Review

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# Fungal disease management in cotton using plant protection products: An Australian perspective

Noel L Knight,[a*] Linda J Smith,[a,b,c] Sambasivam Periyannan[a,c] and Levente Kiss[a]

## Abstract

**Cotton production faces persistent challenges from pathogens that compromise plant establishment, yield, and fibre quality. In Australia, seedling diseases and vascular wilts are the most widespread constraints, whereas foliar diseases and boll rots may exert further pressure when environmental conditions are conducive. Effective management of these diseases remains limited despite the availability of plant protection products. This review critically examines plant protection products, including fungicides and plant defence activators, currently registered for Australian cotton, while integrating perspectives from international approaches to cotton disease management. Particular attention is given to the characteristics of target diseases, products commonly applied in Australian cotton, and challenges regarding availability of efficacy data. We emphasize that realistic expectations are essential, as most products provide suppression rather than complete control, and their efficacy is shaped by multiple factors within integrated management frameworks. Future progress will depend on collaborative integration of existing and novel chemistries with complementary approaches, including pathogen diversity assessments, inoculum quantification tools, fungicide sensitivity screening and long-term, multilocation trials. Continued advances in resistance breeding, soil health management and precision agriculture will be critical to achieving sustainable, evidence-based disease management and strengthening cotton resilience in Australia and globally.**


**Keywords:** biological control; disease management; fungicide; Gossypium; pathogen; plant defence activator; seed treatment; stewardship; sustainability

## 1 INTRODUCTION

Cotton (*Gossypium* spp.) is the world's most widely cultivated natural fibre crop, underpinning global textile industries and rural economies. In 2024/2025, the leading producers of cotton worldwide were China (27%), India (20%), Brazil (14%), the United States (12%) and Australia (5%).[1] As one of Australia's major summer crops, cotton generates an estimated AU$2 billion in annual export value, making it a significant contributor to the Australian agricultural sector.[2]

Like most crops, cotton production faces many challenges, including impacts from pests and diseases, competition with weeds, and variable environmental conditions. Management of these challenges encompasses a range of strategies, each of which fit together to support a sustainable production approach. In Australia, for instance, almost all commercial cotton production comprises genetically modified (GM) cotton cultivars containing insecticidal genes for management of major Lepidopteran pests.[3] Disease management, however, still relies on more conventional strategies, including traditional breeding and integrated disease management. Despite continued development of crop protection strategies, global losses in cotton resulting from disease have been estimated at 11% of attainable yield.[4] In Australia, where cotton production is highly intensive and concentrated in areas of Queensland and New South Wales, crop protection practices are estimated to safeguard up to 65% of potential yield,[4] underscoring the importance of effective management strategies in a production system characterized by limited cultivar diversity and recurring disease issues. Against this backdrop, our review explores the management of cotton fungal and oomycete diseases with plant protection products, primarily from an Australian perspective, and highlights opportunities for new products or approaches.

* Correspondence to: NL Knight, Centre for Crop Health, School of Science, Engineering and Digital Technologies, University of Southern Queensland, Toowoomba, QLD 4350, Australia, E-mail: noel.knight@unisq.edu.au (Knight)

a Centre for Crop Health, School of Science, Engineering and Digital Technologies, University of Southern Queensland, Toowoomba, QLD, Australia

b Ecosciences Precinct, Department of Primary Industries, Dutton Park, QLD, Australia

c Australian Cotton Disease Collaboration Virtual National Centre, Institute for Agriculture, Climate and the Environment, University of Southern Queensland, Toowoomba, QLD, Australia

Cotton can be affected by a broad range of pathogens, including fungi, oomycetes, bacteria, nematodes and viruses.[5] The diseases can affect the roots, stems, foliage and reproductive structures, appearing across all the developmental stages of the plant. In Australia, several fungal and oomycete pathogens present ongoing pressures to cotton production, as outlined in Table 1. Disease complexes, where multiple pathogens co-infect cotton plants, add to the challenge of disease management. A critical message to promote on-farm biosecurity to Australian cotton growers has been 'Come clean. Go clean.' as a method of avoiding disease risk.[6] Beyond this, growers rely on integrated disease management strategies to reduce the impact of diseases on cotton production, which includes selection of less susceptible cultivars, reducing pathogen inoculum and disrupting disease expression with the application of plant protection products. An ideal plant protection product can be defined by key attributes: it must demonstrate proven efficacy and yield benefits, be supported by transparent and reproducible evidence, maintain durability through low resistance risk or strong stewardship, and integrate effectively with other management tools and agronomic practices.[7–9] Adoption also depends on practicality, including cost, registration feasibility and market acceptance.[10] Together, these attributes provide a framework to guide evaluation and deployment of plant protection products (Fig. 1).

Conventional plant protection products, such as fungicides, disrupt critical functions in fungal cells to suppress growth or cause death. The efficacy of fungicides in agricultural settings is determined not only by the molecular target site, but also the ability to deliver the chemical to the environment where the fungus is located, at a time when the fungus is active, and at concentrations which disrupt cell functions.[11] Plant developmental stages are critical, as they influence fungicide uptake and define the opportunities for fungicide–pathogen interaction. Some stages, such as seed and the surrounding soil zone, provide only a single opportunity for application, whereas foliage and bolls allow repeated interventions.[8,12] Environmental conditions add another dimension, affecting fungicide persistence, stability and movement within plant tissues, while also influencing pathogen activity and disease expression. Timing and frequency of fungicide applications therefore play a key role in determining efficacy. These can be challenging requirements to meet, and failure to align them may limit fungicide efficacy by missing the critical window of plant–pathogen–fungicide interactions. Alternative plant protection products face similar application requirements, but may act in different ways, from triggering plant defence responses to biological competition with pathogens.

A clear message is that plant protection products should be part of an integrated disease management strategy, not as a standalone solution.[8] They can help manage plant diseases, but they cannot compensate for poor agronomic practices. If a cropping system lacks proper crop rotation, plant protection product rotation, soil health management, or less susceptible cultivars, plant protection product effectiveness is limited. Another major risk is the emergence of resistance to plant protection products which were previously effective at managing disease, owing to changes in pathogen populations.[13] With the challenges involved in managing diverse pathogens, and the disease complexes that can arise from pathogen co-infections, the roles of plant protection products in cotton production, and modern approaches to soil health, are becoming increasingly relevant.

This review presents the major disease concerns in Australian cotton systems and the plant protection products currently registered in Australia, while also exploring global approaches for new products or strategies for disease management. This information is also relevant in a global context, as many of the same diseases are significant constraints to cotton production around the world. The analysis was triggered by the objectives of the Australian Cotton Disease Collaboration (ACDC), a national initiative launched in 2024, investing in cotton disease-related research and development.[14,15] By consolidating current knowledge and highlighting future directions, this work provides a foundation for developing realistic, integrated, and sustainable disease management strategies that will strengthen the resilience of Australian cotton production and offer insights of global relevance.

## 2 FUNGAL AND OOMYCETE DISEASES OF COTTON IN AUSTRALIA

Cotton in Australia is affected by a range of diseases caused by fungi and oomycetes (Table 1; Fig. 1). This review will focus on six major diseases that are considered to be the most frequent and impactful on cotton production in Australia, along with having registered plant protection products in Australia.[16] A brief description of minor or emerging cotton pathogens in Australia will also be provided, with these considered to be recently described or intermittent across seasons and environments. Plant protection product chemical names are briefly mentioned in this section for completeness, with more detail on mode-of-action (MoA) and role in disease management provided in subsequent focussed sections.

### 2.1 Verticillium wilt

Verticillium wilt of cotton, caused by the fungus *Verticillium dahliae*, is a significant vascular disease that disrupts water transport within infected plants, leading to wilting, chlorosis, necrosis and vascular discolouration.[17] The pathogen may persist for years in soil or crop residues as microsclerotia and melanized hyphae, which germinate under favourable conditions and invade roots, subsequently colonizing the xylem and impeding water flow.[17,18] Conidia (asexual spores) also play a role in the infection cycle, enabling rapid movement through the plant and short-distance dispersal between plants.[17,19] Seedborne *V. dahliae* may also allow for long-distance movement.[20,21] Yield losses estimated by growers in Australia range from 10% to 62%,[22] with disease severity influenced by environmental conditions, nutrition, host resistance and fungal strain. Verticillium wilt of cotton was first reported from northern New South Wales in Australia in 1959,[23] and is now found across New South Wales and Queensland, with the greatest severity associated with northern New South Wales.[24] Nondefoliating strains predominate in Australia, whereas defoliating strains are more common in other cotton-growing regions.[25]

The genetic diversity of *V. dahliae* is reflected in its vegetative compatibility groups (VCGs), which classify isolates based on their ability to undergo hyphal fusion.[26] In Australian cotton, VCG 1A (defoliating) and VCG 2A (nondefoliating) are the most relevant, with both reported to cause severe disease.[27–29] Additionally, *V. dahliae* exhibits heterothallic mating behaviour, meaning it requires two compatible mating types for sexual reproduction, although sexual structures have not been observed in nature.[30]

Beyond cotton, *V. dahliae* has a broad host range, infecting >400 plant species, including economically important crops and weeds.[31,32] Some hosts may remain asymptomatic but still



  

**Table 1.** Diseases of cotton caused by fungi and oomycetes in Australia and their causal agents, diagnostic features, and recommended management strategies. Details have been adapted from the 2025–2026 Cotton Pest Management Guide[81]

| Disease | Pathogen(s) | Tissues affected | Key symptoms | Favoured conditions | Management |
|---|---|---|---|---|---|
| Fusarium wilt | *Fusarium oxysporum* f. sp. *vasinfectum* | Vascular tissue | Stunting, wilting, leaf chlorosis, vascular discolouration | Warm soils | Less susceptible/tolerant cultivars; residue reduction; hygiene; protection product |
| Verticillium wilt | *Verticillium dahliae* | Vascular tissue | Stunting, wilting, leaf chlorosis, vascular discolouration | Cool–moderate temperatures; moist soils | Less susceptible /tolerant cultivars; residue reduction; irrigation control; protection product |
| Black root rot | *Berkeleyomyces rouxiae* | Roots | Blackened roots, stunting | Cool, wet soils | Residue reduction; treated seed; avoid cool planting |
| Seedling disease | *Rhizoctonia solani* AG 4 | Seed, roots, hypocotyl | Poor emergence, damping off | Cool, wet soils | Treated seed; avoid cool, wet planting |
| Seedling disease | *Pythium* spp.[a] | Seed, roots, hypocotyl | Poor emergence, damping off | Cool, wet soils | Treated seed; avoid cool, wet planting |
| Seedling disease | *Fusarium* spp. | Seed, roots, hypocotyl | Poor emergence, damping off | Cool, wet soils | Treated seed; avoid cool, wet planting |
| Alternaria leaf spot | *Alternaria alternata*, *A. macrocarpa* | Leaves | Necrotic lesions | Warm, humid; plant stress | Residue reduction; reduce stress; canopy management; fungicides |
| Boll rot | *Fusarium*, *Colletotrichum*, *Phytophthora*, *Aspergillus*, Rhizopus spp. | Bolls | Discolouration, decay, shedding | Humid; rainfall; insect damage | Residue reduction; canopy management; insect control |
| Sclerotinia stem rot | *Sclerotinia sclerotiorum* | Stems, bolls | Stem lesions, white mycelium, sclerotia | Cool, humid; dense canopy | Residue reduction; hygiene; canopy management |
| Reoccurring wilt | *Eutypella* spp. | Vascular tissue | Vascular streaking, wilting | Dry soils | Hygiene; residue reduction |
| Charcoal rot | *Macrophomina phaseolina* | Roots, stems | Vascular browning, stem weakening | Hot, dry soils | Maintain moisture; residue reduction |
| Collar rot | *Agroathelia rolfsii* | Stem base | Girdling, wilting | Warm, moist soils | Residue reduction; avoid excessive moisture |
| Ramularia leaf spot | *Ramulariopsis* spp. | Leaves | Necrotic lesions, defoliation | Humid, wet; dense canopy | Canopy management; residue reduction; fungicide |
| Target spot | *Corynespora cassiicola* | Leaves | Large concentric lesions, defoliation | Warm, humid; dense canopy | Canopy management; residue reduction; fungicide |
| Leaf spots | *Cercospora*, *Stemphylium* spp. | Leaves | Necrotic lesions, leaf blight | Humid, wet | Canopy management; residue reduction |

[a] Although the genus name *Pythium* remains widely used in applied and diagnostic contexts, several species formerly recognized as *Pythium* affecting cotton have been reassigned to the genus *Globisporangium*.

contribute to pathogen persistence in agricultural systems. Disease severity is also influenced by infection timing,[22] with early-season infections, before flowering, potentially resulting in more severe vascular colonization. Additionally, planting time may affect susceptibility, with cotton plants exhibiting more resistance at 25 to 27 °C, whereas cooler temperatures (20 to 22 °C) increase vulnerability to infection.[33]

Effective management relies on integrated approaches, including the use of less susceptible cultivars, crop rotation strategies and soil health maintenance to limit inoculum levels and suppress disease development. In Australia, the only product currently registered for Verticillium wilt is an extract of butterfly pea (*Clitoria ternatea*), which is described to impact microsclerotia formation (Table 2). Given the complexity of host–pathogen interactions, ongoing research continues to refine sustainable management strategies for *V. dahliae* in cotton.

### 2.2 Fusarium wilt

Fusarium wilt of cotton, caused by the fungus *Fusarium oxysporum* f. sp. *vasinfectum* (Fov), is a vascular disease that leads to

  

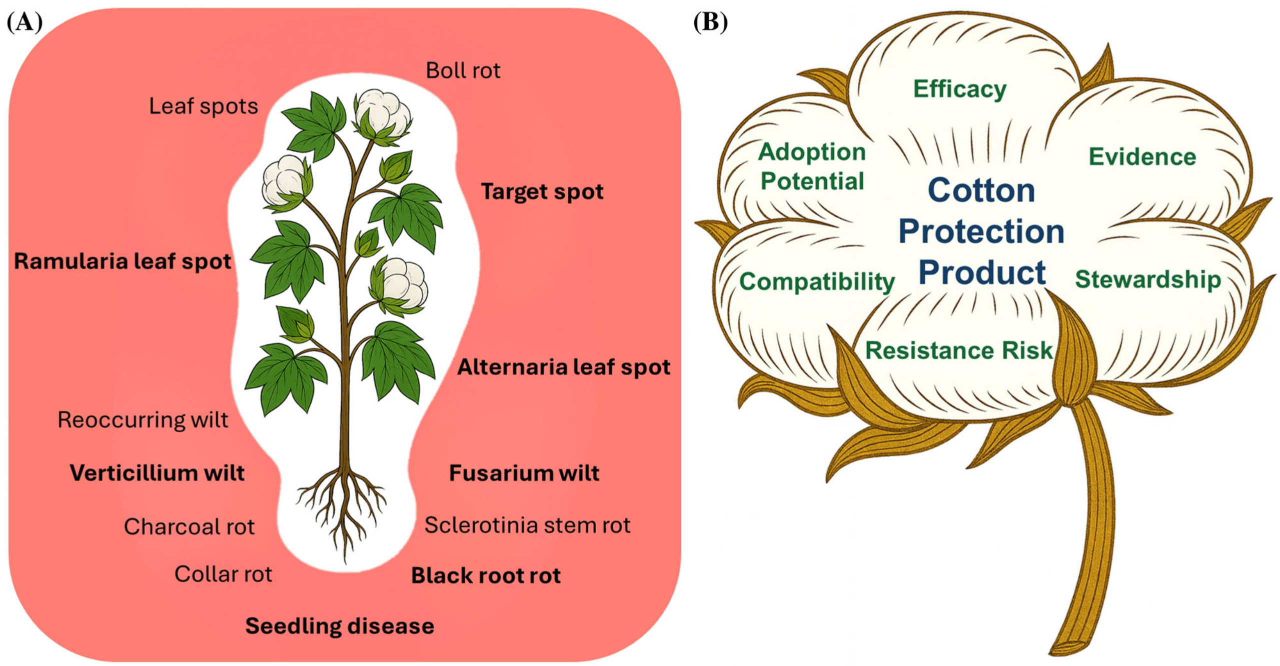


**Figure 1.** (A) Major diseases of cotton in Australia caused by fungal and oomycete pathogens. Diseases in bold have plant protection products registered for management. (B) Schematic summarizing attributes of an ideal plant protection product: proven efficacy and yield benefit, transparent and reproducible evidence, durability through strong stewardship, low resistance risk, integration with agronomic practices, and adoption framed by practical considerations such as cost and market acceptance. These criteria provide a framework for product evaluation. Images were created in Microsoft Copilot and PowerPoint.

wilting, chlorosis, necrosis and plant stunting.[34] The pathogen infects cotton roots, colonizing the xylem and disrupting water transport, ultimately causing plant decline. Within the vascular tissue, the fungi may spread via hyphal growth or microconidia, moving up the plant along the transpiration stream, and growing across xylem vessels by penetrating cell walls or entering through pit openings in end walls.[35] The fungus may persist on alternative hosts, be spread via seed and water, while also producing chlamydospores which enable it to survive in the environment for many years, making management challenging.[36] Fusarium wilt of cotton in Australia was first reported in 1993 in south-east Queensland[37] and is now found across both Queensland and New South Wales, being most prevalent in the northern inland regions.[24,38]

The genetic diversity of Fov is reflected in its vegetative compatibility groups (VCGs) and races, which vary in virulence and host interactions. In Australia, strains of Fov are distinct from those found overseas, with evidence suggesting they evolved from native *F. oxysporum* populations associated with wild *Gossypium* species.[39–41] Race 1 of Fov, reported overseas, typically requires co-infection with nematodes to cause severe disease.[42–44] By contrast, Australian strains have been described as aggressive pathogens capable of causing disease independent of nematode presence.[34]

Disease severity is influenced by infection timing, with symptoms appearing at seedling emergence or later during boll development. Environmental factors such as cool, wet conditions, waterlogging, nutrition and root damage exacerbate disease progression.[38] Management strategies focus on less susceptible cultivars, crop rotation, soil health maintenance and nematode control.[45] Delayed planting until soil temperatures exceed 16 °C is also recommended to reduce disease risk. In Australia, a plant activator product (acibenzolar-*S*-methyl) is available as a seed treatment to enhance plant defences against Fov, along with a fungicide seed treatment combination (penflufen and trifloxystrobin) and a treatment (metalaxyl-M) for seed disinfection (Table 2), which are discussed below. Ongoing research of cotton–*Fusarium* interactions continues to refine disease resistance mechanisms and sustainable management strategies for Fov in cotton.

### 2.3 Black root rot

Black root rot of cotton, caused by the fungus *Berkeleyomyces rouxiae* (syn. *Thielaviopsis basicola*), is a disease that primarily affects seedlings, leading to root blackening, stunted growth and delayed maturity.[46–48] This fungus infects cotton roots, colonizing the cortical tissue, which results in characteristic dark lesions, a reduction in lateral root development and disruption of nutrient and water uptake.[49] Disease severity is influenced by infection timing, where disease may be more severe at soil temperatures below 24 °C owing to slow seedling growth, leading to reduced vigour and yield losses of up to 46%, particularly in fields with high inoculum levels.[49,50] However, as temperatures increase, plants may compensate for the initial infection damage.[49] Black root rot has been detected in all cotton growing regions in Australia; however, disease incidence and severity increase from north to south, with more severe disease reported in southern New South Wales where cooler soil temperatures occur during seedling establishment.[24] Black root rot of cotton was first described from north-western New South Wales in Australia in 1989,[51] and following revised taxonomic classification,[52] the causal pathogen in Australia has most recently been identified as *B. rouxiae*.[46] This recent taxonomic change has highlighted the need to re-assess our knowledge of the

**Table 2.** Cotton pathogens and diseases targeted by registered plant protection products in Australia in 2025

| Target pathogen/s | Disease | Application | Active ingredients | FRAC group |
|---|---|---|---|---|
| *Pythium* spp.[a], *Rhizoctonia solani* | Seedling disease | Seed | Azoxystrobin[b] | 11 |
| *Pythium*, *Phytophthora*, *Fusarium* spp.[c] | Seedling disease, Fusarium wilt | Seed | Metalaxyl-M[bd] | 4 |
| *R. solani* | Seedling disease | Seed | Sedaxane[b] | 7 |
| *Pythium* spp., *R. solani* | Seedling disease | Seed | Fludioxonil[b] | 12 |
| *Fusarium* spp., *Thielaviopsis basicola*[e] | Fusarium wilt, black root rot | Seed | Acibenzolar-S-methyl[f] | P01 |
| *Pythium*, *Phytophthora* spp., *R. solani*, *F. oxysporum* f. sp. *vasinfectum*, *T. basicola* | Seedling disease, Fusarium wilt, black root rot | Seed | Penflufen[g] | 7 |
| *Pythium*, *Phytophthora* spp., *R. solani*, *F. oxysporum* f. sp. *vasinfectum*, *T. basicola* | Seedling disease, Fusarium wilt, black root rot | Seed | Trifloxystrobin[g] | 11 |
| *Rhizoctonia* spp. | Seedling disease | In furrow | Quintozene | 14 |
| *R. solani* | Seedling disease | In furrow | Tolclofos-methyl | 14 |
| *Verticillium dahliae* | Verticillium wilt microsclerotia | Foliar | *Clitoria ternatea* extract | No group |
| *Alternaria* spp. | Alternaria leaf spot | Foliar | Tebuconazole | 3 |
| *Alternaria* spp. | Alternaria leaf spot | Foliar | Mancozeb | M3 |
| *Ramulariopsis* spp.; *Corynespora cassiicola* | Ramularia leaf spot; Target spot | Foliar | Mefentrifluconazole | 3 |
| *Ramulariopsis* spp. | Ramularia leaf spot | Foliar | Prothioconazole[h] | 3 |
| *Ramulariopsis* spp. | Ramularia leaf spot | Foliar | Azoxystrobin[h] | 11 |
| *C. cassiicola* | Target spot | Foliar | Fluxapyroxad[i] | 7 |
| *C. cassiicola* | Target spot | Foliar | Pyraclostrobin[i] | 11 |
| NA[j] | Seedborne disease | Seed | Carboxin[j] | 7 |
| NA[j] | Seedborne disease | Seed | Thiram[j] | M3 |

[a] Although the genus name *Pythium* remains widely used in applied and diagnostic contexts, several species formerly recognized as *Pythium* affecting cotton have been reassigned to the genus *Globisporangium*.
[b] Active ingredients (azoxystrobin, metalaxyl-M, sedaxane, fludioxonil) available as a mixture for seed application.
[c] Active ingredient (metalaxyl-M) labelled for disinfection of Fusarium wilt on cotton seed.
[d] Active ingredient (metalaxyl-M) also available as a single active product.
[e] Product registration documents refer to *Thielaviopsis basicola*. Taxonomic revision to *Berkeleyomyces* spp. warrants reassessment of products.
[f] Acibenzolar-*S*-methyl is available in conjunction with the active ingredients for footnote [b].
[g] Active ingredients (penflufen, trifloxystrobin) available as a mixture for seed application.
[h] Active ingredients (prothioconazole, azoxystrobin) available as a mixture for foliar application.
[i] Active ingredients (fluxapyroxad, pyraclostrobin) available as a mixture for foliar application.
[j] Label indicates control of seedborne disease, but no specific pathogens (NA, not applicable). Active ingredients (carboxin, thiram) available as a mixture for seed application before export.

pathosystem and investigate variation among species previously identified as *T. basicola*.[48]

Limited information on the genetic diversity of black root rot causing fungi is available for Australian and global isolates,[53,54] yet a heterothallic mating system has been suggested.[55,56] The pathogen produces chlamydospores, which serve as long-term survival structures in soil, allowing the pathogen to persist for years.[47] Beyond cotton, *T. basicola* was reported to have a broad host range of >230 species;[47] however, this needs to be reviewed in light of new species designations.[48] Some hosts may remain asymptomatic but contribute to pathogen persistence in agricultural systems. Management strategies focus on planting time and temperature, inoculum reduction, crop rotation, soil health and seed treatments.[47] A fungicide-based seed treatment containing penflufen and trifloxystrobin, along with a plant activator seed treatment (acibenzolar-*S*-methyl), are registered in Australia for black root rot on cotton (Table 2).[57] Black root rot is an increasing concern in Australian cotton,[58] and with the causal species now re-classified,[52] existing registrations and management strategies based on *T. basicola* require reassessment to ensure efficacy and relevance.

### 2.4 Alternaria leaf spot

Alternaria leaf spot of cotton, reportedly caused by *Alternaria alternata*, *A. macrospora* and *A. argyroxiphii* in Australia, is a fungal disease that can affect cotyledons, leaves, bracts and bolls, leading to necrotic lesions, premature defoliation and reduced fibre quality.[59–61] The disease is favoured by high humidity, physiological stress and potassium deficiency, with symptoms typically appearing late in the growing season but occasionally developing earlier under conducive conditions.[60,62]

In Australia, the cause of Alternaria leaf spot in cotton has historically been understood at a genus level, which is likely to be a consequence of it being considered a minor disease, yet recent work has begun to describe species.[59–61,63] The longstanding absence of species-level identification has hampered understanding of genetic diversity, host range, environmental adaptability, and plant protection product efficacy. In general, the pathogen produces airborne conidia, which facilitate rapid pathogen spread, and it survives between seasons on cotton residues, on alternative hosts, or on infested seed.[64] Disease severity is influenced by infection timing, with symptoms appearing from seedling emergence to boll maturation.

Management strategies focus on crop residue reduction, potassium supplementation and fungicide (mancozeb, tebuconazole) application for severe disease (Table 2).[65] Burying infested residues reduces inoculum levels, while acid-delinting seed may minimize seedborne inoculum. Given the sporadic nature of severe Alternaria leaf spot in Australia, along with multiple causal agents and widespread distribution, integrated disease management remains essential for mitigating its impact on cotton production. This needs to be supported by improving our knowledge of the causal pathogens, including virulence, genetic diversity and fungicide sensitivity.

### 2.5 Rhizoctonia seedling disease

Rhizoctonia seedling disease of cotton, caused by *Rhizoctonia solani*, is responsible for pre- and post-emergence damping-off, and patchy or stunted growth.[66,67] *R. solani* is a necrotrophic fungus which persists as sclerotia or mycelium in plant debris, yet it is often grouped with *Pythium* spp. and *Fusarium* spp. as a disease complex.[68] The disease is characterized by sunken, reddish-brown lesions on the hypocotyl, which ultimately leads to seedling death or delayed plant development. Infection is favoured by cool temperatures, excessive soil moisture and poor drainage, conditions that slow seedling growth and increase susceptibility.[68] Factors such as soil structure and nutrition also may impact infection. Rhizoctonia seedling disease is widespread across all Australian cotton-growing regions, with consistently high incidence in New South Wales and regular detections in Queensland.[24]

The genetic diversity of *R. solani* is reflected in its anastomosis groups (AG), which classify isolates based on their ability to undergo hyphal fusion. Globally, the most common AG associated with cotton is AG-4, although additional AGs may contribute to disease development.[69–71] Beyond cotton, *R. solani* has a broad host range, infecting crops such as soybeans, peanuts, potatoes, and various vegetables, as well as weed species that serve as alternative inoculum reservoirs.[72,73] Limited information is available for the AGs occurring on cotton in Australia,[71] along with their host range.

Management strategies focus on high-quality seed, optimal planting conditions, residue reduction, crop rotation and chemical interventions. Combined seed treatment fungicides, specifically azoxystrobin, sedaxane and fludioxonil, or penflufen and trifloxystrobin, are registered in Australia to suppress early infections, whereas in-furrow fungicide applications of quintozene or tolclofos-methyl at planting may limit pathogen activity (Table 2). However, translation to field efficacy across susceptible crops has been poor.[74,75] Given the complexity of *R. solani* interactions within the cotton seedling disease complex, ongoing research is required to understand disease dynamics and integrated disease management strategies for cotton production.

### 2.6 Pythium seedling disease

Pythium seedling disease of cotton, caused by *Pythium* spp., primarily affects seed germination and early seedling development, leading to pre- and post-emergence damping-off.[68] The pathogen infects cotton seeds and roots, causing water-soaked lesions, root decay and seedling collapse, particularly under cool, wet soil conditions.[68,76] Disease severity can also be influenced by infection timing and soil nutrition. Pythium seedling disease is considered widespread across Australian cotton-growing regions, with the cooler areas of New South Wales expected to experience greater disease severity compared to the warmer areas of Queensland.[68,71] *Pythium* spp. are commonly grouped with *R. solani* and *Fusarium* spp. as the cause of a seedling disease complex, limiting the ability to describe *Pythium*-specific impacts.

*Pythium* spp. are oomycetes, producing zoospores which are motile spores that spread through water films in soil.[77] The pathogen also forms oospores, which serve as long-term survival structures, allowing *Pythium* spp. to persist in soil for extended periods. It can spread through infested soil, irrigation water and contaminated equipment. *Pythium* spp. affecting cotton are not typically described to species level, with *P. ultimum* and *P. helicoides* the only described species from Australia,[68,71] along with *P. aphanidermatum*, *P. debaryanum* and *P. irregulare* being among the most commonly associated with cotton seedling disease.[76,78] Although the genus name *Pythium* remains widely used in applied and diagnostic contexts, several species formerly recognized as *Pythium* affecting cotton have been reassigned to the genus *Globisporangium*.[79,80]

Beyond cotton, *Pythium* spp. have a broad host range, infecting crops and weed species that serve as alternative inoculum reservoirs.[77] Management strategies focus on crop rotation, seed treatments, and soil health. Mixed seed treatment fungicides, such as metalaxyl-M, azoxystrobin and fludioxonil, or penflufen and trifloxystrobin, are registered to suppress early *Pythium* spp. infection of cotton in Australia (Table 2). Delayed planting until soil temperatures are optimal can reduce disease risk, whereas raised bed planting improves soil drainage and reduces pathogen activity.[68] Because *Pythium* spp. may be part of a broader seedling disease complex in cotton, and with species identities still poorly characterized, further research is needed to clarify their roles and identify opportunities to strengthen current management strategies.

### 2.7 Minor and emerging diseases

In Australia a number of diseases occur sporadically, are regionally restricted, or are only recently recognized in cotton production systems. These include, but are not limited to, boll rots, Cercospora leaf spot, charcoal rot, collar rot, grey mildew, reoccurring wilt, Sclerotinia boll rot and stem blight, Stemphylium leaf spot, and target spot.[81] Although their overall contribution to national yield loss is currently lower than the major diseases, several have the potential to cause significant localized damage under favourable environmental conditions or in susceptible cultivars. Many also share epidemiological features with major diseases, including specific environmental triggers, survival on crop residues and the need for integrated management approaches. Table 1 summarizes the key biological and epidemiological characteristics of these minor and emerging diseases, along with their principal management options, based on current Australian extension and research sources.

### 2.8 Cotton disease complexes

Disease complexes arise from the interaction of two or more pathogens within a plant, potentially leading to compounded effects that significantly impact plant health, yield and quality. These interactions may be synergistic, where one pathogen predisposes the host to another, or additive, where multiple infections occur concurrently and increase disease impacts.[82,83] In cotton, such complexes may involve combinations of pathogens in the roots, shoots, leaves or bolls, with severity influenced by environmental stress, nutrition and wounding.[84]

Seedling disease has been associated with *R. solani*, *Pythium* spp., *B. rouxiae* and *Fusarium* spp., which may reduce emergence.[85] Nematodes have also been observed to impact infection by several cotton pathogens, including *R. solani*, *B. rouxiae*, Fov and *V. dahliae*.[42,85–89] Boll rot has been associated with a multi-pathogen complex;[81,90,91] however, the identities of co-occurring pathogens contributing to disease have not been formally described in Australia. Adding to this challenge is the potential for seedborne pathogens to contribute to cotton disease,[20,92–96] with research required to investigate the situation in Australian cotton seed.

These complexes become increasingly relevant for disease management with crop protection products, where broad activity on multiple pathogens, or mixtures targeting a range of pathogens, may be necessary for effective management. However, in practice, effective management may not be achievable, as studies have shown that fungicides which suppress individual pathogens can be ineffective when those same organisms occur together in soilborne complexes.[97] The impacts of applications need to be considered, as each active chemical may affect different pathogens to different extents, shifting the balance of the interactions within cotton plants. The location and longevity of active products, along with the time that plants interact with the pathogens may also have important impacts.[83] Overall, more information is required to understand which pathogens are present in Australian cotton fields and how they interact with each other and crop protection products.

## 3 MANAGEMENT APPROACHES WITH PLANT PROTECTION PRODUCTS

Plant protection products are used primarily to protect yield potential by reducing the impact of diseases during vulnerable growth stages. Their role is generally preventive rather than curative, aiming to protect seedlings and foliage before infection becomes established.[12,98] Fungicides and plant defence activators are the major tools for this purpose. Fungicides act directly on pathogens, whereas plant activators stimulate the plant's own defence pathways. Approaches for management often include mixtures or combinations of products to broaden protection, particularly where multiple pathogens are present in disease complexes. Such strategies may combine systemic fungicides, which move within the plant to protect internal tissues, with contact fungicides, which shield exposed surfaces.[12] These products are deployed through a range of delivery methods, including soil fumigation, in-furrow treatments, seed coatings and foliar sprays, with effectiveness determined by timing, placement and chemical mobility.

Mixtures and combined methods can broaden protection, yet reliance on fungicides also brings well-documented challenges, including ecological disturbance, impacts on nontarget organisms and the risk of resistance development.[13] These issues highlight the importance of careful stewardship, centred on rotation of MoAs, integration of plant activators, and the complementary use of biological, cultural and genetic strategies.

### 3.1 Registered plant protection products in Australian cotton

Chemicals in the following section are described according to the Fungicide Resistance Action Committee (FRAC) MoA grouping system.[99] The MoA groups used in Australian agriculture[100] correspond directly to FRAC groups, ensuring consistency between local and international frameworks.

A range of products are registered for use on cotton in Australia (Table 2). The primary application of fungicides occurs on seeds, where the commercial supplier of GM cotton seed applies a mixture of four actives (groups 4, 7, 11 and 12) to reduce the impact of pathogens, primarily *Pythium* spp. and *R. solani*, on seedling establishment. A plant activator (Group P01) may also be added to the combination. Australian industry-funded studies of a range of fungicides have also been performed, although much of the data remain inconclusive.[75,101] Assessments of cotton seed treatments in the United States provide a relevant example of an evaluation framework that could be adopted in Australia to improve consistency and transparency, along with perspective of what disease impacts are possible.[102–104]

### 3.2 Seed treatments

The first industry-standard cotton seed treatment in Australia was registered in 2005, combining metalaxyl-M, a phenylamide (Group 4), azoxystrobin, a strobilurin (Group 11), and fludioxonil, a phenylpyrrole (Group 12). In 2019, this formulation was updated to include sedaxane, a Group 7 succinate dehydrogenase inhibitor (SDHI) with documented activity against *Rhizoctonia* spp.[105] Company-funded, multisite trials in Australian cotton regions have reported modest (4%) increases in plant stand compared with the earlier three-active mix, with a 27% increase in plant stand over the untreated control.[106] However, these results are derived from proprietary datasets, and independent, peer-reviewed evaluations in cotton are limited. An industry report assessing seedling survival and seed treatments indicated varying results based on environment, demonstrating the challenge of maintaining protection across diverse growing conditions.[75] Another mixed seed treatment, containing penflufen (Group 7) and trifloxystrobin (Group 11), and combined with metalaxyl-M, was registered in 2018 for seedling disease, Fusarium wilt and black root rot (Table 2); however, it is not applied by the commercial seed supplier, and no evidence of its efficacy on cotton diseases in Australia is available. Although this is a potentially useful alternative, owing to minimal usage these fungicides will not be reviewed thoroughly.

In some cases, the mix of four fungicides is combined with a plant defence activator (benzothiadiazole chemistry) that induces systemic acquired resistance. This addition is promoted as providing suppression of vascular wilts and root rots caused by Fov and *B. rouxiae*. Although the impact of such elicitors is established in other crops, the extent and consistency of their contribution to disease suppression in Australian cotton production systems has not been comprehensively quantified in independent field studies.

### 3.3 Individual seed treatment chemicals

As a mixture of chemicals, it is important to understand which organisms each are targeting, along with where each chemical is interacting with target pathogens.[107] The following sections describe characteristics of each chemical used in the seed treatment mixture.

#### *3.3.1 Metalaxyl-M*

Metalaxyl-M (Group 4) is a xylem-mobile chemical which inhibits RNA polymerase I in oomycetes, disrupting rRNA synthesis and reducing mycelial growth, sporulation and spore germination.[108,109]

From the seed coat, the metalaxyl-M dissolves into water in the adjacent rhizosphere,[110,111] where it can interact with soil microbes and emerging roots, which absorb the chemical, allowing it to bind to root cell walls or move upward in the xylem to emerging shoots.[112,113] This binding to root tissues maintains a protective effect in the root system during early plant establishment. For cotton in Australia, metalaxyl-M is currently registered for *Pythium* spp., *Phytophthora* spp. and for disinfection of *Fusarium* spp. from cotton seed,[57] however data on its individual effect on the associated diseases or pathogens in Australia are not available. Notably, Phytophthora root rot has not been described in Australian cotton.

#### 3.3.2 Sedaxane

Sedaxane (Group 7) binds to the ubiquinone-binding site of complex II in the mitochondrial electron transport chain, disrupting oxidative phosphorylation and energy production in target organisms.[114] Applied as a seed treatment, sedaxane dissolves from the seed coat into the surrounding rhizosphere water,[105,115,116] where it can act directly on soil microbes and be absorbed by emerging roots. Direct assessments of sedaxane movement in plant tissues or associations with specific cells are still lacking in the scientific literature, but based on its effects on disease it is likely that sedaxane binds to root cells and also enters the xylem, moving acropetally into the shoots, and providing protection against infection or subsequent fungal growth during seedling establishment. In Australia, sedaxane is registered as part of a cotton seed treatment for management of seedling-damping-off caused by *Pythium* spp. and *R. solani*,[57] yet data on its individual effect on the associated diseases or pathogens in Australia are not available. Sedaxane has also been shown to act as a biostimulant in some crops, which should be considered when examining its effect on seedling establishment.[117]

#### 3.3.3 Azoxystrobin

Azoxystrobin (Group 11) is a quinone outside inhibitor (QoI) fungicide that disrupts mitochondrial respiration by binding to the Qo site of cytochrome b in complex III, blocking electron transfer and ATP synthesis in target microbes.[118] When applied as a seed treatment, azoxystrobin is released from the seed coat into the soil water solution surrounding the seed, from where it can act directly on microbes and be absorbed by emerging roots, although strong soil binding, low mobility and soil type may affect the molecule dynamics.[119] Uptake studies in various crops have shown that azoxystrobin is absorbed via roots and accumulates primarily in root tissues, with limited upward translocation in the xylem to shoots.[119–121] This distribution pattern provides local protection in the root zone. In Australia, azoxystrobin is registered as part of a cotton seed treatment for management of seedling-damping-off caused by *Pythium* spp. and *R. solani*,[57] yet data on its individual effect on the associated diseases or pathogens in Australia are not available.

#### 3.3.4 Fludioxonil

Fludioxonil (Group 12) disrupts osmotic signal transduction in target fungi by interfering with the high-osmolarity glycerol (HOG) pathway, leading to uncontrolled glycerol accumulation and cell death.[122] Applied as a seed treatment, fludioxonil remains largely on the seed surface and in the immediate rhizosphere owing to its very low water solubility and strong adsorption to soil particles.[123] In chrysanthemum, fludioxonil has been demonstrated to concentrate in roots tissues, with low concentrations in shoots.[124] Consequently, fludioxonil acts primarily as a contact protectant at the seed and root surface, limiting infection by microbes at the point of interaction. In Australia, fludioxonil is registered as part of a cotton seed treatment for management of seedling-damping-off caused by *Pythium* spp. and *R. solani*,[57] yet data on its individual effect on the associated diseases or pathogens in Australia are limited. Field research from New South Wales suggests that fludioxonil provides minimal or no benefit to cotton plant stands.[125]

#### 3.3.5 Acibenzolar-S-methyl

Acibenzolar-*S*-methyl (ASM; Group P01) is a benzothiadiazole plant activator that functions as a structural analogue of salicylic acid, triggering the plant's systemic acquired resistance (SAR) pathway.[126] This activation induces the expression of pathogenesis-related (PR) proteins and other defence compounds, enhancing the plant's ability to resist subsequent pathogen attack.[127,128] When applied as a seed treatment, ASM needs to be absorbed during early stages of imbibition and germination and is subsequently hydrolysed to acibenzolar acid, which is translocated within the seedling.[129] ASM has a short half-life (<1 day) and is considered to have low mobility in the soil.[130] In Australia, ASM is registered as an addition to cotton seed fungicide treatments for suppression of Fusarium wilt and black root rot.[57] For Fov, Whan *et al*.[131] demonstrated that seed-applied ASM primes systemic acquired resistance, markedly increasing expression and activity of defence-related enzymes, although without large, quantified reductions in wilt severity. Against black root rot, Mondal *et al*.[132] reported partial disease symptom suppression in pot and field trials, with seed soak or in-furrow applications reducing disease severity by 20 to 33%, and improved root characteristics and fruit set. However, in field trials, no significant improvements in seedling establishment, plant biomass or yield were observed. Another field study using foliar application of ASM analogues, including benzothiadiazole and 2,6-dichloroisonicotinic acid, demonstrated significantly reduced symptom severity of Alternaria leaf spot, Xanthomonas blight and Verticillium wilt in cotton,[133] although subsequent industry evaluations have had inconsistent results. In each case, ASM is best positioned as a complementary component within an integrated disease management program.

While this combination of chemicals aims to protect cotton seedlings from target pathogens, there are limited data on the combined or individual effects on the associated diseases or pathogens in Australia. Temperature-driven effects on specific diseases, together with variability in chemical mobility across soil types and moisture levels, potential impacts on both target and nontarget microorganisms, and cultivar-specific responses, underscores the need for a methodical investigation.[98,103]

### 3.4 In-furrow treatments

Two actives are available as in-furrow treatments for cotton in Australia, quintozene (Group 14) and tolclofos-methyl (Group 14). Product labels indicate these are for cotton seedling disease caused by *Rhizoctonia* spp. and *R. solani*, respectively. Although no cotton-specific studies describing their efficacy in Australia are available, there is evidence from international studies to support their potential impacts.[134,135]

### 3.5 Foliar treatments

#### 3.5.1 Alternaria leaf spot

Alternaria leaf spot has been the target of a range of fungicide trials in cotton in Australia. However, at the time of writing this review, only mancozeb is permitted for use on Alternaria leaf spot on cotton (Table 2). Field research in the Northern Territory demonstrated that foliar applications of mancozeb, applied preventatively at 14-day intervals from early symptom onset, significantly reduced disease incidence and severity, although yield and fibre quality responses were inconsistent.[61] Mancozeb is a coordination complex of manganese and zinc with ethylene bisdithiocarbamate that acts as a multisite, contact protectant fungicide, inhibiting fungal spore germination on the plant surface.[136]

Across subsequent industry-funded studies, mancozeb is described as the most reliable single active for Alternaria management, with tebuconazole also capable of reducing disease severity in New South Wales.[101] *In vitro* assays of both chemicals also demonstrated high levels of fungal growth suppression, albeit with variability between isolates. This variability indicates the need for population-level sensitivity screening and resistance-management strategies. A range of undisclosed fungicides have also been assessed,[101] indicating that other MoAs may also be useful for Alternaria management, especially in mixtures which support resistance-management objectives.

#### *3.5.2 Target spot and grey mildew*

Target spot and grey mildew have emerged as foliar disease threats, particularly in pivot-irrigated systems in Queensland and rainfed crops in northern Australia.[137] At the time of writing this review, two fungicide products containing either mefentrifluconazole (Group 3) or fluxapyroxad and pyraclostrobin (Groups 7 + 11) are permitted for use against target spot under minor use permits (Table 2). These permits support foliar application during early canopy development, with preliminary field trials indicating reduced disease severity in upper canopy leaves, although protection of lower tissues remains limited. For grey mildew, fungicide use is permitted under existing minor use provisions for two products containing either mefentrifluconazole or prothioconazole and azoxystrobin (Groups 3 and 11), but efficacy data are sparse and region-specific. Grey mildew infections typically occur late in the season, and may not justify intervention in all systems.[81] Further research is needed to clarify optimal timing, yield impact and population-level sensitivity to registered actives, particularly in high-risk irrigated environments.

#### *3.5.3 Verticillium wilt*

A plant-derived bio-pesticide formulated from *C. ternatea* extract, described to reduce the formation of *V. dahliae* microsclerotia, is registered as a foliar application in Australia to assist with managing Verticillium wilt.[57] This same product is also registered for the management or suppression of several insect pests. Although the MoA has not been described for Verticillium wilt on cotton, a peptide extracted from *C. ternatea* (Ct-AMP1) has been reported to impact *in vitro* growth of *V. albo-atrum*.[138] Industry-based reports have indicated that multiseason company-led trials showed reduced *V. dahliae* DNA abundance compared with untreated controls.[139] However, these findings have not yet been independently replicated or published in peer-reviewed literature. Given the well-documented challenges of achieving consistent field suppression of *V. dahliae*, more evidence is required to support fungicidal or disease-suppressive activity under Australian cotton-growing conditions. Independent trials with robust experimental design, along with knowledge of the MoA and fungal sensitivity, are needed to position this product as a reliable component of integrated Verticillium wilt management.

### 3.6 Fungicide stewardship and resistance management

Fungicides represent substantial investments in research, development and registration, and their long-term value depends on keeping them effective for as long as possible. Although the sensitivity of Australian cotton pathogens to currently registered fungicides is unclear, the emergence of fungicide resistance in plant pathogens more broadly is a recognized threat to product performance in many crops.[7] Several of the key MoAs used on Australian cotton, including groups 3, 4, 7, 11 and M03, have documented cases of reduced fungicide sensitivity or resistance described in closely related seedling and foliar pathogens from international studies.[140–146] Unpublished work on *Pythium* and *Rhizoctonia* isolates from cotton in Australia has reported decreased sensitivity in *P. helicoides* to metalaxyl-M and in *R. solani* to azoxystrobin; further investigation is required, yet these findings indicate a potential risk to disease management. Sustainable management therefore requires integrated disease management that combines chemical, cultural and biological measures, alongside routine screening of pathogen populations to detect changes in sensitivity over time.

Key stewardship practices include crop rotation to disrupt pathogen cycles, products incorporating multiple MoAs to reduce selection pressure, data on baseline sensitivity values, and the strategic use of plant activating or biological control alternatives.[147] Fungicides should be targeted to situations where high disease risk or unavoidable cropping constraints make chemical intervention necessary, rather than applied as a blanket practice. Achieving this depends on site-specific knowledge of pathogen inoculum levels, soil characteristics, microbial diversity and weather conditions.

### 3.7 Plant defence activators and biological strategies

Current chemical seed treatments and varietal resistance remain central to cotton disease management, yet their performance is often constrained by environmental variability, pathogen diversity and the persistence of inoculum sources. Plant defence activators and growth stimulators have demonstrated potential to reduce early-season disease incidence under high pathogen pressure, but field-scale results have been inconsistent and yield benefits limited.[132,133] Likewise, microbial products based on *Trichoderma* spp., *Bacillus* spp. or *Pseudomonas* spp. have achieved suppression of seedling diseases in controlled trials,[148–150] yet have not consistently delivered reliable outcomes in Australian investigations. Recent work from India has shown that combined seed treatments of *Trichoderma asperellum*, *Pseudomonas fluorescens* and arbuscular mycorrhizal fungi can reduce root rot and wilt severity caused by *R. solani* and Fov by 50% under field conditions.[151] Likewise, a combination of *Paenibacillus xylanilyticus*, *P. polymyxa* and *Bacillus subtilis*, was shown to reduce the impacts of Verticillium wilt in China.[152] These studies highlight the potential for synergy between microbes but also the need to identify their suitability in cotton management systems before deployment. The mycoparasite *Coniothyrium minitans* (syn. *Paraphaeosphaeria minitans*), has been used to degrade sclerotia of *Sclerotinia* spp.,[153,154] and has also shown experimental activity against *Verticillium* microsclerotia[155] and *R. solani*,[156] although field efficacy in cotton remains unproven. Products based on this mycoparasite are not currently available in Australia.

Stubble management and crop rotation are recommended to reduce inoculum levels, but their impact may be variable owing to broad host ranges and robust pathogen survival structures. Emerging products designed to accelerate stubble breakdown, either through direct chemical action or by stimulating decomposer microbes, may help degrade inoculum sources,[157,158] although their efficacy is likely to be constrained for persistent pathogens such as *V. dahliae* and *B. rouxiae*.

Biofumigation crops such as mustard, canola and oilseed radish have been investigated in Australian cotton systems for their potential to suppress soilborne diseases. When incorporated into moist soil, their glucosinolates hydrolyze to release isothiocyanates, which can impact the soil microbiome,[159] potentially reduce inoculum of pathogens including *R. solani* and *Pythium* spp.,[160,161] and under some conditions reduce black root rot disease.[162,163] Verticillium wilt is also a disease of interest for this approach. However, international evidence suggests that effective concentrations of isothiocyanates may be challenging to achieve in the field,[164] along with the potential for biofumigant plants species to serve as hosts of *V. dahliae*.[165,166] Approaches using green manures have shown impacts on Verticillium wilt of potato,[167–169] yet adoption in cotton systems has not occurred.

Future research should focus on refining and integrating these emerging options within robust, regionally tailored integrated disease management programmes. For plant defence activators, priorities include optimizing application timing and method, identifying MoAs and responsive cultivars, and evaluating combinations with chemical and biological controls for additive effects. For microbial products, emphasis should be placed on multisite, multiseason field trials, compatibility testing with existing seed treatments, and formulation improvements to enhance rhizosphere colonization and persistence. Inoculum breakdown strategies, including biofumigation crops, targeted residue incorporation, green manure and microbial decomposer products, warrant systematic evaluation to maximize pathogen suppression while maintaining soil health.

These efforts should be underpinned by improved diagnostics and monitoring to quantify inoculum levels, assess pathogen sensitivity to control measures, and guide product deployment to high-risk situations. By combining validated chemical tools with optimized plant defence activators, proven microbial inoculants, effective stubble management and improved cultivars, the Australian cotton industry can build more resilient, sustainable disease management programmes that preserve the efficacy of existing products and expand the range of reliable options available to growers.

## 4 RESEARCH GAPS AND FUTURE DIRECTIONS

Effective future plant protection in Australian cotton will depend on closing critical knowledge gaps while ensuring that new tools are economically, operationally and socially viable. A first priority is to quantify the cost of major diseases in terms of yield loss, as this underpins the economic justification for any intervention.[58] Across the industry, disease is considered to have significant impacts on production, with one grower estimating disease costs them 20% of their gross income *per annum*;[170] however, limited information is available for specific diseases, their impacts or how losses are estimated. Loss estimate figures should be weighed against the combined costs of product application and regulatory registration, modelled across multiple seasons to capture long-term profitability, resistance risk and system resilience.

In order to support such decisions, we need scientifically rigorous, publicly available datasets on regional pathogen sensitivity to crop protection products. This begins with laboratory-based baseline sensitivity assays for key pathogens (both target and nontarget), progressing through glasshouse trials and into multisite, multiseason field evaluations. Laboratory detection of reduced sensitivity, confirmed via effective concentration ($EC_{50}$) shifts or molecular markers, is a critical early-warning tool, but must be linked to field efficacy data to guide practice. This is particularly relevant in light of the emergence of fungicide resistance across multiple broad-acre crop pathogens in Australia.[100] Equally important is the capacity to detect, identify and quantify pathogen presence in seed, soil and air, as this should inform disease-risk assessment and fungicide use, enabling efficacy to be interpreted against actual disease pressure.[171–173]

At the systems level, there are several key considerations for different management approaches. Management factors such as row spacing, canopy density, irrigation, nutrition, growth regulators or hormone-modifying compounds may influence disease dynamics by altering microclimate, crop architecture, host physiology and chemical application, but these interactions remain under-explored. Smaller seed sizes in modern cotton cultivars may also contribute to reduced vigour and emergence, impacting disease severity.[174,175] For fungicides, applications across all crops in a rotation should be considered, along with the fate and biological activity of fungicide residues, particularly in irrigated cotton rotations. Biological products may have potential to play a valuable role in cotton disease management, but their effectiveness, along with fungicide-biological interactions, requires more research. Plant defence elicitors also need further investigation, particularly in terms of MoA, consistency and genotype-specific responses. Targeted approaches such as gene-silencing through RNA interference[176] and genetic modification of cotton may offer promising avenues for management of intractable diseases.[3,177]

Looking ahead, innovation will draw from novel fungicides, plant stimulants, biologicals, molecular technologies and soil-health interventions. Adoption of these products must be guided by fit-for-purpose evidence that meets industry expectations for the magnitude and timing of disease suppression, and by clear integration plans that map how new inputs fit within existing agronomic systems. This includes anticipating any required changes to management frameworks and ensuring that strategies remain regionally adaptive to variation in pathogen pressure and environmental conditions. Importantly, these approaches also must align with the sustainability priorities of brands, retailers and other buyers of Australian cotton, who increasingly require demonstrable progress on environmental performance, chemical stewardship, and transparency through initiatives such as the Australian Cotton Sustainability Framework.[178]

## 5 CONCLUSIONS

This review provides a perspective on fungicides and plant defence activators used in Australian cotton disease management, along with global insights on disease management. It highlights that fundamental knowledge to support the efficacy or registration of cotton protection products needs to be generated. Sustainable application solutions require a balanced integration of chemical products and biological stimulants to support host resistance and integrated disease management strategies. An emphasis on resistance management, environmental sustainability and long-term crop resilience is also required. Progress will depend on refining current practices for plant protection products and exploring alternative pathways. Future research should prioritize evidence-based approaches to innovative formulations and integrated disease management strategies to ensure Australian cotton production remains both productive and sustainable.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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