



REVIEW ARTICLE

Integrated approach for managing groundnut stem rot caused by *Sclerotium rolfsii* Sacc.

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Abstract

Groundnut (*Arachis hypogaea* L.), often referred to as the King of oil seeds, is a vital oil seed crop cultivated globally. However, its productivity is hampered by numerous abiotic and biotic stresses, with biotic stresses predominantly due to fungal and bacterial diseases. Among these, soil-borne fungal pathogens cause significant yield losses. Specifically, stem rot disease, caused by *Sclerotium rolfsii* Sacc., poses a substantial threat, leading to yield losses of up to 80%. This pathogen forms sclerotia, a resilient resting structure that can survive in the soil for many years and germinate under favorable environmental conditions. The persistence of sclerotia and the pathogen's broad host range make managing this disease particularly challenging through a single method. Effective management of stem rot disease necessitates an integrated disease management (IDM) approach, which combines cultural, chemical and biological strategies. Cultural practices such as crop rotation, deep ploughing and moisture regulation help to reduce inoculum levels in the soil. Chemical control involves the use of fungicides to reduce the pathogen load in the soil and protect the plants during vulnerable growth stages. Biological control employs antagonistic microorganisms that can inhibit the growth and activity of *S. rolfsii*. By integrating these diverse strategies, it is possible to effectively manage stem rot disease in groundnut, thereby enhancing productivity and sustainability in groundnut cultivation.

Keywords

groundnut; integrated disease management; sclerotia; *Sclerotium rolfsii*; stem rot

Introduction

Groundnut (*A. hypogaea* L.) is one of the essential oilseed crops grown in India. It is also called the 'King of oil seeds' because of its massive uses and it has different names like earth nut, groundnut, goober pea, pig nut, pygmy nut and monkey nut (1). It is the world's third most important oilseed crop and thirteenth most important food crop. Groundnut contains 45-50% oil, 27-33% easily digestible protein, 18% carbohydrates and minerals like Ca, Mg and Fe, as well as vitamins B1, B2 and niacin (2). It is the world's fourth-most significant source of edible seeds and the third-most significant source of vegetable protein (3). Groundnut oil is rich in fatty acids such as oleic (18:1), linoleic (18:2) and linolenic acid (18:3) (4). The groundnut root secretes flavonoids that promote the growth of nitrogen-fixing bacteria, forming root nodules that help the plant in uptake of nitrogen and enhance soil fertility. In India, it is grown under rainfed as well as irrigated conditions. Groundnut crop survives best in tropical and warm temperate climates and requires 20°C to 30°C temperature and 50-75 cm rainfall (5).

Groundnut production covers 327 lakh ha worldwide, yielding 539 lakh tonnes and productivity of 1648 kg/ha. About 80% of the overall groundnut area and production in India is grown in the states of Gujarat, Andhra Pradesh, Telangana, Tamil Nadu, Karnataka, Rajasthan and Maharashtra (6). It covers 4.09 lakh ha in Tamil Nadu, producing 10.23 lakh tonnes and has a 2502 kg/ha productivity. The pod yield of the groundnut is highly affected by several biotic factors including foliar and soilborne diseases. Among the foliar diseases, late leaf spot and rust cause a yield loss of about 50 to 70% (7). The main limiting pathogens among soil-borne diseases are *Aspergillus niger* Tiegh, which causes collar rot/crown rot/seedling blight; *S. rolfii* Sacc., causing stem rot/Sclerotium wilt and *Rhizoctonia bataticola* Taub., causing root rot (8). Among the soil-borne diseases, stem rot disease in groundnut significantly impacts crop yield, leading to substantial losses.

Distribution, severity and yield losses

Stem rot disease, caused by the fungus *S. rolfii*, poses a significant threat to groundnut cultivation globally, especially in Asia, Africa, America and Australia, where warm temperatures, high humidity and light soils provide ideal conditions for its survival and spread (Fig. 1). For groundnut produced under irrigation, stem rot disease has a significant economic impact, especially during the post-rainy (rabi) season. This disease caused groundnut production to lose between 10 to 20 million USD in the first half of the 20th century. In New Mexico, yield losses of up to 75 to 80% have been reported. The most significant soilborne disease affecting peanut in China is stem rot, which causes yield losses of about 50% (9). In eastern Ethiopia, where the crop is widely cultivated, the groundnut root rot complex has emerged as a significant barrier to groundnut production (10). In fields in North Carolina, incidence rates of groundnut stem rot ranged from 5% to 32%, indicating a clustered distribution pattern (11). Along with other diseases, including leaf spots and rosette, stem rot is one of the devastating disease that cause substantial crop losses in West Africa (12). It was observed that prevalence of stem and pod rot with 27% or more yield loss in all groundnut growing states of India, particularly severe in Maharashtra, the Saurashtra region of Gujarat and the Raichur area of Karnataka (13). Stem rot disease causes pod losses of 10-25%, but in the case of severe infections,

yield losses can reach up to 80%. According to some researches stem rot, rust and leaf spot, either separately or in combination, can cause a 15-70% reduction in groundnut production (14). Significant yield losses of more than 80% have been reported in recent years due to *S. rolfii*-induced stem rot disease (1, 15).

Host range

S. rolfii, the causal organism of stem rot disease, exhibits a remarkably wide host range, infecting over 500 species across 100 families. Among its susceptible hosts are groundnut, soybean, sunflower, tomato, pepper, rose, chrysanthemum, chickpea, cowpea, maize, sorghum, nutsedge and morning glory (16-19). This broad spectrum of susceptible plants underscores the versatility and adaptability of *S. rolfii* as a pathogen. Its ability to infect a diverse array of crops, vegetables, ornamental plants, legumes, cereals and herbaceous species poses significant challenges for disease management strategies. Due to its wide host range, *S. rolfii* requires integrated disease management to reduce its impact on agriculture and protect diverse plant ecosystems (Table 1).

Symptomology

S. rolfii attacks all stages of the crop and produces symptoms like seed rot, seedling blight, stem rot and pod rot, the most prevalent of which is stem rot. The symptoms are usually most prominently visible at 45 DAS. Though *S. rolfii* can infect any part of the plant, including roots, petioles, flowers and leaves, it mostly targets the stem of the host. The first sign of stem rot includes yellowing of the leaves and rotting of the branches close to the base of the plant. The fungus produces an abundance of white masses of mycelium around the infected tissue and on the surface soil. On the mycelium, sclerotia of comparatively uniform size are formed. When young, these structures are spherical and white, but as they grow, they turn dark brown or black. Sclerotia at maturity resembles mustard seeds ranging from 4.8 mg to 14.0 mg (20). The fungus rarely produces basidiospores around the edges of the infected tissue (21). Seedlings are more susceptible and they die quickly after infection. This disease also causes indirect losses, such as a decrease in oil content and dry weight. When a plant reaches an advanced stage of infection, its kernels shrivel and become tiny.

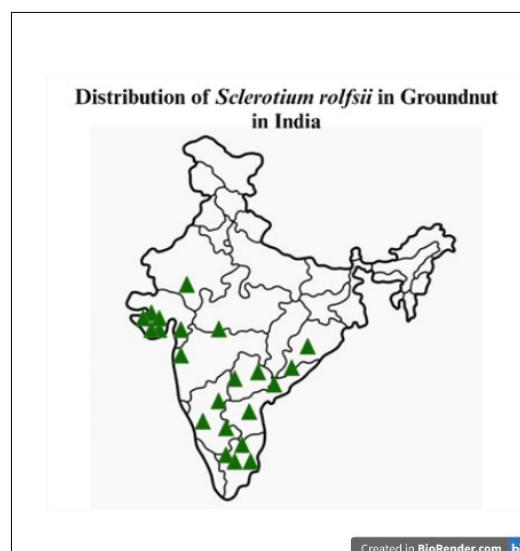


Fig. 1. Distribution of *S. rolfii* worldwide and in India.

Table 1. Host range of *S. rolfsii*

S. No	Name of the host	Disease caused by the pathogen	Yield loss	Reference
1	Tomato	Collar rot, foot and root rot	20% to 50%	(89)
2	Groundnut	Stem rot	80%	(90)
3	Sunflower	Damping-off and charcoal-rot	10% to 50%	(91)
4	Betel vine	Sclerotial wilt	60%	(92)
5	Lentil	Sclerotium stem rot or southern stem rot	20% to 50%	(93)
6	Chickpea	Collar rot	30% to 50%	(58,94)
7	Jute	Soft rot	15% to 40%	(95)
8	Crossandra	Collar rot	40% to 50%	(96)
9	Elephant foot yam	Collar rot	20% to 100%	(97)
10	Finger millet	Footrot	>50%	(98)
11	Cowpea	Stem rot	53.4%	(99)
12	Pepper	Southern blight	15% to 30%	(32)
13	Mung bean	Southern blight	20% to 40%	(100)
14	Carrot	Southern blight	20%	(101)
15	Chili	Southern blight	10% to 60%	(62, 102)
16	Bell pepper	Southern blight	50%	(103)

Pathogen

S. rolfsii survives well at or near the soil line and affects the plant. It can take 2 to 10 days for the pathogen to develop a mass of mycelium on the plant surface before it enters the host tissue. The pathogen develops an enzyme that breaks the outer cell of the host and enters the host tissue (22). After the decomposition of tissue, further mycelial formation and sclerotial production takes place. The latter two processes depend on environmental conditions. Sclerotia germinates either through hyphal germination or eruptive germination. In hyphal germination, individual hyphal strands are grown on the sclerotial surface. In eruptive germination, clusters of mycelia erupt through the surface of the sclerotia (23). Three layers constitute mature sclerotia; the cortical layer, the medullary layer in the center and the outer rind (24). It is very rare to see the teleomorph of *S. rolfsii* (*Athelia rolfsii*) on the host or in the culture plate. *A. rolfsii* forms basidia on an exposed hymenium, which produces 4 haploid basidiospores. The appressed hymenium usually develops in small, tiny and uneven patches. Basidiospores are hyaline and measure 1.0 to 5 µm × 5 to 12 µm, while clavate basidia measure 4 to 6 µm × 7 to 14 µm.

Epidemiology

Epidemiology of *S. rolfsii* is influenced by specific environmental conditions. It thrives in soil with a moderate moisture content, approximately 70% of field capacity and temperatures from 25° C to 30°C (25). Hyphal growth can occur within a wide temperature range, from 8°C to 40°C, while sclerotial formation is favoured at temperatures between 27°C and 35°C. Although *S. rolfsii* prefers acidic soils, it can tolerate various pH levels, with mycelial growth occurring within a pH range of 3 to 5 and sclerotial germination within a pH range of 2 to 5. Germination is restricted at pH levels above 7. Some researchers investigated the influence of varied soil moisture levels on *S. rolfsii* survival and discovered that the fungus thrived at lower moisture levels (26). The survival rate was highest between 20% and 40% soil moisture. It was discovered that the fungus had very little saprophytic activity at soil moisture levels of 60 and 70%, while more saprophytic activity was seen at moisture levels of 40%. According to (27) the incidence of root rot disease was higher in sandy soils than in clay soils and it was more common in crops grown during the Kharif season than the Rabi season. Sclerotia, the resting structures of the fungus, exhibit resilience to cold

temperatures, surviving down to -10°C, while the mycelium is killed at 0°C. Optimal growth of the fungus requires high moisture levels, with sclerotia germinating best at a relative humidity range of 25% to 35% (28). Below the saturation point, relative humidity prevents sclerotia from germinating. Understanding these environmental factors is essential for developing effective strategies to manage stem rot disease caused by *S. rolfsii*.

Survival and spread

Depending on the conditions of the environment, sclerotia of the pathogen could live in soil for about 2 months to 7 years. Sclerotia has a lower probability of surviving cycles of freezing and thawing as well as cycles of dry and wet conditions. It was found that 94% of sclerotia survived in a soil depth of 10 cm, whereas it was just 11% on the soil's surface (29). Greater survivability at the soil depth of 10 cm may be explained by the relative lack of soil drying. Sclerotia survival may also be impacted by the pH and texture of the soil. Lower survival in clay loam was described by (30) as a larger ability to retain water, which influenced soil drying and wetting and increased microbial activity.

S. rolfsii spreads through various mechanisms, each contributing to its persistence and dissemination. Firstly, its hard survival structures, sclerotia, survive in soil for years, serving as reservoirs of inoculum. Secondly, infected plant debris, such as crop residues and roots, acts as sources of inoculum for subsequent plantings. Thirdly, water facilitates sclerotia movement via irrigation, rain splash, or flooding, particularly in poorly drained fields. Fourthly, contaminated equipment can transport sclerotia to new areas, exacerbating disease spread. Additionally, sclerotia may adhere to seeds or reside within seed lots, potentially introducing the pathogen during planting. Furthermore, soil-dwelling organisms like ants or nematodes aid in short-distance dispersal, contributing to localized disease transmission. These diverse modes of spread underscore the challenges of managing *S. rolfsii* effectively (31). Addressing multiple vectors of transmission through integrated disease management strategies is essential for controlling stem rot and minimizing its impact on agricultural productivity. By understanding and mitigating these spread mechanisms, growers can adopt proactive measures to limit disease spread and protect crop yields sustainably.

Disease cycle

During transportation, sclerotia in plant debris or soil are used for long-distance movement (32) (Fig. 2). *S. rolfsii* secretes cellulase and oxalic acid, which break down tissue, when infected. Oxalic acid plays a critical role in the pathogenic process by interacting with calcium and removing it from its interaction with pectic chemicals in plant cell walls. This action reduces the pH of the cell walls, promoting the activity of enzymes such as endo polygalacturonase and cellulase, which degrade the plant cell wall. The pathogen produces larger amounts of oxalic acid through extensive mycelial development on plant tissues, aiding hyphal penetration into the tissue. Tissue maceration occurs as a result of the breakdown of cell walls by oxalic acid and tissue-degrading enzymes. This macerated tissue serves as a nutrient source for the pathogen to absorb. Symptoms such as wilting, yellowing and necrosis manifest due to tissue maceration, hindering the transport of water and nutrients to plant tissues. By disrupting normal physiological processes, *S. rolfsii* impairs the overall health and vitality of the infected plant, leading to further disease progression and potential crop loss. Understanding the mechanisms by which *S. rolfsii* causes tissue degradation is essential for developing effective strategies to manage stem rot disease and minimize its impact on agricultural productivity (33).

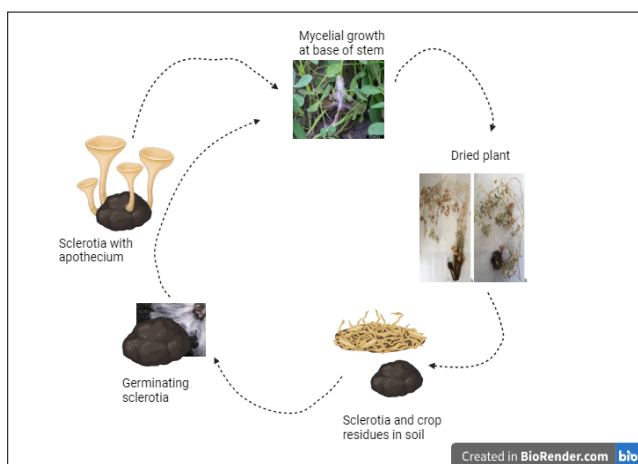


Fig. 2. Disease cycle of *S. rolfsii*.

Management of stem rot disease

S. rolfsii presents a formidable challenge among soil-borne pathogens due to its persistent sclerotia, rapid growth and broad host range. Historically, fumigation and soil-applied fungicides were employed to suppress its spread, particularly in the mid-1900s. Chemical control techniques are ineffective in preventing plant diseases and long-term application of chemical fungicides results in pollution of the environment, pathogen resistance and residual toxicity. Instead, soil-borne plant infections could be managed by using bio-control agents, which are safer for the environment and more affordable than chemical control techniques (34). Today, integrated management strategies are favored, incorporating cultural practices, chemical treatments, biocontrol agents and the use of resistant cultivars. By combining multiple approaches, growers aim to effectively manage *S. rolfsii* while minimizing environmental impacts and ensuring sustainable crop production. This holistic approach acknowledges the complex nature of the pathogen and seeks to address its control through diverse and complementary methods.

Cultural methods

Cultural management practices for *S. rolfsii* involve removing crop debris, aerification, adding lime and deep ploughing. These methods aim to disrupt the pathogen's lifecycle and reduce its inoculum in the soil. Removing crop debris removes potential sources of infection, while aerification enhances soil drainage and oxygenation, inhibiting fungal growth. Lime addition helps raise soil pH, making it less favorable for *S. rolfsii*, while deep ploughing buries sclerotia deeper in the soil, reducing their viability (23, 35). Integrating these cultural practices into agricultural systems can contribute to effectively manage stem rot disease caused by *S. rolfsii*.

Sanitary measures

Effective control of foliar pests and diseases plays a crucial role in managing stem rot caused by *S. rolfsii*. By reducing the fall of dried leaves, which contributes to the buildup of litter in the pegging zone and crown area, the availability of a food source required by the fungus is diminished. Additionally, employing pathogen-free seeds as planting materials helps prevent the introduction of *S. rolfsii* into new areas. Prompt removal and destruction of infected plants are essential to prevent them from acting as sources of inoculum. In nurseries, *S. rolfsii* infection can be eradicated through soil replacement and removal. However, care must be taken during soil movement to avoid inadvertently spreading the pathogen to other areas. Furthermore, used potting media in nurseries or greenhouses should not be reused for subsequent planting to prevent the recurrence of *S. rolfsii* infection. These proactive measures, combined with integrated disease management strategies, are crucial for effectively controlling stem rot disease and minimizing its impact on groundnut cultivation. By implementing these practices, growers can reduce the spread of *S. rolfsii* and safeguard crop yields sustainably (36).

Tillage

The primary disease-causing agent of *S. rolfsii* is its overwintering structure, the sclerotia. These sclerotia can be found either freely in the soil or in association with plant debris. Those present on the soil surface remain viable and may germinate in response to alcohol and other volatiles released during the decomposition of plant materials. Therefore, tillage practices that disrupt sclerotia's ability to survive at the soil surface can effectively control *S. rolfsii*. Soil stirring before sowing or after harvesting is commonly recommended to facilitate sclerotia drying and reduce their viability. By burying sclerotia deeper into the soil profile, tillage practices help prevent their germination and subsequent infection of susceptible crops. Incorporating such cultural practices into agricultural routines can contribute significantly in managing stem rot disease caused by *S. rolfsii* (37).

Crop rotation

Considering the wide host range of *S. rolfsii* and the dormant structure of sclerotia, crop rotation is recommended as a major management strategy for the management of groundnut stem rot. Stem rot incidence and severity can be reduced by rotating the groundnut with non-susceptible crops like corn, cotton and wheat (38). Crop rotation of groundnut with cotton decreased the sclerotial count, reducing the incidence of stem rot. This kind of crop rotation was earlier followed in regions with vertisol, but it is

now followed in all the cotton-growing regions where there is severe infestation of stem rot. Groundnut can also be rotated with wheat and corn to prevent stem rot. This is a widely used technique in many regions of North India (39, 40). Stem rot can be prevented by rotating crops with onion and garlic (41, 42). Castor can also be used in crop rotation to prevent stem rot disease (38). Crop break for 2 to 3 years with non-susceptible crops reduces the disease incidence, but the longer crop break of 4 to 5 years is recommended for the most effective control of stem rot.

Physical methods

These methods manipulate environmental factors or crop surroundings to disrupt disease cycles, reduce pathogen populations, or enhance plant resilience. Integrating physical methods with other control measures offers a comprehensive approach to combat stem rot and safeguard groundnut yields sustainably. By combining physical interventions such as soil solarization with cultural, chemical and biological control measures, growers can effectively manage *S. rolfii* while minimizing reliance on synthetic chemicals and promoting environmentally friendly practices. This integrated approach maximizes the effectiveness and sustainability of disease management strategies in groundnut cultivation (43).

Organic amendments

In *in vitro* studies, the highest suppression (80%) on the pathogen's mycelial growth (1.79 cm) was seen with a 10% concentration of Mahua oil cake (44). Complete inhibition of *S. rolfii* mycelial growth was achieved by well-decomposed FYM and groundnut cake (45). While gingelly cake (3%) and neem cake (98%) suppressed sclerotia to the greatest degree, neem cake was shown to be the most effective. At all the concentrations evaluated, vermicompost, cotton seed cake, castor cake and farmyard manure completely suppressed the growth of mycelium. Furthermore, the mean inhibition of mycelial growth for goat dung and karankaj cake was found to be 78% and 57%, respectively. However, at concentrations of 5, 7.5 and 10%, goat dung and karankaj cake completely inhibited the radial growth of mycelium (46). Mahua oil cake at a concentration of 20% demonstrated the highest mycelial inhibition (84%) under *in vitro* conditions. It also completely inhibited sclerotial germination at 18 and 24 h and 84% inhibition at 30 min (47).

Soil solarization

Aerated steam treatment of beds or bulk soils may be possible in some nurseries or greenhouses. All surfaces need to be treated between 160 and 180°F. The treated soil should be stored away from the area that is contaminated. The soil surface needs to be covered with clear plastic sheeting that is between 0.025 and 0.4 mm thick for a period of 4 to 8 weeks, depending on the season. *S. rolfii* during solarization was documented by few researchers to create a dynamic model that would convey the pathogens thermal inactivation (48). The population of *S. rolfii* was reduced from 47% to 100% after 20 days of exposure. For the soil pathogen *S. rolfii*, soil solarization works best in the hot summer months when higher soil temperatures kill a lot of significant soilborne bacterial and fungal plant pathogens. Soil solarization is highly effective for treating soil before, during and after planting when combined with a plastic film layer to prevent soil-borne pathogens. Solarization works better with organic amendments, including fertilizers, compost, green manures and plant leftovers; when combined with these amendments, solarization has a major anti-pathogen effect.

Resistant varieties

Among the wild species, *Arachis appressipila* under the section Procumbentes and *A. pusilla* under the section Hetranthae are highly resistant to stem rot with pod infections of 16% and 19%, respectively (49). Of the 33 groundnut varieties tested, 20 varieties are moderately resistant to stem rot with disease incidence of 20 to 29% (KRG-1, R-2001-2, R-2001-3, Kadiri-9, TG-51, TDG-51, DSG-1, ICGV-00351, TG-37A, Dh-101, Dh-216, G2-52, Dharani, Ch-2, TAG-24, TG-51, GPBD-4, GPBD-5 and J-11) (50) (Table 2). A new variety, ALR 3 was released as it had a resistant nature to rust and late leaf spot diseases of groundnut (51). A new high-yielding spanish bunch variety recorded the stem rot incidence of ALG-06-320 recorded the stem rot incidence of 21% (52). Evaluation of onion genotypes against soil-borne pathogen *Fusarium oxysporum f.sp.cepae* was carried out to find out the resistant genotype (53). Genetic diversity in a crop species is explained by the heritable variation registered in minicore germplasm collections within a population of the same species. This tool has presented the crop breeders to evolve new and improved cultures bearing desirable traits through infusing effective selection for use as donors or as a new variety. Genetic variability and heritability studies in groundnut germplasm were conducted at the Agricultural College and Research Institute, Killikulam (6).

Table 2. Resistant varieties for stem rot in groundnut

S. No	Name of the resistant variety	Major growing areas	Reference
1	ICGV 86699	Gujarat, Andhra Pradesh, Telangana, Karnataka, Tamil Nadu and Maharashtra.	(104)
2	TMV 2	Tamil Nadu, Andhra Pradesh, Telangana, Karnataka, Gujarat and Maharashtra.	(104)
3	ICGV 91114	Karnataka, Andhra Pradesh, Telangana, Maharashtra, Tamil Nadu and Gujarat.	(104)
4	ICGV 93437	Andhra Pradesh, Telangana, Karnataka, Maharashtra, Tamil Nadu and Gujarat	(104)
5	ICGV 00350	Andhra Pradesh, Telangana, Karnataka, Maharashtra, Tamil Nadu, Gujarat and parts of Rajasthan.	(104)
6	ICGV 00351	Andhra Pradesh, Telangana, Karnataka, Maharashtra, Tamil Nadu and Gujarat.	(104)
7	TMV 7	Gujarat, Andhra Pradesh, Telangana, Karnataka, Maharashtra, Tamil Nadu, Rajasthan	(50)
8	Georgia 12Y	Georgia state of United States	(105)
9	Georgia Browne	Georgia state of United States	(106)
10	Georgia Green	Southeastern region of the United States.	(106)
11	Early bunch	Southeastern region of the United States, Africa, Asia	(107)
12	Marc 1	Malaysia	(107)
13	Toalson	Georgia, USA	(108)

Biological control

Biological control is employed to manage several soil-borne plant pathogens. *Trichoderma hamatum*, when multiplied in FYM and applied as soil application, reduced the soil-borne pathogen in brinjal (54). Groundnut collar rot disease was found to be less common when *Pseudomonas fluorescens* was applied to seeds and neem cake was applied to the soil (55). Groundnut collar rot was significantly reduced by the application of *P. fluorescens* peat-based inoculum (56). *T. hamatum* seed treatment along with application was found to reduce the root rot disease of groundnut (57). Two species of *Trichoderma*, together with dry biomass of *Chenopodium album*, significantly reduced collar rot of chickpea caused by *S. rolfii* (58). The natural antagonistic properties of microbial agents such as *Trichoderma* spp., *Bacillus* spp. and *Pseudomonas* spp. like the production of siderophore and hydrogen cyanide are used to control the root pathogens (59). These methods aim to suppress *S. rolfii* populations and mitigate disease severity. Additionally, mycorrhizal fungi and rhizobacteria establish symbiotic relationships with groundnut roots, enhancing nutrient uptake and stimulating plant defense mechanisms against pathogen attack (60). Furthermore, plant-based biocontrol agents, including botanical extracts and essential oils, exhibit antifungal properties against *S. rolfii*, contributing to sustainable disease management strategies with minimal environmental impact (61–63).

According to previous study *Bacillus subtilis* controls *S. rolfii* in peanuts grown in greenhouses by 92% (64). The pathogen's growth was reduced by 82% when *P. fluorescens* and *Streptomyces violaceusniger* were applied to seed at 5 g/kg and 10 g/kg, respectively. This was followed by a 75% growth inhibition when *S. violaceusniger* was applied at 10 g/kg of seed (65). The culture filtrate of *T. harzianum* (Th-BKN) at 5% concentration recorded 89% inhibition, followed by *T. viride* (Tv-BKN), which showed an inhibition of 84% (66). Seed treatment with *T. viride* @10 g/kg recorded the lowest incidence of stem rot (6%) (67). Due to the release of volatile and non-volatile diffusible metabolites, *Pseudomonas aeruginosa* AL98 significantly suppressed the growth of *S. rolfii*, up to 94%, affecting its growth in dual culture (68) (Table 3).

Prosopis juliflora showed the greatest inhibition against *S. rolfii* (74%). *Nerium indicum* (54%) and *Agave americana* (68%) were the next best plant extracts (69). Seed + soil

treatment with citronella oil and palma rosa oil @ 0.5% significantly inhibited the growth of *S. rolfii* (70). The next most effective botanicals were *Ocimum sanctum* (84%), *Asparagus racemosus* (74%), *Vitex* spp. (45%) and *Allium cepa* (36%) (45). Neem showed the most inhibition at concentrations of 3% (39%) and 4% (44%). It is followed by garlic crude extract at 3% and 4% concentrations (33% and 34%, respectively), pungam oil, *Calotropis* leaf extract and lemon grass leaf extract. On the seventh day after inoculation, neem oil decreased sclerotial germination by 44%, while a larger neem concentration prevented all stages of sclerotia (immature, partial and mature). The *Calotropis* treatment showed the minimal sclerotia growth periods, which were 7 days, 13 days and 16 days for the immature, partial and mature stages, respectively. African locust bean tree bark, eucalyptus gum and plum seed extract inhibited the growth of *S. rolfii* throughout its period. The effectiveness of these extracts ranged from 8 to 100%. *S. rolfii* was significantly controlled by parkia (100%) followed by plum (100%) and orange seeds (100%). Under *in vitro* conditions, *O. tenuiflorum* (tulsi) at 20% concentration showed the highest mycelial inhibition (75%). It also recorded 100% inhibition of sclerotial germination after 8 and 24 h of incubation and 83% inhibition after 30 min (47).

Chemical control

Chemical control is pivotal in integrated strategies for managing stem rot in groundnut crops. While fungicides effectively combat the disease, they can escalate production costs. Despite this, fungicides play a crucial role, especially in high-disease-pressure scenarios. Integrating chemical control with other management practices like cultural methods and resistant cultivars optimizes disease management while considering economic and environmental factors (71). Various chemical fungicides provide efficient suppression of *S. rolfii* (72). However, sustainable management necessitates thoughtful fungicide selection to avoid residual toxicity, fungicide resistance and environmental pollution. Indiscriminate fungicide usage can exacerbate these issues, compromising long-term disease management strategies. Therefore, integrating chemical control with other sustainable practices, such as cultural methods and biological control, is essential for effective disease management while minimizing adverse environmental impacts (73). Integrating chemical methods with cultural practices and biological control agents offers a holistic approach to stem rot management. This

Table 3. Efficacy of different bio-control agents against *S. rolfii*

S. No	Bio-control agent	Efficacy under <i>in vitro</i>	Mode of action	Reference
1	<i>Trichoderma viride</i>	69.40%	Competition for resources, production of anti-microbial compounds	(86)
2	<i>T. harzianum</i>	71.67%	Competition for resources, induction of systemic resistance	(109)
3	<i>T. hamatum</i>	72.86%	Competition, production of antimicrobial compounds, induction of plant defense responses	(45)
4	<i>Pseudomonas fluorescens</i>	64.40%	Production of antibiotics, lytic enzymes and siderophores.	(86)
5	<i>P. aeruginosa</i> AL 98	94.44%	Production of siderophores and antibiotics. Promotion of plant growth.	(68)
6	<i>Streptomyces</i> spp	64–67%	Production of antibiotics and lytic enzymes, as well as induction of systemic resistance	(110)
7	<i>Bacillus subtilis</i>	60.76%	Production of antifungal metabolites, induction of plant defense responses.	(111)
8	Neem	82.67%	Antifungal properties, disruption of fungal growth, induction of systemic acquired resistance in plants	(44)
9	Garlic	90.89%	Inhibition of fungal growth, induction of systemic acquired resistance in plants	(45)
10	Tulsi	83.61%	Antifungal properties, inhibition of fungal growth	(45)

strategy ensures optimal disease control while minimizing environmental impacts, promoting sustainable agricultural practices for long-term crop health and productivity.

Growth regulators also influence the disease and yield. Seeds soaked in IAA solution at 10^{-5} M concentration for 24 h produced the highest significant yield (486.8 g/m²), the lowest disease incidence (26%) and the lowest disease severity (22%) (74). Seed treatment of 10^{-4} to 10^{-7} diluted solutions with four growth-regulating chemicals like 2,4-dichloro acetic acid, indole acetic acid, cycocel (chlormequat) and 2,4,5-trichloro acetic acid reduced mortality in plants that were already inoculated with the pathogen and also inhibited the development of symptoms. Based on biochemical studies, it was observed that the treated plants have significantly higher calcium, o-dihydroxy phenol and total phenol concentrations than untreated plants. On the other hand, the pectolytic enzyme activity is highly decreased (75).

Seed treatment with tebuconazole 2% DS at a rate of 1 g/kg seed has demonstrated exceptional efficacy in managing groundnut stem rot, resulting in a minimal disease incidence of 7% and the highest pod production recorded at 2664 kg/ha. Moreover, field trials have shown a significant yield increase of approximately 10% compared to the recommended fungicide carbendazim (3 g/kg of seed). This highlights the effectiveness of tebuconazole seed treatment as a superior option for stem rot management in groundnut cultivation, offering both excellent disease control and enhanced yield potential (76). Under field conditions, the seeds treated with 1.5 mL/kg of tebuconazole (250 EC) had the maximum pod production (466 kg/ha) and the lowest incidence of stem rot (9%). The fungicide exhibited the lowest mean percent stem rot incidence (3% and 9%) in sick soil and pot culture studies conducted 30 to 105 days after sowing. These percentages were 94% and 52% lower than the control (67) (Table 4).

Molecular approaches

Groundnut being a self-pollinated crop, the possibility of genetic variability through conventional breeding is not feasible (77). Hence, genetic mapping studies aim to identify genomic regions associated with resistance to stem rot in groundnut. To map these locations, scientists use molecular markers like SNPs (single nucleotide polymorphisms) and SSRs (simple sequence repeats). Once identified, markers linked to resistance traits can

be used for MAS in breeding programs to select and develop groundnut varieties with enhanced resistance to stem rot. Though certain sources of stem rot resistance in peanuts have recently been revealed by several researches (49), little is known about the genetics of resistance and the markers associated with resistant genes. Therefore, to use them in marker-assisted breeding programs, it is imperative to identify molecular markers associated with the stem rot resistance QTLs.

Accurate QTL mapping and variety development rely on permanent mapping populations called MAGIC (Multiparent Advanced Generation Intercross) populations. One of the main benefits of the MAGIC populations is the production of new allele combinations through generations of merging founder genomes (78). To attain characteristics like fresh seed dormancy, oil content, seed mass, kernel Fe and Zn content, aflatoxin tolerance, stem rot tolerance and PBNB tolerance, the first MAGIC population (ICGV 88145, ICGV 00308, ICGV 91114, ICGV 06040, ICGV 00440, ICGV 05155, GPBD 4 and 55-437) was found (79). Successful crosses between wild and farmed species can result from the production of synthetic groundnut, which is the doubling of the chromosomal number of the hybrid created from two diploid wild species. Many amphidiploids and autotetraploid groundnuts have been developed using A- and B-genome accessions that exhibit high levels of resistance to a variety of stressors (such as late leaf spot, stem rot and collar rot diseases). The tetraploid ($2n = 4x = 40$) peanut (*Arachis hypogaea* subsp. *hypogaea* var. *hypogaea*) lines GP-NC WS 16 and GP-NC WS 17 (SPT 06-07) with resistance to multiple diseases including early leaf spot (ELS), *Cylindrocladium* black rot, *Sclerotinia* blight and tomato spotted wilt were produced through interspecific hybridization from the diploid ($2n = 2x = 20$) wild species *A. cardenasii* (80). Three dense genetic maps (585 to 2753 SNP loci) and the successful identification of genomic areas and candidate genes for stem rot resistance in TG37A × NRCG-CS85 were produced using the GBS-based sequencing technique (81). Some interspecific hybrid derivatives (e.g., 326, 988, 1019) were shown to have consistent and stable resistance to stem and pod rot. Furthermore, breeding lines that showed reduced susceptibility to these diseases include ICGV 86034 and 86124 (82).

Integrated approach

Table 4. Efficacy of different chemicals tested *in vitro* against *Sclerotium rolfii*

S. No	Chemical	Concentration tested in <i>in vitro</i>	Efficacy in <i>in vitro</i>	Reference
1	Carboxin	100, 250, 500 ppm	100% growth inhibition	(112)
2	Hexaconazole	100, 250, 500 ppm	100% growth inhibition	(112)
3	Propiconazole	100, 250, 500 ppm	100% growth inhibition	(112)
4	Tebuconazole	500, 1000 ppm	92.97% and 94.36% inhibition respectively	(113)
5	Azoxystrobin	500, 1000, 1500, 2000 ppm	100% growth inhibition	(114)
6	Fosetyl-Al	500 ppm	27.28% growth inhibition	(112)
7	Thiophanate methyl	500 ppm	16.67% growth inhibition	(112)
8	Carbendazim	500 ppm	11.85% growth inhibition	(112)
9	Mancozeb	100, 250, 500 ppm	100% growth inhibition	(112)
10	Thiram	100, 250, 500 ppm	100% growth inhibition	(112)
11	Captan	500 ppm	99.96% growth inhibition	(113)
12	Carbendazim 50WP + Mancozeb 75WP	500, 1000, 1500, 2000 ppm	100% growth inhibition	(112)
13	Cymoxanil 8% + Mancozeb 64%	1000, 1500, 2000 ppm	100% growth inhibition	(112)
14	Carbendazim 50WP + Thiram 75 WP	1000, 1500, 2000 ppm	100% growth inhibition	(112)
15	Captan + Thiram	100 ppm	99.96% growth inhibition	(113)
16	Carboxin 37.5% + Thiram 37.5%	1500, 2000 ppm	94.35% and 94.44% growth inhibition respectively	(113)

Researches found that soaking the soil with 0.2% carbendazim and applying *Trichoderma harzianum* inoculum reduced groundnut stem rot by 44-60% and increased pod yields by 17%-47%. In a field study, the treatment combination of *T. viride* + neem cake recorded the lowest disease incidence (5%), followed by carbendazim (6%) when compared to the control (15%) (32). The next best treatment was *T. Viride* + FYM, which recorded a disease incidence of 7% (83). According to some researches, TG-2 biological agent combined with vermicompost and neem cake was found to be superior against *S. rolfii* with the least PDI of 7% (84). *S. rolfii* can also be controlled by seed treatment with *T. asperellum* (2%) along with soil application of *T. asperellum* (10 g/m²) + VAM (15 g/m²) + vermicompost (250 g/m²), which recorded the lowest incidence of 20% (85). In some experiments, it has been examined the organic amendments in a greenhouse environment and found that mahua cake combined with *T. viride* at a rate of 5 g/kg of soil caused a 4% incidence of stem rot as compared to 40% in the control (68). Applying a fungicide (mancozeb) to seeds together with a putative native antagonist (Th-3) and a potential bacterial antagonist (Pf1) to the soil found a minimum plant height of 30.66 cm and a maximum root length of 29.13 cm for groundnuts, with a disease incidence percentage of 7%. Mahua cake combined with *T. viride* at a rate of 5 g/kg of soil produced a 4% incidence of stem rot among the organic amendments examined in the greenhouse, compared to a 40% incidence in the control (86). PAL (0.298 changes in absorbance/minute/gram of leaf tissue), PO (0.291 changes in absorbance/minute/gram of leaf tissue/minute/gram), PPO (0.296 μ mole of transcinnamic acid/minute/gram) and phenol (781 μ g of catechol/g) activity were highest in plants treated with *Trichoderma* spp. and mahua oil cake in field conditions (87). The lowest stem rot incidence (10%) was recorded by seed treatment with *T. viride* @ 10 g/kg + soil application of neem cake

Plant diseases, notably stem rot-causing sclerotia, threaten global agricultural productivity. Chemical methods, like broad-spectrum fungicides, have traditionally managed stem rot but pose environmental risks. Stricter regulations prompt the need for sustainable alternatives. IDM emerges as a holistic approach to combat stem rot in groundnut cultivation, reducing reliance on synthetic chemicals and promoting eco-friendly practices. IDM integrates biological control, cultural methods and targeted chemical applications to effectively manage diseases while preserving ecosystem health. Biological control harnesses natural enemies or beneficial microbes to suppress pathogens, promoting sustainability and long-term disease control. Despite longer efficacy demonstration, biological control benefits sustainably. IDM optimizes cost-effectiveness in groundnut cultivation, enhancing profitability through reduced input costs and minimized yield losses. IDM signifies a shift towards sustainable agriculture, minimizing chemical residues, preserving soil health and promoting biodiversity. By mitigating adverse agricultural impacts, IDM ensures both environmental and human health. In summary, IDM is the paramount method for combating stem rot, offering a balanced approach to disease management aligning with modern agricultural sustainability goals.

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Authors' contributions

BD conceptualized and drafted the manuscript. JS contributed in the literature review of the manuscript. NI provided expertise and critical manuscript review. The manuscript was revised and finalized by JS and RK. KN provided valuable insights. All authors have read and approved the final manuscript.

Compliance with ethical standards

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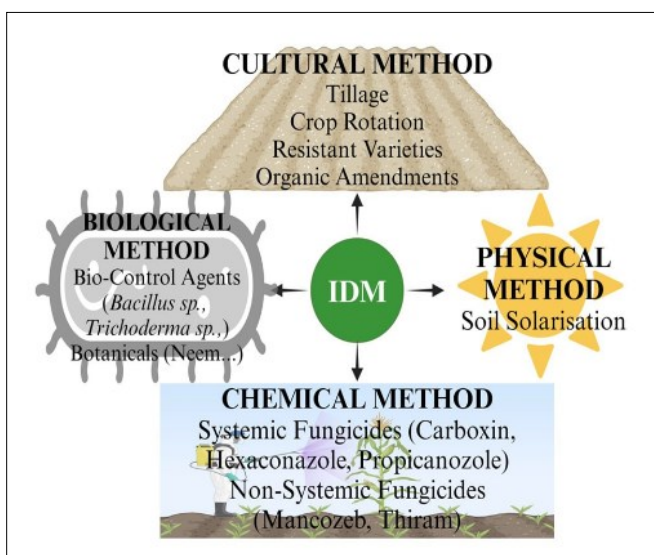


Fig. 3. Components of integrated disease management of *Sclerotium rolfii*.

(50 g/kg soil) (48). The module that utilized a mould board plough for deep summer ploughing, together with the addition of 4 kg/ha of *Trichoderma* enhanced with 250 kg FYM/ha and Tebuconazole 2DS seed treatment, resulted in a minimum incidence of 9% of stem rot. The pod and haulm yields were 2566 kg/ha and 6428 kg/ha, respectively (88) (Fig. 3).

Conclusion

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