PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol x(x): xx–xx
https://doi.org/10.14719/pst.3995

HORIZON
e-Publishing Group
HePG

REVIEW ARTICLE

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

B Deepika[1], J Sheela[2*], N Indra[1], R Kalaiyarasi[3] & K Nelson Navamaniraj[4]

[1]Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Plant Pathology, VOC Agricultural College and Research Institute, Killikulam, Vallanad 628 252, Tamil Nadu, India

[3]Department of Oilseeds, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[4]Department of Seed Science and Technology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Email: sheela.j@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 08 July 2024
Accepted: 01 October 2024
Available online
Version 1.0 : 19 January 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Deepika B, Sheela J, Indra N, Kalaiyarasi R, Navamaniraj KN. Integrated approach for managing groundnut stem rot caused by *Sclerotium rolfsii* Sacc. Plant Science Today (Early Access).
https:/doi.org/10.14719/pst.3995

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 rolfsi;* stem rot

Introduction

Groundnut (*Arachis 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; *Sclerotium rolfsii 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 *Sclerotium rolfsii*, 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 devasting 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 (14), stem rot, rust and leaf spot, either separately or in combination, can cause a 15-70% reduction in groundnut production. Significant yield losses of more than 80% have been reported in recent years due to *S. rolfsii*-induced stem rot disease (1, 15).

Host range

Sclerotium rolfsii, 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. rolfsii* 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. rolfsii* requires integrated disease management to reduce its impact on agriculture and protect diverse plant ecosystems (Table 1).

Symptomology

Sclerotium rolfsii 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. rolfsii* 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.

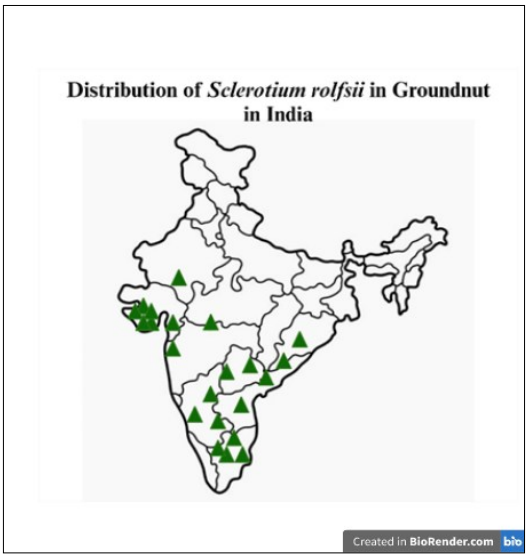

Fig. 1. Distribution of *S. rolfsii* worldwide and in India.

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

Sclerotium 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). *Sclerotium 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).

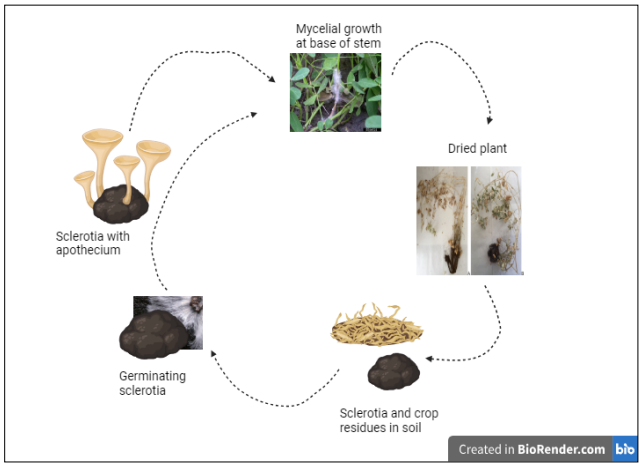

Fig. 2. Disease cycle of *S. rolfsii.*

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 *Sclerotium 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. rolfsii* 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. rolfsii* 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. rolfsii* during solarization was documented by (48) to create a dynamic model that would convey the pathogens thermal inactivation. The population of *S. rolfsii* was reduced from 47% to 100% after 20 days of exposure. For the soil pathogen *S. rolfsii*, 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. rolfsii* (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. rolfsii* 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. rolfsii,* contributing to sustainable disease management strategies with minimal environmental impact (61-63).

According to (64), *Bacillus subtilis* controls *S. rolfsii* in peanuts grown in greenhouses by 92%. 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. rolfsii*, up to 94%, affecting its growth in dual culture (68) (Table 3).

Prosopis juliflora showed the greatest inhibition against *S. rolfsii* (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. rolfsii* (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. rolfsii* throughout its period. The effectiveness of these extracts ranged from 8 to 100%. *S. rolfsii* 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. rolfsii* (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 strategy ensures optimal disease control while minimizing environmental impacts, promoting sustainable agricultural practices for long-term crop health and productivity.

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

S. No	Bio-control agent	Efficacy under *in vitro*	Mode of action	Reference
1	*Trichoderma viride*	69.40%	Competition for resources, production of anti-microbial compounds	(86)
2	*T. harzianum*	71.67%	Competition for resources, induction of systemic resistance	(109)
3	*T. hamatum*	72.86%	Competition, production of antimicrobial compounds, induction of plant defense responses	(45)
4	*Pseudomonas fluorescens*	64.40%	Production of antibiotics, lytic enzymes and siderophores.	(86)
5	*P. aeruginosa* AL 98	94.44%	Production of siderophores and antibiotics. Promotion of plant growth.	(68)
6	*Streptomyces* spp	64–67%	Production of antibiotics and lytic enzymes, as well as induction of systemic resistance	(110)
7	*Bacillus subtilis*	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)

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/m^2), 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 PBND 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

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).

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

S. No	Chemical	Concentration tested in *in vitro*	Efficacy in *in vitro*	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)

The next best treatment was *T. Viride* + FYM, which recorded a disease incidence of 7% (83). According to some researches (84), TG-2 biological agent combined with vermicompost and neem cake was found to be superior against *S. rolfsii* with the least PDI of 7%. *S. rolfsii* can also be controlled by seed treatment with *T. asperellum* (2%) along with soil application of *T. asperellum* (10 g/m^2) + VAM (15 g/m^2) + vermicompost (250 g/m^2), 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 µmole of transcinnamic acid/minute/gram) and phenol (781 µg 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 (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).

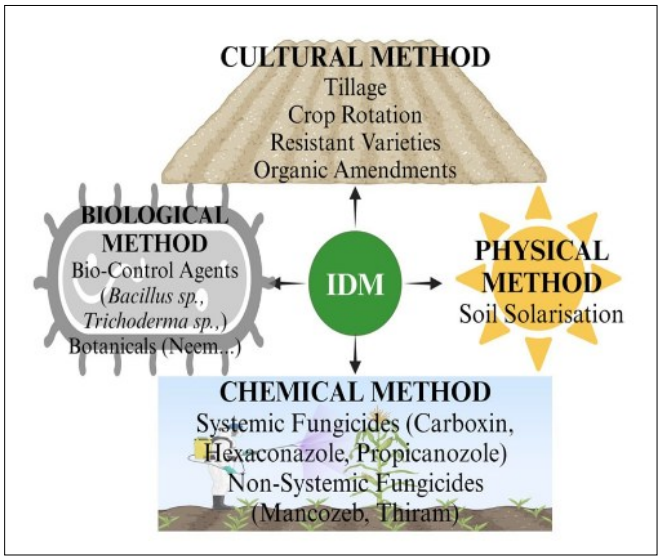

Fig. 3. Components of integrated disease management of *Sclerotium rolfsii*.

Conclusion

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. Integrated Disease Management (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.

Acknowledgements

The authors are very grateful to thank the Faculties, Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore and Dr. N. Senthil, Ph.D., The Dean, School of Postgraduate Studies, Tamil Nadu Agricultural University, Coimbatore for their insightful discussions and feedback that helped strengthen this review article.

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

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. Kanmani S, Rajinimala N, Sheela J, Jeberlin Prabina B. Bio-efficacy of oilcake extracts to control *Macrophomina phaseolina* Tassi (Goid) causing dry root rot disease in groundnut (*Arachis hypogea* L.). Int J Curr Microbiol Appl Sci. 2020;9(8):1190-95. https://doi.org/10.20546/ijcmas.2020.908.132
2. Subbiah G, Indra N. Management of seed and collar rots caused by *Aspergillus niger* Van Tiegham in groundnut (*Arachis hypogaea* L.) by biocontrol method. Madras Agric Journal. 2003;90(apr-jun):1.
3. Paramasivan M, Karthikeyan M, Sheela J. Drought mitigation and root rot disease management in groundnut under rainfed condition by *Bacillus subtilis*. International Conference on Global Perspectives in Crop Protection for Food Security. TNAU: Book of Extended Abstracts; 2021.
4. Eevera T, Chinnasamy GP, Venkatesan S, Navamaniraj KN, Albert VA, Anandhan J. Attenuated total reflectance-fourier transform infrared (ATRFTIR) spectroscopy: A tool to determine groundnut seed quality. Legume Research. 2024;47(7):1165-71. https://doi.org/10.18805/LR-5120

5. Chitra K, Ragupathi N, Dhanalakshmi K, Mareeshwari P, Indra N, Kamalakannan A, et al. Induction of peroxidase and polyphenol oxidase in *Arachis hypogaea* in response to treatment with *Pseudomonas fluorescens* and inoculation with *Alternaria alternata*. Archives of Phytopathology and Plant Protection. 2006;39(4):315-21. https://doi.org/10.1080/03235400600655297

6. Vaishali G, Saravanan S, Arumugam Pillai M, Sheela J, Kavitha Pushpam A, Jerish JR. Genetic variability and heritability studies in groundnut (*Arachis hypogea* L.) germplasm. The Pharma Innovation Journal. 2023;12(9):970-73.

7. Subrahmanyam P, Ghanekar A, Nolt B, Reddy D, McDonald D. Resistance to groundnut diseases in wild *Arachis* species. Proceedings of an International Workshop on Cytogenetics of *Arachis.* 1985;ICRISAT. 49-55.

8. Jadon K, Thirumalaisamy P, Kumar V, Koradia V, Padavi R. Management of soil borne diseases of groundnut through seed dressing fungicides. Crop Protection. 2015;78:198-203. https://doi.org/10.1016/j.cropro.2015.08.021

9. Xu L, Li G, Jiang D, Chen W. *Sclerotinia sclerotiorum*: an evaluation of virulence theories. Annual Review of Phytopathology. 2018;56:311-38. https://doi.org/10.1146/annurev-phyto-080417-050052

10. Tarekegn G, Sakhuja PK, Swart WJ, Tamado T. Integrated management of groundnut root rot using seed quality and fungicide seed treatment. International Journal of Pest Management. 2007;53(1):53-57. https://doi.org/10.1080/09670870601058940

11. Shew B, Beute M, Campbell C. Spatial pattern of southern stem rot caused by *Sclerotium rolfsii.* Phytopathology. 1984;74:730-35. https://doi.org/10.1094/Phyto-74-730

12. Subrahmanyam P, Greenbergj D, Savary S, Bosc J. Diseases of groundnut in West Africa and their management: research priorities and strategies. International Journal of Pest Management. 1991;37 (3):259-69. https://doi.org/10.1080/09670879109371596

13. Ghewande M, Desai S, Basu M. Diagnosis and management of major diseases of groundnut. NRCG Bull. 2002;1:8-9.

14. Adiver S. Influence of organic amendments and biological components on stem rot of groundnut. National Seminar on Stress Management in Oilseeds For Attaining Self Reliance in Vegetable Oil. Indian Society of Oilseeds Research, Directorate of Oil seeds Research, Hyderabad form; 2003.

15. Baskey S, Khalko S, Hembram S, Sharma B, Ali S. Survey for the incidence of stem rot of groundnut in North Bengal districts of West Bengal, India. International Journal of Current Microbiology and Applied Sciences. 2020;9(01):328-33. https://doi.org/10.20546/ijcmas.2020.901.037

16. Yaqub F, Shahzad S. Pathogencity of *Sclerotium rolfsii* on different crops and effect of inoculum density on colonization of mungbean and sunflower roots. Pakistan Journal of Botany. 2005;37(1):175-80.

17. Amein T. Soil-borne pathogens infecting sugar beet in southern Sweden. Plant Pathol J. 2006;5(3):356-61. https://doi.org/10.3923/ppj.2006.356.361

18. Derbalah AS, Dewir YH, El-Sayed AE. Antifungal activity of some plant extracts against sugar beet damping-off caused by *Sclerotium rolfsii.* Annals of Microbiology. 2012;62:1021-29. https://doi.org/10.1007/s13213-011-0342-2

19. Sultana J, Pervez Z, Rahman H, Islam M, Pervez Z, Rahman H, et al. Integrated approach of mitigating root rot of chilli caused by *Sclerotium rolfsii*. Bangladesh Res Pub J. 2012;6(3):270-80.

20. Sivakumar T, Sanjeevkumar K, Balabaskar P. Variability in *Sclerotium rolfsii* Sacc. causing Stem rot of groundnut. Bull Env Pharmacol Life Sci[Spl Issue 2]. 2016;92:99.

21. Taylor C, Rodrıguez-Kábana R. Optimal rotation of peanuts and cotton to manage soil-borne organisms. Agricultural Systems. 1999;61(1):57-68. https://doi.org/10.1016/S0308-521X(99)00034-7

22. Fery RL, Dukes Sr PD. Southern blight (*Sclerotium rolfsii* Sacc.) of cowpea: yield-loss estimates and sources of resistance. Crop Protection. 2002;21(5):403-08. https://doi.org/10.1016/S0261-2194(01)00122-3

23. Mehan V, Mayee C, McDonald D. Management of *Sclerotium rolfsii*-caused stem and pod rots of groundnut-a critical review. International Journal of Pest Management. 1994;313-20. https://doi.org/10.1080/09670879409371906

24. Willetts H, Bullock S. Developmental biology of sclerotia. Mycological Research. 1992;96(10):801-16. https://doi.org/10.1016/S0953-7562(09)81027-7

25. Pinheiro VdR, Seixas CDS, Godoy CV, Soares RM, Oliveira MCNd, Almeida ÁMR. Development of *Sclerotium rolfsii* sclerotia on soybean, corn and wheat straw, under different soil temperatures and moisture contents. Pesquisa Agropecuária Brasileira. 2010;45:332-34. https://doi.org/10.1590/S0100-204X2010000300014

26. Palakshappa M, Srikant Kulkarni SK, Hegde R. Studies on foot rot of betelvine caused by *Sclerotium rolfsii* Sacc. in Karnataka. 1986;17.

27. Chavan AR, Chavan S, Yadav AM, Chavan V. Effect of vermicompost, rock phosphate, PSB and different bioproducts on yield and economics of groundnut (*Arachis hypogea* L.). International Journal of Current Microbiology and Applied Sciences. 2019;8(12):2031-39. https://doi.org/10.20546/ijcmas.2019.812.240

28. Edmunds BA, Gleason ML, Wegulo SN. Resistance of hosta cultivars to petiole rot caused by *Sclerotium rolfsii* var. *delphinii.* HortTechnology. 2003;13(2):302-05. https://doi.org/10.21273/HORTTECH.13.2.0302

29. Maiti S, Sen C. Effect of moisture and temperature on the survival of sclerotia of *Sclerotium rolfsii* in soil. Journal of Phytopathology. 1988;121(2):175-80. https://doi.org/10.1111/j.1439-0434.1988.tb00969.x

30. Alexander B, Stewart A. Survival of sclerotia of *Sclerotinia* and *Sclerotium* spp. in New Zealand horticultural soil. Soil Biology and Biochemistry. 1994;26(10):1323-29. https://doi.org/10.1016/0038-0717(94)90213-5

31. Mullen J. Southern blight, southern stem blight, white mold. The Plant Health Instructor. 2001;10(1):104. https://doi.org/10.1094/PHI-I-2001-0104-01

32. Magyar D, Vass M, Li DW. Dispersal strategies of microfungi. Biology of Microfungi. 2016;315-71. https://doi.org/10.1007/978-3-319-29137-6_14

33. Ansari M, Agnihotri S. Morphological, physiological and pathological variations among *Sclerotium rolfsii* isolates of soybean. Indian Phytopathology. 2000;53(1):65-67.

34. Balapreethi M, Sheela J, Ebenezar EG, Arumugam Pillai M, Merina Prem Kumari S, Rajinimala N, et al. *In vitro* evaluation of phylloplane and spermosphere bacterial antagonists from rice land races against *Sarocladium oryzae* causing sheath rot disease of rice. Biological Forum - An International Journal. 2023;15(8):320-25.

35. Ayed F, Jabnoun-Khiareddine H, Aydi-Ben-Abdallah R, Daami-Remadi M. Effects of pH and aeration on *Sclerotium rolfsii* Sacc. mycelial growth, sclerotial production and germination. International Journal of Phytopathology. 2018;7(3):123-29. https://doi.org/10.33687/phytopath.007.03.2688

36. Garren KH GK. Control of *S. rolfsii* through cultural practices. Symposium on *Sclerotium rolfsii.* Phytopathology. 1961;120-24.

37. Cilliers A, Pretorius Z, Van Wyk P. Integrated control of *Sclerotium rolfsii* on groundnut in South Africa. Journal of Phytopathology. 2003;151(5):249-58. https://doi.org/10.1046/j.1439-0434.2003.00715.x

38. Rodriguez-Kabana R, Robertson D, Wells L, Weaver C, King P. Cotton as a rotation crop for the management of *Meloidogyne arenaria* and *Sclerotium rolfsii* in peanut. Journal of Nematology. 1991;23 (4S):652.

39. Garren K. The stem rot of peanuts and its control. Virginia Agric Exp Stn Tech Bull. 1959;144:137.

40. Minton N, Csinos A, Lynch R, Brenneman T. Effects of two cropping and two tillage systems and pesticides on peanut pest management. Peanut Science. 1991;18(1):41-46. https://doi.org/10.3146/i0095-3679-18-1-12

41. Zeidan O, Elad Y, Hadar Y, Chet I. Integrating onion in crop rotation to control *Sclerotium rolfsii.* 1986;426-28. https://doi.org/10.1094/PD-70-426

42. Asghari M, Mayee C. Comparative efficiency of management practices on stem and pod rots of groundnut. Indian Phytopathology. 1991;44(3):328-32.

43. Anahosur K. Mundkur memorial award lecture-integrated management of potato *Sclerotium* wilt caused by *Sclerotium rolfsii*. Indian Phytopathology. 2001;54(2):158-66.

44. Anitha K, Thiruvudainambi S, Harish S, Kumar RA. Bio-efficacy of organic amendments and plant oils against *Sclerotium rolfsii* Sacc.: The incitant of Southern blight of tomato. Journal of Pharmacognosy and Phytochemistry. 2019;8(3):2202-05.

45. Vineela D, Beura S, Dhal A, Swain S. Efficacy of bio-agents, botanicals, organic amendments against groundnut pathogens *Sclerotium rolfsii* and *Aspergillus niger in-vitro*. Journal of Pharmacognosy and Phytochemistry. 2020;9(3):1206-10.

46. Babariya V, Kelaiya D, Vyas U, Davaria P. Evaluation of water soluble soil amendments against *Sclerotium rolfsii* Sacc. causing stem and pod rot of groundnut under *in vitro* condition. The Pharma Innovation Journal. 2023;12(6);2594-96.

47. Bagul V. *In vitro* evaluation of botanicals and organic amendments on mycelial growth and viability of the sclerotia of *Sclerotium rolfsii* Sacc. The Pharma Innovation Journal. 2023;12(12):3752-56.

48. Shlevin E, Saguy IS, Mahrer Y, Katan J. Modeling the survival of two soilborne pathogens under dry structural solarization. Phytopathology. 2003;93(10):1247-57. https://doi.org/10.1094/PHYTO.2003.93.10.1247

49. Thirumalaisamy P, Kumar N, Radhakrishnan T, Rathnakumar A, Bera S, Jadon K, et al. Phenotyping of groundnut genotypes for resistance to *Sclerotium* stem rot. Journal of Mycology and Plant Pathology. 2015;44:459-62.

50. Palaiah P, Narendrappa T, Mallesh S. Screening of groundnut varieties and germplasm against collar rot, stem rot and dry root rot diseases. Int J Curr Microbiol Appl Sci. 2019;8(6):2321-28. https://doi.org/10.20546/ijcmas.2019.806.275

51. Packiaraj D, Varman PV, Joel AJ, Nagaraj P, Raveendran T, Rajamanickam K, et al. ALR 3-a new insect and disease resistant groundnut variety. Madras Agricultural Journal. 1999;581-82. https://doi.org/10.29321/MAJ.10.A00663

52. Nigam S, Reddy L, Janila P, Premalatha N, Vaithiyalingan M, Bapu JK, et al. ALG 06 320–A new high yielding Spanish bunch groundnut variety. Electronic Journal of Plant Breeding. 2019;10(4):1477-81. https://doi.org/10.5958/0975-928X.2019.00190.X

53. Shamyuktha J, Sheela J, Rajinimala N, Jeberlinprabina B, Ravindran C. Survey on onion basal rot disease incidence and evaluation of aggregatum onion (*Allium cepa* L. Var. *Aggregatum* Don.) genotypes against *Fusarium oxysporum* f. sp. *cepae*. Int J Curr Microbiol Appl Sci. 2020;9:529-36. https://doi.org/10.20546/ijcmas.2020.907.058

54. Sheela J, Sivaprakasham K, Seetharaman K. Screening brinjal genotypes against *Fusarium* wilt. Madras Agricultural Journal. 1995;82(4):318-19.

55. Sheela J, Packiaraj D. Management of collar rot of groundnut by *Pseudomonas fluorescens.* International Arachis Newsletter. 2000;50-51.

56. Sheela J, Sivaprakasam K, Seetharaman K. Effect of soil application of *Pseudomonas fluorescens* using different carriers on groundnut collar rot disease incidence. Madras Agricultural Journal. 1998;191-92.

57. Vimala R, Sheela J, Packiaraj D. Management of root rot disease of groundnut by bioagents. Madras Agricultural Journal. 2000;87(4/6):352-54.

58. Ali A, Javaid A, Shoaib A, Khan IH. Effect of soil amendment with *Chenopodium album* dry biomass and two *Trichoderma* species on growth of chickpea var. Noor 2009 in *Sclerotium rolfsii* contaminated soil. Egyptian Journal of Biological Pest Control. 2020;30(1):102. https://doi.org/10.1186/s41938-020-00305-1

59. Chitra K, Dhanalakshmi K, Kavitha K, Indra N, Rajinimala N, Nageswari R, et al. Disease resistance could be augmented by bacterial metabolites. Agricultural Mechanization in Asia. 2022;53(11):10507-10.

60. Lioussanne L, Perreault F, Jolicoeur M, St-Arnaud M. The bacterial community of tomato rhizosphere is modified by inoculation with arbuscular mycorrhizal fungi but unaffected by soil enrichment with mycorrhizal root exudates or inoculation with *Phytophthora nicotianae*. Soil Biology and Biochemistry. 2010;42(3):473-83. https://doi.org/10.1016/j.soilbio.2009.11.034

61. Khan IH, Javaid A, Al-Taie AH, Ahmed D. Use of neem leaves as soil amendment for the control of collar rot disease of chickpea. Egyptian Journal of Biological Pest Control. 2020;30:1-8. https://doi.org/10.1186/s41938-020-00299-w

62. Sharf W, Javaid A, Shoaib A, Khan IH. Induction of resistance in chili against *Sclerotium rolfsii* by plant-growth-promoting rhizobacteria and *Anagallis arvensis*. Egyptian Journal of Biological Pest Control. 2021;31:1-11. https://doi.org/10.1186/s41938-021-00364-y

63. Jabeen N, Khan IH, Javaid A. Fungicidal potential of leaf extract of *Datura metel* L. to control *Sclerotium rolfsii* Sacc. Allelopathy J. 2022;56(1):59-68. https://doi.org/10.26651/allelo.j/2022-56-1-1387

64. Abd-Allah E. Effect of a *Bacillus subtilis* isolate on southern blight (*Sclerotium rolfsii*) and lipid composition of peanut seeds. Phytoparasitica. 2005;33:460-66. https://doi.org/10.1007/BF02981395

65. Yamunarani K, Muthamizhan A. Biological control of ground nut stem rot fungus, *Sclerotium rolfsii* (Sacc.) by *Streptomyces violaceusniger* along with organic ammendments. IJCS. 2020;8(6):582-86. https://doi.org/10.22271/chemi.2020.v8.i6i.10835

66. Meena MC, Meena AK, Meena PN. Efficacy of different bioagents against stem rot of groundnut incited by *Sclerotium rolfsii* under *in vitro* conditions. IJCS. 2019;7(6):259-63.

67. Bhosale D, Karjule A, Shelar V. Management of stem rot by chemical fungicide, bioagents and organic amendments in groundnut. The Pharma Innovation Journal. 2021;10(7): 799-803.

68. Rakh R, Dalvi S, Raut L, Manwar A. Microbiological management of stem rot disease of groundnut caused by *Sclerotium rolfsii* Sacc., by exploiting *Pseudomonas aeruginosa.* AL98 Res Jr of Agril Sci. 2022;13:415-21.

69. Kiran K, Linguraju S, Adiver S. Effect of plant extract on *Sclerotium rolfsii,* the incitant of stem rot of ground nut. Journal of Mycology and Plant Pathology. 2006;36(1):77-79.

70. Awasthi D, Mishra N, Dasgupta B. Management of stem rot of groundnut (*Sclerotium rolfsii* Sacc.) by plant oils. Journal of Pharmacognosy and Phytochemistry. 2018;7(4):2309-11.

71. Chitra K, Ragupathi N, Dhanalakshmi K, Mareeshwari P, Indra N, Kamalakannan A, et al. Salicylic acid induced systemic resistant on peanut against *Alternaria alternata.* Archives of Phytopathology and Plant Protection. 2008;41(1):50-56. https://doi.org/10.1080/03235400600655263

72. Khan IH, Javaid A. Chemical control of collar rot disease of chickpea. Pakistan Journal of Phytopathology. 2015;27(1):61-68.

73. Sheela J, Packiaraj D. Biological control of root rot of groundnut. Madras Agricultural Journal. 1999;599-601. https://doi.org/10.29321/MAJ.10.A00669

74. Awasthi DP, Mishra NK, Dasgupta B. Use of non-conventional chemicals against stem rot of groundnut (*Arachis hypogaea* L.) caused by *Sclerotium rolfsii* Sacc. Int J Curr Microbiol Appl Sci. 2018;7(2);1288-92.

75. Chowdhury A. Control of *Sclerotium* blight of groundnut by plant growth substances. Crop Research (Hisar). 2003;25(2):355-59.

76. Sunkad G. Tebuconazole: a new triazole fungicide molecule for the management of stem rot of groundnut caused by *Sclerotium rolfsii.* The Bioscan. 2012;7(4):601-03.

77. Manjunath N, Saravanan S, Sushmitha R, Pillai MA, Sheela J, Shoba D. Mutagenic efficiency and effectiveness of gamma rays and EMS in groundnut (*Arachis hypogaea* L.). Electronic Journal of Plant Breeding. 2020;11(3):875-80. https://doi.org/10.37992/2020.1103.143

78. Huang BE, Verbyla KL, Verbyla AP, Raghavan C, Singh VK, Gaur P, et al. MAGIC populations in crops: current status and future prospects. Theoretical and Applied Genetics. 2015;128:999-1017. https://doi.org/10.1007/s00122-015-2506-0

79. Gangurde SS, Kumar R, Pandey AK, Burow M, Laza HE, Nayak SN, et al. Climate-smart groundnuts for achieving high productivity and improved quality: Current status, challenges and opportunities. Genomic Designing of Climate-smart Oilseed Crops. 2019;133-72. https://doi.org/10.1007/978-3-319-93536-2_3

80. Tallury S, Hollowell J, Isleib T, Stalker H. Greenhouse evaluation of section *Arachis* wild species for *Sclerotinia* blight and *Cylindrocladium* black rot resistance. Peanut Science. 2014;41(1):17-24. https://doi.org/10.3146/PS13-02.1

81. Dodia SM, Joshi B, Gangurde SS, Thirumalaisamy PP, Mishra GP, Narandrakumar D, et al. Genotyping-by-sequencing based genetic mapping reveals large number of epistatic interactions for stem rot resistance in groundnut. Theoretical and Applied Genetics. 2019;132:1001-16. https://doi.org/10.1007/s00122-018-3255-7

82. Mehan V, Ramakrishna N, Rao RN, McDonald D. Preharvest aflatoxin contamination of groundnuts subjected to terminal drought stress in postrainy season. Mycotoxin Research. 1995;11:103-09. https://doi.org/10.1007/BF03192072

83. Sheela J, Vimala R, Packiaraj D. Management of root rot of groundnut. Madras Agricultural Journal. 2001;87:510-12.

84. Rajani T. Integrated management of *Sclerotium rolfsii* Sacc.-The incitant of stem rot of groundnut. Agricultural and Food Sciences. 2004.

85. Indra N. Ecofriendly management of seedling diseases of mango (*Mangifer indica* L.). Int J Curr Microbiol App Sci. 2021;10(06):519-26. https://doi.org/10.20546/ijcmas.2021.1006.056

86. Karthikeyan V, Sankaralingam A, Nakkeeran S. Biological control of groundnut stem rot caused by *Sclerotium rolfsii* (Sacc.). Archives of Phytopathology and Plant Protection. 2006;39(3):239-46. https://doi.org/10.1080/03235400500094688

87. Ayyandurai M, Akila R, Manonmani K, Theradimani M, Vellaikumar S. Phytostimulation and growth promotion activities of *Trichoderma* spp. on groundnut (*Arachis hypogaea* L.) crop. Journal of Applied and Natural Science. 2021;13(4):1172-79. https://doi.org/10.31018/jans.v13i4.2936

88. Ushamalini C, Meena B, Sudhalakshmi R, Indra N. Development of IPM module for the management of soil borne diseases in groundnut. The Pharma Innovation Journal. 2022;11(5S):1479-83.

89. Ahmed H, Hossain M. Crop disease survey and establishment of a herbarium at BARI. Final report. Plant Pathol Div, BARI Joydebpur, Gazipur. 1985;107.

90. McClintock J. Peanut-wilt caused by *Sclerotium rolfsii.* 1917.

91. Chakravarty S, Bhowmik T. Symptoms and techniques of inducing collar-rot of sunflower caused by *Sclerotium rolfsii* Sacc. Indian Journal of Agricultural Sciences. 1983;53(7):570-73.

92. Mridha M, Alamgir S. Prevalence of sclerotial wilt of betelvine (*Piper betle* L.) caused by *Sclerotium rolfsii.* Bangladesh Journal of Plant Pathology. 1989;107-08.

93. Iqbal S, Bakhsh A, Hussain S, Malik B. Microbial antagonism against *Sclerotium rolfsii*, the cause of collar rot of lentil. Lens Newsletter. 1995;48-49.

94. Sugha S, Sharma B, Tyagi P. A modified technique for screening chickpea (*Cicer arietinum*) varieties against collar rot caused by *Sclerotium rolfsii.* Indian Journal of Agricultural Sciences. 1991;61 (4);289-90.

95. Hosen S, Shamsi S, Bashar M. *In vitro* biological control of *Colletotrichum gloeosporioides* (Penz.) Sacc. and *Sclerotium rolfsii* Sacc., causal agent of anthracnose and soft rot of *Corchorus capsularis* L. L Bangladesh J Bot. 2016;45(1):175-80.

96. Naidu PH. Crossandra-a new host record for *Sclerotium rolfsii.* Indian Phytopathology. 2000;53(4):496-97.

97. Arunasri P, Chalam T, Reddy N, Reddy ST. Collar rot disease of crossandra induced by *Sclerotium rolfsii* and its management: a critical review. International Journal of Applied Biology and Pharmaceutical Technology. 2011;2(2):307-14.

98. Kumar B, Prasad D. A new record on foot rot or wilt disease of finger millet caused by *Sclerotium rolfsii* from mid hills of Uttarakhand. J Mycol Pl Pathol. 2010.

99. Kachhadia M, Patel P. *In vitro* evaluation of fungicides against stem rot of cowpea caused by *Sclerotium rolfsii* Sacc. Trends in Biosciences. 2017;10(13):2347-49.

100. Sun S, Sun F, Deng D, Zhu X, Duan C, Zhu Z. First report of southern blight of mung bean caused by *Sclerotium rolfsii* in China. Crop Protection. 2020;130:105055. https://doi.org/10.1016/j.cropro.2019.105055

101. Ahmed MU, Bhuiyan M, Hossain M, Rubayet MT, Khaliq Q. Efficacy of chitosan and bio-agent in controlling southern blight disease of carrot caused by *Sclerotium rolfsii* and improvement the crop production. Research in Agriculture and Veterinary Science. 2019;3 (3):113-25.

102. Javaid A, Afzal R, Shoaib A. Biological management of southern blight of chili by *Penicillium oxalicum* and leaves of *Eucalyptus citriodora.* Intl J Agric Biol. 2020;23:93-102.

103. Jabeen N, Javaid A, Shoaib A, Khan IH. Management of southern blight of bell pepper by soil amendment with dry biomass of *Datura metel.* Journal of Plant Pathology. 2021;103(3):901-13. https://doi.org/10.1007/s42161-021-00874-6

104. Divya Rani V, Sudini H, Narayan Reddy P, Vijay Krishna Kumar K, Uma Devi G. Resistance screening of groundnut advanced breeding lines against collar rot and stem rot pathogens. International Journal of Pure and Applied Bioscience. 2018;6(1):467-74. https://doi.org/10.18782/2320-7051.5494

105. Standish J, Culbreath A, Branch W, Brenneman T. Disease and yield response of a stem-rot-resistant and-susceptible peanut cultivar under varying fungicide inputs. Plant Disease. 2019;103(11):2781-85. https://doi.org/10.1094/PDIS-04-19-0771-RE

106. Shokes F, Róźalski K, Gorbet D, Brenneman T, Berger D. Techniques for inoculation of peanut with *Sclerotium rolfsii* in the greenhouse and field. Peanut Science. 1996;23(2):124-28. https://doi.org/10.3146/i0095-3679-23-2-11

107. Shokes F, Weber Z, Gorbet D, Pudelko H, Taczanowski M. Evaluation of peanut genotypes for resistance to southern stem rot using an agar disk technique. Peanut Science. 1998;25(1):12-17. https://doi.org/10.3146/i0095-3679-25-1-4

108. Branch W, Brenneman T. Stem rot disease evaluation of mass-selected peanut populations. Crop Protection. 1999;18(2):127-30. https://doi.org/10.1016/S0261-2194(98)00103-3

109. Murthy PS, Kumari JPR, Basavaraju N, Janardhan D, Devamma MN. *In vitro* influence of bio-controlling agents against *Sclerotium rolfsii* causing stem rot sickness of groundnut (*Arachis hypogaea* L.). Pharm Innov. 2018;7:05-08.

110. Jacob S, Sajjalaguddam RR, Sudini HK. Streptomyces sp. RP1A-12 mediated control of peanut stem rot caused by *Sclerotium rolfsii*. Journal of Integrative Agriculture. 2018;17(4):892-900. https://doi.org/10.1016/S2095-3119(17)61816-1

111. Pawar G, Gholve V, Navale M. Ecofriendly management of stem rot of groundnut (*Arachis hypogaea* L.) caused by *Sclerotium rolfsii* Sacc. The Pharma Innovation Journal. 2022;11(8):37-42.

112. Rakholiya K. Screening of fungicides against *Sclerotium rolfsii* causing stem rot of groundnut. The Bioscan. 2015;10(2):691-94.

113. Pawar G, Gholve V, Navale M. *In vitro* efficacy of fungicides against stem rot of groundnut (*Arachis hypogaea* L.) caused by *Sclerotium rolfsii* Sacc. The Pharma Innovation Journal. 2021;10(12);2150-54.

114. Raghavendra B, Srinivas T. *In vitro* studies on the effect of different fungicides against mycelia growth of *Sclerotium rolfsii,* the causal agent of stem rot in groundnut. Andhra Pradesh J Agril Sci. 2020;6 (1):29-35.