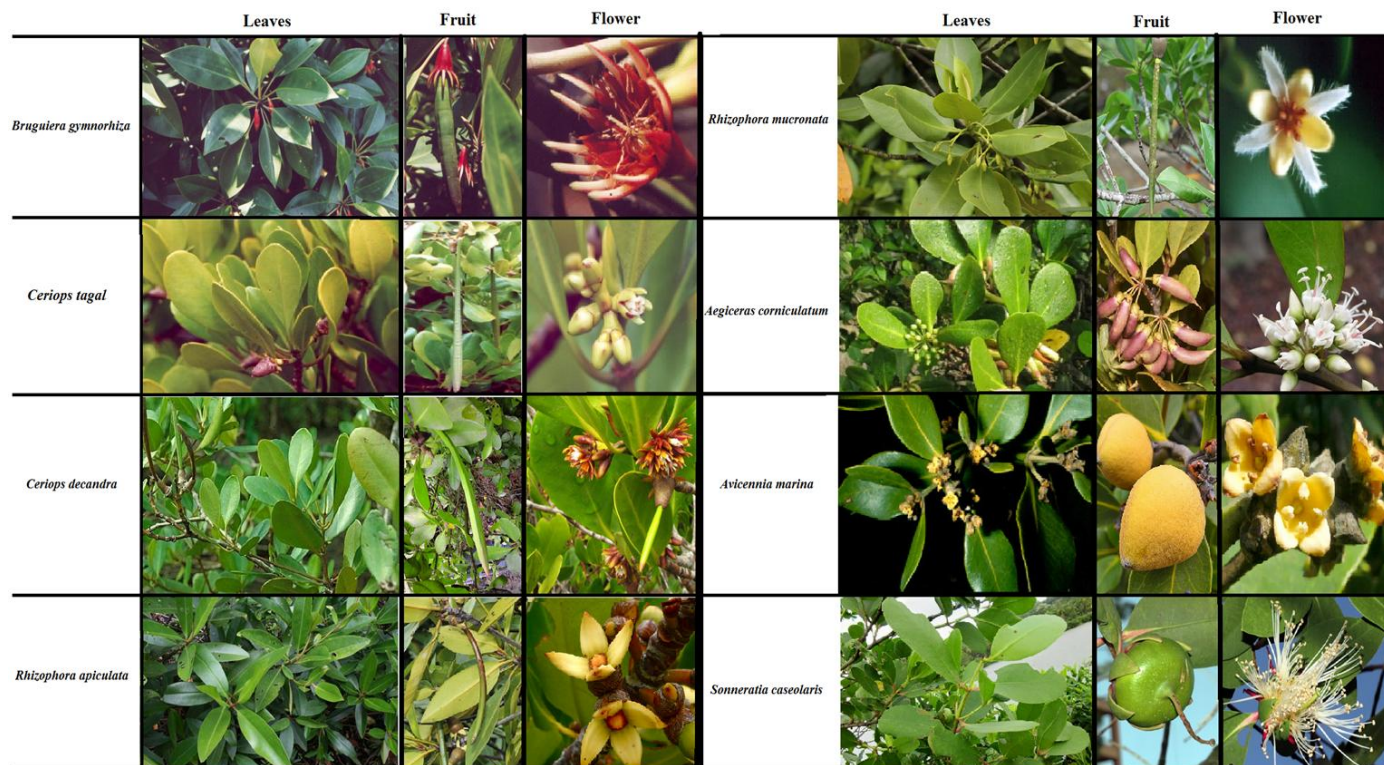


Figure 2: Important plant species from Indus River Delta-Arabian Sea mangroves.

THE FOREST RESOURCES OF THE INDUS DELTA

Gazetteer of Sindh (Hamilton *et al.*, 2013) has mentioned three specific species.

Avicennia officinalis (Timer) and *Rhizophora mucronata* (Kandal). These species, which grow where freshwater and saltwater meet, are thought to use their roots to bind soil, preventing erosion and giving marine animals a place to nest. However, locals frequently use these species as fuel. In the early years of British control, its wood was the greatest fuel available for river streamers, and their foliage was thought to be a great source of camel feed. Streamers used the wood of *Tamarix gallica* and *T. dioica* (Jhao), as fuel. Streamside communities have traditionally relied on *Tamarix gallica* and *Tamarix dioica* (locally known as Jhao) as a source of fuelwood due to their abundance in arid and semi-arid regions.

These halophytic species are well adapted to saline soils and harsh environments (Souddi *et al.*, 2025). *Typha elephantina* (Elephant Grass) found grown on more highland are reported to have binding effects on soil. The Gazetteer reported that the locals were careful to cut the plants close to the soil. They used it for manufacturing matting and baskets.

FLORA AND VEGETATION

Approximately 80 mangrove species are recognized. Species diversity is much greater in Southeast Asian region. The trees of numerous genera are used for timber, specifically *Rhizophora* species. Although alluvial material can accumulate as a bedrock for mangrove colonization along protected, damp tropical beaches, mangroves thrive there. According to Flora of Pakistan (Shorto, 2003) eight species have been described from mangroves of Pakistan (Table 1).



Figure 3. Mangroves distribution in coastline of Sindh.

Table 1. Mangrove Species and Their Distribution in Pakistan

Family	Species	Geographical Distribution
<i>Rhizophoraceae</i>	<i>Bruguiera gymnorhiza</i>	Found in Karachi and the Indus Delta (Hassan).
	<i>Ceriops tagal</i>	Occurs along the Karachi coastline and Sindh coast (Stocks); also reported at the Indus mouth and Salt Water Creek (Murray).
	<i>Ceriops decandra</i>	Reported from the tidal zones of Sindh; however, its presence remains uncertain.
	<i>Rhizophora apiculata</i>	Located in tidal marshes near the Indus mouth, including Miani Hor and Lasbela (T&S).
	<i>Rhizophora mucronata</i>	Grows along muddy shores and tidal creeks at the Indus mouth (Henslow); also found along the Lasbela and Makran coasts (Burkill).
<i>Myrsinaceae</i>	<i>Aegiceras corniculatum</i>	Present in mangrove swamps at the Indus mouth (Stocks, Ritchie); also recorded in Karachi.
<i>Avicenniaceae</i>	<i>Avicennia marina</i>	Widespread in tidal mangrove swamps; observed at Sandspit (Stern), and Kalamat Hor.
<i>Sonneratiaceae</i>	<i>Sonneratia caseolaris</i>	Found at the Indus mouth and tidal zones; considered common according to Murray, though no herbarium specimens have been documented from the Indus Delta region.

TRADITIONAL USES OF MANGROVES IN COASTAL VILLAGES OF SINDH

Mangroves species are utilized by inhabitants of the coastal villages of Sindh, irrespective of their earnings. The coastal communities of Sindh used mangroves for three main functions: as a source of wood for construction; fodder for livestock; and as a source of fuel (Hamilton *et al.*, 2013). The most common plant in this area is the species *Avicennia marina*, whose curved bark is unsuitable for use as a building framework. Thus, it is only used by individuals who cannot afford high-quality lumber. Mangroves were originally widely used for grazing, but their use has significantly decreased.

Table 2. Ethnomedicinal and bioactivities of Indus Delta mangroves species.

Species	Ethno medicinal Uses	Bio Activities	References
<i>Bruguiera gymnorrhiza</i>	Malaria, diarrhoea, fish Poisoning, stop bleeding from wounds, tumour inhibitor, eye disease, fever, angina, diarrhoea, hypertension, and intestinal worms.	Growth hormone tests on plants	(Villaseñor <i>et al.</i> , 2004)
<i>Ceriops tagal</i>	Diarrhoea, vomiting, amoebiasis and ulcers.	antioxidant, antimicrobial	(Uddin <i>et al.</i> , 2005)
<i>Ceriops decandra</i>	Stop haemorrhage and treat ulcers, pain and hepatitis.	Antiviral, antibacterial	(Zaib-Un-Nisa and Siddiqui, 2000)
<i>Rhizophora apiculata</i>	Antiseptic, insecticide	Antiviral,	(Thatoi <i>et al.</i> , 2014)
<i>Rhizophora mucronata</i>	Astringent, angina, haemorrhage, diabetes, diarrhoea, dysentery and hematuria	Antiviral, anti-HIV,	(Roome <i>et al.</i> , 2008)
<i>Aegiceras corniculatum</i>	anti-inflammatory and hepatoprotective	Antiviral, toxicity to fish	(Ravindran <i>et al.</i> , 2005)
<i>Avicennia marina</i>	Treatment for haemorrhage, haemorrhoids, rheumatism, swellings, throat ailments, Antiulcer, treatment for rheumatism,	Antimicrobial activity, antitumor	(Matavele and Habib, 2000)
<i>Sonneratia caseolaris</i>	Fruit extract is used as an anthelmintic medicine.	Toxicity against mosquito larvae	(Pagarra <i>et al.</i> , 2022)

The decrease in domestic animals in the area as a result of rising poverty and the improvement of forest management techniques are the causes. Fuel wood is the most accessible and affordable way to use mangroves. When natural gas is unavailable, mangroves are used as fuel wood. The regular usage of mangrove wood per week is valued to be slightly less than 30 kg per household.

Tanbark Extraction

Mangrove forests are valued for their role in providing tannins. High-quality tannins can be obtained from the bark of several mangrove species, including *Rhizophora mucronata*, *Bruguiera gymnorrhiza*, and *Ceriops tagal*. The bark of *B. gymnorrhiza* is particularly rich in tannins and is traditionally used in leather tanning and fabric dyeing. In contrast, tannins from *R. mucronata* have applications as natural hair dye and are also incorporated into pottery paints.

Ethnomedicinal Applications of Indus Delta Mangroves

Mangrove plants are recognised to own therapeutic properties and have been utilized for conventional treatment of various diseases by residents (Table 1). The indigenous people are completely or partially dependent on these plants for treating various ailments. Mangroves species of Indus delta are widely documented in literature for management of a wide range of ailments i.e. of rheumatism, pregnancy, ulcer and smallpox. As cited in Table 2 they are mainly utilized to treat hypertension, diabetes, and gastrointestinal disorders, i.e. dyspepsia, hematuria, stomach pain, constipation, dysentery and diarrhoea.

The most commonly used plant species is *Avicennia marina*. It has also been reported that the other species are used to combat infectious disorders. In traditional remedies Species with a variety of medicinal uses include *B. gymnorrhiza*, *R. mucronata*, and *R. apiculata*. *B. gymnorrhiza* (Rhizophoraceae) leaves and roots are used to cure intestinal worms, fever, angina, diarrhoea, eye problems, and hypertension. *Rhizophora apiculata* and *R. mucronata* are said to contain up to 70% tannins, which are what give them their medicinal qualities. It is traditionally utilized against hematuria, constipation, diarrhoea, nausea, and diabetes. *Ceriops tagal* is stated to be hemostat and astringent, it is a folk therapy for sores and malaria (Duke, 2017). The decoction of young twigs shoot are utilized as a hemostat, as a quinine substitute (Rani *et al.*, 2021). The lotion made from its bark is used for malignant ulcers (Chakre, 2010).

Ceriops decandra is also an ethno medicinally important plant reported to contain diterpenoids, triterpenoids and lignin's and is mainly specified for treating gastrointestinal disorders, infection, heart diseases, haemorrhage, pain, dermatological problems, liver disorders, and inflammation.

Fruits from *Sonneratia caseolaris* are used to treat piles, bleeding, sprain poultices and hemorrhages. Study revealed the presence of two flavonoids, luteolin and luteolin 7-O- β -glucoside in *Sonneratia caseolaris* that may be responsible for its therapeutic effect (Hibino *et al.*, 2001).

Ethnomedicinal Preparations

Beyond their ecological significance, mangrove species serve as vital reservoirs of ethnomedicinal knowledge, particularly in coastal communities where access to modern healthcare may be limited.

These communities have long relied on indigenous knowledge systems to harness the therapeutic potential of mangrove flora. The diverse pharmacological applications of these plants reflect a deep-rooted understanding of their bioactive properties, passed down through generations. *Rhizophora mucronata* and *Sonneratia caseolaris* exhibit a range of ethnomedicinal applications that extend from nutritional to therapeutic domains. The detoxified fruit of *R. mucronata* serves as a supplementary food source, while *S. caseolaris* is employed in treating respiratory and parasitic infections. The use of its semi-ripe fruits for cough and aged fruit walls for intestinal worms suggests the presence of bioactive compounds with expectorant and anthelmintic properties, which merit further pharmacological validation (Bandaranayake, 2002).

The integration of traditional knowledge with modern scientific inquiry offers a promising pathway for novel drug discovery. Ethnobotanical leads from mangrove species can guide targeted phytochemical screening and bioassays, streamlining the search for effective therapeutic agents. This approach not only honors indigenous wisdom but also contributes to the conservation of mangrove ecosystems by highlighting their medicinal value. In conclusion, the ethnomedicinal applications of mangrove species such as *Avicennia marina*, *Ceriops decandra*, *Ceriops tagal*, *Rhizophora mucronata*, and *Sonneratia caseolaris* underscore their potential as sources of novel pharmacological agents. Continued interdisciplinary research bridging ethnobotany, phytochemistry, and clinical pharmacology is essential to fully realize the therapeutic promise of these unique coastal plants while promoting their sustainable use and conservation.

METABOLITES AND NOVEL CHEMICALS FROM MANGROVES

Recently, scientific and therapeutic organizations have been urged to take into account traditionally used mangrove plant species. This involves isolating and characterizing secondary metabolites from medicinal plant species and using these active metabolites in therapeutic compositions (Spalding et al., 2007). The therapeutic potential of mangrove species has recently been a major issue for pharmaceutical societies. It has been found that many of the chemicals identified from mangrove plant species are inactive precursors that only become active when tissue damage or pathogen infection occurs. A survey states that 200 of the approximately 349 metabolites found in mangrove species are unique to mangrove species (Matavele and Habib, 2000). The chemical compounds isolated from mangroves are illustrated in Table 3.

BIOACTIVITY OF MANGROVE PLANTS

Bioactivities Of *Ceriops tagal* (Perr.) C.B. Robin

Antibacterial activity

The roots of *Ceriops tagal* have been shown to produce a bioactive diterpenoid compound, 6-hydroxyisopimar-8(14)-en-15-one, which exhibits notable antibacterial properties against a range of pathogenic microorganisms. Laboratory assays using minimum inhibitory concentration (MIC) techniques demonstrated that this metabolite suppressed the growth of *Streptococcus pyogenes* at 0.5 mg/mL. Even stronger antibacterial activity was observed against *Bacillus cereus*, *Staphylococcus aureus*, and *Micrococcus kristinae*, with MIC values recorded as low as 0.1 mg/mL. Moderate inhibition was also detected against *Salmonella pooni*, with an MIC of 0.25 mg/mL. These results emphasize the therapeutic potential of root-derived metabolites from *C. tagal* as natural antimicrobial agents, particularly in light of the global challenge of increasing antibiotic resistance (Tiwari et al., 2008).

Anti-fouling activity

Marine biofouling has long been a problem for the maritime sector, leading to the quest for eco-friendly antifouling agents. In this respect Diterpenoids isolated from the roots of *Ceriops tagal*, including methoxyent-16-hydroxypimarenely-15-one and ent-8(14)-pimarene-15,16-diol, have shown antifouling activity by preventing the settlement of *Balanus albicostatus* larvae (Lawag et al., 2012). The findings indicated a substantial prevention of larval settlement, indicating that these compounds interact with the settlement cues or physiological mechanisms necessary for larval attachment. The promising activity of these compounds places *C. tagal* as a promising source of biodegradable antifouling agents, providing a green alternative to traditional toxic paints (Lawag et al., 2012).

Anti-feedant activity

The twigs and stems of *Ceriops tagal* have been shown to possess a series of triterpenoids, namely tagalsins Q, R, and U, which display moderate anti-feedant activity. The triterpenoids were tested against the larvae of *Brontispa longissima*, a well-known pest that causes extensive damage to coconut trees and other valuable crops. At a concentration of 1 mg/mL, the triterpenoids were shown to effectively prevent larval feeding, thus establishing their potential in plant defense mechanisms.

Table 3. Phytochemical composition of plants from Indus Delta Mangroves.

Plant Species	Plant Part	Compound(s)	Compound Class	Reference
<i>Bruguiera gymnorrhiza</i>	Flowers	4-hydroxydithiolane, Brugierol, Isobrugierol	Organosulfur/ Diterpenoid	(Uddin <i>et al.</i> , 2005)
	Stem	ent-8(14)-pimarene-1 α ,15R,16-triol, etc.), Bruguierols A–C	Diterpenoid	
	Whole plant	Gymnorrhizol, Gibberellins A3, A4, A7, Tannins (catechin-3-O-rhamnoside units)	Polydisulfide/ Polyphenol	
	Leaves	Cholesterol, Campesterol, Stigmasterol, 28-isofucosterol, Gramrione (new flavone)	Sterols / Flavonoid	
	Roots	Steviol, ent-kaur-16-en-13,19-diol,	Diterpenoid	
<i>Ceriops tagal</i>	Leaves	Tagalsins, Lupeol, Betulin, Betulinic acid, Cereotagalols, β -Sitosterol, Ursolic acid, Oleanolic acid	Diterpenoid/ Triterpenoid	(Tiwari <i>et al.</i> , 2008)
	Fruit	Amino acids (Threonine, Valine, Phenylalanine, Tryptophan, Proline), Dammarane triterpenes, Cereotagaloperoxide	Amino acids/ Triterpenoid	
<i>Ceriops decandra</i>	Leaves	3 β -E-coumaroylbetulinic acid, Lupeol esters, Betulonic acid, Betulinic acid, Lupenone, Chlorophyll a	Triterpenoid/ Pigment	(Yang <i>et al.</i> , 2008)
<i>Rhizophora apiculata</i>	Leaves	2-(2-ethoxyethoxy) ethanol, Kaur-16-ene, Butyl cyclohexyl ester, Benzenedicarboxylic acid, Cyclononasiloxane	Alcohol/ Diterpenoid	
	Stem	Epicatechin derivatives, Catechin, Afzelechin, Proanthocyanidin B2, Taraxerol derivatives, Glabraosides A & B	Flavonoid/ Triterpenoid	(Chaudhuri and Guha, 2010)
<i>Rhizophora mucronata Lamk</i>	Whole plant	Alkaloids, Anthocyanidins, Carbohydrates, Carotenoids, Flavonoids, Amyrins, β -Sitosterol, Dimyristyl ketone	Mixed classes	(Taylor <i>et al.</i> , 2001)
<i>Aegiceras corniculatum</i>	Whole plant	Resveratrol, Quercetin, Lupeol, Embelin derivatives, Anthraquinones, Dibenzofuran derivatives, Gomphilactone	Polyphenol/ Triterpenoid	(Sadhu <i>et al.</i> , 2006)
<i>Avicennia marina</i>	Whole plant	Stigmasterol glycoside, Lauric acid, Palmitic acid, Stearic acid, Avicennones A–F, Betulinic acid, Ellagic acid	Sterol/ Triterpenoid	(Koster <i>et al.</i> , 1959)
<i>Sonneratia caseolaris</i>	Whole plant	Nyasol derivatives, Maslinic acid, Oleanolic acid, Ellagic acid derivatives, Luteolin, Aldehydes, Hydrocarbons	Flavonoid/ Triterpenoid	(Hu <i>et al.</i> , 2010)

The results indicate that these secondary metabolites may interact with the insect's gustatory receptors or digestive enzymes, thereby making the plant less palatable to the insect. This work underscores the potential of *C. tagal* as a source of botanical insect deterrents (Mohammad *et al.*, 2015).

Anti-hyperglycaemic activity

The ethanol extract of *Cerriops tagal* leaves has been studied for its antidiabetic properties, especially in experimental models of diabetes. In experiments conducted on streptozotocin (STZ)-induced diabetic rats, oral treatment with the extract resulted in a marked improvement in glucose tolerance, with a 33% increase in glucose uptake noted. In addition, the extract helped in the reduction of blood glucose levels by 11%, suggesting its ability to regulate glucose levels. These properties can be ascribed to the presence of biologically active phytochemicals like flavonoids, tannins, and terpenoids, which have been shown to affect insulin secretion, glucose uptake, and carbohydrate metabolism. These results provide evidence for the traditional use of *C. tagal* in the treatment of hyperglycemia and justify further studies on its mechanisms and uses (Takara *et al.*, 2008)

Bioactivities of *Rhizophora stylosa* and *Rhizophora apiculata*

Antioxidant activity

The antioxidant potential of *Rhizophora stylosa* has been extensively studied, particularly in its twigs and stems. Several polyphenolic compounds isolated from these tissues, including proanthocyanidin B2, cinchonain IB, (–)-epicatechin, and (+)-catechin, exhibit strong free radical scavenging activity. In DPPH assays, proanthocyanidin B2 demonstrated an IC₅₀ value of 4.3 µg/mL, indicating high antioxidant potency. Cinchonain IB showed an IC₅₀ of 7.8 µg/mL, while both (–)-epicatechin and (+)-catechin recorded IC₅₀ values of 6.5 µg/mL. These values are comparable to those of standard antioxidant compounds, confirming *R. stylosa* as a promising natural source of antioxidants. Similarly, leaf extracts of *Rhizophora apiculata* have displayed strong antioxidant activity in both DPPH and ABTS assays, attributed to their high phenolic and flavonoid content (Banerjee *et al.*, 2008).

Cytotoxic activity

Isolated compounds from *R. stylosa* have shown cytotoxic activity against different human cancer cell lines. Specifically, exposure to these compounds suppressed the growth of HeLa (cervical carcinoma) and BGC-823 (gastric carcinoma) cells by IC₅₀ values of 73.4 µmol/L and 73.3 µmol/L, respectively. Another compound, cis-careaborin, also derived from *R. stylosa*, showed higher cytotoxicity, suppressing BGC-823 and MCF-7 (breast carcinoma) cells by IC₅₀ values of 45.9 µmol/L and 116 µmol/L, respectively. These results indicate that *R. stylosa* contains active compounds that can trigger apoptosis or interfere with the proliferation of cancer cells, thus justifying further research (Kalasuba *et al.*, 2023)

Antiviral properties

Members of the Rhizophoraceae family, specifically *Rhizophora apiculata* and *R. mucronata*, have exhibited promising antiviral properties. The polysaccharides derived from the leaves of these species have been shown to possess inhibitory properties against simian immunodeficiency virus (SIV) and human immunodeficiency virus (HIV) in vitro. These polysaccharides are thought to act by inhibiting the entry or replication of the virus, possibly through binding to viral envelope proteins or host cell receptors. Such observations underscore the potential of *R. apiculata* as a source of new antiviral drugs, particularly in light of the emergence of new viral pathogens and the need for new approaches to therapy (Banerjee *et al.*, 2008).

Antimicrobial Activity

Studies on *Rhizophora stylosa* and *Rhizophora apiculata* have revealed that their bark and leaf extracts possess broad-spectrum antimicrobial activity. Both methanolic and ethanolic extracts demonstrated inhibitory effects against Gram-positive bacteria, as well as Gram-negative bacteria. The antimicrobial potential of these species is attributed to secondary metabolites like tannins, flavonoids, and terpenoids, which are known to disrupt microbial cell walls and interfere with essential enzymatic processes (Lakshmanan *et al.*, 2019)

Antidiabetic Activity

Preliminary work has revealed that leaf extracts of *R. apiculata* have antidiabetic properties, especially through α-glucosidase inhibition, which is useful in the regulation of postprandial blood glucose levels. In vitro experiments demonstrated strong enzyme inhibition, indicating that the active compounds of *R. apiculata* could potentially slow down carbohydrate digestion and glucose uptake. In vivo experiments using diabetic animal models have also shown improved glucose tolerance and decreased fasting blood glucose levels (Selvaraj *et al.*, 2015)

Bioactivities of *Cerriops decandra*

Cerriops decandra exhibits diverse pharmacological activities, including potent antinociceptive, antimicrobial, and antioxidant effects. These bioactivities are attributed to its rich phytochemical profile, making it a promising candidate for therapeutic and industrial applications.

Antinociceptive Activity

The ethanol extract of *Ceriops decandra* has been found to possess strong antinociceptive effects, as it significantly inhibited acetic acid-induced writhing response in mice. In the experiment carried out by Uddin *et al.*, the extract showed a marked inhibitory effect on pain-related behavior, thus pointing to both peripheral and central mechanisms of action. This indicates that the active compounds in *C. decandra*, which are presumably flavonoids, saponins, and tannins, may affect nociceptive pathways by inhibiting the synthesis or activity of pro-inflammatory mediators like prostaglandins. These results thus confirm the traditional use of *C. decandra* in folk medicine for the treatment of pain and inflammation-related disorders (Mahmud *et al.*, 2019)

Antimicrobial Activity

Various studies have established the broad-spectrum antimicrobial properties of *Ceriops decandra*, especially its leaf, bark, and pneumatophore extracts. Chaudhuri and Guha demonstrated that the plant parts possessed potent antibacterial properties against both Gram-positive and Gram-negative bacteria (such as *Escherichia coli*, *Pseudomonas aeruginosa*). Moreover, the plant parts demonstrated good antifungal properties against the phytopathogen *Fusarium oxysporum*, which causes substantial crop damage. Simlai and Roy further emphasized the thermal and pH-resistant nature of the antimicrobial compounds, which can be used to formulate stable antimicrobial agents. The antimicrobial properties are attributed to the presence of phenolic acids, terpenoids, and alkaloids, which interfere with microbial cell membranes and impair their crucial enzymatic activities (Shahjahan *et al.*, 2025)

Antioxidant Activity

The antioxidant potential of *Ceriops decandra* has been demonstrated through several in vitro investigations. In one study, the ethanolic stem bark extract exhibited a notably high ferric reducing antioxidant power (FRAP), equivalent to 13.04 mg of ascorbic acid per gram of extract. The same extract also showed strong free radical scavenging capacity in DPPH assays, with an IC₅₀ value of 0.65 mg/mL, confirming its effectiveness in neutralizing reactive oxygen species. These antioxidant properties are ascribed to the high polyphenol, flavonoid, and tannin content of the extract, which serve as electron donors and thus inhibit oxidative chain reactions. The antioxidant activity of *Ceriops decandra* underscores its potential role in mitigating oxidative stress, thereby contributing to the prevention of disorders linked to free radical damage, including cardiovascular conditions, neurodegenerative diseases, and age-related problems (Shahjahan *et al.*, 2025)

Cytotoxic and Anticancer Activity

Recent findings indicate that *Ceriops decandra* has cytotoxic activity against different cancer cell lines. The methanolic and ethanolic extracts of the bark and leaves of *C. decandra* have shown dose-dependent cytotoxicity in brine shrimp lethality assays, with moderate to strong toxicity as indicated by the LC₅₀ values. The mechanism of this cytotoxicity may be attributed to triterpenoids, flavonoids, and phenolic compounds, which inhibit cell proliferation and induce apoptosis. Although the mechanism of action has not been extensively investigated, the preliminary results suggest that *C. decandra* is worth further investigation as a potential source of anticancer drugs.

Hepatoprotective Activity

The hepatoprotective properties of *Ceriops decandra* extracts have also been documented in various studies. In animal models of chemically induced liver injury, pre-treatment with ethanolic extracts of the bark was found to significantly decrease the serum levels of liver enzymes like ALT, AST, and ALP, indicating the protective effects of the extract against liver damage. Histopathological analysis also confirmed the decrease in necrosis and inflammation in liver tissues. The protective effects of the extract can be attributed to its antioxidant and anti-inflammatory compounds.

Antidiabetic and Enzyme Inhibitory Activity

In addition to its antioxidant properties, *C. decandra* has been demonstrated to have potential in the regulation of diabetes via enzyme inhibition. In vitro experiments have shown that the extracts of *C. decandra* possess the ability to inhibit major carbohydrate-hydrolyzing enzymes such as α -amylase and α -glucosidase, which are involved in the regulation of glucose release after meals. The IC₅₀ values for the inhibitory effects of the extracts on these enzymes indicate moderate to strong potential for the use of *C. decandra* in the regulation of diabetes. Furthermore, in vivo experiments using diabetic rats have indicated a reduction in blood glucose levels after the administration of the extracts (Acharyya *et al.*, 2026)

Wound Healing Activity

The topically applied leaf and bark extracts of *C. decandra* have been linked to rapid wound contraction and epithelialization in the excision wound model. This rapid healing is due to the presence of tannins and flavonoids, which accelerate collagen production, decrease microbial load, and regulate the inflammatory response. The results indicate

that *C. decandra* can be formulated into herbal products for wound healing and skin regeneration (Nahar, Begum, Hasan, Aziz, & Jui, 2023)

Bioactivities of *Avicennia marina* (Forsk.) Vierh

Antimicrobial activity

A. marina has been widely investigated for its antimicrobial activity. (Nagababu and Rao, 2012) showed that the extracts were effective against a broad spectrum of bacterial strains, including *Agrobacterium tumefaciens*, *Klebsiella pneumoniae*, *Bacillus cereus*, *Enterococcus faecalis*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Streptococcus mutans*, *Bacillus subtilis*, *Staphylococcus aureus*, *Proteus spp.*, and *Shigella spp.* further validated the potent antibacterial property against *E. coli*, *B. subtilis*, *S. aureus*, *Proteus mirabilis*, and *Salmonella paratyphi*. Fungal pathogens are also vulnerable; the extracts of *A. marina* inhibited *Penicillium digitatum* by up to 80%, and antifungal activity was also observed against *Aspergillus flavus* when acetone and ethyl acetate fractions were evaluated (Nagababu and Rao, 2012). More recent studies have isolated tannins, saponins, and sterols as major components responsible

Antioxidant activity

A. marina was reported to display very high radical scavenging effect. A study on *A. marina* leaves and fruits showed a strong antioxidant effect against 2, 2'-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid), Ferric ion and Chromium peroxide (Ilmiah et al., 2018).

Antidiabetic Activity

Methanolic extracts of *A. marina* leaves and bark have been found to possess significant α -glucosidase inhibitory activity, which is a well-proven strategy for the regulation of postprandial hyperglycemia (Premanathan et al., 2011). The extracts work by slowing down carbohydrate digestion and glucose absorption in the intestine, thus regulating blood glucose levels. Further studies have also shown the improvement of glucose tolerance and insulin sensitivity in diabetic animal models treated with *A. marina* extracts. These findings confirm the traditional use of mangroves in the treatment of diabetes and indicate their potential as natural antidiabetic agents.

Hepatoprotective Properties

Some metabolites of *A. marina*, such as triterpenoids and phenolic compounds, have been found to possess hepatoprotective properties against chemically induced liver injury (Behbehani, 2017). The experimental studies demonstrated that these extracts significantly decreased serum levels of liver injury markers (ALT, AST, and ALP) and enhanced the activity of antioxidant enzymes in liver tissue. The hepatoprotective property of these mangrove compounds can be ascribed to their capacity to neutralize free radicals, protect cell membranes, and inhibit lipid peroxidation. This property may find application in the prevention of liver ailments like hepatitis and cirrhosis.

Bioactivities of *Sonneratia caseolaris* (L.) Engler

Antiproliferative Activity

Avicennia marina has shown strong antiproliferative activity, especially against cancerous and proliferating cells. In a research study conducted that the bioactive compounds derived from the mangrove plant *Avicennia marina* were tested on L-929 mouse fibroblast cells and K562 human chronic myeloid leukemia cells. The study showed strong inhibition of cell proliferation, suggesting that the phytoconstituents in the plant have strong cytostatic or cytotoxic activity. This is probably due to mechanisms such as cell cycle arrest, apoptosis, or disruption of cell signaling pathways. The study suggests that *Avicennia marina* can be a potential source of natural compounds for the development of anticancer drugs, especially for the treatment of hematological malignancies and fibroblast-related disorders (Cerri et al., 2022)

Antimicrobial Activity

The antimicrobial properties of *Avicennia marina* have been well acknowledged, and various studies have confirmed its efficacy against a wide spectrum of pathogenic microorganisms. Sharief and Umamaheswararao tested various extracts of the plant against a wide spectrum of bacterial strains, including *Agrobacterium tumefaciens*, *Klebsiella pneumoniae*, *Bacillus cereus*, *Enterococcus faecalis*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Streptococcus mutans*, *Bacillus subtilis*, *Staphylococcus spp.*, *Staphylococcus aureus*, *Proteus spp.*, *Pseudomonas spp.*, and *Shigella spp.* The extracts showed significant inhibitory actions, thus establishing broad-spectrum antibacterial properties. Supporting evidence from Ruba et al. further established the efficacy of the plant against *E. coli*, *B. subtilis*, *S. aureus*, *Proteus mirabilis*, and *Salmonella paratyphi*. Interestingly, the *A. marina* extracts also showed 80% inhibition against the fungal pathogen *Penicillium digitatum*, and acetone and ethyl acetate fractions were most effective against *Aspergillus flavus*, a food-contaminating fungus. These findings establish the potential of *A. marina* as a source of antimicrobial compounds for use in pharmaceuticals and agriculture (Sulaiman et al., 2022).

Antioxidant Activity

The antioxidant capacity of *Avicennia marina* has been extensively validated through diverse in vitro assays, highlighting its effectiveness in neutralizing reactive oxygen species (ROS) and mitigating oxidative stress. Research by Sharief demonstrated that extracts from the leaves and fruits of *A. marina* exhibited strong radical scavenging activity, particularly against ABTS radicals, ferric ions in the FRAP assay, and chromium peroxide radicals. These findings suggest that the plant's phytochemical constituents, especially phenolics, flavonoids, and tannins play a central role in its antioxidant properties. The pronounced antioxidant activity of *A. marina* not only substantiates its traditional medicinal applications for oxidative stress-related disorders but also positions it as a promising candidate for the development of natural antioxidant therapeutics (Sharief and Rao, 2014)

Anti-inflammatory Activity

Avicennia marina has exhibited strong anti-inflammatory properties in both in vitro and in vivo studies. Leaf and bark extracts of *A. marina* have been found to suppress the production of pro-inflammatory mediators like nitric oxide (NO), tumor necrosis factor-alpha (TNF- α), and interleukin-6 (IL-6) in lipopolysaccharide (LPS)-activated macrophages. In animal studies, topical and oral treatment with *A. marina* extracts suppressed paw edema and ear inflammation induced by carrageenan, indicating both systemic and topical anti-inflammatory activity. These properties are ascribed to the presence of flavonoids, iridoid glycosides, and triterpenoids in *A. marina* (Zhou *et al.*, 2025)

Wound Healing Activity

The wound healing potential of *A. marina* has been validated through excision and incision wound models in rats. Application of leaf or bark extracts accelerated wound contraction, enhanced epithelialization, and increased hydroxyproline content, indicating improved collagen synthesis. Histological analysis revealed better tissue regeneration and reduced inflammatory cell infiltration. These effects are likely due to the plant's antioxidant, antimicrobial, and anti-inflammatory properties, which collectively promote tissue repair and prevent infection (Saputra, 2021).

Hepatoprotective Activity

Experimental research has also demonstrated that *Avicennia marina* extracts possess the ability to protect the liver against chemical damage. In carbon tetrachloride (CCl₄) or paracetamol-induced hepatotoxicity, pre-treatment with *A. marina* resulted in a significant decrease in serum levels of liver enzymes such as ALT, AST, and ALP. The hepatoprotective action is thought to be due to the antioxidant compounds of the plant, which neutralize free radicals and stabilize the hepatocyte membrane (Gholami and Mirazi, 2016)

Antidiabetic and Enzyme Inhibitory Activity

Avicennia marina has been found to possess promising antidiabetic properties, both through enzyme inhibition and glucose regulation in vivo. The extracts have been found to inhibit α -amylase and α -glucosidase, enzymes involved in carbohydrate breakdown, thus lowering postprandial glucose levels. In diabetic animal models, the treatment of *A. marina* extracts resulted in a significant decrease in fasting blood glucose levels. These properties are ascribed to polyphenolic compounds that increase insulin sensitivity and modulate glucose metabolism (Hardoko *et al.*, 2019)

Larvicidal and Mosquito Repellent Activity

The ecological significance of *A. marina* can also be seen in vector control. The leaves and seeds of the plant have exhibited larvicidal properties against certain species of mosquitoes like *Aedes aegypti* and *Culex quinquefasciatus*. The active components of the plant hinder the growth and development of the larvae, resulting in death at a lower concentration. Moreover, the plant extracts have exhibited mosquito repellent activity (Karthi *et al.*, 2020)

Bioactivities of *Bruguiera gymnorhiza*

Bruguiera gymnorhiza has been found to possess diverse bioactivities such as antimicrobial, antioxidant, and antinociceptive properties with low cytotoxicity, thus making it a promising candidate for natural therapeutic development. Recent research also emphasizes its anti-inflammatory and antidiabetic properties.

Antimicrobial Activity

Extract (Ethanol) derived from the leaves and bark of *Bruguiera gymnorhiza* have showed a broad-spectrum activity against Gram-positive bacteria, including *Staphylococcus aureus* and *Bacillus cereus*, as well as Gram-negative species such as *Escherichia coli* and *Pseudomonas aeruginosa*. The antimicrobial effect is due to the presence of secondary metabolites particularly tannins, flavonoids, and alkaloids which are known to disrupt microbial cell membranes and interfere with essential enzymatic functions. Such findings provide scientific validation for the traditional use of *B. gymnorhiza* in treating infectious diseases and highlight its potential as a source of plant-based antimicrobial agents.

Cytotoxic Activity

In cytotoxicity tests, the toxicity of *Bruguiera gymnorhiza* extracts was found to be very low, with IC₅₀ values above 2.5 mg/mL when tested on mouse fibroblast cell lines. The low cytotoxicity of the plant's extracts indicates that they are less toxic to normal cells, making them desirable for use as medicines. Although the cytotoxicity of the plant's extracts against cancer cells has not been thoroughly investigated, their low toxicity to non-cancerous cells makes them suitable for use in the formulation of medicines for antimicrobial, antioxidant, or anti-inflammatory agents with minimal side effects.

Antinociceptive Activity

The methanolic root extract of *Bruguiera gymnorhiza* has been found to possess potent antinociceptive properties. At a dose of 500 mg/kg body weight, the extract caused a statistically significant decrease ($P < 0.001$) in acetic acid-induced writhing in mice, thus establishing its potential in the management of peripheral pain. The analgesic activity is believed to be mediated through the suppression of inflammatory mediators such as prostaglandins, perhaps due to the presence of flavonoids and triterpenoids in the plant.

Anti-inflammatory Activity

Recent works have also shown anti-inflammatory effects of *B. gymnorhiza* extracts. In vitro studies showed the suppression of cytokines and enzymes i.e. COX-2 and iNOS, while in vivo studies showed decreased edema and inflammatory cell infiltration. These activities validate the traditional use of the plant in the treatment of inflammatory disease.

Antidiabetic Activity

Preliminary studies on the antidiabetic activity of *Bruguiera gymnorhiza* have also yielded promising results. The plant's leaf and bark extracts have shown α -glucosidase and α -amylase inhibitory activity, suggesting their use in the delay of carbohydrate digestion and glucose absorption. In diabetic animal models, the plant extracts caused a decrease in blood glucose levels, suggesting their use as natural antidiabetic agents in the management of type 2 diabetes.

Bioactivities of *Aegiceras corniculatum* (L.) Blco.

Aegiceras corniculatum (L.) Blanco, a mangrove species widely distributed in tropical and subtropical coastal regions, exhibits a diverse range of pharmacological properties. Its bioactive constituents contribute to significant anticancer, antioxidant, and antidiabetic effects, with emerging evidence supporting additional therapeutic potentials.

Anticancer Activity

Derivatives of hydroquinone, which have been isolated from the stem and twigs of *Aegiceras corniculatum*, have shown strong antiproliferative properties against different human cancer cell lines. When tested in vitro, these compounds were found to significantly reduce the proliferation of malignant cells with relatively low toxicity to normal marsupial kidney cells (PTK2), thus indicating selectivity. The antiproliferative property is presumably due to cell cycle arrest, apoptosis, and/or modulation of oxidative stress. These results indicate that *A. corniculatum* can be a promising source of lead compounds for the development of new anticancer drugs, especially those acting on solid tumors with low cytotoxicity to normal cells.

Antioxidant Activity

The antioxidant properties of *A. corniculatum* have been attributed to its symbiotic relationship with *Trichoderma* spp., a fungal genus recognized for the production of antioxidants. It has been observed that the tissues of *A. corniculatum* with higher *Trichoderma* colonization showed increased antioxidant activity, indicating a synergistic effect that increases the plant's defense mechanisms. This property is also supported by the presence of phenolic compounds, flavonoids, and tannins, which help in free radical scavenging, metal ion chelation, and lipid peroxidation inhibition. *A. corniculatum*, therefore, proves to be a promising candidate for the development of antioxidant formulations for the treatment of oxidative stress-related disorders.

Leaf extracts of *Aegiceras corniculatum* have been found to possess promising antidiabetic properties in experimental studies. Oral treatment with the extract at a dose of 100 mg/kg resulted in a significant decrease in blood glucose levels from 382 ± 34 mg/dL to 105 ± 35 mg/dL, thus establishing a strong hypoglycemic effect. Biochemical analysis indicated a reduction in the activity of gluconeogenic enzymes such as fructose-1,6-bisphosphatase and glucose-6-phosphatase, accompanied by an augmentation in hexokinase activity in the liver, which helps in glucose uptake. These observations clearly indicate that *A. corniculatum* alters major metabolic pathways associated with glucose regulation and thus provides evidence for its use as a natural drug for the treatment of type 2 diabetes.

Antimicrobial Activity

Although not as much work has been done as in other mangrove species, *A. corniculatum* has been found to possess moderate antimicrobial activity in preliminary screening. Leaf and bark extracts of this species have been found to

exhibit inhibitory activity against Gram-positive bacteria such as *Staphylococcus aureus* and fungal organisms such as *Candida albicans*. The antimicrobial property of this species can be attributed to the presence of alkaloids, saponins, and phenolic acids, which target the cell membranes and enzymatic activity of microbes.

Anti-inflammatory and Analgesic Activity

Experimental studies have provided strong evidence supporting the anti-inflammatory and analgesic properties of *Aegiceras corniculatum*. In vivo assays, including the carrageenan-induced paw edema and acetic acid-induced writhing models in rodents, revealed that methanolic extracts of the plant produced significant reductions in both inflammation and pain. These effects are believed to arise from the suppression of pro-inflammatory mediators such as cytokines, along with the inhibition of cyclooxygenase (COX) activity (Bandaranayake, 2002). Furthermore, the extracts have been shown to influence oxidative stress pathways, thereby minimizing tissue damage associated with inflammatory responses (Premanathan *et al.*, 2011).

The pharmacological findings are consistent with the traditional use of *A. corniculatum* in coastal communities for treating inflammatory ailments. This alignment between ethnomedicinal practices and experimental validation highlights the plant's potential as a source of novel phytomedicines for managing conditions such as arthritis, rheumatism, and other inflammation-related disorders (Kathiresan and Bingham, 2001). Continued investigation into its bioactive constituents may pave the way for the development of safe, plant-derived anti-inflammatory therapeutics.

DRUG DISCOVERY AND POTENTIAL APPLICATION OF MANGROVE PLANTS

A complex approach that combines plants, chemical compounds, botanical practices, and molecular techniques is used in the investigation of medication creation from plant species. In contrast to many pharmaceutical objectives, such as microbial infections, HIV, cancer, etc., therapeutic drug development continues to provide new and important hints. Mangroves in the Indus River Delta are a source of innovative and distinctive phytochemicals that could lead to the development of natural and semi-synthetic medications. Many chemical compounds extracted from these plants exhibit therapeutic activity and aid in the development of medications for a variety of deadly illnesses, such as cancer, arthritis, and acquired immunodeficiency syndrome (AIDS), though other compounds have been proven to be analgesics or anti-inflammatory. These salt-tolerant plant species sequester a variety of physiologically active chemicals, some of which have been validated for medication development through clinical studies. Clinical usage of *Rhizophora* species in the treatment of diabetes has been documented. *Ceriops tagal* plant extracts have been the subject of numerous clinical trials, and some of its isolated chemicals have demonstrated potential as anti-HIV, anticancer, and antiviral medicines (Spalding *et al.*, 2010).

In addition to their pharmacological promise, mangrove-derived compounds are increasingly being explored for their role in combating antimicrobial resistance. With the global rise of drug-resistant pathogens, the search for novel bioactive agents from underexplored ecosystems like mangroves has gained momentum. Secondary metabolites such as flavonoids, terpenoids, and alkaloids from mangrove species have shown inhibitory effects against multidrug-resistant bacterial strains, suggesting their potential as templates for next-generation antibiotics.

Furthermore, advances in metabolomics and genomic tools have enhanced the ability to identify and characterize bioactive constituents from mangrove flora. Techniques such as high-throughput screening, molecular docking, and gene expression profiling are now being integrated with traditional ethnobotanical knowledge to accelerate the discovery of lead compounds. This integrative strategy not only validates traditional uses but also opens new avenues for the development of eco-friendly, plant-based therapeutics tailored to address emerging global health challenges.

Recent reviews emphasize the sustainable potential of mangrove ecosystems in drug discovery, particularly highlighting their role in yielding antioxidant, anticancer, and antimicrobial agents. For instance, research on mangrove-associated *Streptomyces* has revealed novel compounds with cytotoxic activity against cancer cell lines, while other studies underscore the importance of preserving these habitats for future pharmacological exploration.

MAJOR THREATS TO INDUS DELTA MANGROVE ECOSYSTEMS

The major environmental evils in the Indus Delta region is the radically low river discharge mainly due to additional upstream building of dams. The discharge is currently about 5% of what it was before their construction. This issue especially affected the mangrove forests. This area has been fronting constant human pressures for local needs and developmental actions. The undiscerning exploitation by coastal populations for fodder and fuelwood has produced a projected reduction in mangrove forests. Previously authors and agencies have identified internal and external factors responsible for mangrove depletion.

Ecological Status, Degradation Mechanisms, and Restoration of Pakistan's Mangroves

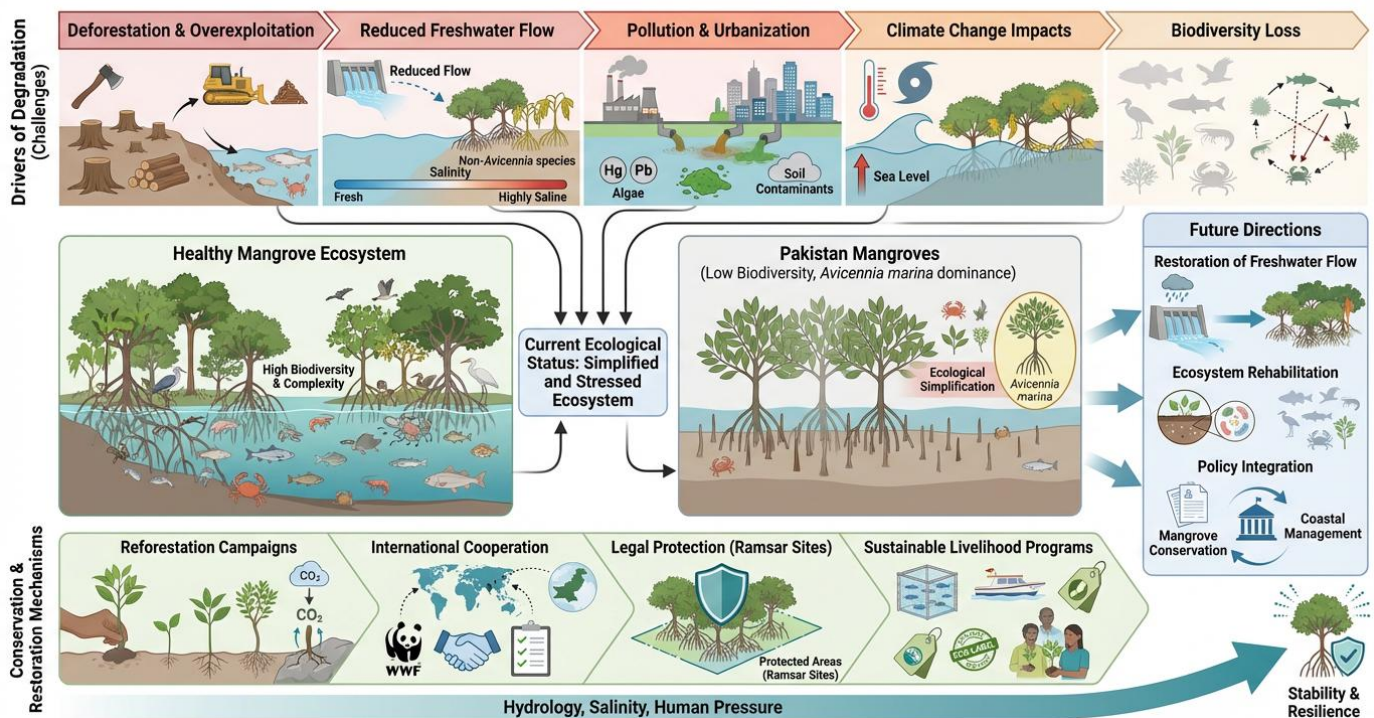


Figure 4. Mangroves conservation challenges and efforts in Pakistan.

External Factors

Mangroves are under severe stress due to an array of external factors that are beyond the control of authorities. Key external factors are:

- Insufficient and Uneven Incursions of Fresh Water and Silt Load from Indus: The Indus delta ecosystem is chiefly reliant on upon silt-laden, and discharge of fresh water from River Indus is the only source (Spalding *et al.*, 2010). The reduction in freshwater discharge is one of the important causes of mangroves degradation. This might be due to water diversion for hydroelectricity, agriculture, and other uses in the upper reaches.
- Sea Water Intrusion: The incessant reduction in freshwater inflow results in saltwater intrusion that changes the geomorphology of the delta. It is projected that sea water incursion has taken place up to 67 km thus destructing ecosystem in deltaic region (Kamal and Phinn, 2011).
- Gradual Increase in Sea Level: Global warming is recognized as a major driver of rising sea levels. Long-term observations indicate that the sea level along Karachi's coast has increased at an average rate of about 1.1 mm per year over the past century. Research further suggests that the Indus Delta has experienced significant encroachment, with an estimated loss of nearly 1,700 km² of land during the last fifty years.
- Inflow of Pollutants: Pollution is also a proximate cause of loss of biodiversity along Pakistan coastal area. Over half of the industrial units of country are based in Karachi and according to a report about 25 years industries are raised from 10,000 to about 30,000. Due to rapid urbanisation Karachi is emerged among the largest cities in the world. But weak urban planning results in intrusion of industrial and domestic effluents. Pollution in Indus Delta results in stunted growth of mangroves. It is projected that approximately 37,000 tons/ year of industrial waste is being deserted in the coast of Karachi while, 20,000 tons// year oil catches the beaches and ports of. Additionally, municipal sewers produce around 110 mil. Gallons per day (Amjad and Rizvi, 1999).

Internal Factors

There are numerous factors resulting from anthropogenic activities as shown in the Figure 4, some of them are described below

- Over Harvesting: Over harvesting fish and mangroves by local communities is additional cause of mangrove degradation. It is, though, hard to measure the degree of damage due to utilization by local communities. Mangroves are sources of fuel, timber, and fodder for coastal inhabitants. As a result of poor physical infrastructure, raised population and Lack of alternative resources the demand of mangrove wood for fuel is

increased by local. Alternatives, like natural gas or kerosene oil are too expensive for locals (Kamal and Phinn, 2011).

- b. Fodder Harvesting: The leaves of *Avicennia marina* are preferred as fodder for animals. These are frequently collected by the residents around the coastal mangroves. This harvesting puts substantial pressure on the existing mangrove. The mangroves are overpopulated with sheep, camel's cattle, goats and cows beyond their capacity results in their depletion.
- c. Disposal of Left Bank Outfall Drain (LBOD) Effluents: Recently Left Bank Outfall Drain has been constructed with aimed to reclaim the agricultural lands by reducing the salinity. It was intended to manage the problem of salinity and water logging by providing a complete scheme of surface and sub-surface drainage. The considerable amounts of saline effluents with salinity i.e. 30 mS/cm and more are discharged into Indus delta. This results in increased salinity of the area which is harmful to mangroves, marine life, and coastal communities (Kamal and Phinn, 2011).

ECOLOGICAL STATUS AND THREATS

Historical Extent and Current Status

As shown in Figure 4, the mangrove forests in Pakistan have suffered a drastic reduction in the last century. They originally covered an area of over 600,000 hectares but are now limited to less than 90,000 hectares, as estimated in recent surveys (Masood, He, Shah, & Rehman, 2024). This loss is a result of human utilization, changes in river patterns, industrialization, and climate change, which have all contributed to the reduced resilience of this ecosystem (Iqbal *et al.*, 2024).

Human Utilization and Overexploitation

The mangrove forests in Pakistan have been traditionally used by local communities for fuelwood, pasture, and construction purposes. *Avicennia marina* and *Rhizophora mucronata* have been overexploited for domestic fuel, fishing boats, and fencing. Overexploitation has surpassed the natural regeneration rate of these forests, and grazing by livestock has further suppressed regeneration. This has led to the fragmentation of mangrove forests, making them susceptible to erosion and destruction.

Hydrological Alterations

The Indus River was a major source of freshwater and nutrient-rich sediments that supported mangrove forest development. But due to the development of dams, barrages, and irrigation channels in the upper reaches of the Indus River, the freshwater discharge has been significantly reduced. This has resulted in hypersaline environments that are not favorable for the nutrient intake of non-*Avicennia marina* species. Sediment deprivation has also resulted in the degradation of deltaic mudflats, which have reduced the area for colonization. As a result, the ecosystem has been dominated by monocultures of salt-tolerant species, while other species like *Ceriops tagal* and *Sonneratia caseolaris* are now rare or locally extinct (Masood *et al.*, 2024).

Industrial and Urban Expansion

The Indus Delta's close proximity to Karachi's industrial center has resulted in mangrove ecosystems being affected by pollution and land use change. The discharge of untreated effluents, heavy metals, and oil into the creeks has caused water pollution. Coastal development projects, such as the expansion of ports and the development of housing schemes, have resulted in the direct cutting down of mangrove forests. Shrimp farming and aquaculture have also resulted in the conversion of extensive mangrove forests into ponds, thus further reducing the extent of natural forests (Iqbal *et al.*, 2024).

Effects of Climate Change

Climate change in Pakistan has introduced an additional stress factor for mangroves. Rising sea levels flood mangrove habitats, causing changes in salinity and suffocation of mangrove seedlings. Increased storm surges and tidal velocities destroy mudflats, which in turn reduces the regeneration area. Sedimentation patterns, which are essential for mangrove establishment, are affected by climate change. It is anticipated that these effects will worsen in the future, thereby jeopardizing the survival of already stressed mangrove forests (Masood *et al.*, 2024).

Consequences for Biodiversity

The cumulative impacts of human utilization, hydrological disturbance, industrial pollution, and climate change have resulted in a decrease in biodiversity in the mangrove forests of Pakistan. Currently, *Avicennia marina* is prevalent in more than 90 percent of the mangrove forest area due to its ability to withstand high levels of salt and pollution. Other species, such as *Rhizophora mucronata*, *Ceriops tagal*, and *Sonneratia caseolaris*, are found in patches or have

become extinct in many areas. This is because of the decrease in biodiversity, which has resulted in a loss of resilience in the ecosystem, thereby impacting fisheries, carbon sinks, and shoreline protection (Masood et al., 2024).

CONSERVATION AND MANAGEMENT EFFORTS

Government programs

The Sindh Forest Department, in partnership with the Ministry of Climate Change in Pakistan, has launched massive reforestation activities to reclaim the degraded mangrove ecosystems. The activities involve the re-planting of salt-resistant species like *Avicennia marina* in the Indus Delta and mangrove creeks. Pakistan has been registering record-breaking mangrove plantation campaigns in recent years, placing it among nations that have made substantial efforts in reforestation activities. Despite the success in increasing mangrove coverage in some regions, the sustainability of the activities has remained in question.

International collaborations:

International bodies like the International Union for Conservation of Nature (IUCN) and World Wide Fund for Nature (WWF) have been crucial in mangrove conservation efforts in Pakistan. Their initiatives include community-managed conservation, replanting, and raising awareness. For example, WWF-Pakistan has been collaborating with fishing communities to encourage sustainable fishing practices and other means of livelihood, thus decreasing their reliance on mangrove timber (Iqbal et al., 2024). While these efforts have improved the conservation capacity, they are not on a sufficient scale to address the extent of degradation.

Protected Status under Ramsar Convention

The mangroves in the Indus Delta are identified as a site of international significance under the Ramsar Convention, which emphasizes the significance of the site from an ecological perspective (Rattan et al., 2021). However, the Ramsar Convention has not been able to ensure the implementation of protection measures effectively. This is because there is no effective management of the coastal zone.

Challenges in Implementation

Despite the existence of various projects, the conservation of mangrove forests is still piecemeal. Lack of monitoring, insufficient funding, and a lack of coordination among institutions are some of the factors that impede the conservation process. Furthermore, a lack of policy coordination between mangrove conservation and coastal development contributes to the conflict between mangrove conservation and industrialization.

Comparative Regional Perspective

Mangrove forests in South and Southeast Asia are highly heterogeneous in terms of species richness, resilience, and conservation. Compared to their counterparts in South and Southeast Asia, mangrove forests in Pakistan are less diverse and more susceptible to environmental changes. The Sundarbans in Bangladesh and India are the largest continuous mangrove forests in the world, spanning 10,000 square kilometers with over 30 species of mangroves (Giri et al., 2011). These forests are essential habitats for a variety of species, such as the Bengal tiger, estuarine crocodiles, and various fish and bird species.

The biodiversity of the Sundarbans indicates the ability of complex mangrove ecosystems to resist climate change and human-induced factors. In contrast, the mangrove forests in Pakistan are relatively smaller in size, fragmented, and dominated by a single species, *Avicennia marina*. The dominance of a single species is mainly due to the high salinity levels, low freshwater discharge, and extensive human use (Masood et al., 2024). Other species like *Rhizophora mucronata*, *Ceriops tagal*, and *Sonneratia caseolaris* are found in small patches or have become extinct in many places, thus contributing to low biodiversity.

Countries in Southeast Asia, such as Indonesia, Malaysia, and Thailand, have some of the most biodiverse mangrove forests in the world, with over 40 species found there (Spalding et al., 2010). The mangrove forests in these countries enjoy favorable hydrological conditions, large coastal areas, and better conservation policies. In contrast, the mangrove forests in Pakistan are under threat from the cumulative effects of industrial pollution, urbanization, and climate change, thus being much more susceptible to degradation.

This is a reflection of the pressing need for conservation approaches tailored to the Pakistani environment. Contrary to the Sundarbans or Southeast Asian mangrove forests, the Pakistani mangrove forests cannot fall back on biodiversity as a safeguard against environmental stress. Rather, conservation measures must focus on the restoration of freshwater discharge, increasing species by means of re-planting, and incorporating mangrove forest conservation into the country's coastal management policies.

FUTURE DIRECTIONS

Integrated coastal zone management

An effective framework for the management of the coastal zone is required to ensure a balance between conservation and economic development. The existing policies are more inclined towards the development of industries and urbanization rather than the conservation of natural resources. By incorporating the conservation of mangroves into the national coastal plan, Pakistan can ensure that the development of infrastructure, fishing, and tourism are managed alongside conservation. This will also assist in managing the freshwater flow, pollution, and biodiversity (Masood *et al.*, 2024).

Community-based stewardship

The local fishing communities are the key stakeholders in mangrove forests. Raising awareness among these communities through community-based management initiatives can help improve conservation efforts. Community-based activities like participatory mangrove replanting, sustainable harvesting, and livelihood development initiatives can help decrease reliance on mangrove timber while promoting a sense of ownership. Successful community-managed initiatives in South Asia show that community engagement is essential for long-term conservation (Iqbal *et al.*, 2024).

Blue Carbon Initiatives

Mangroves are well known worldwide for their importance as blue carbon ecosystems, which have the potential to sequester a substantial amount of carbon in biomass and sediment. The association of mangrove restoration with carbon credits, a climate finance tool, may act as an economic stimulus for mangrove conservation. The inclusion of mangrove afforestation in Pakistan's Nationally Determined Contributions (NDCs) under the Paris Agreement indicates the potential of mangroves in climate change mitigation.

Pharmaceutical Exploration

The phytochemical richness of mangroves provides valuable leads for the development of pharmaceuticals and agrochemicals. Systematic studies and bioassays of species like *Ceriops tagal*, *Rhizophora mucronata*, and *Sonneratia caseolaris* can help in the discovery of new compounds with antimicrobial, anticancer, and antidiabetic activities. The combination of ethnobotanical studies with modern pharmacological research will not only contribute to advancements in healthcare but also focus on the medicinal importance of mangrove conservation (Behbehani, 2017).

Education and awareness programs

Raising public awareness is still a fundamental approach to conservation. Educational campaigns aimed at schools, colleges, and coastal settlements can be used to emphasize the ecological, economic, and medicinal value of mangroves. Public awareness campaigns conducted by NGOs and government bodies can help bring about a behavioral shift, minimize unproductive exploitation, and promote conservation policies. Educational programs incorporating mangrove ecology in school and college curricula can also encourage future generations to conserve these resources (Spalding *et al.*, 2010).

CONCLUSION

They may be protected from extremely salt-rich conditions by unique bioactive chemical substances. They also possess antiviral, antioxidant, anticancer, and numerous other qualities that have been proven by numerous studies conducted by various authors. These mangrove plant species have been used in traditional medicine, and more recently, it has been established that some mangrove plants have antibacterial qualities against human infections. Conversely, the ethnomedical uses of these plants remain undiscovered. The potential uses of the mangrove species in this area have been uncovered by contemporary research, necessitating numerous attempts to gather and disseminate information in this area. The pharmaceutical sector may value such information in order to find new medicinal medicines.

AUTHOR CONTRIBUTIONS

KZ performed manuscript writing, AN handled data compilation, and YB developed the study concept.

CONFLICT OF INTEREST

Authors declare no conflict of interest.

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