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Charcoal Rot of Soybean: A Silent Threat to Farmers

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ABSTRACT:

Soybean (*Glycine max* (L.) Merrill) is a vital oil-seed crop cultivated globally for its high nutritional value and industrial applications. However, its productivity is significantly threatened by charcoal rot, a destructive disease caused by the soil-borne fungus *Macrophomina phaseolina*. This pathogen thrives in hot, dry environments, has a wide host range, and can persist in the soil for extended periods through resilient microsclerotia. The disease cycle begins with asymptomatic biotrophic colonization, progressing rapidly to necrotrophy, leading to vascular blockage, wilting, and yield loss. Symptoms vary with environmental stress and plant growth stages, complicating timely diagnosis. Given the pathogen's complex biology and adaptability, effective management of charcoal rot necessitates an integrated approach. Various strategies such as crop rotation, tillage, irrigation, weed control, use of resistant cultivars, chemical treatments, and biological control agents have been explored for the management of charcoal rot, each with its own set of limitations and potential benefits. While individual methods offer partial control, their synergistic integration, tailored to agroecological conditions has emerged as the most sustainable and effective framework. Emphasis is placed on conservation tillage and irrigation to reduce stress, strategic fungicide uses for early suppression, and the role of biocontrol and genetic resistance in long-term disease management. Together, these approaches offer a comprehensive path toward reducing the impact of charcoal rot in soybean cultivation systems.

KEYWORDS: Soybean, *Macrophomina phaseolina*, Charcoal rot, Disease management

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INTRODUCTION:

Soybean (*Glycine max* (L.) Merrill) is a globally significant oil-seed crop, highly valued for its nutritional richness and industrial versatility. Originating in China, where it was recognized as one of the five sacred grains integral to early agriculture (Hymowitz, 1970), soybean has since achieved global cultivation. Its seeds are an excellent source of plant-based protein (~36%), oil (~19%), carbohydrates (~35%, including ~17% dietary fiber), and a variety of vitamins and minerals (~5%) (Liu & Liu, 1997). Additionally, soybean is rich in essential amino acids, antioxidants, and nutraceutical compounds that contribute to human health by lowering cholesterol, improving immune response, and reducing the risk of chronic conditions such as cardiovascular disease and diabetes (Sharma *et al.,* 2008; Kumar *et al.,* 2014).

In India, although soybean was likely introduced centuries ago, its commercial cultivation began only in the 1970s. The crop rapidly expanded across the state of Madhya Pradesh, which now accounts for the largest share of national production and is often referred to as the “Soybean State” of India (Pratap *et al.,* 2012). With its dual role as a vital source of oil and protein, soybean has become indispensable to India’s agricultural economy and food security. Despite its increasing importance, soybean cultivation faces significant challenges due to numerous diseases both globally and within India. In the Indian context alone, as many as 35 distinct diseases affecting soybean have been reported.

Among the various diseases affecting soybean, charcoal rot-caused by the soil-borne fungus *Macrophomina phaseolina* (Tassi) Goid. is one of the most economically destructive, particularly in dryland and rainfed agro-ecosystems (Goidanich, 1947; Romero Luna *et al.,* 2017). The pathogen is globally distributed and is especially prevalent in hot and arid climates, where it causes significant losses during mid to late summer under high temperatures and low soil moisture conditions (Kaur *et al.,* 2012). It infects more than 500 plant species, including soybean, maize, sesame, and canola, making it a classic example of a generalist pathogen with an extensive host range (Dhingra & Sinclair, 1977). Infection typically occurs during the seedling or early vegetative stage and progresses as environmental stress intensifies, leading to symptoms such as stem and root discoloration, wilting, and eventual plant collapse (Mengistu *et al.,* 2007; Wrather *et al.,* 2010). The pathogen's ability to survive in the soil for prolonged periods without a host, through the formation of melanized microsclerotia, further complicates control efforts. Historically classified as a necrotroph, *M. phaseolina* is now recognized as a hemibiotroph due to the presence of a transient biotrophic phase in early infection, which remains asymptomatic and hinders early detection (Chowdhury *et al.,* 2017).

DISEASE CYCLE:

The infection cycle of *M. phaseolina* begins when hyphal tips identify host root cells and form appressoria, specialized structures that enable penetration through the epidermal layer (Ammon *et al.,* 1974). Following entry, the fungus colonizes the intercellular spaces and middle lamella of root tissues. In early stages, it remains intercellular, primarily in the cortical region (Short *et al.,* 1980; Gupta *et al.,* 2012), but as the soybean plant enters reproductive phases, the fungus advances into the vascular tissues, particularly the xylem. This transition leads to the formation of melanized, hard microsclerotia, survival structures that clog xylem vessels, impair nutrient and water flow, and facilitate long-term persistence in the soil (Crous *et al.,* 2006). These microsclerotia germinate across a wide temperature range (20-40°C) and are capable of infecting both seedlings and mature plants, highlighting the pathogen's flexibility throughout the crop's lifecycle (Bristow & Wyllie, 1986; Collins *et al.,* 1991). Their development is closely associated with the flowering and pod-setting stages and often precedes visible disease symptoms or plant death (Short & Wyllie, 1978). The pathogen secretes cell wall-degrading enzymes and phytotoxins that aid in tissue penetration and rapid colonization, often leading to extensive damage within two to three weeks post-infection. Importantly, *M. phaseolina* follows a hemibiotrophic lifestyle, initiating infection with a short biotrophic phase, up to 36 hours, wherein host cells remain metabolically active. This is followed by a sharp transition to necrotrophy, marked by aggressive hyphal invasion and tissue necrosis, a process known as the "biotrophy-to-necrotrophy switch" (Chowdhury *et al.*, 2017).

SYMPTOMS:

Charcoal rot caused by *M. phaseolina* presents a broad range of symptoms that vary depending on the growth stage of the soybean plant and environmental conditions. Early signs often include leaf yellowing, reduced growth, reddish-brown discoloration of the roots and lower stems, and general wilting, symptoms that become more severe under hot, dry conditions (Gupta & Chauhan, 2005; Khan, 2007). Infected seeds may appear healthy but can harbour dark microsclerotia lodged in cracks of the seed coat.

As the disease progresses, plants develop a dull, silvery-gray appearance, particularly in the lower stem and root zones, where dense aggregations of black microsclerotia are commonly observed (Bradley & Rio, 2003; Gupta *et al.*, 2012). This discoloration gives the disease its name, charcoal rot and marks severe vascular colonization, which impairs water and nutrient transport (Wrather *et al.*, 2008). A notable diagnostic feature in advanced stages is the retention of dried, necrotic leaves that remain attached to the petioles even after plant death (Mengistu *et al.*, 2007; Luna *et al.*, 2017). In seedlings, initial symptoms include brown to black lesions on cotyledons and hypocotyls, which may spread upward during early vegetative growth. These symptoms intensify when prolonged high temperatures (>35°C) and soil dryness coincide, often resulting in rapid seedling collapse (Gupta *et al.*, 2012). Although infection may begin early, visible symptoms typically peak between the R5 and R7 reproductive stages (Mengistu, 2015).

MANAGEMENT:

M. phaseolina demonstrates remarkable adaptability, capable of surviving under a wide range of environmental conditions, including sodium salt concentrations from 1% to 8% and pH levels ranging from 3.5 to 10 (Islam *et al.,* 2012). Despite numerous efforts, no single, economically viable or environmentally sustainable method exists to eliminate the pathogen from infested fields. However, a well-established link exists between the level of inoculum, disease incidence, and subsequent yield loss. Management strategies are generally categorized into agronomic practices, selection of cultivar, chemical control, host resistance, and biological control, with numerous approaches explored to suppress the disease under different production systems. Given its persistent nature in soil and ability to infect multiple hosts across diverse agro-ecological zones highlight the urgent need for effective and sustainable management practices, which include:

1. **CROP ROTATION:**

Due to the extensive host range of *M. phaseolina*, conventional crop rotation alone is not considered a consistently effective strategy for disease management. Short *et al.*, (1980) demonstrated a direct correlation between the population density of viable microsclerotia in the soil and the number of consecutive years under soybean or maize cultivation, indicating that rotation with other susceptible crops does little to suppress pathogen buildup. However, long-term crop rotation studies suggest that even when soybean is rotated with other hosts of *M. phaseolina*, a reduction in pathogen population can be achieved compared to continuous soybean monoculture. Almeida *et al.,* (2003), in a 20-year field study, evaluated the impact of a no-tillage crop rotation system on *M. phaseolina*-infested fields and reported that conservation tillage practices reduced both microsclerotia density and disease incidence. They attributed this effect to improved soil moisture retention in no-till systems, which may suppress fungal propagation and delay disease development. These findings highlight the potential benefits of integrating crop rotation with conservation tillage as part of a broader, site-specific disease management strategy.

2. TILLAGE:

Tillage has been explored as a cultural practice to manage charcoal rot, primarily by enhancing the decomposition of microsclerotia or by promoting antagonistic microbial interactions in the soil. Olanya and Campbell (1988) observed that a single tillage operation to a depth of 15 cm led to a reduction in *M. phaseolina* populations. However, the effectiveness of this method is influenced by the initial density of microsclerotia in the soil, making outcomes variable across different field conditions. In contrast, a more recent study by Mengistu *et al.,* (2009) reported higher colony-forming units of *M. phaseolina* in soybean tissues under conventional tillage compared to no-tillage systems, suggesting that reduced soil disturbance may better suppress disease development. These contrasting findings highlight the inconsistent impact of tillage on charcoal rot severity and underscore the challenge of recommending tillage as a universally reliable management strategy.

3. IRRIGATION:

Although *M. phaseolina* is capable of infecting soybean across a broad spectrum of environmental conditions, severe disease outbreaks and significant yield losses are most associated with dry soils and drought stress during the reproductive stages of crop development. Under such conditions, irrigation can play a crucial role in mitigating charcoal rot severity by alleviating plant stress. While disease symptoms may still appear despite irrigation, yield losses can often be reduced, typically ranging between 6% and 30%. Kendig *et al.,* (2000) reported that water management strategies can influence disease progression. Their findings showed that plants exposed to water stress early in the season exhibited greater disease severity than those maintained under adequate moisture, even when both were infected with *M. phaseolina*. These results suggest that minimizing early-season drought stress through timely irrigation may be an effective component of integrated charcoal rot management.

4. BIOLOGICAL CONTROL

Biological control agents (BCAs) have received increasing attention in the last few decades. Some impact the pathogens directly, inhibiting their growth, while others affect the pathogen indirectly by eliciting defense pathways in the host plant. They offer a sustainable and environmentally friendly approach to managing *M. phaseolina*, particularly as alternatives to chemical control become increasingly necessary. The pathogen's low competitive saprophytic ability has been effectively targeted by various fungal and bacterial antagonists. For instance, species of *Bacillus* have demonstrated significant suppression of *M. phaseolina* in soybean, common bean, and cowpea under both laboratory and field conditions (Yasmin *et al.,* 2020). Similarly, fungal BCAs like *Trichoderma viride* and *T. harzianum* have shown strong antagonistic activity and have also been linked to enhanced plant growth (Khaledi and Taheri, 2016). However, challenges such as limited shelf life, inconsistent field performance and low awareness among end users continue to hinder widespread adoption. Overcoming these constraints through improved formulations, commercialization, and farmer education is essential for integrating BCAs into effective charcoal rot management strategies.

5. WEED CONTROL:

Competition for water and nutrients can stress soybean plants, making effective weed management essential to minimize stress-related factors. Various greenhouse and field studies have investigated the impact of herbicides on stem and root colonization of soybean by *M. phaseolina* (Edgar and Dhingra 1980). Certain herbicides influence the colonization process. Mengistu *et al.,* (2013) reported that while glyphosate inhibited *M. phaseolina* growth in vitro, disease severity in the field was reduced only when glyphosate was applied once during the early to mid-vegetative stages (V3-V6) in tilled conditions.

6. SELECTION OF CULTIVAR:

Due to the limited management options available for charcoal rot, research has primarily focused on developing genetic resistance. Efforts have centered on creating reliable screening methods and breeding resistant cultivars. Although only moderately resistant cultivars are currently available commercially, substantial progress has been made in understanding the genetic basis of resistance. In recent years, numerous studies under both controlled and field conditions have identified soybean cultivars with enhanced resistance to charcoal rot.

7. CHEMICAL:

Chemical control of *M. phaseolina* has met with limited success, primarily due to the absence of systemic fungicides capable of translocating effectively to the root zone, where the pathogen colonizes. Despite this limitation, chemical control remains a primary strategy for many farmers due to the broad-spectrum activity and rapid action of fungicides. Patidar *et al.,* (2023) evaluated an integrated approach of seed treatment followed by foliar spray where seed treatment was applied with penflufen 13.28% + trifloxystrobin 13.28% FS at 1 ml/kg of seed and this was followed by foliar applications of tebuconazole 25% EC at 0.1% concentration, at 45, 60, and 75 days after sowing. Their findings concluded that this integrated approach significantly reduced charcoal rot severity in soybean. Recently, Rajput *et al.,* (2025) reported that the combination of thiophanate methyl + pyraclostrobin at 2 ml/kg proved to be the most effective, offering robust suppression of disease symptoms even under epiphytotic field conditions.

8. INTEGRATED DISEASE MANAGEMENT (IDM):

Given the complex etiology and survival mechanisms of *M. phaseolina*, a single management approach is often insufficient. Its complex nature, with a wide host range and long survival as microsclerotia demands an integrated disease management approach where multiple practices work in synergy. While crop rotation alone offers limited success due to the pathogen's ability to infect many crops, its combination with conservation tillage enhances effectiveness by improving soil moisture retention and suppressing microsclerotia proliferation. This increased soil moisture directly ties into irrigation practices, which are particularly crucial during the reproductive stages of soybean when drought stress exacerbates charcoal rot severity. Thus, conservation tillage not only aids in crop rotation but also complements irrigation by maintaining favorable soil conditions. Furthermore, managing weeds becomes essential in this context, as weed competition intensifies plant stress and reduces the benefits gained from moisture conservation and irrigation; targeted herbicide application during early vegetative stages has been shown to reduce colonization by *M. phaseolina*. While chemical fungicides have limited root-targeting ability, their integration through seed treatments and timely foliar sprays can reduce disease severity, especially when used alongside moisture-conserving practices that lower pathogen pressure. In parallel, biological control agents such as *Trichoderma* and *Bacillus* species thrive better in stable, less-disturbed soils and can be more effective when tillage is minimized, and chemical use is balanced. These beneficial microbes not only suppress *M. phaseolina* but also enhance plant vigor, potentially reducing the overall dependency on chemical inputs. Finally, all these strategies are reinforced using moderately resistant cultivars, which provide a genetic backbone of defense, helping the crop tolerate low-to-moderate disease pressure when cultural, chemical, and biological measures are integrated effectively. Together, these components form a dynamic and interrelated system, where the strength of each method is enhanced through its interaction with the others.

CONCLUSION:

Charcoal rot, caused by *M. phaseolina*, poses a significant and persistent threat to soybean production, particularly in drought-prone and high-temperature regions. Its broad host range, ability to survive in soil as microsclerotia, and complex hemibiotrophic infection strategy make it exceptionally difficult to manage through single control measures. Although progress has been made in understanding the pathogen's biology, disease cycle, and symptomatology, effective and sustainable management still depends on the integration of multiple strategies. Agronomic practices such as crop rotation with conservation tillage, timely irrigation, and weed control can significantly reduce disease pressure by minimizing plant stress and disrupting pathogen proliferation. Complementary approaches, including the deployment of moderately resistant cultivars, judicious use of fungicides, and application of biological control agents, further enhance disease suppression when implemented in a site-specific and coordinated manner. Moving forward, a systems-based integrated disease management (IDM) approach supported by ongoing research, farmer education, and improved formulations offers the most viable path toward mitigating the impact of charcoal rot and securing soybean yield stability under changing environmental conditions.

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