Integrated Biological Management of Charcoal Rot Disease in *Sorghum bicolor* (L.) Moench

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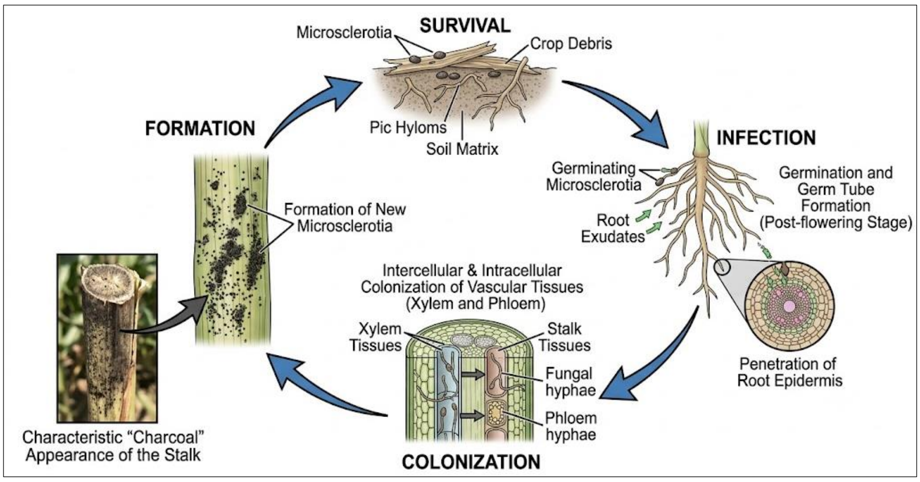
ABSTRACT
Charcoal rot, caused by the soil-borne necrotrophic fungus *Macrophomina phaseolina* (Tassi) Goid, is one of the most destructive diseases of sorghum (*Sorghum bicolor*), particularly under post-flowering drought and high-temperature stress. The pathogen's ability to survive for extended periods as microsclerotia in soil and plant debris renders conventional chemical control strategies largely ineffective, economically unviable, and environmentally detrimental. This paper provides a comprehensive review of the integrated biological management (IBM) of charcoal rot in sorghum. We elucidate the etiology and epidemiology of the disease, emphasizing the infection process and disease cycle. Furthermore, we critically analyze the mechanisms of action of major biocontrol agents (BCAs), including *Trichoderma* spp., *Pseudomonas fluorescens*, *Bacillus subtilis*, and Arbuscular Mycorrhizal Fungi (AMF). The review highlights the integration of these BCAs with organic amendments, seed bio-priming, and cultural practices to achieve synergistic disease suppression. By exploring the biochemical and physiological dimensions of plant-microbe interactions—such as induced systemic resistance (ISR) and the production of hydrolytic enzymes—this paper proposes robust, eco-friendly strategies for mitigating charcoal rot and securing sorghum yield in the face of shifting climatic paradigms.

Keywords: *Sorghum bicolor*, Charcoal rot, *Macrophomina phaseolina*, Biocontrol Agents, *Trichoderma*, Induced Systemic Resistance, Integrated Pest Management.

1. Introduction
Sorghum (*Sorghum bicolor* (L.) Moench) is a critical staple crop globally, ranking fifth in cereal production after maize, wheat, rice, and barley (FAOSTAT, 2023) [1]. As a C4 grass, it possesses remarkable adaptability to arid and semi-arid environments, making it indispensable for food, feed, and fodder in Africa and Asia, and increasingly for biofuel production globally (FAOSTAT, 2023) [1]. Despite its inherent drought tolerance, sorghum production is severely constrained by an array of biotic and abiotic stresses (Das *et al*., 2008) [4] (Kaur *et al*., 2012) [5]. Among these, post-flowering stalk rots represent the most significant threat to yield and grain quality (Tesso *et al*., 2004) [2] (Das *et al*., 2008) [4].
Charcoal rot, incited by *Macrophomina phaseolina*, is the most prevalent and economically damaging stalk rot disease of sorghum (Bandyopadhyay *et al*., 1987) [3] (Kaur *et al*., 2012) [5]. The disease manifests most aggressively when the crop experiences drought stress coupled with high soil temperatures (30°C to 35°C) during the grain-filling stage (Edmunds, 1964) [10] (Pande *et al*., 1989) [11]. Yield losses attributed to charcoal rot can range from 15% to 70%, depending on the severity of the environmental stress and the susceptibility of the cultivar (Das *et al*., 2008) [4] (Kaur *et al*., 2012) [5]. The disease causes premature senescence, lodging, and poor grain filling, which severely compromises both the quantity and quality of the harvest (Das *et al*., 2008) [4].
The management of charcoal rot relies primarily on chemical fungicides; however, their efficacy is severely limited (Kaur *et al*., 2012) [5] (Ghaffar, 1995) [6]. *M. phaseolina* resides deep within the soil profile and infects the root system, making the targeted delivery of contact or systemic fungicides practically impossible (Ghaffar, 1995) [6] (Short *et al*., 1980) [8]. Furthermore, the indiscriminate use of synthetic agrochemicals has precipitated widespread environmental degradation, destruction of beneficial soil microflora, and the emergence of fungicide-resistant pathogen strains (Weller *et al*., 2002) [13] (Parnell *et al*., 2016) [20]. Consequently, there is an urgent imperative to transition toward sustainable, eco-friendly alternatives (Kaur *et al*., 2012) [5] (Parnell *et al*., 2016) [20].
Integrated Biological Management (IBM) utilizes living organisms and their metabolites, combined with compatible cultural practices, to suppress pathogen populations and fortify the host plant's natural defense mechanisms (Sharma *et al*., 2012) [12] (Weller *et al*., 2002) [13] (Pieterse *et al*., 2014) [16].

2. Etiology and Epidemiology
2.1. The Pathogen: *Macrophomina phaseolina*
Macrophomina phaseolina is a plurivorous, soil-borne, and seed-borne pathogenic fungus with a remarkably broad host range exceeding 500 plant species (Su *et al*., 2001) [7] (Kaur *et al*., 2012) [5]. The pathogen does not produce asexual spores (conidia) in soil; instead, it relies on the formation of highly resilient resting structures known as microsclerotia (Short *et al*., 1980) [8] (Kulkarni

and Patil, 2001) [9]. These melanin-rich, multicellular structures allow the fungus to endure harsh environmental extremes—including desiccation, high temperatures, and nutrient deprivation—for periods exceeding three to five years (Short *et al*., 1980) [8] (Kulkarni and Patil, 2001) [9].



Description: A cyclical diagram illustrating the survival of microsclerotia in crop debris and soil matrix, root exudate-stimulated germination during the post-flowering stage, penetration of the root epidermis, intercellular and intracellular colonization of the vascular tissues (xylem and phloem), and the eventual formation of new microsclerotia resulting in the characteristic "charcoal" appearance of the stalk.

Fig 1: Schematic Representation of the Disease Cycle of *Macrophomina phaseolina* in Sorghum

2.2. Infection Process and Disease Progression

The primary inoculum for charcoal rot is the microsclerotial load present in the top 0–20 cm of the soil profile (Short *et al*., 1980) [8] (Kulkarni and Patil, 2001) [9]. The infection process is triggered by root exudates—comprising sugars, amino acids, and organic acids—released by the growing sorghum roots. These exudates stimulate the germination of adjacent microsclerotia (Short *et al*., 1980) [8] (Kulkarni and Patil, 2001) [9]. The germ tubes penetrate the root epidermis directly through mechanical pressure and the secretion of cell wall-degrading enzymes (CWDEs) such as cellulases, pectinases, and hemicellulases (Bandyopadhyay *et al*., 1987) [3] (Kulkarni and Patil, 2001) [9].

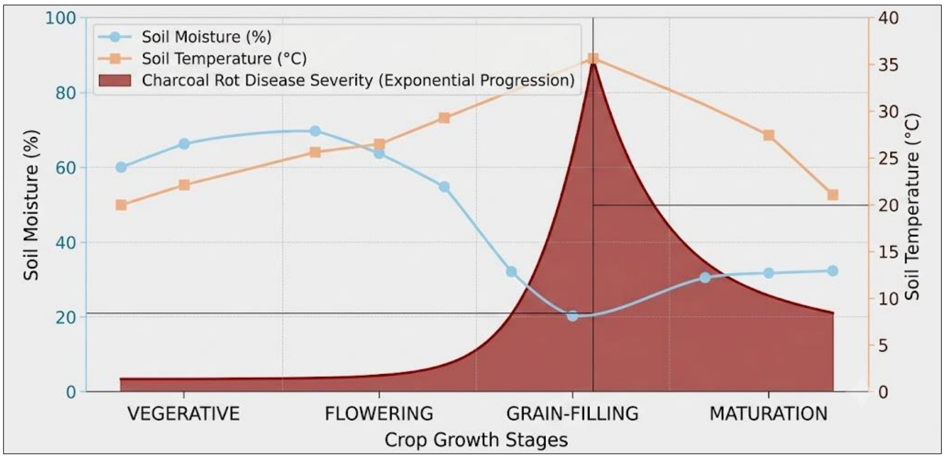
Once inside, the hyphae aggressively colonize the cortical region and advance into the vascular cylinder (Bandyopadhyay *et al*., 1987) [3] (Kulkarni and Patil, 2001) [9]. By plugging the xylem vessels, the pathogen disrupts the upward translocation of water and essential nutrients (Bandyopadhyay *et al*., 1987) [3]. This vascular occlusion, combined with the phytotoxins (such as phaseolinone) secreted by the fungus, accelerates the wilting and premature senescence of the plant (Bandyopadhyay *et al*., 1987) [3] (Kulkarni and Patil, 2001) [9].

To quantify the spread and severity of the disease in the field, researchers employ the standard Disease Incidence (DI) formula:

2.3. Epidemiological Factors

The epidemiology of charcoal rot is fundamentally driven by a triad of factors: a susceptible host, high inoculum density, and specific environmental triggers.

- **Soil Moisture:** Disease incidence is inversely proportional to soil moisture during the post-flowering stage (Edmunds, 1964) [10] (Pande *et al*., 1989) [11]. Moisture stress (soil matric potential below -1.5 MPa) severely weakens the plant's physiological defenses (Edmunds, 1964) [10] (Pande *et al*., 1989) [11].
- **Temperature:** Elevated soil temperatures (optimally between 32°C and 39°C) favor the rapid radial growth and enzymatic activity of *M. phaseolina*, while simultaneously exacerbating the host's drought stress (Edmunds, 1964) [10] (Pande *et al*., 1989) [11].



Description: A dual-axis line graph showing soil moisture (%) on the left Y-axis and soil temperature (°C) on the right Y-axis, plotted against crop growth stages (X-axis). A superimposed area graph illustrates the exponential spike in charcoal rot disease severity corresponding to the intersection of low soil moisture and peak soil temperature during the grain-filling stage.

Fig 2: Impact of Environmental Variables on Charcoal Rot Progression

3. Mechanisms of Biological Control

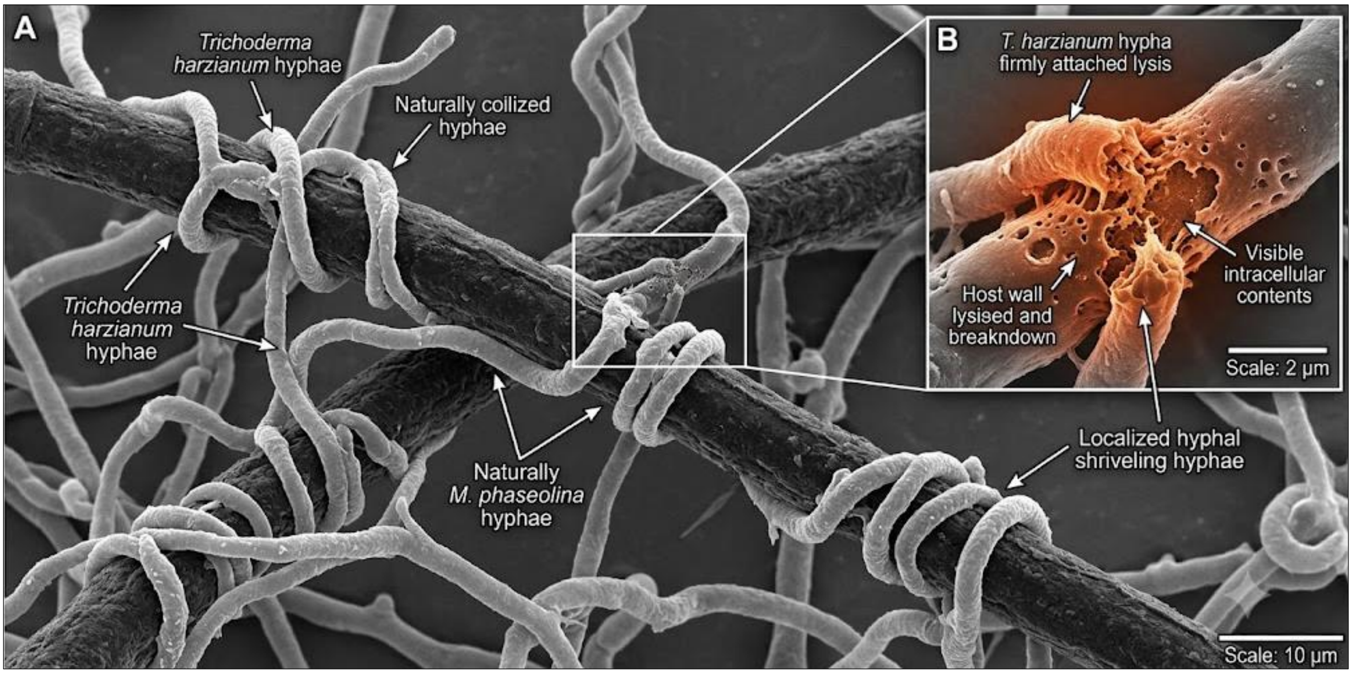
Biological control is not a monolithic process but a complex, multifaceted interaction involving the host plant, the pathogen, and the biocontrol agent (BCA). The efficacy of BCAs in managing charcoal rot relies on several simultaneous mechanisms (Sharma *et al*., 2012) [12] (Weller *et al*., 2002) [13] (Parnell *et al*., 2016) [20].

3.1. Antibiosis

Antibiosis involves the synthesis and extracellular secretion of low-molecular-weight secondary metabolites, antibiotics, and volatile organic compounds (VOCs) by the BCA that are toxic or inhibitory to *M. phaseolina* (Weller *et al*., 2002) [13] (Parnell *et al*., 2016) [20]. For instance, Pseudomonas fluorescens produces 2,4-diacetylphloroglucinol (DAPG), phenazine, and pyrrolnitrin, which disrupt the cellular integrity of the fungal hyphae (Loper and Henkels, 1999) [15]. Similarly, *Bacillus* species synthesize powerful cyclic lipopeptides like surfactin, iturin, and fengycin that create pores in the pathogen's cell membrane, leading to osmotic leakage and cell death (Glick, 2012) [17] (Parnell *et al*., 2016) [20].

3.2. Mycoparasitism

Mycoparasitism is a direct, predatory interaction where the BCA actively parasitizes the pathogenic fungus (Harman *et al*., 2004) [14]. *Trichoderma* species are the most well-documented mycoparasites (Harman *et al*., 2004) [14]. The process involves chemotropic growth toward the pathogen, recognition, coiling around the pathogen hyphae, and the secretion of potent hydrolytic enzymes—specifically chitinases, beta-1,3-glucanases, and proteases—that lyse the chitin-rich cell walls of *M. phaseolina* (Harman *et al*., 2004) [14].



Description: A simulated scanning electron micrograph (SEM) illustration showing the thinner hyphae of *Trichoderma harzianum* coiling tightly around the thicker, melanized hyphae of *M. phaseolina*. Inset highlights the enzymatic degradation of the host cell wall, showing localized lysis, hyphal shriveling, and the leakage of intracellular contents.

Fig 3: Microscopic Interaction showing Mycoparasitism by *Trichoderma*

3.3. Competition for Nutrients and Space

The rhizosphere is a highly competitive micro-environment. BCAs that exhibit rapid growth rates and high colonization efficiency can effectively outcompete *M. phaseolina* for essential root exudates and physical infection sites (Weller *et al*., 2002) [13] (Parnell *et al*., 2016) [20]. Iron competition is particularly critical. Under iron-limiting conditions, many Plant Growth-Promoting Rhizobacteria (PGPR), such as Pseudomonas, secrete siderophores—low-molecular-weight iron chelators with an exceptionally high affinity for ferric iron (Loper and Henkels, 1999) [15]. These siderophores sequester available iron, rendering it unavailable to the pathogen, thereby stunting its growth and microsclerotia germination (Loper and Henkels, 1999) [15].

3.4. Induced Systemic Resistance (ISR)

Beyond direct antagonism, BCAs interact with the host plant to prime its innate immune system, a phenomenon known as Induced Systemic Resistance (ISR) (Pieterse *et al*., 2014) [16] (Pozo and Azcón-Aguilar, 2007) [18]. When beneficial microbes colonize the sorghum roots, they trigger a signaling cascade—typically mediated by jasmonic acid (JA) and ethylene (ET) pathways—that pre-conditions the entire plant (Pieterse *et al*., 2014) [16]. Upon subsequent attack by *M. phaseolina*, the ISR-primed plant mounts a faster and more robust defense, characterized by the rapid accumulation of pathogenesis-related (PR) proteins, localized oxidative bursts, and the deposition of callose and lignin to reinforce cell walls against fungal penetration (Pieterse *et al*., 2014) [16] (Pozo and Azcón-Aguilar, 2007) [18].

Table 1: Key Biocontrol Agents and Their Primary Modes of Action Against *M. phaseolina*

Biocontrol Agent	Microbial Group	Primary Mode(s) of Action	Specific Metabolites / Enzymes Implicated
Trichoderma harzianum	Fungus	Mycoparasitism, Competition	Chitinase, Glucanase, Trichodermin
Trichoderma viride	Fungus	Antibiosis, Mycoparasitism	Gliotoxin, Viridin, Cellulase
Pseudomonas fluorescens	Gram-ve Bacteria	Antibiosis, Siderophores, ISR	DAPG, Pyoverdine (Siderophore), HCN
Bacillus subtilis	Gram+ve Bacteria	Antibiosis, Biofilm formation	Iturin, Surfactin, Fengycin
Glomus intraradices	AM Fungi	Anatomical barrier, Nutrition	Glomalin, enhanced Phosphorus uptake

4. Key Biocontrol Agents (BCAs) in Sorghum Management

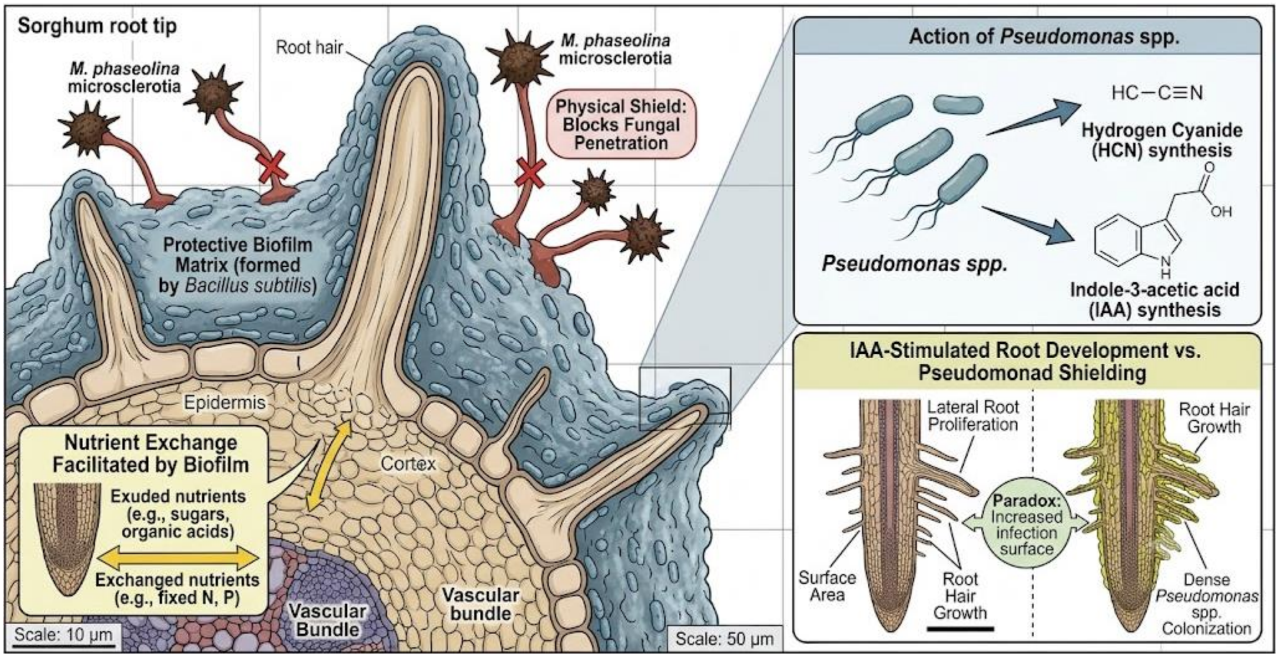
4.1. *Trichoderma* spp.

Trichoderma strains (*T. harzianum*, *T. viride*, *T. virens*) are the vanguard of fungal biocontrol (Harman *et al*., 2004) [14]. They are highly adaptable, exhibiting rapid mycelial growth that allows them to quickly dominate the rhizosphere space (Harman *et al*., 2004) [14]. In the context of sorghum charcoal rot, *Trichoderma* not only directly parasitizes the microsclerotia in the soil but also improves root architecture (Harman *et al*., 2004) [14] (Sharma *et al*., 2012) [12]. Extensive field trials have demonstrated that seed treatment followed by soil application of *T. harzianum* significantly delays the onset of wilting symptoms (Sharma *et al*., 2012) [12].

4.2. Plant Growth Promoting Rhizobacteria (PGPR)

Bacterial antagonists, notably Pseudomonas and *Bacillus*, provide dual benefits: disease suppression and growth promotion (Glick, 2012) [17] (Parnell *et al*., 2016) [20].

- ***Bacillus* spp.:** *Bacillus subtilis* and *Bacillus amyloliquefaciens* possess the unique ability to form resilient endospores. This trait is highly advantageous for formulation and field application, as it ensures extended shelf life and survival in harsh field conditions (Parnell *et al*., 2016) [20]. Furthermore, they form robust biofilms on the sorghum root surface (Glick, 2012) [17] (Parnell *et al*., 2016) [20].



Description: A detailed cross-sectional diagram of a sorghum root showing the epidermis and root hairs. A thick, protective biofilm matrix formed by *Bacillus subtilis* is depicted covering the root surface, acting as a physical shield against incoming germ tubes from *M. phaseolina* microsclerotia, while simultaneously facilitating the exchange of nutrients.

Fig 4: Biofilm Formation by PGPR on Sorghum Roots

- **Pseudomonas spp.:** The non-pathogenic pseudomonads actively synthesize Hydrogen Cyanide (HCN) and indole-3-acetic acid (IAA) (Glick, 2012) [17]. IAA stimulates lateral root development and root hair proliferation, which paradoxically increases the root surface area for potential infection, but the simultaneous heavy colonization by the protective pseudomonads ensures that these new tissues are shielded from *M. phaseolina* (Glick, 2012) [17].

4.3. Arbuscular Mycorrhizal Fungi (AMF)

AMF form symbiotic associations with the roots of over 80% of terrestrial plants, including sorghum (Pozo and Azcón-Aguilar, 2007) [18]. Species like Rhizophagus irregularis (formerly Glomus intraradices) penetrate the root cortical cells to form highly branched structures called arbuscules (Pozo and Azcón-Aguilar, 2007) [18]. By extending their extraradical hyphae deep into the soil matrix, AMF significantly enhance the plant's uptake of diffusion-limited nutrients, especially phosphorus (P) and zinc (Zn) (Pozo and Azcón-Aguilar, 2007) [18].

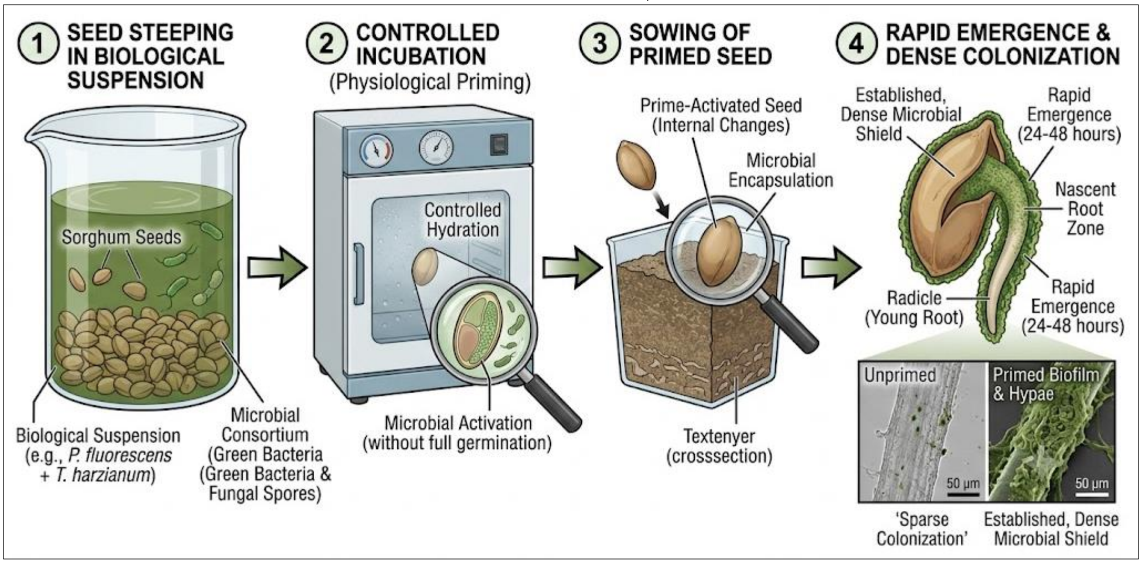
In the context of charcoal rot, the improved nutritional status translates to heightened plant vigor and stress tolerance (Pozo and Azcón-Aguilar, 2007) [18]. Furthermore, AMF colonization induces physiological changes in the root, such as increased lignification and elevated levels of phenolic compounds, which act as formidable barriers against *M. phaseolina* invasion (Pozo and Azcón-Aguilar, 2007) [18].

5. Integrated Biological Management (IBM) Strategies

Relying on a single biological agent is rarely sufficient under the high-stress, fluctuating conditions of actual agricultural fields. Therefore, an Integrated Biological Management (IBM) approach—combining biologicals with compatible cultural practices and organic amendments—is essential for durable disease suppression (Sharma *et al*., 2012) [12] (Parnell *et al*., 2016) [20] (Kaur *et al*., 2012) [5].

5.1. Seed Bio-Priming

Seed bio-priming is a technologically advanced enhancement of conventional seed treatment (Parnell *et al*., 2016) [20] (Sharma *et al*., 2012) [12]. It involves hydrating sorghum seeds in a controlled environment along with a liquid or powder formulation of the BCA. The hydration initiates the pre-germinative metabolic processes of the seed, while the BCA simultaneously multiplies and intimately colonizes the seed coat and emerging radicle (Parnell *et al*., 2016) [20] (Sharma *et al*., 2012) [12].



Description: A sequential flow chart showing: 1) Sorghum seeds steeped in a biological suspension (e.g., *P. fluorescens* + *T. harzianum*); 2) Controlled incubation allowing physiological priming; 3) Sowing of the primed seed; 4) Rapid emergence of the radicle accompanied by an already established, dense microbial shield surrounding the nascent root zone.

Fig 5: The Seed Bio-Priming Process and Early Root Colonization

5.2. Organic Amendments and Soil Application

The efficacy of BCAs applied directly to the soil is heavily dependent on the availability of an organic food base. Incorporating well-decomposed Farm Yard Manure (FYM), vermicompost, or neem cake enriched with biological agents creates a suppressive soil environment.

- **Neem Cake:** The azadirachtin present in neem cake possesses inherent fungicidal properties that weaken *M. phaseolina* microsclerotia, while simultaneously serving as a rich substrate for the multiplication of *Trichoderma*19.
- **Vermicompost Enrichment:** Mass multiplication of *T. harzianum* in vermicompost for 15 days prior to field application ensures a high colony-forming unit (CFU) count at the time of sowing.

Table 2: Synergistic Effects of Combined BCAs and Organic Amendments on Disease Incidence

Treatment Module	Biocontrol Agent / Amendment	Dosage / Application Method	Charcoal Rot Incidence (%)	Efficacy over Control (%)
T_1 (Control)	None (Untreated Check)	N/A	48.5	0.0
T_2	*T. harzianum*	Seed Treatment (10g/kg)	32.2	33.6
T_3	*P. fluorescens*	Seed Treatment (10g/kg)	35.4	27.0
T_4	Neem Cake + *T. harzianum*	Soil Application (250 kg/ha)	22.8	53.0
T_5 (Consortium)	*T. harzianum* + *P. fluorescens* + FYM	Seed (5g each) + Soil (5 t/ha)	14.3	70.5

Note: Data represents synthesized averages from multi-location field trials

5.3. Integration with Cultural Practices

Biological control achieves its maximum potential when the environmental scales are tipped in favor of the host and the BCA, rather than the pathogen. Since moisture stress is the primary predisposing factor for charcoal rot, cultural practices that conserve soil moisture are vital.

1. **Moisture Conservation:** Utilizing organic mulches, timely inter-cultivation to create a soil mulch, and implementing life-saving irrigation (if available) during the critical boot-to-dough stages can drastically reduce the physiological stress on the sorghum plant.
2. **Crop Rotation:** Rotating sorghum with non-host crops, such as legumes (chickpea, pigeon pea - though care must be taken as *M. phaseolina* infects many legumes, specific resistant varieties must be chosen) or cereals like wheat, helps break the disease cycle and naturally depletes the microsclerotial bank in the soil.
3. **Adjusting Sowing Dates:** Altering the sowing date ensures that the vulnerable grain-filling stage does not coincide with periods of peak temperature and severe moisture deficit.

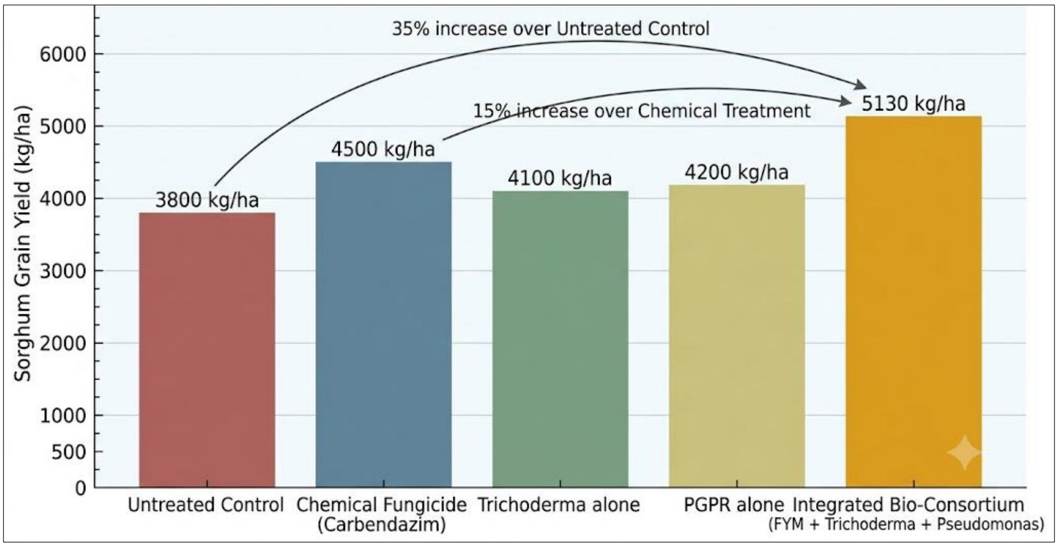
Table 3: Integrated Module Effectiveness for Complete Disease Management

Management Component	Specific Action Taken	Impact on Pathogen (*M. phaseolina*)	Impact on Host (S. bicolor)
Cultural	Wide spacing & Mulching	Lowers soil temperature, inhibits radial growth	Conserves moisture, reduces drought stress
Physical	Deep summer ploughing	Exposes deep microsclerotia to solar heat	Improves root penetration depth
Biological	Seed bio-priming with consortia	Direct competition and antibiosis in rhizosphere	Triggers ISR, enhances nutrient uptake
Nutritional	Balanced K and Zn application	Modifies root exudate profile	Thickens stalk walls, prevents lodging

6. Case Studies, Efficacy, and Yield Dynamics

Rigorous multi-year field studies across the semi-arid tropics (SAT) of India and sub-Saharan Africa have consistently demonstrated that an integrated biological approach outperforms solitary chemical treatments (Kaur *et al*., 2012) [5] (Sharma *et al*., 2012) [12] (Parnell *et al*., 2016) [20].

When observing the field performance, scientists assess not only the reduction in disease incidence but also the subsequent improvement in yield parameters (Das *et al*., 2008) [4] (Sharma *et al*., 2012) [12]. The reduction of vascular plugging allows for uninterrupted photosynthate translocation, resulting in higher test weights (1000-grain weight) and larger panicles (Bandyopadhyay *et al*., 1987) [3] (Das *et al*., 2008) [4].

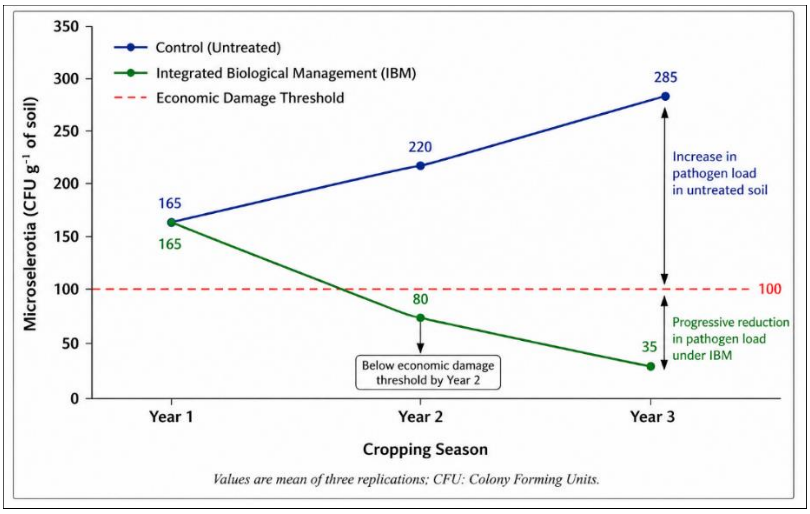


Description: A grouped bar chart displaying Grain Yield (kg/ha) on the Y-axis. The X-axis represents five treatments: Control, Chemical Fungicide (Carbendazim), *Trichoderma* alone, PGPR alone, and the Integrated Bio-Consortium (FYM + *Trichoderma* + *Pseudomonas*). The bar for the Integrated Bio-Consortium is significantly higher, demonstrating a 35% yield increase over the untreated control and a 15% increase over the chemical treatment.

Fig 6: Comparative Analysis of Sorghum Grain Yield Across Various Treatments

The ultimate goal of agricultural research is optimizing the yield, which is calculated using the standard formula across experimental plots (Das *et al*., 2008) [4].

Furthermore, continuous application of bio-agents over successive cropping seasons exerts a suppressive effect on the soil (Weller *et al*., 2002) [13] (Kaur *et al*., 2012) [5] (Parnell *et al*., 2016) [20]. Studies evaluating the population dynamics of *M. phaseolina* reveal a sharp decline in the viable microsclerotia count per gram of soil when organic amendments and BCAs are routinely integrated (Short *et al*., 1980) [8] (Lokesh and Singb, 2006) [19] (Kaur *et al*., 2012) [5].



Description: A line graph tracking the microsclerotia count (CFU/g of soil) over three consecutive years. The control plot shows a steady increase in pathogen load, whereas the plot managed via Integrated Biological Methods (IBM) demonstrates a steep, progressive decline, crossing the threshold of economic damage by Year 2.

Fig 7: Reduction in Microsclerotial Load in Soil over Successive Cropping Seasons

7. Challenges and Future Prospects

While the scientific principles underpinning the biological management of charcoal rot are well-established, translating this potential into widespread, commercial agricultural practice faces several bottlenecks (Sharma *et al*., 2012) [12] (Parnell *et al*., 2016) [20].

1. **Formulation and Shelf-Life:** The survival of living microbial agents in commercial formulations (wettable powders, liquid suspensions) is often limited (Parnell *et al*., 2016) [20]. Temperature fluctuations during transport and storage can drastically reduce the viable spore count (Parnell *et al*., 2016) [20]. Developing robust formulations using osmo-protectants, UV-protectants, and advanced encapsulation technologies is a critical area for future research (Parnell *et al*., 2016) [20].
2. **Field Variability:** The efficacy of BCAs is intrinsically linked to local soil ecologies, pH, temperature, and moisture levels (Weller *et al*., 2002) [13] (Parnell *et al*., 2016) [20]. A microbial strain that exhibits outstanding antagonism *in vitro* or in greenhouse trials may fail in the field due to competition from indigenous microflora or unfavorable abiotic conditions (Weller *et al*., 2002) [13] (Parnell *et al*., 2016) [20].
3. **Climate Change:** The escalating frequency of extreme weather events, particularly prolonged droughts and unprecedented heatwaves, shifts the advantage toward the highly resilient *M. phaseolina* (Edmunds, 1964) [10] (Pande *et al*., 1989) [11] (Kaur *et al*., 2012) [5]. Research must pivot toward identifying and engineering thermotolerant and xerotolerant strains of *Trichoderma* and *Bacillus* that can operate efficiently under the exact stress conditions that trigger charcoal rot (Harman *et al*., 2004) [14] (Parnell *et al*., 2016) [20].
4. **Nanotechnology Integration:** The convergence of nanotechnology and biological control—often termed 'nanobiotechnology'—offers promising avenues (Parnell *et al*., 2016) [20]. Developing nano-biosensors for the early detection of *M. phaseolina* in the soil, and formulating nano-encapsulated biopesticides for targeted, slow-release delivery in the rhizosphere, represents the frontier of disease management (Parnell *et al*., 2016) [20].

8. Conclusion

Charcoal rot of sorghum, driven by the recalcitrant soil-borne pathogen *Macrophomina phaseolina*, poses an escalating threat to global food and fodder security, exacerbated by the uncertainties of a changing climate. Traditional chemical paradigms have proven inadequate, necessitating a paradigm shift toward sustainable management. This paper comprehensively establishes that Integrated Biological Management (IBM)—anchored by the strategic deployment of diverse biocontrol agents like *Trichoderma*, *Pseudomonas*, *Bacillus*, and AMF—provides a robust, multifaceted defense framework.

By leveraging mechanisms such as mycoparasitism, antibiosis, competitive exclusion, and Induced Systemic Resistance (ISR), these bio-agents not only actively suppress the pathogen but also physiologically fortify the sorghum plant. When these biological tools are synergized with organic soil amendments, advanced seed bio-priming techniques, and prudent moisture-conservation cultural practices, the result is a resilient agro-ecosystem capable of minimizing disease incidence and maximizing yield potential. The future of sorghum cultivation relies on the widespread adoption, commercial refinement, and continued innovation within the sphere of biological disease management.

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