

Review

Insect Pests and Diseases in Chinese Coastal Mangroves: Challenges and Integrated Control Approaches

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Abstract

Mangrove forests along China's coastline serve as vital ecological barriers and blue carbon reservoirs. However, pests and diseases have become the primary biotic threats driving stand decline and diminished carbon sequestration capacity. This review synthesizes current knowledge on the major insect pests and plant diseases affecting Chinese coastal mangroves, focusing on their species profiles, characteristic damage symptoms, occurrence dynamics, and integrated control strategies. Fungal pathogens predominate among the diseases, with outbreaks most common during periods of high temperatures and humidity or low temperatures combined with high humidity; these often interact synergistically with insect pests. The dominant insect pests comprise leaf-feeding Lepidoptera, sap-sucking Hemiptera, and wood-boring Coleoptera, which spread through diverse pathways and can rapidly produce extensive "scorched" damage across mangrove stands during epidemic events. Control efforts follow the principle of "prevention first and integrated management," incorporating cultural practices, chemical interventions, biological control agents, physical trapping methods, and rigorous quarantine-monitoring protocols. When applied in concert, these measures effectively limit damage to acceptably low levels. Recent studies identify pest–disease interactions and climate change as the foremost challenges in current management. Future priorities should include advancing molecular identification techniques, breeding disease-resistant varieties, and developing environmentally friendly biopesticides to establish precision ecological control systems. Such advances will deliver robust scientific support for mangrove conservation and the achievement of China's dual-carbon goals.

Keywords: mangroves; pests and diseases; integrated control; management strategies



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1. Introduction

Mangroves, as unique wetland ecosystems at the land–sea interface, constitute one of the world's most important blue carbon reservoirs. Unlike general carbon sequestration, which refers to the process of capturing and storing atmospheric carbon dioxide, blue carbon reservoirs specifically denote the long-term storage of carbon in coastal vegetated ecosystems such as mangroves, salt marshes, and seagrass beds, characterized by exceptionally high carbon burial rates in sediments. They deliver a suite of critical ecosystem services, including protection against wind and waves, sediment accretion and land formation, carbon sequestration and storage, maintenance of biodiversity, pollutant degradation, and the provision of fishery resources and ecotourism opportunities [1]. In China, mangroves are

primarily distributed along the southern coastal provinces of Hainan, Guangxi, Guangdong, Fujian, and Zhejiang, where they serve as natural ecological barriers safeguarding the tropical and subtropical coastal zones [2,3]. Historical records indicate that mangrove coverage in China once reached approximately 250,000 hm² [4], but had declined sharply to 17,000–23,000 hm² by the 1980s [3,5]. Following decades of conservation and ecological restoration, the national total has stabilized at around 27,000 hm² [2,5,6]. Core distribution areas include the Beibu Gulf in Guangxi, Yingluo Bay in Zhanjiang (Guangdong), and Dongzhai Harbor in Hainan [7–9], with dominant species comprising *Avicennia marina*, *Aegiceras corniculatum*, *Kandelia obovata*, *Rhizophora stylosa*, and *Sonneratia caseolaris* [10]. These mangrove plants play a vital role in maintaining coastal ecological balance while providing essential habitats for diverse benthic organisms, birds, and fish. Their annual carbon sequestration capacity ranges from 0.7×10^5 to 1.5×10^5 t C/a [9–11].

However, under the combined pressures of global climate change, intensified human activities, and biological invasions [12,13], Chinese coastal mangroves face severe degradation risks. In recent years, in addition to abiotic stressors such as reclamation, pollution, and sea-level rise, pests and diseases have emerged as one of the primary biotic threats responsible for stand decline, seedling mortality, and loss of ecological functions [2,14]. These biotic stresses frequently result in extensive leaf abscission, weakened tree vigor, markedly reduced photosynthesis, and even widespread dieback of individual trees or entire stands, thereby directly compromising natural regeneration and carbon sequestration capacity [15–17]. For instance, dominant species such as *Avicennia marina* and *Aegiceras corniculatum* are highly susceptible to fungal infections during periods of high temperature and humidity or low temperature combined with high humidity [18,19]. Outbreaks of leaf-feeding Lepidoptera can rapidly defoliate canopies, producing the characteristic “scorched” appearance across mangrove stands [13,19]. Field surveys indicate that more than 128 insect pest species have been recorded in Chinese mangroves, with leaf-feeding insects being the most prevalent [13]; the dominant diseases are fungal leaf spots, anthracnose, and sooty molds [18]. These pests and diseases exhibit notable host specificity and are capable of long-distance dispersal via seedling transport, water currents, and wind, substantially increasing the risk of regional epidemics [12].

Considerable disparities exist between domestic and international research on mangrove pests and diseases. While international studies have largely focused on pests and diseases associated with invasive mangrove species or on modeling their potential spread under future climate scenarios, research on native pest and disease assemblages in relatively undisturbed or restored mangrove systems remains limited worldwide [20]. This global research emphasis on invasive species has resulted in comparatively fewer systematic investigations into the pests and diseases affecting native mangrove flora. In China, domestic research on mangrove pests and diseases began in the 1980s [21], with early efforts centered on field surveys in protected areas of Guangxi, Guangdong, and Hainan. Notable examples include the classic descriptions of anthracnose and sooty mold by Huang Zeyu and colleagues, as well as more recent investigations into the control of leaf-feeding moths and wood-boring longhorn beetles [14,19]. Nevertheless, the majority of the existing literature consists of case-specific reports on individual pests or diseases [13,17], with a notable lack of comprehensive syntheses that integrate pest and disease characteristics, occurrence patterns, and management strategies. In particular, analyses of pest–disease interactions (e.g., sap-sucking insects inducing sooty mold or wood-boring insects exacerbating stem rot) and climate sensitivity remain insufficient [2,15]. Furthermore, current control measures still rely predominantly on conventional chemical spraying, underscoring the urgent need to develop green and ecologically based integrated pest management approaches [2,14].

To address these research gaps, the present review systematically synthesizes the species composition, damage symptoms, occurrence dynamics, and control strategies of the major pests and diseases affecting mangrove forests along China's coastline, with particular attention to the ecological drivers influencing their outbreaks.

2. Major Insect Pests of Mangrove Forests Along China's Coastline

Mangrove forests along China's coastline support a rich diversity of insect pests, primarily from the orders Lepidoptera, Hemiptera, and Coleoptera. These pests cause substantial damage through leaf consumption, sap feeding, and wood boring, frequently resulting in complete defoliation, reduced tree vigor, and in severe cases, whole-tree mortality. Such impacts directly impair photosynthetic capacity, natural regeneration, and the ecological functions of mangrove ecosystems [15,17]. While Table 1 provides a summary of the key characteristics of major insect pests, the following sections offer a more detailed analysis of their damage patterns, monitoring methods, management options, and existing knowledge gaps (Table 1).

2.1. Leaf-Feeding Lepidoptera

Leaf-feeding Lepidoptera are among the most damaging insect pests in Chinese coastal mangroves. Major species include the mangrove fruit borer (*Acrobasis* sp.), *Aegicerus corniculatus* leafroller (*Lasiognatha cellifera*), bagworms (*Chalia larminati*, *Chalioides kondonis*, *Acanthopsyche subferalbata*), cotton leafworm (*Orgyia postica*), and teak defoliator (*Hyblaea puera*) [22]. These pests primarily attack young leaves, buds, and shoots of dominant mangrove species such as *Kandelia obovata*, *Aegicerus corniculatus*, *Avicennia marina*, and *Sonneratia caseolaris*.

Outbreaks often cause rapid and extensive defoliation, producing the characteristic “scorched” appearance across stands. Bagworms and leafrollers construct protective cases or shelters, making early detection and control difficult. Repeated defoliation not only reduces photosynthetic capacity but can also lead to branch dieback and tree mortality, particularly in restored plantations [19,22]. In high-density planting areas, such outbreaks may significantly affect restoration outcomes and carbon sequestration functions.

Monitoring of leaf-feeding Lepidoptera in Chinese mangroves currently relies mainly on visual surveys and light traps during peak seasons [14]. However, standardized early detection methods and pheromone-based monitoring tools remain underdeveloped. Management strategies include physical removal of bagworm cases, application of *Bacillus thuringiensis* (Bt) formulations, and the use of light traps [22]. In nurseries, seedling quarantine and removal of infested material are important preventive measures. Chemical control is generally regarded as a last resort due to environmental concerns in intertidal zones.

Despite these efforts, effective long-term management remains challenging. Key knowledge gaps include the lack of long-term population dynamics data, limited understanding of natural enemy complexes specific to mangrove ecosystems, and insufficient evaluation of integrated pest management strategies under field conditions [14]. The potential application of drone-based monitoring and precision technologies for large-scale mangrove pest management has also not been explored.

2.2. Sap-Sucking Hemiptera

Sap-sucking insects, including scale insects (e.g., *Pseudaulacaspis cockerelli*) and planthoppers (*Ricania* spp.), are widespread in Chinese mangroves [13,23]. These pests feed on leaves, tender shoots, and branches, causing nutrient deficiency, leaf chlorosis, and reduced growth. A major secondary effect is the excretion of honeydew, which promotes sooty mold development and further reduces photosynthetic efficiency.

Because sooty mold is closely associated with sap-sucking insect outbreaks, these two groups often interact to cause compounded damage, particularly in low-salinity inner estuary areas dominated by *Aegiceras corniculatum* [14]. Heavy infestations can lead to significant defoliation and branch dieback.

Current monitoring methods mainly depend on visual inspection and sticky traps. There is a lack of standardized sampling protocols and early warning systems tailored to mangrove environments. Management primarily relies on cultural practices such as pruning heavily infested branches and improving stand ventilation [14]. Biological control using predatory insects and parasitoids shows promise but has received limited systematic study in Chinese mangrove systems. Chemical control is rarely applied in natural stands due to environmental risks.

Important knowledge gaps remain regarding the population dynamics of sap-sucking insects in relation to salinity and tidal gradients, the effectiveness of natural enemies under field conditions, and the development of integrated strategies that simultaneously manage both the insects and resulting sooty mold [13,14].

2.3. Wood-Boring Coleoptera

Wood-boring insects, primarily longhorn beetles such as *Anoplophora chinensis*, damage mangroves by tunneling into branches and roots [23,24]. Larval feeding destroys vascular tissues, leading to weakened vigor, leaf yellowing, brittle branches, and eventual tree death. Adult feeding on tender bark and leaves causes additional injury. Wood-boring activity also creates entry points for pathogenic fungi, thereby exacerbating stem and root rot diseases.

These pests are particularly problematic in restored plantations where trees may already be stressed. Infestations can contribute to long-term stand decline.

Monitoring of wood-boring beetles is challenging because damage occurs internally. Current practices mainly involve visual inspection for exit holes, frass, and wilting symptoms. Pheromone traps and acoustic detection methods, successfully used in other forest systems, have not been adapted for mangrove environments in China.

Management options are limited. Removal of severely infested trees and the use of healthy seedlings for planting are the primary recommended practices. Biological control using parasitoids has shown potential in other regions but remains largely unexplored in Chinese mangroves. There is an urgent need for research on effective monitoring tools and environmentally friendly control strategies suitable for intertidal wetland ecosystems.

2.4. Overall Impacts and Knowledge Gaps of Mangrove Insect Pests

Insect pests cause significant direct and indirect damage to Chinese mangrove ecosystems through defoliation, sap depletion, and facilitation of diseases. These impacts not only affect individual tree health but also compromise stand-level ecological functions such as carbon sequestration and coastal protection [15,17]. Outbreaks are often exacerbated by simplified stand structures in restored plantations and changing climatic conditions [25].

Despite their ecological importance, research on mangrove insect pests in China remains fragmented. Major knowledge gaps remain, including the lack of long-term population dynamics data, limited understanding of natural enemy communities in mangrove ecosystems, and insufficient development of monitoring, early warning, and validated IPM strategies suitable for intertidal environments [14,21,22]. Future research should prioritize the integration of ecological monitoring, molecular tools, and emerging technologies to develop sustainable management solutions.

Table 1. Characteristics of major insect pests in mangrove forests along China’s coastline.

Insect Pest	Order/Family	Feeding Guild	Host Species	Damaged Plant Part	Symptoms/Damage	Distribution in China	Ecological Impact	Natural Enemies	Climate Change Sensitivity	Management Options	References
Mangrove fruit borer (<i>Acrobasis</i> sp./ Guangzhou small spotted moth)	Lepidoptera	Leaf and fruit feeder	<i>Avicennia marina</i>	Buds, leaves, fruits	Early-instar larvae bore into buds or fruits; later instars spin silk webs on the leaf underside, consuming mesophyll and leaving only the upper epidermis. Outbreaks result in complete defoliation and “scorched” appearance	Guangxi, Guangdong, Hainan	Severe reduction in photosynthesis and fruiting; rapid stand-level damage during outbreaks	Parasitoids	High (favored by warm conditions)	Light traps, <i>Bacillus thuringiensis</i> (Bt) formulations, remove infested seedlings, chemical control as last resort	[14,26,27]
<i>Aegicerus corniculatus</i> leafroller (<i>Lasiognatha cellifera</i>)	Lepidoptera	Leaf feeder	<i>Aegicerus corniculatus</i>	Young leaves near terminal bud	Larvae spin silk to tie young leaves into a shelter and feed inside on mesophyll, causing leaf desiccation and shoot dieback. Severe damage leaves only leaf veins	Guangxi, Guangdong, Hainan	Affects growth, flowering and fruiting; can cause shoot dieback	Parasitoids	Medium-High	Physical removal, light traps, biological control	[22,28]
Cotton leafworm (<i>Orgyia postica</i>)	Lepidoptera	Leaf feeder	<i>Sonneratia caseolaris</i> , <i>Sonneratia apetala</i>	Leaves	Larvae feed gregariously on leaves; heavy infestations completely defoliate trees, leaving only midribs and branches	Guangxi, Guangdong, Hainan	Severe loss of photosynthetic capacity and reduced growth	Parasitoids, predatory insects	High	Bt formulations, light traps, remove infested material	[22]
Bagworm (<i>Chalioa larminati</i>)	Lepidoptera (Psychidae)	Leaf feeder	<i>Kandelia obovata</i> , <i>Aegicerus corniculatus</i> , <i>Bruguiera gymnorrhiza</i> , <i>Avicennia marina</i>	Leaves	Larvae carry portable cases made of silk and plant debris; create holes and notches. High densities cause rapid and complete defoliation, reduced photosynthesis and even tree mortality	Widespread in southern coastal provinces	Significant reduction in photosynthetic capacity and tree vigor; can cause mortality	Parasitoids, birds	Medium-High	Physical removal of cases, light traps, biological control (parasitoids), seedling quarantine	[22,29,30]
Green slug caterpillar (<i>Latoia lepida</i>)	Lepidoptera	Leaf feeder	<i>Kandelia obovata</i> , <i>Aegicerus corniculatus</i>	Leaves	Early-instar larvae feed gregariously on mesophyll leaving translucent patches; later instars feed individually creating notches or complete defoliation	Guangxi, Guangdong	Reduced photosynthesis and growth	Parasitoids	Medium	Bt formulations, physical control	[28,30]

Table 1. Cont.

Insect Pest	Order/Family	Feeding Guild	Host Species	Damaged Plant Part	Symptoms/Damage	Distribution in China	Ecological Impact	Natural Enemies	Climate Change Sensitivity	Management Options	References
Teak defoliator (<i>Hyblaea puera</i>)	Lepidoptera	Leaf feeder	<i>Avicennia marina</i>	Young leaves, tender shoots, fruits	Larvae consume young leaves (cutting notches at margins) and fold leaves with silk while feeding. Outbreaks rapidly strip leaves, shoots and fruits	Guangxi, Guangdong	Halts photosynthesis and causes growth decline or death	Limited information	High (can migrate long distances)	Light traps, biological control, monitoring migration	[31,32]
White bagworm (<i>Chalioides kondonis</i>)	Lepidoptera (Psychidae)	Leaf feeder	<i>Kandelia obovata</i> , <i>Sonneratia apetala</i> , <i>Aegiceras corniculatum</i>	Leaves	Larvae feed on leaves producing notches and holes. Severe infestations cause complete defoliation and reduced growth	Guangxi, Guangdong, Hainan	Loss of photosynthetic capacity and reduced growth	Parasitoids	Medium-High	Physical removal, light traps, biological control	[33,34]
Small bagworm (<i>Acanthopsyche subferalbata</i>)	Lepidoptera (Psychidae)	Leaf feeder	<i>Kandelia obovata</i> , <i>Aegiceras corniculatum</i> , <i>Avicennia marina</i> , <i>Sonneratia caseolaris</i>	Leaves	Larvae feed on leaves; heavy damage leads to complete defoliation, branch dieback or whole-tree mortality	Guangxi, Guangdong, Hainan	Severe impact on tree vigor and survival	Parasitoids	Medium-High	Physical removal of cases, light traps, biological control	[22,33,34]
Litchi fruit borer (<i>Cryptophlebia ombrodelta</i>)	Lepidoptera	Borer	<i>Bruguiera gymnorhiza</i> , <i>Aegiceras corniculatum</i>	Hypocotyls, flower calyces	Larvae bore into hypocotyls and flower calyces, damaging internal tissues, causing calyx necrosis and abnormal hypocotyl development	Guangxi, Guangdong	Severely impairs reproduction and natural regeneration	Limited information	Medium	Seedling quarantine, remove damaged material	[35,36]
White shield scale (<i>Pseudaulacaspis cockerelli</i>)	Hemiptera (Diaspididae)	Sap-sucker	<i>Kandelia obovata</i> (mainly)	Leaves (especially along midribs), tender shoots	Nymphs and adult females cluster and suck sap, causing yellow chlorotic spots. Heavy infestations cover leaves with white scales, leading to twisting, yellowing and massive defoliation	Guangxi, Guangdong, Hainan	Impaired photosynthesis and growth; weakens tree vigor	Limited natural enemies recorded	Medium	Control on seedlings, prune heavily infested branches	[37,38]

Table 1. Cont.

Insect Pest	Order/Family	Feeding Guild	Host Species	Damaged Plant Part	Symptoms/Damage	Distribution in China	Ecological Impact	Natural Enemies	Climate Change Sensitivity	Management Options	References
Broad-winged planthopper (<i>Ricania</i> sp.)	Hemiptera	Sap-sucker	<i>Avicennia marina</i> , <i>Aegiceras corniculatum</i> , <i>Kandelia obovata</i>	Tender branches, leaf undersides, buds	Adults and nymphs suck sap causing nutrient deficiency and weakened vigor. Females slit branches to lay eggs (often killing branches). Honeydew promotes sooty mold	Guangxi, Guangdong, Hainan	Reduced vigor, flower/fruit drop, and sooty mold outbreaks	Predatory insects	Medium	Prune affected branches, sticky traps, control honeydew-producing insects	[13,23]
Three-spotted broad-winged planthopper (<i>Ricania</i> sp.)	Hemiptera	Sap-sucker	<i>Avicennia marina</i> , <i>Rhizophora stylosa</i> , <i>Sonneratia apetala</i>	Tender branches, leaves, buds	Damage similar to <i>Ricania</i> sp.: sap-sucking causes nutrient deficiency, flower/fruit drop and branch dieback from oviposition slits. Larvae tunnel into branches and roots destroying vascular tissues; causes weakened vigor, leaf yellowing, brittle branches and eventual tree death. Adults feed on tender bark and leaves	Guangxi, Guangdong, Hainan	Reduced vigor and reproductive output	Predatory insects	Medium	Prune affected branches, sticky traps	[13,23]
Citrus longhorn beetle (<i>Anoplophora chinensis</i>)	Coleoptera (Cerambycidae)	Wood borer	<i>Kandelia obovata</i> , <i>Sonneratia apetala</i> , <i>Sonneratia caseolaris</i>	Branches, roots		Guangxi, Guangdong	Exacerbates stem and root rot diseases; long-term stand decline	Limited known natural enemies in mangroves	Medium	Control adult beetles, remove severely infested trees, use healthy seedlings for planting	[24,39]

3. Major Diseases of Mangrove Forests Along China's Coastline

Fungal diseases are the predominant pathogens affecting mangrove forests along China's coastline. The main types include anthracnose, sooty mold, red spot disease, leaf spot diseases, gray mold, rust, and stem/root rot [18,40]. These diseases primarily target leaves, twigs, hypocotyls, seedlings, and root collars, resulting in widespread leaf wilting and abscission, weakened tree vigor, substantially impaired photosynthesis, and in severe cases, the death of individual trees or entire stands. Such damage poses a serious threat to natural regeneration and the overall ecological functioning of mangrove ecosystems [41,42]. While Table 2 summarizes the key characteristics of major diseases, the following sections provide a more in-depth analysis of their damage patterns, impacts, monitoring methods, management strategies, and existing knowledge gaps (Table 2).

3.1. Anthracnose

Anthracnose, primarily caused by *Colletotrichum gloeosporioides* and its species complex (including *C. siamense* and *C. fructicola*), is one of the most widespread and destructive diseases in Chinese coastal mangroves [43,44]. It has been reported on multiple host species, including *Sonneratia caseolaris*, *Excoecaria agallocha*, *Aegiceras corniculatum*, *Bruguiera gymnorhiza*, and *Avicennia marina*, with particularly high incidence in Guangxi, Guangdong, and Hainan provinces.

The disease typically produces round or irregular brown to black lesions with yellow halos on leaves and twigs. Under warm and humid conditions, lesions expand rapidly, coalesce, and cause extensive tissue necrosis, premature defoliation, and shoot dieback. Severe infections can significantly reduce photosynthetic capacity and tree vigor, especially in young plantations and natural stands [45].

Although quantitative economic loss data specific to Chinese mangroves are limited, anthracnose outbreaks have been observed to cause noticeable stand-level defoliation, potentially affecting carbon sequestration and coastal protection functions. In seedling nurseries, the disease can lead to high mortality if not properly managed.

Current monitoring mainly relies on visual field surveys during the rainy season. Early detection remains challenging due to the lack of rapid molecular diagnostic tools for mangrove-associated *Colletotrichum* species. Management strategies include the use of healthy seedlings, removal of infected plant debris, and preventive application of fungicides such as carbendazim, chlorothalonil, and thiophanate-methyl in nursery settings [44]. In field conditions, chemical control is often impractical due to tidal inundation and environmental concerns.

Despite these measures, several important knowledge gaps persist. The population structure, genetic diversity, and host specificity of *Colletotrichum* species infecting mangroves in China remain poorly understood. There is also limited information on the effectiveness of biological control agents and resistant mangrove genotypes. Long-term monitoring data linking disease severity with environmental factors (especially under climate change scenarios) are urgently needed [45].

3.2. Sooty Mold

Sooty mold is a common secondary disease in Chinese mangroves, caused by a complex of saprophytic fungi including *Capnodium anona*, *Asterina maesae*, *Fumago vagans*, and *Coniothyrium* species [46]. It frequently develops on leaves following outbreaks of sap-sucking insects such as scale insects and planthoppers. The disease is particularly prevalent in inner estuary areas with low salinity and poor ventilation, especially in *Aegiceras corniculatum* stands in Guangxi and Guangdong [14,44].

Infected leaves become covered with black, sooty mycelial mats that severely reduce light penetration and photosynthetic efficiency. Heavy infections often lead to chlorosis and premature leaf abscission, weakening tree vigor over time. Although sooty mold does not directly kill trees, repeated outbreaks can contribute to long-term stand decline, particularly in restored monoculture plantations.

Because sooty mold development is closely linked to honeydew-producing insects, its occurrence and severity are strongly influenced by the population dynamics of sap-sucking pests [14]. Current management largely depends on controlling the primary insect vectors through pruning, sticky traps, and biological control. Direct fungicide application (e.g., prochloraz or thiophanate-methyl) is occasionally used in severe cases but is generally discouraged in natural mangrove ecosystems due to environmental risks.

Research on sooty mold in Chinese mangroves remains limited. There is a lack of quantitative data on its impact on carbon assimilation and tree growth. The interactions between sooty mold fungi, their insect vectors, and mangrove hosts under different salinity and tidal regimes are not well understood. Developing integrated management approaches that simultaneously address both the insect vectors and the resulting sooty mold is considered a research priority.

3.3. Red Spot Disease

Red spot disease, primarily caused by *Pestalotiopsis* species (especially *P. clavispora* on *Aegiceras corniculatum* and *P. versicolor* on *Rhizophora stylosa*), is a widespread foliar disease in southern Chinese mangroves, particularly in Guangxi [44,47]. The disease is favored by slightly acidic conditions ($\text{pH} < 6$) and temperatures of 25–30 °C during summer.

Infected leaves develop reddish-brown to dark red circular or irregular lesions with distinct margins. As the disease progresses, black pycnidia appear within the lesions. In severe cases, multiple lesions coalesce, leading to extensive leaf necrosis and premature defoliation. High infection rates have been recorded in some areas of Yingluo Bay, raising concerns about impacts on natural regeneration and restoration success.

Current monitoring relies primarily on visual inspection during summer. Management strategies include prompt removal of infected leaves and preventive fungicide application in nurseries. Large-scale chemical control in natural stands is generally avoided due to environmental regulations and practical difficulties.

Significant knowledge gaps remain regarding the epidemiology of red spot disease. The overwintering mechanisms of *Pestalotiopsis* species, their host specificity, and the influence of environmental factors (particularly salinity and tidal regimes) on disease development are poorly understood. There is also limited research on resistant mangrove genotypes and potential biological control agents.

3.4. Leaf Spot Diseases

Leaf spot diseases in Chinese mangroves are caused by a variety of fungi, including *Alternaria* spp., *Corynespora cassiicola*, *Nigrospora laticolonia*, *Lasioidiplodia theobromae*, and *Phyllosticta* spp. [45,48,49]. These diseases usually begin at leaf tips or margins and are often associated with weakened tree vigor or the presence of wounds under humid conditions.

Symptoms include brown, dark brown, or grayish-white spots of varying shapes and sizes. Severe infections can cause premature leaf drop and reduced photosynthetic capacity. Although generally considered sporadic, leaf spot diseases can become noticeable under favorable environmental conditions or in stressed stands.

Management mainly focuses on enhancing tree vigor, avoiding mechanical wounds, and timely removal of fallen leaves. Fungicides such as carbendazim or mancozeb are

sometimes used in nurseries. However, the diversity of causal agents and the lack of specific diagnostic tools make targeted management difficult.

Key knowledge gaps include the relative importance and pathogenicity of different fungal species under mangrove conditions, as well as the lack of long-term data on disease dynamics in relation to climate and restoration practices.

3.5. Gray Mold

Gray mold, caused by *Botrytis cinerea*, primarily affects mangrove seedlings, especially *Sonneratia caseolaris*, in nursery environments across Guangxi, Guangdong, and Hainan [45,50]. The disease is most prevalent during cool and humid periods (November–March) when seedling density is high and ventilation is poor.

Infected seedlings show water-soaked, light-brown soft rot on stems, shoot tips, and leaves, followed by rapid development of grayish-white mycelium. Severely affected seedlings often defoliate within 2–3 days and die within one week, leading to substantial losses in nursery production.

Management relies heavily on cultural practices, including the use of well-decomposed organic fertilizer, control of sowing density, promotion of seedling lignification, and covering seedbeds during cold periods. Disinfection of substrates and removal of diseased seedlings are also important. When necessary, fungicides such as thiophanate-methyl or chlorothalonil are applied.

Research on gray mold in mangrove systems is limited. There is a lack of information on the genetic diversity of *B. cinerea* populations infecting mangroves and the potential of biological control agents in nursery settings. Developing integrated disease management strategies suitable for mangrove seedling production remains an important need.

3.6. Rust

Rust disease in Chinese mangroves is caused by an unidentified rust fungus (*Uredinales*) and has been reported to severely affect seedlings of *Bruguiera gymnorhiza*, *Kandelia obovata*, and *Rhizophora stylosa*, particularly in Guangxi (e.g., Yingluo Bay) [22]. In some areas, infection rates of up to 70% of seedlings have been recorded.

The disease causes severe damage to leaves, young twigs, fruit stalks, and young fruits. However, its infection dynamics, overwintering mechanisms, and environmental requirements remain largely unknown, making chemical control extremely difficult in tidal environments.

Because of the lack of basic biological and epidemiological information, rust remains one of the most poorly understood diseases in Chinese mangroves. Further research on its life cycle and potential management options is urgently needed.

3.7. Stem and Root Rot

Stem and root rot diseases are caused by various pathogens, including *Fusarium* species (e.g., *F. equiseti* on *Avicennia marina*, *F. solani* on *Acanthus ilicifolius*) and *Phytophthora* species [45,51]. These diseases typically occur in poorly drained areas and spread through wounds or wood-boring insect damage.

Infected plants show stem lesions with cortical necrosis and blackening, root decay, leaf yellowing, wilting, and eventual whole-plant death in severe cases. These diseases are particularly problematic in waterlogged or mechanically damaged stands.

Management focuses on using healthy seedlings, controlling wood-boring insects to reduce wounds, and promptly removing severely diseased trees. However, effective control remains difficult in natural mangrove environments.

Table 2. Characteristics of major diseases in mangrove forests along China’s coastline.

Disease Type	Causal Pathogen (s)	Pathogen Group	Mangrove Host Species	Major Symptoms	Plant Part Affected	Geographic Distribution in China	Disease Severity/ Impact	Favorable Environmental Conditions	Management Approaches	Climate Change Risk	Research Priority	References
Anthracnose	<i>Colletotrichum gloeosporioides</i> and species complex (e.g., <i>C. siamense</i>)	Fungi	<i>Sonneratia caseolaris</i> , <i>Excoecaria agallocha</i> , <i>Aegiceras corniculatum</i> , <i>Bruguiera gymnorhiza</i> , <i>Avicennia marina</i>	Round or irregular brown to black lesions with yellow halos; lesions coalesce causing leaf wilting and abscission	Leaves, twigs, hypocotyls	Guangxi, Guangdong, Hainan (widespread)	Moderate to high; significant defoliation and reduced vigor	High temperature + high humidity	Improve tree vigor, minimize wounds, remove infected leaves, apply carbendazim/ chlorothalonil/ thiophanate-methyl at seedling stage	High (prolonged warm-humid periods)	High	[43,45,52]
Sooty mold	<i>Capnodium anona</i> , <i>Asterina maesae</i> , <i>Fumago vagans</i> , <i>Coniothyrium</i> sp., etc.	Fungi	Mainly <i>Aegiceras corniculatum</i> , occasionally others	Black sooty mycelial mats covering leaves; reduces photosynthesis, causes chlorosis and premature defoliation	Leaves	Inner estuary areas (low salinity) in Guangxi, Guangdong	Moderate; forms distinct disease centers in poorly ventilated stands	Low salinity (<3‰), poor ventilation, following sap-sucking insect outbreaks	Prioritize control of sap-sucking insects, thin and prune for better ventilation, apply prochloraz or thiophanate-methyl during peak periods	Medium-High	Medium	[14,44,46]
Red spot disease	<i>Pestalotiopsis</i> spp. (e.g., <i>P. clavispora</i> on <i>Aegiceras corniculatum</i> , <i>P. versicolor</i> on <i>Rhizophora stylosa</i>)	Fungi	<i>Aegiceras corniculatum</i> , <i>Rhizophora stylosa</i>	Reddish-brown to dark red circular or irregular lesions with distinct margins; black pycnidia appear later; severe cases cause lesion coalescence and leaf death	Leaves	Guangxi (especially Yingluo Bay), Guangdong	Moderate to high in summer	Slightly acidic conditions (pH < 6), 25–30 °C, summer	Remove infected leaves promptly, apply protective fungicides early, intensify field monitoring during summer	High	Medium-High	[44,47]
Leaf spot disease	<i>Alternaria</i> spp., <i>Corynespora cassicola</i> , <i>Nigrospora laticolonia</i> , <i>Lasiodiplodia theobromae</i> , <i>Phyllosticta</i> spp., etc.	Fungi	Wide range across mangrove species	Brown, dark brown, or grayish-white spots of varying shape and size, usually starting at leaf tips or margins; may expand and cause premature leaf drop	Leaves	Guangxi, Guangdong, Hainan	Usually sporadic but noticeable under favorable conditions	Humid conditions, weakened tree vigor, or presence of wounds	Enhance tree vigor, avoid creating wounds, remove fallen leaves timely, apply carbendazim or mancozeb in nurseries	Medium	Medium	[45,48,49]

Table 2. Cont.

Disease Type	Causal Pathogen (s)	Pathogen Group	Mangrove Host Species	Major Symptoms	Plant Part Affected	Geographic Distribution in China	Disease Severity/ Impact	Favorable Environmental Conditions	Management Approaches	Climate Change Risk	Research Priority	References
Gray mold	<i>Botrytis cinerea</i>	Fungi	<i>Sonneratia caseolaris</i> (mainly seedlings)	Water-soaked light-brown soft rot on upper stems, shoot tips and leaves; dense grayish-white to gray-brown mycelial growth; seedlings defoliate in 2–3 days and die within one week	Seedlings (stems, leaves, shoot tips)	Guangxi, Guangdong, Hainan (nurseries)	High in dense seedling beds during cool periods	Cool and humid conditions (Nov–Mar), high seedling density	Disinfect seedbeds, use well-decomposed organic fertilizer, control sowing density, promote lignification, cover with plastic film in cold periods, remove diseased seedlings and spray thiophanate-methyl or chlorothalonil	Medium (may increase with more cool–humid events)	Medium	[45,50]
Rust	Unidentified rust fungus (Uredinales)	Fungi	<i>Bruguiera gymnorhiza</i> , <i>Kandelia obovata</i> , <i>Rhizophora stylosa</i>	Severe damage to leaves, young twigs, fruit stalks and young fruits	Leaves, young twigs, fruits	Guangxi (Yingluo Bay up to 70% seedlings affected)	High in affected areas	Unknown (overwintering and infection dynamics unclear)	Chemical control extremely difficult in tidal environments; further research urgently needed	Unknown (needs more study)	High	[22]
Stem/root rot	<i>Fusarium</i> spp. (e.g., <i>F. equiseti</i> on <i>Avicennia marina</i> , <i>F. solani</i> on <i>Acanthus ilicifolius</i>), <i>Phytophthora</i> spp., etc.	Fungi/Oomycetes	<i>Avicennia marina</i> , <i>Acanthus ilicifolius</i> , others	Stem lesions expand causing cortical necrosis and blackening; root rot leads to leaf yellowing, wilting and whole-plant death in severe cases	Stems, roots	Poorly drained areas in Guangxi, Guangdong, Hainan	High in waterlogged or weakened trees	Poorly drained, waterlogged areas; wounds created by insects or mechanical damage	Use healthy seedlings, control wood-boring insects to reduce wounds, promptly remove and destroy severely diseased trees	Medium-High (increased waterlogging risk)	High	[45,51]

3.8. Overall Impacts and Knowledge Gaps of Mangrove Diseases

Fungal diseases cause significant damage to Chinese coastal mangroves through defoliation, reduced photosynthesis, and direct mortality. These impacts threaten both natural stands and restoration efforts. Many diseases are favored by warm and humid conditions, and their severity may increase under climate change scenarios.

Despite their importance, research on mangrove diseases in China remains largely descriptive. Major knowledge gaps include limited understanding of pathogen population biology, epidemiology under mangrove conditions, effective monitoring tools, and sustainable management strategies. There is also a lack of quantitative data on the economic and ecological impacts of individual diseases. Future research should focus on integrating ecological, molecular, and management studies to develop more effective and environmentally friendly disease control approaches.

4. Ecological Drivers of Pest and Disease Outbreaks

In recent years, the frequency and severity of pest and disease outbreaks in Chinese coastal mangroves have shown a clear upward trend [15,53]. This phenomenon is closely linked to global climate change, large-scale ecological restoration programs, and alterations in ecosystem structure [53]. These ecological drivers not only directly influence the population dynamics of pathogens and insect pests but also exacerbate outbreak risks and pest–disease synergistic damage by modifying host plant resistance and microenvironmental conditions [17].

4.1. Climate Change as a Driver of Pest and Disease Outbreaks

Climate change represents one of the major drivers of pest and disease occurrence in mangrove ecosystems [15,53,54]. The fungal diseases mentioned in this review, including anthracnose, sooty mold, and various leaf spot diseases, are known to thrive under high-temperature and high-humidity or low-temperature and high-humidity conditions [45,54]. With global warming, the duration of hot and humid weather in southern coastal China has significantly increased, providing more favorable conditions for the infection and spread of *Colletotrichum* spp. and sooty mold fungi [45,53].

In addition, the increased frequency of extreme weather events such as typhoons and heavy rainfall not only causes mechanical damage that creates entry points for pathogens but also alters salinity and moisture regimes in mangrove forests, thereby influencing pest and disease dynamics. Climate change may also intensify pest damage by affecting insect reproduction cycles, dispersal capacity, and overwintering survival. For example, warmer conditions can increase the number of generations of bagworms and leafrollers per year [33], leading to rapid population growth. Furthermore, rising temperatures may disrupt the balance between pests and their natural enemies, weakening natural regulatory mechanisms.

Currently, research on the specific mechanisms by which climate change affects mangrove pests and diseases in China remains limited, and long-term monitoring combined with modeling studies are urgently needed [15,53,54].

4.2. Impacts of Large-Scale Mangrove Restoration on Pest and Disease Dynamics

Since the early 2000s, China has implemented large-scale mangrove ecological restoration programs, increasing the national mangrove area from a historical low of approximately 17,000 hm² to the current level of around 27,000 hm² [55]. While these initiatives have enhanced carbon sequestration and ecological functions, they have also exerted complex influences on pest and disease dynamics [56,57].

On one hand, the extensive planting of exotic or fast-growing species such as *Sonneratia apetala* has resulted in relatively simple community structures, reducing ecosystem resilience to disturbances [58]. Although *Sonneratia apetala* exhibits rapid growth and high survival rates, its relatively weak resistance to pests and diseases has led to higher outbreak frequencies and damage levels in introduced areas compared with native species [55,56,59]. On the other hand, restoration projects often rely on seedling transplantation. If seedlings carry pests or pathogens, or if quarantine is inadequate, pests and diseases can spread over long distances. In addition, the high initial planting density and simplified stand structure, together with poor ventilation and light penetration, create microenvironments favorable for diseases such as sooty mold and gray mold [57,58].

Therefore, species diversity and the use of healthy seedlings should be prioritized during mangrove restoration to minimize pest and disease risks [55,58].

4.3. Effects of Ecosystem Simplification and Reduced Genetic Diversity

Simplification of mangrove ecosystem structure is an important intrinsic factor contributing to pest and disease outbreaks. Many restored areas adopt monoculture or low-diversity planting, resulting in reduced genetic diversity and overall decline in plant resistance to biotic and abiotic stresses [60,61]. When pests or diseases occur, monoculture stands are more prone to large-scale contiguous damage, often producing the characteristic “scorched” appearance across entire forests [61].

Studies have shown that mixed forests with higher genetic diversity exhibit significantly greater resistance to pests and diseases compared with monocultures [62]. In addition, habitat fragmentation and anthropogenic disturbances (e.g., reclamation and pollution) weaken ecosystem self-regulation capacity and reduce populations of natural enemies, further diminishing natural pest control [61]. Synergistic interactions between pests and diseases—such as sap-sucking insects inducing sooty mold or wood-boring insects exacerbating stem and root rot—are more likely to amplify in structurally simple stands, creating vicious cycles [63].

4.4. Synergistic Effects Among Climate Change, Restoration, and Ecosystem Structure

Climate change, large-scale restoration programs, and ecosystem imbalance do not operate independently. Instead, they interact synergistically to promote the outbreak and spread of pests and diseases [64]. Climate change may exacerbate the vulnerability of monoculture stands established during restoration, while simplified ecosystem structure can amplify the negative impacts of climate change.

For example, under extreme high-temperature and high-humidity conditions, monoculture *Sonneratia apetala* stands are more susceptible to anthracnose and sooty mold outbreaks [65,66]. Simultaneously, rising populations of sap-sucking insects further promote sooty mold development, resulting in compounded “pest–disease” damage [65,66]. In the future, as climate change continues and mangrove restoration expands, these synergistic effects are likely to become more pronounced [67].

Therefore, pest and disease management must be integrated into ecosystem-level planning during mangrove conservation and restoration. Measures such as promoting species diversity, strengthening monitoring and early warning systems, and developing environmentally friendly control technologies should be adopted to enhance the resistance and resilience of mangrove ecosystems to biotic threats [68].

4.5. Pest–Disease Interactions

In addition to the external drivers discussed above, interactions between insect pests and plant diseases themselves constitute an important internal ecological driver that amplifies damage in mangrove ecosystems. Many insect pests and pathogens do not

act independently; instead, they interact synergistically, often resulting in more severe and complex damage than either would cause alone.

A typical example is the relationship between sap-sucking insects (such as scale insects and planthoppers) and sooty mold. The honeydew excreted by these insects provides a substrate for sooty mold fungi, leading to blackened leaf surfaces that further reduce photosynthesis and tree vigor [69]. Similarly, wood-boring insects (such as longhorn beetles) create wounds and galleries in stems and roots, which serve as entry points for pathogenic fungi, thereby exacerbating stem and root rot diseases [70]. These pest–disease interactions are particularly pronounced in structurally simplified stands, such as monoculture plantations of *Sonneratia apetala*, where reduced plant diversity and weakened tree vigor facilitate the spread and impact of both pests and pathogens.

Although pest–disease interactions have been observed in Chinese mangroves, quantitative studies on their prevalence, mechanisms, and ecological consequences remain limited. Most existing reports are descriptive, and there is a lack of systematic research on how environmental factors (such as salinity, tidal regime, and stand structure) influence the strength of these interactions. Furthermore, integrated management strategies that simultaneously target both pests and their associated diseases are still underdeveloped [71].

Understanding and managing pest–disease interactions is therefore critical for effective mangrove protection. Future research should focus on elucidating the mechanisms of these interactions and developing integrated control approaches that address both biotic agents concurrently.

5. Impacts of Mangrove Restoration on Pest and Disease Dynamics

Since the early 2000s, China has carried out extensive mangrove restoration programs, significantly increasing the national mangrove area from approximately 17,000 hm² to around 27,000 hm² [72,73]. While these initiatives have contributed substantially to coastal protection, carbon sequestration, and biodiversity conservation [74], they have also exerted notable influences on the dynamics of pests and diseases in mangrove ecosystems. The large-scale planting of seedlings, changes in stand structure, and choice of species have created new conditions that influence both the occurrence and spread of pests and diseases [75].

One of the most prominent impacts stems from species selection during restoration. A considerable proportion of restored mangroves, particularly in Guangdong and Guangxi, have involved the widespread planting of *Sonneratia apetala*, an exotic fast-growing species introduced from Bangladesh [76]. Although *Sonneratia apetala* demonstrates high survival rates and rapid biomass accumulation, making it attractive for large-scale restoration, it has shown relatively lower resistance to certain pests and diseases compared with native species such as *Avicennia marina*, *Aegiceras corniculatum*, and *Kandelia obovata* [77]. Field observations indicate that *Sonneratia apetala* stands often experience higher frequencies of anthracnose, sooty mold, and leaf-feeding insect outbreaks. The monoculture planting of this species has resulted in simplified community structures with reduced genetic diversity, which weakens the overall resilience of restored forests to biotic disturbances. In contrast, mixed-species plantations tend to exhibit lower pest and disease incidence due to greater ecological stability and more diverse natural enemy communities [78].

In addition to species composition, the restoration practices themselves influence pest and disease dynamics. Many restoration projects rely on seedling transplantation from nurseries or distant sources. If quarantine protocols are insufficient, this practice can facilitate the long-distance dispersal of pests and pathogens [79]. Furthermore, high initial planting densities and simplified stand structures during the early stages of restoration often lead to poor ventilation and light penetration, creating favorable microenvironments

for fungal pathogens such as sooty mold and gray mold [80]. Dense seedling beds are particularly susceptible to damping-off diseases caused by *Botrytis cinerea* under cool and humid conditions [79,81]. As restored stands mature, the accumulation of leaf litter and changes in canopy structure can further alter microclimatic conditions, potentially favoring certain pest populations [80,81].

The interaction between restoration activities and climate change may amplify these effects [82]. Prolonged periods of high temperature and humidity, which are becoming more frequent due to climate change, can accelerate disease development in monoculture *Sonneratia apetala* stands [83]. At the same time, extreme weather events linked to climate change may physically damage trees, creating entry points for pathogens and increasing the vulnerability of restored ecosystems [84]. These combined pressures highlight the need for more careful planning in future restoration projects [83,85].

To mitigate the negative impacts of restoration on pest and disease dynamics, several strategies are recommended. First, greater emphasis should be placed on species diversity rather than monoculture planting. Incorporating a mixture of native mangrove species can enhance ecosystem resilience and reduce the risk of large-scale outbreaks [86,87]. Second, strict quarantine and health inspection of seedlings should be enforced to prevent the introduction and spread of pests and pathogens [88]. Third, restoration designs should consider long-term stand structure, including appropriate spacing and thinning practices to improve ventilation and reduce disease-favorable microenvironments [87]. Finally, integrating pest and disease monitoring into restoration programs from the outset can enable early detection and timely intervention, thereby improving the sustainability of restored mangrove forests [88].

In summary, while mangrove restoration programs have achieved significant ecological benefits [89,90], their influence on pest and disease dynamics must be carefully considered. In some cases, the widespread planting of *Sonneratia apetala* and the use of monoculture practices have increased ecosystem vulnerability to biotic threats. Future restoration efforts should adopt more ecologically informed approaches that balance rapid establishment with long-term resilience against pests and diseases [91]. Such strategies will be essential for ensuring the success and sustainability of mangrove conservation in the context of ongoing climate change [90,91].

6. Integrated Pest and Disease Management Strategies for Mangrove Forests Along China's Coastline

Pest and disease management in Chinese coastal mangroves should adhere to the principle of “prevention first and integrated control” [22], establishing a comprehensive system that combines cultural practices, chemical interventions, biological control, physical methods, and quarantine-monitoring protocols. Biological control has already formed the core framework for insect pest management in Chinese mangroves [22,92] and can be further extended to address pest–disease interactions (e.g., sap-sucking insects triggering sooty mold, or wood-boring insects exacerbating stem and root rot), thereby reducing outbreak risks and preserving ecosystem functions [93]. Key priorities include disrupting dispersal pathways (seedling transport, water currents, and wind), improving stand microenvironments, enhancing tree vigor, and accounting for the practical difficulties of pesticide application in the intertidal zone while meeting stringent environmental standards to prevent secondary contamination of benthic organisms and water bodies [14].

It is noteworthy that pest and disease management strategies for mangrove forests differ substantially from those used in terrestrial forests. Mangroves occur in unique intertidal wetland ecosystems shaped by periodic tidal inundation, high salinity, elevated humidity, and hypoxic soils. Consequently, management practices must consistently place

ecological protection as the highest priority [94]. Compared with typical forests, mangrove ecosystems are far more sensitive to chemical agents; any improper application can lead to persistent secondary pollution of benthic organisms, fish populations, and nearshore waters via tidal transport [95]. Therefore, in mangrove pest and disease management, biological control, cultural practices, physical methods, and rigorous quarantine–monitoring–early warning systems should take precedence, while chemical interventions must be reserved strictly as a last-resort emergency measure and applied with the utmost caution [94].

6.1. Prevention and Regulatory Measures

Prevention remains the most cost-effective and ecologically sound strategy for managing pests and diseases in mangrove ecosystems. Strict quarantine measures during seedling transportation are essential to prevent the long-distance dispersal of pests and pathogens. Only healthy, pest- and disease-free seedlings should be used for planting, as the introduction of infested material can lead to widespread outbreaks in restoration sites.

Regular monitoring and early warning systems are critical, particularly during high-risk periods. Summer months are associated with increased outbreaks of red spot disease and Lepidopteran pests, while cool and humid seasons favor the development of gray mold. The use of digital technologies such as drone patrols and Internet-of-Things (IoT) sensors is recommended to enable real-time surveillance, especially under prolonged high-temperature and high-humidity conditions exacerbated by climate change [15]. These technologies can significantly improve the timeliness and coverage of monitoring efforts in large or remote mangrove areas.

Overall, integrating regulatory measures with modern monitoring tools provides a proactive and sustainable foundation for pest and disease management in Chinese coastal mangroves.

6.2. Cultural and Agronomic Practices

Cultural practices form the foundation of sustainable pest and disease management in mangrove ecosystems. Recommended measures include planting healthy seedlings, minimizing wounds caused by insects or mechanical activities, promptly removing and destroying diseased leaves and infected plants, and conducting timely thinning and pruning to improve ventilation and light penetration. Optimizing planting density promotes seedling lignification and reduces conditions favorable for gray mold. Covering seedbeds with plastic film during cool, humid periods and regularly clearing fallen leaves can further enhance overall tree vigor. These practices have been proven effective in reducing the incidence of anthracnose, leaf spot, gray mold, stem/root rot, and leaf-feeding Lepidoptera [14].

In addition, the selection of healthy, pest-free seedlings is particularly important in mangrove restoration projects, as it can significantly lower the risk of introducing pathogens and pests into new planting areas. Timely pruning of infested branches also helps reduce the spread of both insect pests and associated diseases such as sooty mold. While these cultural measures are generally low-cost and environmentally friendly, their effectiveness can be influenced by local site conditions, planting density, and the timing of implementation. When properly applied, cultural practices can substantially decrease reliance on chemical control and contribute to long-term ecological stability in mangrove stands.

6.3. Physical Control and Monitoring–Early Warning

Physical methods provide important non-chemical options for both monitoring and direct suppression of pests and diseases in mangrove ecosystems. Light traps and sticky boards are effective tools for monitoring Lepidopteran pests, while intensified field patrols during peak seasons can help detect early centers of red spot disease, sooty mold, and leaf-

feeding insect outbreaks. Severely infested or infected plants should be promptly removed and destroyed to prevent further spread. Strict enforcement of quarantine measures during seedling transport remains essential to avoid regional dissemination of pests and pathogens [14,17].

In addition, the integration of physical control with regular monitoring allows for timely intervention, which is particularly important in mangrove restoration areas where outbreaks can rapidly affect large numbers of seedlings and young trees. These practices are environmentally friendly and can significantly reduce the need for chemical interventions when implemented consistently.

6.4. Biological Control

Biological control represents an ecologically friendly and sustainable component of integrated pest and disease management in mangrove ecosystems. It generally includes two main approaches: classical biological control, which relies on the introduction, augmentation, or conservation of natural enemies such as parasitoids and predators [96], and microbial control, which utilizes microorganisms or their bioactive compounds to suppress pests and pathogens [97]. It should be clarified that *Bacillus thuringiensis* (Bt) formulations, although derived from a bacterium, function primarily as microbial insecticides through the production of Cry toxins rather than as classical biological control agents that establish self-sustaining populations in the environment [98].

For the management of insect pests, predatory insects, parasitoids, and spiders play important roles in naturally regulating populations of leaf-feeding Lepidoptera and sap-sucking Hemiptera in mangrove habitats [96]. Parasitoids, particularly those in the genus *Trichogramma*, have been applied on a large scale in China for the biological control of lepidopteran pests in forestry and agricultural systems for decades, covering millions of hectares. Notably, in a 500 ha mangrove forest trial, *Trichogramma pintoi* achieved a parasitism rate of 92% on target pests, significantly reducing populations of bagworms and leafrollers. Although systematic long-term evaluations in mangrove ecosystems remain limited, these results indicate that conservation and augmentation of indigenous natural enemy communities represent a promising strategy for sustainable pest suppression with reduced reliance on chemical pesticides [99]. Predatory insects and spiders also contribute to the suppression of scale insects and planthoppers in mangrove habitats. However, systematic evaluations of these natural enemies under field conditions in Chinese mangroves remain limited, and their potential has not been fully exploited in practical management programs [71].

For disease management, antagonistic microorganisms isolated from mangrove sediments and associated plant tissues have shown promising inhibitory effects against several fungal pathogens. For instance, *Bacillus* strains screened from mangrove sediments have demonstrated strong biocontrol potential against multiple fungal pathogens, with laboratory assays showing inhibition rates of 60%–85%, and some isolates significantly suppressing pathogen growth and sporulation [92]. Similarly, natural product extracts from *Bacillus* and *Pseudoalteromonas* isolates obtained from mangrove soil have been shown to inhibit *Colletotrichum* species causing anthracnose, with certain extracts achieving inhibition rates of 70%–90% in laboratory tests [93]. These findings indicate that microbial antagonists represent a valuable resource for developing environmentally friendly strategies to manage diseases in mangrove nurseries and restoration areas.

Despite these advances, the practical application of biological control in mangrove ecosystems faces considerable challenges. Most existing research remains at the laboratory or small-scale trial stage, and robust multi-year field data evaluating the efficacy and ecological impacts of biological control agents under realistic tidal and saline conditions in natural

mangrove stands are still largely lacking [100]. In addition, large-scale implementation is often limited by high production costs, difficulties in formulation development suitable for tidal zones, and the lack of region-specific studies on the ecological safety and long-term effectiveness of these agents. Most existing research remains at the laboratory or small-scale trial stage, and robust long-term field data evaluating the efficacy of biological control agents under realistic tidal inundation and salinity conditions in natural mangrove stands are still scarce [67,91].

To advance the application of biological control in Chinese coastal mangroves, future research should prioritize the screening and evaluation of indigenous natural enemies and antagonistic microorganisms adapted to mangrove conditions [101], the development of formulations resilient to tidal and saline environments [102], and especially the conduct of multi-year field trials to generate robust data on their practical efficacy and ecological impacts under realistic tidal inundation and salinity fluctuations. Integrating biological control with cultural practices and monitoring systems within a comprehensive IPM framework will be essential for achieving sustainable and environmentally sound pest and disease management in these sensitive coastal ecosystems [103].

6.5. Chemical Control

Chemical control should be used strictly as a last-resort emergency measure due to its potential negative impacts on intertidal ecosystems. During the seedling stage or at the early onset of disease, broad-spectrum fungicides such as carbendazim, chlorothalonil, or thiophanate-methyl (800–1000× dilution) may be applied to prevent anthracnose, red spot disease, leaf spot, and gray mold. For sooty mold outbreaks, alternating applications of prochloraz and thiophanate-methyl are recommended. When controlling insect outbreaks, only low-toxicity insecticides should be used in rotation to delay resistance development. Application must be restricted to non-sensitive zones and timed according to pest life cycles [44].

It should be emphasized that chemical pesticides can pose risks to non-target organisms and water quality in mangrove environments. Therefore, their use should be minimized through integrated approaches that prioritize prevention, cultural practices, and biological control whenever possible.

6.6. Emerging Technologies

Emerging technologies offer promising opportunities for precision pest and disease management in mangrove ecosystems. Drone-based remote sensing, IoT sensor networks, and intelligent early-warning platforms enable real-time monitoring and timely intervention across large or remote areas. Molecular diagnostic tools, such as eDNA and metagenomics, together with AI-based image recognition systems, are increasingly valuable for the rapid and accurate identification of pests and pathogens. Integrating these technologies into routine monitoring programs can gradually replace conventional manual methods and significantly improve management efficiency [15].

However, the widespread application of these technologies in mangrove environments still faces challenges, including high equipment costs, technical training requirements, and the need for adaptation to dynamic tidal and saline conditions. Future efforts should focus on developing cost-effective, mangrove-specific monitoring systems and validating their effectiveness through long-term field studies.

7. Conclusions and Prospects

A systematic review of the major pests and diseases affecting mangrove forests along China's coastline reveals that fungal diseases are dominated by anthracnose, sooty mold,

red spot disease, leaf spot diseases, gray mold, rust, and stem/root rot. These pathogens are typically favored by high-temperature/high-humidity or low-temperature/high-humidity conditions and frequently interact with sap-sucking insects or wood-boring damage to produce compounded harm, resulting in extensive leaf abscission, weakened tree vigor, and even stand-level dieback. Insect pests are led by leaf-feeding Lepidoptera (e.g., the mangrove fruit borer, *Aegiceras corniculatum* leafroller, and bagworms), supplemented by sap-sucking Hemiptera and wood-boring Coleoptera (e.g., the citrus longhorn beetle). Dispersal occurs mainly through adult flight, larval silk threads carried by wind or water, tidal drifting of bagworm cases, and long-distance transport via infested seedlings. These pests predominantly damage dominant species such as *Kandelia obovata*, *Avicennia marina*, and *Aegiceras corniculatum*, often causing characteristic “scorched” defoliation. These patterns align closely with field surveys conducted in protected areas of Guangxi, Guangdong, and Hainan, confirming that pests and diseases now represent the primary biotic threat to mangrove carbon sequestration, natural regeneration, and ecosystem services.

Integrated management strategies combining cultural practices, targeted chemical applications, biological control, physical monitoring, and quarantine measures have proven effective in keeping pest- and disease-related losses at acceptably low levels. The symptom descriptions, occurrence patterns, and control recommendations provided in this review offer practical guidance for routine management and ecological restoration in mangrove reserves. Field experience demonstrates that the “prevention-first, integrated control” approach holds clear advantages in the sensitive intertidal wetland environment.

Nevertheless, several important research gaps remain. Long-term population dynamics data for both insect pests and pathogens are still insufficient. The epidemiology and overwintering mechanisms of certain diseases, such as rust, remain poorly understood. Research on pest–disease interactions and their ecological consequences is limited, despite their frequent occurrence and amplifying effects. Monitoring and early warning systems suitable for mangrove environments are underdeveloped, and the effectiveness of integrated pest and disease management strategies under field conditions has not been systematically evaluated. Furthermore, quantitative assessments of the economic and ecological impacts of pests and diseases on mangrove carbon sequestration and restoration success are largely lacking.

Looking ahead, future efforts should prioritize the following directions to address these gaps: (1) employing high-throughput sequencing and molecular markers to clarify pathogen and pest population structures, with emphasis on rust fungi and key insect species complexes; (2) strengthening research on the mechanisms of pest–disease interactions and their responses to climate change and stand structure; (3) developing and validating drone-based, IoT-sensor, and AI-assisted monitoring platforms to enable real-time surveillance and early warning in mangrove ecosystems; (4) accelerating the breeding of climate-resilient mangrove varieties with enhanced resistance to major pests and diseases, and promoting mixed-species planting in restoration projects; (5) advancing the screening and application of environmentally friendly biopesticides and classical biological control agents, and evaluating their efficacy in mangrove field conditions; and (6) fostering interdisciplinary collaboration to construct regional pest- and disease-risk assessment models that integrate ecological drivers, pest–disease interactions, and management options, thereby providing scientific support for mangrove conservation under China’s dual-carbon goals.

Mangrove forests along China’s coastline serve as natural ecological barriers and vital blue carbon reservoirs. Effective pest and disease management is therefore essential not only for biodiversity conservation but also for advancing national ecological civilization and the marine power strategy. Sustained research, continuous improvement of integrated control systems, strengthened multi-sectoral collaboration, and greater public engagement

are required to ensure that mangrove ecosystems remain stable, healthy, and sustainable, contributing meaningfully to carbon peak and neutrality targets.

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