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Review Article

INTEGRATED AND ECO-FRIENDLY STRATEGIES FOR DISEASE MANAGEMENT IN COTTON: A COMPREHENSIVE REVIEW

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ABSTRACT

Cotton (*Gossypium* spp.) is the most significant commercial crop in the world, providing a critical source of fiber, oil, and revenue for millions of farmers, particularly in less-developed nations. Yet, its productivity is gravely endangered by several diseases caused by fungi, bacteria, viruses, and nematodes. Major diseases like *Fusarium* wilt, *Verticillium* wilt, bacterial blight, cotton leaf curl virus, and root-knot nematodes result in significant yield loss and downgrade fibre quality. While effective in the short term, traditional chemical-based management practices are detrimental to the environment and human health and tend to create resistance in pathogens. Therefore, integrated and eco-friendly disease management practices need to be adopted that use host resistance, cultural practices, biological control agents, and botanical extracts. This review emphasizes the primary diseases of cotton and reviews recent developments and environmentally friendly management strategies for these diseases. Special emphasis is placed on the potential of integrated disease management (IDM) practices as long-term, environmentally friendly solutions to ensure cotton health and productivity. The article concludes with the holistic strategies with the integration of modern biotechnological tools and traditional ecological knowledge for effective and sustainable disease management in cotton.

Keywords: Cotton, Diseases, Integrated disease management, Root-knot nematodes.

INTRODUCTION

Cotton (*Gossypium* spp.) is one of the most important fibre crops in the world, contributing substantially to the agricultural economies of many countries. This crop serves several purposes and is prized for its lint, which is used to make textiles, as well as for its ability to produce cottonseed oil and animal feed. In areas that produce cotton, the crop is a major pillar of the rural economy, supporting the livelihoods of almost 100 million households (ICAC, 2023). India is the world's largest producer of cotton, with 11.7 million hectares under cultivation, nearly 36% of the world's total cotton area (Ministry of Agriculture, 2023). The cotton sector is vital to India's economy, supporting around 6 million farmers directly and millions more through associated sectors such as ginning, spinning, and textile manufacturing. Despite these achievements, cotton production in India faces significant constraints due to a complex of biotic and abiotic stresses, among which diseases are a primary cause of concern (Kamboj *et al*. 2023). An estimated 34.3 million bales of cotton were produced in India during the 2022-2023 season. However, because of unpredictable weather patterns and a rise in pest and disease cases, productivity fell to 29.5 million bales in 2023-2024, the lowest level in 15 years (CAI, 2024). Declining productivity in major cotton-growing states like Maharashtra and Telangana is attributed to both climatic variability and the increased prevalence of cotton diseases (Economic Times, 2023).

Cotton plants are impacted by a diverse range of pathogens, such as bacteria, viruses, nematodes, and fungi. The most destructive fungal diseases are Alternaria leaf spot, Fusarium wilt (*Fusarium oxysporum* f.sp. *vasinfectum*), and Verticillium wilt (*Verticillium dahliae*). In northern India, bacterial blight is caused by

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Xanthomonas citri pv. *malvacearum* and viral infections like Cotton Leaf Curl Virus (CLCuV) are severe threats. Infestations of nematodes, particularly root-knot nematodes (*Meloidogyne incognita*), lower the fibre quality and reduce yield (Kumar and Kamboj, 2024). These diseases have the potential to cause crop losses of over 30% under ideal environmental conditions, which would significantly reduce farm profitability (Sandipan *et al*., 2019). Furthermore, the frequent use of chemical fungicides and bactericides, among other traditional disease control methods, frequently results in environmental contamination, pathogen resistance, and negatively impacts beneficial soil microorganisms (Kumar and Saharan, 2020).

These limitations highlight the necessity for sustainable, eco-friendly, and integrated disease management strategies. Integrated Disease Management (IDM) approaches emphasize the combined use of resistant cultivars, cultural practices, biological control agents, and minimal, need-based chemical inputs. Biological control, in particular, is gaining momentum with the use of antagonistic organisms, such as *Trichoderma* spp. and *Pseudomonas fluorescens*, which suppress soilborne pathogens through mechanisms including antibiosis and competition (Mukherjee *et al*., 2022). Botanical extracts and biopesticides derived from neem (*Azadirachta indica*), garlic, and turmeric also offer promising alternatives to synthetic agrochemicals. Additionally, recent advances in molecular breeding and genome editing techniques have opened new avenues for developing disease-resistant cotton genotypes (Chakraborty *et al*., 2021). This review aims to critically analyze the current knowledge on major diseases affecting cotton crops, with a focus on India. It highlights recent research advancements in eco-friendly and integrated disease management techniques, discussing their potential to reduce crop losses and improve sustainability. Special emphasis is placed on bio-intensive approaches, the role of microbial inoculants, and host-plant resistance strategies. The review also identifies current research gaps and provides suggestions for future investigations to develop climate-resilient and disease-tolerant cotton production systems.

Major diseases affecting cotton production

Fungal diseases

Fusarium oxysporum f.sp. *vasinfectum* is a soilborne fungus that causes fusarium wilt, a devastating vascular disease of cotton. It is particularly destructive in areas with high temperatures and alkaline soils. The pathogen enters cotton plants through wounds or the tips of their roots, colonises the vascular tissues, and stops the passage of nutrients and water. The lower leaves first show signs of chlorosis and marginal necrosis, which progressively develop into wilting and interveinal yellowing. When the vascular tissues in the stem and taproot are divided longitudinally, a dark brown to black discolouration is a crucial diagnostic characteristic. Affected plants show early death, leaf drop, and stunting as the disease progresses. Under field conditions, *Fusarium* wilt often occurs in patches and is frequently associated with root-knot nematode infestations, which exacerbate disease severity by creating entry points and increasing plant stress (Hillocks, 1992; Wang *et al*., 2021).

Verticillium wilt

This is a serious disease caused by *Verticillium dahliae,* which is more common in cooler cotton-growing regions. The fungus infects the roots of young plants and lives for years in the soil as microsclerotia. As the infection spreads through the xylem vessels, it leads to vascular obstruction and wilt symptoms. The stages of squaring and flowering are usually when disease expression starts. Plants with the infection show unilateral yellowing, interveinal chlorosis, and leaf necrosis, which can turn bronze or reddish-brown over time (Pegg and Brady, 2002). Foliar symptoms don't always indicate drought stress or nutritional deficits. The vascular tissues of the stem exhibit dark brown streaks that resemble Fusarium wilt. Unlike Fusarium, however, Verticillium wilt can progress slowly and may cause chronic reductions in yield and fiber quality without complete plant collapse. The pathogen's persistence in the soil makes it particularly challenging to manage (Bejarano-Alcázar *et al*., 2020).

Alternaria Leaf Spot

A foliar disease called Alternaria leaf spot is frequently found in environments with excessive humidity and inadequate crop nutrition. It is brought on by *Alternaria macrospora*, also known as *Alternaria alternata*. The disease typically appears late in the growing season and affects senescing leaves. Symptoms begin as tiny, round, dark brown to black spots with concentric rings, the symptoms resemble "target spots." The lesions may clump together, resulting in widespread defoliation and necrosis of the leaves (Ahuja *et al*., 2007). In extreme situations, early defoliation impairs boll development and decreases photosynthetic area; lower leaves are most frequently impacted. Stress from drought and potassium deficit frequently makes Alternaria infections worse. Particularly in poorly managed or rainfed cotton systems, recurring yearly infections can lead to cumulative yield loss and poor lint quality, even though they are typically not fatal (Zhang *et al*., 2023).

Anthracnose

Colletotrichum species, mainly *C. gossypii* and *C. capsici*, are the primary cause of anthracnose, a disease that affects both the leaves and the reproductive organs. It mostly occurs in high-rainfall tropical and subtropical cotton-growing regions. The fungus mostly affects bolls, stems, and cotyledons. The disease results in leaf lesions, stem cankers, and damping-off on seedlings. Symptoms manifest as depressed, round, reddish-brown to black lesions on bolls of mature plants, which may release pinkish spore masses when humid (Singh *et al*., 2010). These lesions can cause rotting, boll cracking, and decreased fibre quality by penetrating the lint and growing seed. Bark cracking and girdling are possible symptoms of infected stems. The pathogen can live on crop waste and is spread by seeds and soil. Favorable conditions include high humidity, rainfall, and poor field drainage, making anthracnose an important disease in rainfed systems (Ali *et al*., 2021).

Root Rot

Macrophomina phaseolina and *Rhizoctonia solani* are primarily responsible for the complex disease syndrome known as cotton root rot. These soilborne diseases damage the basal stem and root system, which impairs water intake and ultimately kills the plant. In case of *Rhizoctonia*, seedlings demonstrate pre or post-emergence damping off symptoms, but older plants display yellowing, reduced growth, and stem lesions. *Macrophomina* causes dry root rot, also known as charcoal rot, which is distinguished by black microsclerotia that are entrenched in the tissues of the roots and stems and give them a burnt look. Even when the soil is sufficiently moist, infected plants wilt quickly and may even collapse. Stress from drought and high soil temperatures frequently makes symptoms worse. Root rot diseases are particularly problematic in poorly drained or heavily compacted soils and are known to persist long in the soil, making rotation and organic amendments key to management (Garrett, 1970; Aveling *et al*., 2020).

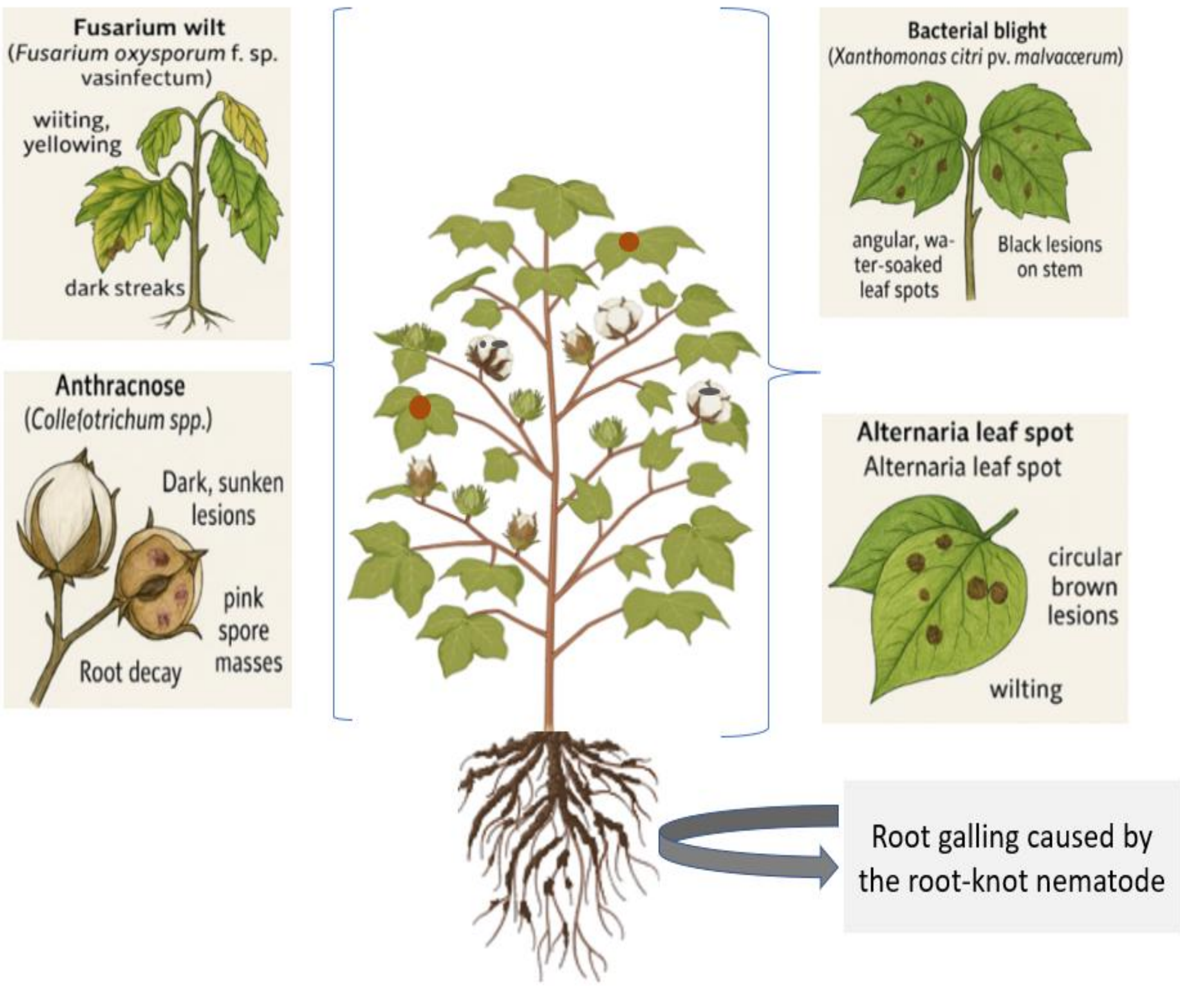

Figure 1. Different diseases of cotton with their typical symptoms.

Bacterial Disease

One of the most significant bacterial diseases affecting cotton, especially in warm and humid cotton-growing countries, is bacterial blight, which is caused by *Xanthomonas citri* pv. *malvacearum*. All the aboveground plant parts, including the leaves, stems, petioles, and bolls, are susceptible to the disease. The characteristic "angular leaf spot" appearance is caused by tiny, water-soaked lesions on the underside of leaves that eventually grow into angular, dark brown to black lesions that are typically restricted by leaf veins. Lesions may induce widespread necrosis as they grow and clump together, which could result in early defoliation. Elongated, deep lesions may form on infected petioles and stems, causing "black arm" symptoms, in which the tissue becomes brittle and branches may fall off. On bolls, the disease produces sunken, dark lesions that may lead to internal rotting of lint and seed, severely reducing lint yield and quality (Kirkpatrick and Rothrock, 2001).

The bacterium survives in infected seeds, crop residues, and on volunteer cotton plants. Seed-borne transmission is particularly important in long-distance dissemination. Rain splash, irrigation water, wind, and contaminated implements assist in local spread. High relative humidity (>80%), temperatures around 28-34°C, and frequent rainfall are conducive to disease development. Despite the availability of resistant cultivars, the emergence of new pathogenic races and climatic variability has led to its re-emergence in some areas, notably in South and Southeast Asia (Zandjanakou-Tachin *et al*., 2007).

Viral Disease

In Pakistan, northwest India, and some regions of Africa and China, cotton production is at risk due to the damaging viral disease known as Cotton Leaf Curl Disease (CLCuD). This condition is brought on by a complex of single-stranded DNA viruses from the genus Begomovirus (family Geminiviridae), primarily Cotton leaf curl Multan virus (CLCuMuV), Cotton leaf curl Kokhran virus, and Cotton leaf curl Alabad virus, as well as related satellite DNAs (α-satellite and β-satellite) that intensify symptoms. CLCuD epidemics are closely linked to whitefly population dynamics, which are favoured by warm temperatures (25-35°C), low rainfall, and reduced natural enemy populations (Sattar *et al*., 2013; Zafar *et al*., 2020). Three to four weeks following infection, symptoms usually show up as thickening and upward curling of the leaves, darkening of the veins, enation (leaf-like growths) on the lower leaf surface, limited growth, and decreased boll formation. In susceptible varieties, the disease causes systemic symptoms and significant yield reductions, sometimes exceeding 50%. Whiteflies (*Bemisia tabaci*), the vectors of the disease, acquire the virus in a persistent-circulative manner and transmit it while feeding on the phloem sap. The disease is not seed-transmitted but spreads rapidly through viruliferous whiteflies and infected plant material (Amrao *et al*., 2010).

Nematode-related diseases

Root-knot nematodes (RKNs), especially *M. incognita*, are one of the most economically significant nematode pests in the world's cotton production. Distribution of root-knot nematodes spans all major cotton-producing regions, including the USA, India, Pakistan, China, and Brazil. These sedentary endoparasites move to the vascular cylinder as second-stage juveniles (J2s), enter the root zone, and penetrate the root tips to create permanent feeding sites by causing the creation of giant cells. Resources are transferred from the plant to the nematode by these cells, which act as metabolic sinks. Depending on the extent of the infestation, infected roots can display normal galling, which can range from little swellings to enormous root knots. The nematode prefers sandy soils and high temperatures (28-32°C), and its population builds up rapidly under monoculture systems without rotation. The interaction between *M. incognita* and soil-borne fungal pathogens, particularly *Fusarium oxysporum*, often results in the wilt complex, which exacerbates damage (Khan *et al*., 2021).

Reniform Nematodes

Reniform nematodes (*Rotylenchulus reniformis*) are semi-endoparasitic nematodes that pose a major problem in cotton fields having clayey or loamy soils. *R. reniformis* produces root necrosis, stunting, and cortical damage. Female nematodes inject secretions that change the metabolism of their hosts after partially embedding themselves in the root cortex. Poor root development, chlorosis, stunted growth, and a marked decrease in boll production are some of the symptoms. Since damage is frequently subtle, it can be challenging to detect it until yield losses are noticeable. Even in dry conditions, the nematode can survive for long periods in the soil and thrives in warm environments. It has a wide host range, including soybean, pineapple, and several vegetables, which complicates crop rotation efforts (Atolani *et al*., 2022). *R. reniformis* is highly prevalent in the southern United States, Central America, parts of India, and West Africa. Management strategies rely on soil fumigation (where permitted), nematode-suppressive crops, green manuring, and developing resistant/tolerant cotton cultivars.

Management of different diseases of cotton

Conventional Management Practices

The use of fungicides, bactericides, and nematicides remains a core component of cotton disease management. Fungicides such as mancozeb and carbendazim are commonly applied to control foliar and soil-borne fungal pathogens, while copper-based bactericides are used against bacterial blight (Kumar *et al*., 2017). Nematicides like carbofuran and oxamyl have shown efficacy against root-knot nematodes (*M. incognita*) but pose environmental risks (Jones *et al*., 2013). Chemical seed treatments, involving agents such as thiram and metalaxyl, protect seedlings from early infections and ensure better crop establishment (Kaur and Aggarwal, 2019). However, repeated use of such chemicals leads to pathogen resistance, environmental contamination, and negative effects on non-target organisms, including beneficial soil microbes (Brent and Hollomon, 2007).

Resistant Varieties

One of the most important aspects of managing cotton diseases sustainably is breeding for cultivars that are resistant to disease. Varieties resistant to bacterial blight and Fusarium wilt have been developed by traditional breeding efforts (Ponnusamy *et al*., 2016). Bollworm resistance provided by genetically modified (GM) cotton, particularly *Bt* cotton, has completely changed pest management. Remarkably, *Bt* cotton may lessen insect-vectored diseases, hence indirectly reducing disease pressure (Fitt, 2008). However, problems include secondary pest and disease introduction, limited availability of multi-disease-resistant lines, and resistance breakdown (Zhang *et al*., 2020).

Cultural and agronomic Practices

Cultural practices, which alter the surroundings to lessen pathogen survival and spread, are an essential component of sustainable disease management. Crop rotation with non-hosts, such as legumes or cereals, lowers soil-borne inoculum and breaks disease cycles. Through competitive and allelopathic effects, intercropping, especially with legumes, can improve biodiversity and inhibit diseases (Ratnadass *et al*., 2012). Tillage practices alter microbial populations and soil structure, which in turn affect disease dynamics. Thorough ploughing can bury contaminated material and minimise inoculum, whereas reduced tillage may assist in preserving beneficial bacteria (Bailey and Lazarovits, 2003). Improving soil health through the addition of compost and organic matter supports microbial antagonists and boosts plant immunity. Field sanitation**,** including the removal of infected plant residues and weed control, limits pathogen sources. Organic amendments, such as neem cake, farmyard manure (FYM), and vermicompost, enhance beneficial rhizosphere activity and suppress nematodes and fungal pathogens (Kumar *et al*., 2021).

Biological control strategies

Biocontrol agents are becoming more and more popular as environmentally friendly substitutes for chemicals. *Trichoderma* species are frequently employed to combat root diseases like *F. oxysporum* and *R. solani* because of their mycoparasitic properties and ability to produce antifungal compounds (Harman *et al*., 2004). Systemic resistance in cotton is increased and pathogen growth is inhibited by the antibiotics and siderophores produced by *Pseudomonas fluorescens* and *Bacillus subtilis* (Raza *et al*., 2015). Mycorrhizal fungi, especially arbuscular mycorrhizae, enhance nutrient uptake and create systemic resistance, which lessens the severity of disease in the field (Smith and Read, 2008). The disease pressure is indirectly decreased by these fungi, which also improve resistance to nutritional stress and drought. Biocontrol of nematodes is possible using fungi like *Paecilomyces lilacinus*, which parasitizes eggs of *Meloidogyne* spp., and *Pochonia chlamydosporia*, which colonizes the rhizosphere and suppresses nematode populations.

Table 1. Novel Biocontrol Agents in Trials (2024).

Agent	Target Pathogen	Efficacy (%)	Advantage
Trichoderma asperellum	*Fusarium oxysporum*	85	Improves soil health
Bacillus subtilis	*Xanthomonas*	78	Compatible with organic farming
Chitosan nanoparticles	*Verticillium dahlia*	92	Slow-release, low toxicity

Source: Rani *et al*. (2023)

Botanical extracts and biopesticides

A natural substitute for synthetic chemicals, botanical pesticides frequently have broad-spectrum antibacterial qualities and pose fewer ecological hazards. Nematicidal, antifungal, and antibacterial properties are displayed by neem-based compounds, especially azadirachtin, which is derived from *Azadirachta indica*. It is well known that neem oil and cake can reduce nematodes like *M. incognita* and pathogens like *F. oxysporum* by preventing hatching and rupturing cell membranes (Chitwood, 2002). Significant cotton pathogens' mycelial proliferation is inhibited by several plant extracts, including those from *Calotropis procera*, *Ocimum sanctum* (tulsi), and *Allium sativum* (garlic) (Meena *et al*., 2011). These extracts contain phenolics, flavonoids, and alkaloids that disrupt protein synthesis and the integrity of fungal cell walls (Rao *et al*., 2010). Essential oils from plants like thyme, clove, and eucalyptus have also shown promising results against fungal diseases such as Alternaria leaf spot and anthracnose in cotton. These oils act by altering fungal membrane permeability and inhibiting spore germination (Bajpai *et al*., 2009). In addition, they are biodegradable and compatible with beneficial microbes, making them suitable for integrated systems.

Integrated Disease Management (IDM)

IDM is a comprehensive method that minimizes agricultural losses while minimizing environmental damage by combining several tactics. Among cultural, biological, botanical, and host resistance-based strategies, IDM prioritises prevention, resilience, and collaboration (Sharma and Kolte, 2005). It depends on threshold-based intervention, consistent illness monitoring, and the application of mutually reinforcing techniques. For example, *Fusarium* wilt incidence in cotton fields has been considerably decreased by combining resistant cultivars with seed biopriming with *T. harzianum* and neem cake treatment (Gopalakrishnan *et al*., 2011). Similarly, it has been discovered that intercropping sorghum and integrating *P. fluorescens* with FYM can lessen the severity of Verticillium wilt (Hebbar *et al*., 2004). Several studies highlight the success of IDM in cotton. In India, the adoption of an IDM module incorporating neem seed kernel extract, FYM enriched with *Trichoderma*, Bt cotton, and intercropping led to a 40-50% reduction in overall disease incidence and a 20% increase in yield (Desai *et al*., 2013).

IDM also reduces chemical dependency, thus lowering pesticide residues in soil and produce. Cotton production worldwide faces significant challenges from fungal, bacterial, and viral pathogens, compounded by the environmental and economic costs of chemical-dependent management systems. In response, integrated disease management (IDM) strategies have been successfully implemented across major cotton-growing regions, demonstrating sustainable alternatives that combine biological control, host resistance, cultural practices, and precision agriculture. The ultimate strength of IDM lies in its adaptability and ecological compatibility. By customizing practices to local disease complexes and environmental conditions, farmers can sustainably manage cotton health while preserving ecosystem services (Savary *et al*., 2012).

Challenges in Conventional Disease Management in Cotton

Conventional disease management in cotton primarily relies on synthetic pesticides, which, despite their efficacy, pose significant environmental, economic, and health risks. The overuse of chemical controls has led to pesticide resistance, ecological disruption, and chronic health hazards, necessitating a shift toward sustainable alternatives (Stenberg *et al*., 2021). Cotton farming accounts for ~16% of global insecticide use (FAO, 2021), with fungicides and bactericides extensively applied to combat pathogens like *Fusarium oxysporum* and *Xanthomonas citri* pv. *malvacearum*. However, excessive pesticide application disrupts natural predator-prey dynamics, harming beneficial organisms such as pollinators and soil microbes (Goulson *et al*., 2022). Frequent pesticide applications increase production costs, particularly for smallholder farmers (Zhang *et al*., 2023). While chemicals provide immediate disease suppression, their declining effectiveness due to improper use exacerbates pest resurgence (Pretty and Bharucha, 2024). Chemical pesticides contribute to soil degradation, water contamination, and biodiversity loss. Prolonged use of methyl bromide and other fumigants reduces microbial diversity, impairing nutrient cycling (Rani *et al*., 2023). Pesticide runoff contaminates aquatic ecosystems, with neonicotinoids detected in 75% of global cotton-growing watersheds (Stehle and Schulz, 2015). Farmers exposed to organophosphates face neurotoxicity, respiratory disorders, and increased cancer risk (Alavanja *et al*., 2023). The WHO estimates 200,000 annual pesticide-related deaths globally, with cotton workers among the most vulnerable (WHO, 2023). The repeated application of site-specific fungicides (e.g., strobilurins, benzimidazoles) has accelerated pathogen resistance. *Verticillium dahliae* strains resistant to triazole fungicides have emerged in India and China (Hawkins *et al*., 2019). *Xanthomonas* spp. exhibit multidrug resistance due to excessive copper-based sprays. RNA viruses like Cotton Leaf Curl Virus (CLCuV) rapidly mutate, rendering chemical controls ineffective (Ali *et al*., 2015).

Advances and challenges in eco-friendly disease management of cotton

The quick and precise identification of cotton pathogens has been enhanced by molecular techniques such as PCR, qPCR, and LAMP (Sharma *et al*., 2020). The creation of disease-resistant cotton is being accelerated by marker-assisted selection (MAS) and genomic selection, which precisely identify and include resistance genes (Kaur and Gaikwad, 2021). Breeders are better equipped to adapt to changing disease populations because of these tools. The application of nanoparticle-based formulations for targeted pesticide distribution and enhanced diagnostics presents a special opportunity for disease management using nanotechnology. Nanoparticles of zinc and silver oxide have demonstrated antifungal qualities against *Verticillium* and *Fusarium* species. Nano-encapsulated agrochemicals lessen the environmental chemical load while improving solubility, stability, and efficacy (Khan and Rizvi, 2018).

Resistance has been conferred by RNAi-based gene silencing, which inhibits the expression of genes in cotton pests and diseases (Raman *et al*., 2021). To confer resistance against *V. dahliae* and *Xanthomonas* spp., CRISPR/Cas9 is being investigated for altering susceptibility genes (Jinek *et al*., 2012). These tools hold immense promise for engineering durable resistance. AI-powered technologies, such as image recognition, remote sensing, and decision-support systems, allow for the real-time identification of cotton diseases using sensor data and aerial photos (Sharma *et al*., 2020). Localised disease surveillance, site-specific therapies, and input optimisation are made possible by precision agriculture technologies, including drones, satellite photography, and GIS mapping (Pinter *et al*., 2021).

Challenges and research gaps

Genetic variation in fungal and bacterial populations tends to break through single-gene resistance, necessitating ongoing monitoring and breeding programs (Chakraborty and Newton, 2011). In addition, climate change is disrupting pathogen life cycles, host susceptibility, and geographic range, driving the development of new disease complexes (Sharma *et al*., 2020). Despite the existence of environmentally friendly tools, several farmers struggle with the implementation of these because of limited exposure, lack of training, and affordability issues (Peshin and Zhang, 2014). Socio-economic limitations and institutional weakness also discourage new technologies, particularly in smallholder-based farming systems. IDM strategies do not work because they are designed in a generic approach. Location-specific modules are needed considering the local agro-ecological zone, cropping system, pathogen pressure, and farmers' socio-economic status (Singh *et al*., 2020). Participatory on-farm research and extension work are most important for developing and implementing location-specific IDM packages.

CONCLUSION

Diseases of cotton, which are brought about by fungi, bacteria, viruses, and nematodes, are significant threats to world production. Although chemical controls are a short-term solution, they are environmentally degrading and increase pathogen resistance. IDM by integrating resistant varieties, biocontrol agents (*Trichoderma*, *Pseudomonas*), botanical pesticides (neem, garlic), and sustainable agricultural practices is an eco-friendly, long-term solution. Advances in CRISPR, RNAi, and nanotechnology further boost disease resistance. Still, there are issues such as climate change, mutating pathogens, and low farmer adoption. The future should emphasize specialized IDM strategies, farmer training, and biotech innovations for sustainable cotton cultivation.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

REFERENCES

Ahuja, S.L., Monga, D., and Khadi, B.M. (2007). Cotton leaf spot diseases and their management. *Central Institute for Cotton Research Bulletin*.

Alavanja, M.C.R., Ross, M.K., Bonner, M.R., and Freeman, L.E.B. (2023). Pesticides and human health: A global risk assessment. *Environmental Health Perspectives*.

Ali, M., Bashir, M., Raza, W., Iqbal, A., Hussain, M., and Ahmad, M. (2021). Epidemiology and management of cotton anthracnose: A review. *Plant Pathology Journal*., 37(4), 344–355.

Ali, Z., Abulfaraj, A., Idris, A., Ali, S., Tashkandi, M., and Mahfouz, M. M. (2015). CRISPR/Cas9-mediated viral interference in plants. *Virology Journal., 12*, 221.

Amrao, L., Amin, I., Shahid, M.S., Mansoor, S., and Briddon, R.W. (2010). Cotton leaf curl disease in resistant cotton is associated with a single begomovirus, the cotton leaf curl Burewala virus. *Virus Research*., 152, 153-163.

Atolani, S. O., Li, Y., and Jenkins, J. N. (2022). Advances in reniform nematode resistance in cotton. *Frontiers in Plant Science*., 13, 821993.

Aveling, T. A. S., Naude, K., and Snyman, H. G. (2020). Charcoal rot of cotton and its management. *Journal of Phytopathology*., 168(2), 75-85.

Bailey, K. L., and Lazarovits, G. (2003). Suppressing soil-borne diseases with residue management and organic amendments. *Soil and Tillage Research*., 72(2), 169-180.

Bajpai, V. K., Baek, K. H., and Kang, S. C. (2009). Control of *Salmonella* in foods by using essential oils: A review. *Food Research International*., 45(2), 722-734.

Bejarano-Alcázar, J., Blanco-López, M. A., Melero-Vara, J. M., and Jiménez-Díaz, R. M. (2020). The vascular wilt fungi of cotton. In: Cotton Diseases and Their Management (pp. 1-29). *Springer*, Cham.

Brent, K. J., and Hollomon, D. W. (2007). *Fungicide resistance in crop pathogens: How can it be managed?* FRAC Monograph No. 1. Fungicide Resistance Action Committee.

CAI (Cotton Association of India). (2024). *Cotton crop estimates for 2023-24*. Retrieved from https://www.caionline.in

Chakraborty, S., and Newton, A. C. (2011). Climate change, plant diseases and food security: an overview. *Plant Pathology*., 60(1), 2-14.

Chakraborty, S., Roy, A., and Dasgupta, A. (2021). Advances in molecular breeding for disease resistance in cotton. *Journal of Cotton Research*., 4(1), 15-25.

Chitwood, D. J. (2002). Phytochemical-based strategies for nematode control. *Annual Review of Phytopathology.*, 40, 221-249.

Desai, S., Kumar, M. V. V., and Sreenivas, A. (2013). Integrated disease management in cotton a case study. *Journal of Cotton Research and Development.*, 27(2), 220-224.

Economic Times. (2023). India's cotton output in 2023-24 estimated to be lowest in 15 years: CAI. *The Economic Times*. Retrieved from https://economictimes.indiatimes.com

FAO. (2023). *World Cotton Production and Pesticide Use Statistics*. Food and Agriculture Organization.

FAO. (2021). *World Food and Agriculture – Statistical Yearbook 2021*. Rome.

Fitt, G. P. (2008). Have Bt crops led to changes in insecticide use patterns and impacted IPM? In *Integration of insect-resistant genetically modified crops within IPM programs* (pp. 303-328). Springer.

Garrett, S. D. (1970). *Pathogenic Root-Infecting Fungi*. Cambridge University Press.

Gopalakrishnan, S., Humayun, P., Srinivas, V., Razdan, V. K., and Alekhya, G. (2011). Evaluation of bacteria isolated from rice rhizosphere for biological control of sorghum charcoal rot and growth promotion in sorghum. *Biological Control.*, 57(3), 224–231.

Goulson, D., Nicholls, E., Botías, C., and Rotheray, E. L. (2015). Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science*, 347(6229), 1255957.

Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., and Lorito, M. (2004). *Trichoderma* species-opportunistic, avirulent plant symbionts. *Nature Reviews Microbiology.*, 2(1), 43-56.

Hawkins, N. J., Bass, C., Dixon, A., and Neve, P. (2019). The evolutionary origins of pesticide resistance. *Nature Reviews Microbiology., 17*(5), 313-320.

Hebbar, K. P., Lokesha, R., and Sreenivasa, M. N. (2004). Integrated management of Verticillium wilt of cotton. *Journal of Biological Control.*, 18(2), 149-154.

Hillocks, R. J. (1992). Fusarium wilt. In *Cotton Diseases* (pp. 127–160). CAB International.

ICAC (International Cotton Advisory Committee). (2023). *World cotton statistics and trends*. Retrieved from https://www.icac.org

Jinek, M., Chylinski, K., Fonfara, I., Hauer, M., Doudna, J. A., and Charpentier, E. (2012). A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity. *Science,* 337(6096), 816-821.

Jones, M. G. K., Moens, M., and Perry, R. N. (2013). *Plant nematology*. CAB International.

Kamboj, R., Kumar, V., and Mann, S.S. (2023). Sustainable approaches to the management of plant-parasitic nematode in cotton crop. *Journal of Cotton Research and Development*. 37, 247-58.

Kaur, R., and Aggarwal, R. (2019). Chemical management of cotton diseases. *Journal of Cotton Research and Development.*, 33(1), 44-50.

Kaur, S., and Gaikwad, K. (2021). Marker-assisted breeding and genome editing: new frontiers for durable resistance in cotton. *Molecular Plant Pathology.*, 22(6), 720-735.

Khan, M. A., Khan, H., and Khan, S. (2021). Plant-parasitic nematodes associated with cotton and their management strategies. *Journal of Nematology.*, 53, e2021-24.

Khan, M., and Rizvi, T. F. (2018). Nanotechnology: Scope and application in plant disease management. *Plant Pathology Journal.*, 17(1), 1-8.

Kirkpatrick, T. L., and Rothrock, C. S. (2001). *Compendium of Cotton Diseases* (2nd ed.). APS Press.

Kumar, A., Sinha, R., and Yadav, R. K. (2021). Organic amendments and their effects on soil health and disease suppression in cotton. *Journal of Applied and Natural Science.*, 13(1), 254-260.

Kumar, S., Meena, P. D., and Verma, A. K. (2017). Efficacy of seed treatment chemicals against seed-borne pathogens in cotton. *Indian Phytopathology.*, 70(1), 109-112.

Kumar, V and Kamboj, R. (2024). Abundance and diversity of plant parasitic nematodes in major cotton growing districts of Haryana. *Journal of Cotton Research and Development.*, 38(2), 213-218.

Kumar, V., and Saharan, M. S. (2020). Environmental implications of chemical pesticide use in cotton. *Indian Journal of Ecology.*, 47(2), 355-361.

Meena, B., Ramjegathesh, R., and Gopalakrishnan, C. (2011). Evaluation of plant extracts against *Alternaria* leaf spot of cotton. *Plant Archives.*, 11(1), 351-353.

Ministry of Agriculture. (2023). *Agricultural statistics at a glance 2023*. Government of India.

Mukherjee, A., Singh, R., and Bera, S. (2022). Bio-agents in cotton disease management: A review. *Journal of Biological Control.*, 36(1), 32-39.

Pegg, G. F., and Brady, B. L. (2002). *Verticillium Wilts*. CABI Publishing, pp. 1-126.

Peshin, R., and Zhang, W. (2014). Integrated pest management and pesticide use. In Integrated Pest Management. *Springer*, pp. 1–15.

Pinter, P. J., Hatfield, J. L., Schepers, J. S., and Barnes, E. M. (2021). Precision agriculture for improved cotton disease management. *Agricultural Systems.*, 191, 103181.

Ponnusamy, M., Suganthi, R., and Subburaj, S. (2016). Breeding for biotic stress resistance in cotton. *Current Science.*, 110(10), 1910–1916.

Pretty, J., and Bharucha, Z. P. (2024). *Sustainable Intensification in Agriculture: Balancing Productivity and Ecology*. Nature Sustainability.

Raman, V., Shivaprasad, P. V., and Kaur, H. (2021). RNAi: a novel strategy to engineer disease resistance in cotton. *Frontiers in Plant Science*, 12, 678900.

Rani, L., Thapa, K., Kanojia, N., Sharma, N., Singh, S., Grewal, A. S., and Srivastav, A. L. (2021). An extensive review on the consequences of chemical pesticides on human health and environment. *Journal of Cleaner Production.*, 283, 124657.

Rao, D. G. V., Reddy, P. P., and Reddy, M. S. (2010). Antifungal properties of certain plant extracts against *Alternaria alternata*, a causal agent of leaf blight in cotton. *Annals of Plant Protection Sciences.*, 18(1), 234-236.

Ratnadass, A., Fernandes, P., Avelino, J., and Habib, R. (2012). Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: A review. *Agronomy for Sustainable Development.*, 32(1), 273-303.

Raza, W., Ling, N., Yang, L., Huang, Q., and Shen, Q. (2015). Response of beneficial microbial populations and suppression of Fusarium wilt pathogen by bio-organic fertilizers in cotton rhizosphere. *Applied Soil Ecology.*, 90, 100-112.

Sandipan, P. B., Prashant, S., and More, P. (2019). Yield losses in cotton due to major foliar diseases. *International Journal of Current Microbiology and Applied Sciences*, 8(10), 2451-2458.

Sattar, M. N., Iqbal, Z., and Briddon, R. W. (2013). The evolving story of cotton leaf curl disease in Pakistan: Virus variants and resistance. *Plant Pathology Journal.*, 29(3), 225-234.

Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., and Nelson, A. (2012). The global burden of pathogens and pests on major food crops. *Plant Disease.*, 96(9), 1206-1216.

Sharma, N., Andersen, S. B., and Ottosen, C. O. (2020). Precision agriculture: Towards sustainable and efficient crop production. *Agronomy.*, 10(1), 1-17.

Sharma, P., and Kolte, S. J. (2005). Integrated disease management in cotton. *Indian Phytopathology.*, 58(1), 1–8.

Singh, D., Sharma, D. P., and Jain, S. K. (2010). Seed-borne fungi of cotton and their management. *Indian Journal of Plant Protection.*, 38(1), 59-63.

Singh, R., Kumar, V., and Chauhan, Y. S. (2020). Development of site-specific IDM modules for cotton-based cropping systems. *Journal of Plant Protection Research.*, 60(3), 265-273.

Smith, S. E., and Read, D. J. (2008). *Mycorrhizal symbiosis* (3rd ed.). Academic Press.

Stehle, S., and Schulz, R. (2015). Agricultural insecticides threaten surface waters at the global scale. *PNAS.*, 112(18), 5750-5755.

Stenberg, J. A. (2017). A conceptual framework for integrated pest management. *Trends in Plant Science.*, 22(9), 759-769.

Wang, B., Li, R., and Wei, Y. (2021). Emerging challenges in Fusarium wilt management. *Frontiers in Plant Science.*, 12, 645308.

WHO. (2023). *Global Pesticide Poisoning Report*. World Health Organization.

Zafar, Y., Amin, I., and Mansoor, S. (2020). Cotton leaf curl disease – an emerging threat to cotton productivity. *CAB Reviews.*, 15(029), 1-9.

Zandjanakou-Tachin, M., Mebs, S., Aouar, A. A., Ndoye, I., Sossou, A. M., and Ahouansou, C. (2007). Assessment of the genetic diversity of *Xanthomonas campestris* pv. *malvacearum*. *European Journal of Plant Pathology.*, 119(4), 463–478.

Zhang, J., Abdelraheem, A., and Wedegaertner, T. (2020). Genetic improvement of cotton for resistance to abiotic and biotic stress: Progress and prospects. *Plants.*, 9(1), 67.

Zhang, T., Yu, S., and Chen, Z. (2023). Biology and management of Alternaria diseases in cotton. *Crop Protection.*, 168, 106095.