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Understanding Phytotoxic Mechanisms in Fungal Bioherbicide Candidates

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SUMMARY

Weeds posed serious problems across different land-use systems, and the rise of herbicide-resistant weeds along with restrictions on pesticide use increased the need for alternative control strategies. Over the past three decades, bacteria, fungi, and viruses gained attention as potential bioherbicides due to their environmental safety, target specificity, lower development costs, and novel modes of action. Fungal genera such as Colletotrichum, Phoma, and Sclerotinia were highlighted, with emphasis on their phytotoxic mechanisms, field-level challenges, and the future prospects of bioherbicide-based weed management.

INTRODUCTION

Weeds have remained a persistent problem in agricultural systems, causing significant yield losses, reduced crop quality, aesthetic damage, and health concerns due to allergenic pollen (Harding, and Raizada, 2015)). The introduction of selective herbicides such as 2,4-D and MCPA after World War II revolutionized weed management by allowing effective control of weeds without harming crops, thereby contributing greatly to increased agricultural productivity (Sreekanth et al., 2025a). However, the repeated and intensive use of a limited number of herbicide modes of action imposed strong selection pressure on weed populations, leading to the widespread evolution of herbicide-resistant species, including glyphosate-resistant weeds (Sreekanth et al., 2025b). The continuous emergence of resistant weed biotypes has highlighted the limitations of sole dependence on chemical herbicides and emphasized the need for alternative and diversified weed management strategies (Sreekanth et al., 2025b). In addition, increasing public concern over environmental contamination and pesticide residues, particularly in residential has accelerated interest in safer and sustainable weed control approaches (Singh et al. 2025). Biological control of weeds involves the use of living organisms such as fungi, bacteria, and viruses to suppress unwanted plant species. This approach includes two major strategies: classical biological control, which aims for long-term weed suppression through establishment of natural enemies, and inundative biological control or bioherbicide strategy, where large quantities of microbial propagules are applied in a manner similar to chemical herbicides. The latter approach is considered more suitable for modern agriculture and managed ecosystems.

Biological Control of Weeds Using Fungi

Fungi have received the greatest attention as biological control agents for weeds, particularly in North America (Charudattan, 2001). Most commercially developed bioherbicides are based on fungal formulations; however, only a few have achieved long-term success due to limitations in field performance, environmental sensitivity, and commercialization challenges (Templeton et al., 1986). Several fungal bioherbicides have been registered in the past. *Colletotrichum gloeosporioides* f.sp. *malvae* was developed as BioMal for the control of round-leaf mallow (*Malva pusilla*) (Mortensen, 1998). Another strain, *C. gloeosporioides* f.sp. *aeschynomene*, was commercialized as Collego for managing northern jointvetch (*Aeschynomene virginica*) (TeBeest et al., 1992). Similarly, *Sclerotinia minor* was formulated for the control of dandelion, white clover, and broadleaf plantain in turfgrass systems (Charudattan, 2001) (Table 1). Among fungal genera, *Colletotrichum*, *Phoma*, and *Sclerotinia* have been most extensively studied as bioherbicide candidates (Bailey et al., 2010; Kumar et al. 2023). Species of *Colletotrichum* such as *C. truncatum* and *C. orbiculare* have shown potential against weeds like hemp sesbania and spiny cocklebur (TeBeest et al., 1992).

The genus *Phoma* has also attracted major interest. *Phoma herbarum* has been evaluated for dandelion control, while *P. macrostoma* demonstrated selective toxicity toward dicot weeds (Bailey et al., 2011). This fungus produces macrocidins photobleaching compounds that inhibit dicot growth without affecting monocots (Graupner et al., 2003). Although the precise mode of action remains unclear, these metabolites have gained attention as templates for novel herbicide development. In addition, *Phoma* species have been reported to produce anthraquinone pigments and diterpenes such as chenopodolin, which induce necrosis in several economically important weeds (Evidente et al., 2000). Species of *Sclerotinia* have also shown strong bioherbicidal activity. *Sclerotinia minor* effectively suppressed dandelion under greenhouse and field conditions (Mortensen, 1998). Its phytotoxicity is largely associated with oxalic acid production, which acidifies host tissues, promotes cell wall degradation, and suppresses plant defense responses including polyphenol oxidase activity and hydrogen peroxide accumulation (Cessna et al., 2000). *S. sclerotiorum* has similarly exhibited toxicity against creeping thistle (Charudattan, 2001). Additional fungal bioherbicides include *Puccinia thlaspeos* (Woad Warrior) for dyer's woad, *Alternaria destruens* for dodder control, and *Phytophthora palmivora* (DeVine) for strangler vine in citrus orchards (Charudattan, 2001). Despite early success, many of these products are no longer commercially available. Overall, fungal bioherbicides offer environmentally safe weed management alternatives with novel mechanisms of action; however, inconsistent field efficacy, strong environmental dependence, and regulatory constraints continue to limit their widespread adoption (Bailey et al., 2010; Pramesh et al., 2020).

Table 1: Major Fungal Bioherbicides and Their Targets

Fungal genus/species	Product name	Target weed(s)	Key phytotoxic mechanism
Colletotrichum gloeosporioides f.sp. *malvae*	BioMal	Round-leaf mallow	Infection, cell wall degradation
C. gloeosporioides f.sp. *aeschynomene*	Collego	Northern jointvetch	Pathogenic enzymes, effectors
Phoma macrostoma		Broadleaf weeds	Macrocidins (photobleaching toxins)
Sclerotinia minor	Sarritor	Dandelion, clover	Oxalic acid production
Phytophthora palmivora	DeVine	Strangler vine	Systemic infection

Factors Affecting Field Efficacy of Bioherbicides

The successful performance of bioherbicides under field conditions is influenced by several environmental, biological, and management-related factors (Auld & Morin, 1995). Although many agents show strong activity under controlled conditions, their transition to field use remains challenging. Adequate and continuous moisture is one of the most critical requirements for bioherbicide infection. Many microbial agents require prolonged leaf wetness, often exceeding 12 hours, to successfully colonize host plants (Auld et al., 2003). Insufficient moisture significantly reduces spore germination and infection efficiency. Techniques such as applying inoculum during early morning or evening have been suggested to extend dew periods; however, their effectiveness remains highly dependent on environmental fluctuations. Attempts to use oil-based emulsions to prolong leaf wetness have shown limited success due to phytotoxic effects on host plants.

Both liquid and solid formulations strongly influence bioherbicide performance. Granular or solid inoculants prepared using carriers such as grains, alginate, oils, or vermiculite can enhance microbial survival by providing nutrients and moisture, thereby prolonging persistence under field conditions (Auld et al., 2003). However, these formulations are often associated with slower infection rates compared to liquid sprays. Consequently, formulation development remains a key factor in improving bioherbicide efficacy under natural conditions. Temperature and relative humidity also play crucial roles in pathogen activity and host infection. High humidity favors infection by reducing evaporation and maintaining leaf wetness following inoculum application. Many bioherbicides perform optimally under cool to moderate temperatures combined with elevated humidity levels. Each microbial agent has a specific temperature range for survival and maximum activity, and deviations from this range can substantially reduce weed suppression (Ghosheh, 2005). Therefore, monitoring environmental parameters is essential during efficacy trials. Microbial behavior may further vary depending on population density through a process known as quorum sensing, which regulates gene expression including virulence-related traits (Rutherford & Bassler, 2012). In some bioherbicidal agents, low population densities may result in latent or asymptomatic infections, contributing to inconsistent field outcomes (Bowden et al., 2013). Despite its importance, quorum sensing is rarely considered during bioherbicide evaluation. In addition, fertilizers and pesticides can significantly influence bioherbicide effectiveness. Nitrogen fertilization has been reported to enhance the efficacy of certain fungal bioherbicides, whereas phosphorus shows minimal influence and potassium fertilizers may reduce pathogen activity. Such agrochemical interactions must therefore be carefully evaluated before recommending combined applications.

CONCLUSION

Despite several limitations, the rising problem of herbicide-resistant weeds and growing public concern over pesticide use strongly support continued research on biological herbicides. These approaches are particularly valuable for organic farming systems and areas with pesticide restrictions. With further advancements, bioherbicides have strong potential to diversify weed management, delay resistance development, meet consumer preferences, and reduce environmental impact. However, achieving consistent and reliable field performance remains the key challenge for their successful adoption.

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