Bio-Intensive Management of Fungal Diseases of Potatoes

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Abstract

Potato is an important food crop in the world including India. Potato crop is affected by various phytopathogens, viz., fungi, bacteria, viruses, and nematodes. Among these, fungal pathogens may cause significant economic yield losses, if proper plant protection measures are not applied. Among the fungal pathogens, *Phytophthora infestans*, *Alternaria* spp., *Rhizoctonia solani*, *Fusarium* spp. are the major pathogens, while *Sclerotinia sclerotiorum*, *Sclerotium rolfsii*, *Synchytrium endobioticum*, *Helminthosporium solani*, and *Spongospora subterranea* f. sp. *subterranea* are considered as minor pathogens. For effective management of these fungal pathogens various methods, i.e., chemical control, biological control, planting resistant varieties, cultural control, and physical control are applied. Chemical management is highly effective to manage the diseases in short span; however, due to continuous and irrational use of the chemicals, pathogens may develop resistance against certain classes of fungicides. Moreover, these chemicals can lead to environmental pollution and toxicity in the crop produce. Bio-intensive management is an integrated approach, which involved biological control, cultural practices/agronomical practices and resistant varieties, etc. These approaches not only aid in managing the diseases but also increased the crop yield with sustainable approaches. In the present chapter major fungal diseases of potato, their causal organism, symptoms, losses, epidemiology, and bio-intensive approaches for management are discussed.

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Keywords

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19.1 Introduction

Potato originated in the hills of Andes and Bolivia in South America. It was introduced into Europe by Spaniards in the second half of the sixteenth century. From there it spread throughout Europe and the rest of the world in the mid-seventeenth to mid of eighteenth century. In India, it was introduced by Portuguese in the seventeenth century. Potato is the third most important food crop in the world in terms of human consumption. It is affected by various diseases and pests. Diseases are the major cause of concern for reducing the economic yield and affecting economy of the potato growers. Among the fungal diseases, late blight, early blight, black scurf and stem canker, *Fusarium* wilt and dry rot, *Sclerotinia* rot, *Sclerotium* rot, silver scurf, powdery scab, wart of potato, etc., are cause of concern. These diseases may cause losses up to 90%, depending upon varieties grown and adopted plant protection measures. These diseases can be managed by various methods, viz., chemical control, cultural control, biological control, and physical and resistant varieties. Chemical control is used extensively for managing the diseases because of quick response and managing the disease effectively. However, due to extensive use of chemicals with non-judicious application for longer periods to manage the diseases, the pathogens have developed resistance against certain chemicals. Moreover, awareness among the environmentalist and consumers about the toxic effect of these chemicals in the nature as well as in the plant produces is increasing. Therefore, it requires adopting strategy like bio-intensive management to avoid development of resistance in pathogens and toxicity in the environment. Use of bioagents/biological control is the best option. In simple way, biological control can be defined as the partial or total inhibition or destruction of pathogen population by other microorganisms. Baker and Cook (1974) defined it as the reduction of inoculum density or disease-producing activities of a pathogen or parasite in its active or dormant state, by one or more organisms, accomplished naturally or through manipulation of environment, host, or antagonist or by mass introduction of one or more antagonist. Cultural practices including nutrients management, crop rotation, and biofumigation are used in bio-intensive management. Besides, host resistance is also widely used in bio-intensive management. Symptoms, causal organism, losses, epidemiology, and management of the fungal diseases are discussed in the following heads.

19.2 Early Blight

19.2.1 Symptoms

For the first time, Ellis and Martin (1882) observed the symptoms on dying potato leaves. The name came from the fact that early blight infects early maturing cultivars more severely than medium or late maturing cultivars (van der Waals et al. 2001). Foliar infection generally becomes visible with the onset of tuber formation (Runno-Paurson et al. 2015). Typical foliage symptoms of early blight infection are characterized as dark brown to black necrosis. The first foliar symptoms usually appear on the lowermost leaves and then progress on the upper leaves just a few weeks after infection. Initially, the infected leaves show dark brown dot-like blotches which may be angular, circular, or oval with a few millimeters in diameter. The spots may enlarge and coalesce to form large necrotic area (Fig. 19.1). The necrotic area gradually expands, and the leaf symptoms grow to take up the whole of the green leaf tissue and to a lesser extent on stems at a late stage of the plant growth. As the lesion enlarges, a series of dark concentric rings are visible as a result of irregular growth patterns of the pathogen. This characteristic "target-spot" or "bull's eye" pattern is typical of early blight symptoms. Subsequently, the necrotic leaf tissue is often surrounded by a chlorotic border caused by fungal mycotoxin (i.e., alternaric acid), which turn the leaf tissue yellow. The chlorosis can extend to the whole infected leaf resulting in dried up leaf which hangs along the stem.

Conidia of *Alternaria* spp. are washed from the leaves and enter in the soil which can also infect potato tubers. The affected tubers show dark brown, slightly sunken lesions on the tubers. Diseased tuber tissue underneath lesion is dark brown, firm, and 10–12 mm deep. The dry or hard rot of tubers causes storage losses, decreases potatoes quality, and reduces emergence capacity of seed tubers.

Fig. 19.1 Symptoms of early blight of potato foliage

19.2.2 Causal Organism

The main causal organism of early blight on potato crop is *Alternaria solani* Sorauer (Ell. and Mart.). However, many other large-spored *Alternaria* spp., which infect potato plants, have also been reported. Rodrigues et al. (2010) observed that *A. grandis* Simmons was the causal organism which infects potato plants in various regions in Brazil. In an artificially inoculated field study, Duarte et al. (2014) found that *A. grandis* can cause infection on potato crops. In Algeria, Ayad et al. (2017) detected *A. protenta* as the causal agent of early blight and together with *A. grandis* and *A. solani* found to be part of the complex of *Alternaria* spp. detected in potato fields in Belgium (Landschoot et al. 2017). Hauslanden and Bassler (2004) reported that in Germany the occurrence of *A. alternata* and *A. solani* in potato crop was almost equal, whereas in Poland, the frequency of *A. alternata* was higher than that of *A. solani* (Kapsa 2007).

19.2.3 Epidemiology

Alternaria spp. overwinter as mycelium, chlamydospores, or conidia in the soil and on crop residues (Wale et al. 2008). The infection occurs through primary inoculum (conidia) carried to the older leaves by rain water. *Alternaria* is able to penetrate the leaf tissue directly through the intact epidermis or through natural openings and wounds. Initially, the lower leaves closer to the ground are infested. The fungus is restricted to the lower leaf level for several days. Formation of conidia starts on the necrotic leaf tissue at temperatures between 5 °C and 30 °C (optimum 20 °C). The secondary inoculum is dispersed through wind and causes infections on the nearby plant leaves and stems. The latent period is about 3–7 days. When a condition becomes favorable for infection, and at a certain age of the plant, *A. solani* colonizes the middle and upper leaves very rapidly. In fields, a cascade-like progression of the pathogen from the lower, via the middle, to the upper leaves is visible. Heavily infected leaves fall off and serve as inoculum source on and in the soil.

Weather conditions, plant growth stage and their health, cultivar maturity, susceptibility of the cultivar, and inoculum level play an important role in the progression of the disease. Temperature above 22 °C and alternating high relative humidity are the favorable weather conditions for *A. solani* infection. Besides potato, early blight can also occur on other crops. It has been observed on many solanaceous host plants such as tomato (*Solanum lycopersicum* L.), eggplants (*S. melongena* L.), hairy nightshade (*S. sarrachoides* Sendt), black nightshade (*S. nigrum* L), horse nettle (*S. carolinense* L.), pepper (*Capsicum* spp.), and non-solanaceous weeds (Jones et al. 1993; Hausladen and Aselmeyer 2017).

19.2.4 Economic Impact

Nowadays, under climatic change scenario early blight is considered to be one of the most important fungal diseases of potato after late blight. It is found in almost all countries where potatoes are cultivated (Woudenberg et al. 2014). However, *A. solani* is described as an important fungal pathogen especially in warmer regions because it requires high temperature for growth and disease development. Depending on the cultivar susceptibility and geographical regions, *A. solani* can cause considerable yield losses up to 2–58% (Shtienberg et al. 1996; van der Waals et al. 2001; Campo Arana et al. 2007; Horsfield et al. 2010). In India, yield loss has been estimated up to 79% due to early blight damage in severe condition.

19.2.5 Management

Crop rotation *A. solani* survives in the form of mycelium or conidia on the crop residue or soil in the field from one growing season to the next. Therefore, crop rotation with nonhost crop and control of the host weed plants like black shadow reduces the inoculum level of the pathogen. Additionally, removal and burning of infected plants also reduce the pathogen inoculum level.

Biofumigation It is an alternative option to reduce the primary pathogen inoculum in the soil. Biofumigation is a process to suppress the pathogen inoculums by isothiocyanates (ITCs), which derive from hydrolyzation of glucosinolates by myrosinase in disrupted plant cells. Bio-fumigant plants such as white mustard, leaf radish, etc., can reduce the early blight incidence in the crop (Volz et al. 2013).

Use of disease-free seed Diseased and virus-infected potato plants are more susceptible to early blight infection than normal healthy plants; therefore planting the diseased or virus-free seed tubers can reduce the pathogen attack.

Abiotic stresses Potato plants stressed by biotic or abiotic factors are more susceptible to early blight disease compared to non-stressed plants. Various abiotic stresses such as drought, frost, high temperature, and over-irrigation affected potato plants during the cropping season. Salt stress enhanced the symptoms of early blight disease. Additionally, prolonged leaves wetness period due to overhead irrigation allows successful fungal infection.

Nutrition management For optimum potato plant growth and tuber yield, a balanced nutrition is required during the growing season. Specially, N-fertilizer should be applied properly; otherwise susceptibility of plant against early blight will be higher. Better soil fertility and plant nutrition can decrease the severity of early blight (Lambert et al. 2005; MacDonald et al. 2007). Under drought condition, when plants are unable to take enough nutrients from the soil through the roots, foliar spraying of fertilizer can decrease the nutrient deficiency that reduces plant susceptibility to the disease. The fertilizer form can also influence the disease progression of *A. solani*. Application of calcium cyanamide results in a delay of early blight disease, as the fungicidal side effects of degradation products of calcium cyanamide can reduce the initial inoculum in the soil (Volz et al. 2013).

Varietal resistant Genetic resistance offers the most effective means to control early blight; however, no completely resistant genotypes have been reported so far. Most of the cultivated potato varieties are much more susceptible to early blight than wild species. Generally, early maturing cultivars are more susceptible to *A. solani* than those of late maturing cultivars. Screening of wild diploid relatives, breeding clones, and some tetraploid cultivars for resistance to early blight have been reported (Xue et al. 2019). Few clones of *Solanum tarijence*, *S. neorossii*, and *S. commersonii* showed high degree of resistance (Jansky et al. 2008), while moderate resistance was observed in *S. chacoense*. Some potato cultivars such as "Kufri Jeevan," "Kufri Pukhraj," "Kufri Badshah," "Kufri Sherpa," and "Kufri Sindhuri" show moderate resistance to early blight.

Biological control Biocontrol is the application of microorganism (bioagents) to reduce the plant pathogen population and is considered to be an eco-friendly alternative for disease management. Several potential antagonists have been evaluated; among them PGPR (*Pseudomonas* spp., *Bacillus* spp.) and fungi (*Trichoderma polysporum*, *T. harzianum*, *T. viride*, *Chaetomium globosum*) are common. In a field study, *T. viride* (0.5%) was found effective against early blight for reducing disease intensity (Yadav and Pathak 2011). A combination of *T. harzianum* and *P. fluorescens* was applied as seed treatment and foliar spraying for reducing the disease intensity under field conditions (Mane et al. 2014). *Trichoderma longibrachiatum* inhibited mycelial growth of *A. solani* by up to 87.6% under in vitro conditions (Prabhakaran et al. 2015). Volatile organic compounds (VOCs) produced by *B. subtilis* ZD01 can inhibit the conidia germination and reduce the lesion areas in vivo (Zhang et al. 2020). Recently, Gorai et al. (2021) evaluated the biocontrol efficacy of endophytic *B. velezensis* SEB1 and concluded that cell-free extract at 1000 ug/ml was effective to inhibit the conidial germination and reduces the radial growth up to 82.34% in vitro and decrease disease severity up to 52.5% under field conditions.

19.3 Late Blight

19.3.1 Symptoms

The aerially dispersed asexual sporangia are responsible for epidemics on potato crops. When the flying sporangia arrive on the plant surface, it can germinate directly or release zoospores, which encyst, germinate, and penetrate the host tissues (Fry et al. 2015). This infection stage is not seen by naked eye, but inside the cells, complex mechanism of molecular interactions takes place. After entering, formation of haustoria begins inside the plant cells, from where many effector proteins are secreted (Whisson et al. 2016; Wang et al. 2017). At this stage *P. infestans* follow biotrophic mechanism to obtain nutrients.

The visible symptoms started to appear within 2–3 days when the pathogen achieves the necrotrophic stage. Symptoms appear at first as water-soaked irregular pale green lesions, usually at edges of lower leaves. These lesions grow rapidly and

Fig. 19.2 Symptoms of late blight of potato foliage

turn brown to purplish black within 1–2 days. During morning, a white mildews growth develops around the lesion on the underside of leaves (Fig. 19.2), which consists of sporangiophores and sporangia, which emerge through the stomata (Nowicki et al. 2012) and are the typical characteristics of potato late blight. On stems or petiole dark brown lesions develop which elongate and encircle the stems. Underground tubers may be infected by sporangia which are washed off the diseased foliage and enter the soil. Infected tubers show irregular, slightly depressed areas with brown coloration which extend deep in to the tubers.

19.3.2 Causal Organism

Phytophthora infestans (Mont.) de Bary is the main causal organism of late blight disease of potato. Previously, it was described as a fungus due to the superficial resemblance to filamentous fungi but is now classified as oomycete in the kingdom of stramenopiles (Kamoun et al. 2014). The vegetative stage of *P. infestans* is diploid, whereas it is haploid in true. Recent research has shown that in the present-day lineages the progenies from sexual *P. infestans* populations are diploid, while the clonal lineages responsible for most important pandemic are triploid (Li et al. 2017).

Phytophthora infestans populations are constantly evolving and novel, and usually highly pathogenic races appear periodically dominating the previously existing races. Divergence, recombination, and migration are the main reasons responsible for the emergence of new genotypes (Knaus et al. 2016). *Phytophthora infestans* reproduce mainly through asexual reproduction, and diverse numbers of clonal lineages occur in different countries and locations. Many studies have found that emergence of new races can often be credited to migration (Fry et al. 2015; Knaus et al. 2016; Saville et al. 2016). Previously, the mating type A1 was dominating worldwide, except its presumed center of origin, Central Mexico, where both mating types (A1 and A2) exist in equal frequencies (Goodwin et al. 1992). This situation has changed dramatically, and migration of A2 mating type to various countries of the world during late 1980s has resulted in increased emergence and severity of late blight disease (Goodwin 1997; Zhu et al. 2015; Chowdappa et al. 2015; Montes et al. 2016; Rojas and Kirk 2016; Rekad et al. 2017). Existence of both A1 and A2 genotypes at the same location has opened up the possibility of development of thick-walled oospores which could survive either extreme winter (Medina and Platt 1999) or summers conditions. Recent investigations have shown that these self-fertile isolates are found more frequently, constituting a new threat to potato crops because of their increased genotypic variability, better fitness, and greater aggressiveness (Zhu et al. 2016; Casa-Coila et al. 2017).

19.3.3 Epidemiology

Phytophthora infestans overwinters as mycelium in infected seed tubers, refuse piles, and host plant. Infected seed tubers serve as a primary source of inoculum. When A1 and A2 mating types are present, formation of oospore takes place which has potential to initiate the disease (Stevenson et al. 2001). Under favorable environmental conditions, the pathogen may sporulate and discharge zoospores in the soil which move upward and infect the plant at ground level. Older leaves touching soil level get infected first. Severe infection takes place under low temperature and high relative humidity with heavy dews or alternate raining. Sporangia are produced rapidly at 18–20 °C and high relative humidity (>90%). Sporangia are sensitive to desiccation, and, after dispersal by wind or splashing water, they require free water to germinate. The sporangia may germinate by two ways: indirect or direct. The optimal temperature for indirect germination via zoospores is 10 °C, whereas that for direct germination of sporangia via germ tubes is 24 °C. In the presence of water, zoospore enters to the host tissue through germ tubes and appresoria within few hours at 8 °C and 25 °C. After entering in the plant, subsequent development of the diseases is most rapid at 21 °C, and lesions with new sporangia appear within few days.

19.3.4 Economic Impact

The potential economic and social impact of potato late blight disease is best illustrated by the well-publicized role it played in the Irish Famine in the middle of the nineteenth century when it completely destroyed potato crop, either by killing foliage prior to the harvest or by causing massive tuber rot in storage condition. As a result of the famine, millions of Irish people died or emigrated (Bourke 1993).

Haverkort et al. (2009) recorded the global costs and losses due to late blight that take 16% of all global potato production. The yield loss due to late blight ranged from 20% to 70%, and it can destroy the whole crop under epidemic conditions (Haq et al. 2008; Lal et al. 2015; Lal et al. 2019).

19.3.5 Management

Late blight disease can be controlled by a combination of integrated disease management approaches. Various management measures include elimination or reduction of initial inoculum sources such as infected seed, cull piles, infected neighboring fields, and host plants, spraying fungicide before the appearance of disease, and use of resistant cultivars to reduce the rate of disease development. Planting early-maturing cultivars to reduce the crop duration or planting the crop in seasons or locations where the environment is not favorable for the disease development may also be helpful.

Cultural practices Cultural practices include all the activities carried out during cropping season for agronomic management which change the microclimate, host condition, and pathogen behavior to reduce phytopathogen activity, viz., their survival, dispersal, and reproduction (Garrett and Dendy 2001). Control of inoculum sources such as host weed plants and cull piles and plant debris, disease in neighboring fields can help in management of the disease (Turkensteen and Mulder 1999). Use of disease-free certified seed, growing resistant varieties, well-drained aerated fields, adequate space between rows and plants, rotation with nonhost, adequate hilling, timely mechanical weeding, harvesting in dry conditions, and when the tubers are mature could minimize late blight (Garrett and Dendy 2001; Perez and Forbes 2010). Scouting all stored potatoes frequently and removing diseased tubers from storage are desirable to prevent disease spread. Increased use of nitrogen fertilizers can lead to increase in disease severity resulting in yield reduction; therefore, moderate nitrogen fertilization is often recommended as cultural practices to delay the development of late blight. However, higher use of phosphorus and potassium fertilizers gives a positive response to yield in a late blight year (Roy et al. 2001).

Varietal resistance The use of resistant cultivars is among the most effective and eco-friendly means of controlling the late blight disease particularly in tropical conditions. Cultivars having high degree of resistance can allow them to be grown without fungicide application or less fungicide either by lowering the fungicide dose or using longer application intervals (Liljeroth et al. 2016; Haverkort et al. 2016). Ideally, a late blight resistance variety should have high level of resistance to both foliage and tuber blight. Binyam et al. (2014) observed that appearance of the potato late blight disease was delayed almost by 20 days on the moderately resistant varieties as compared to the moderately susceptible and susceptible varieties. Advanced hybrid “Kufri Garima” derived from cross PH/F-1045 X MS/82-638 has been released for commercial cultivation. “Kufri Mohan,” “Kufri Fryom,” “Kufri Sangam,” and “Kufri Karan” are new varieties with field resistance to late blight. However, the race-specific oligogenic resistance in the existing released potato varieties can be rapidly broken down by compatible races of *P. infestans* rendering the varieties to be susceptible to the disease within a short period (Shtienberg et al. 1994). Potato breeders are therefore working to develop late-resistant genotypes to improve tolerance in genes of indigenous species that have been hit hard by non-native invasive plant pathogens.

Organic amendments Application of compost in crop production not only improves the physicochemical properties and soil fertility but also controls various soilborne diseases and increase crop yields (Adebayo and Ekpo 2001; Remade 2006; Yadessa et al. 2010). Different organic materials such as seashells, vegetable waste, farmyard manure, and other waste products are used to promote plant growth. The most common soil organic amendments are compost and animal manure. The efficiency of compost in controlling plant diseases is attributed to its content in antagonistic microorganisms such as bacteria and actinomycetes (Yadessa et al. 2010). Various benefits derived from the application of compost as fertilizer include increase in organic carbon content and microbial activity (Scotti et al. 2015), a greater concentration of plant macro- and micronutrients, i.e., N, P, K, and Mg, and root reinforcement (Donn et al. 2014). Organic compost has capability to influence soil microflora by suppressing various soilborne pathogens diseases such as *Pythium*, *Phytophthora*, and *Fusarium* spp. (Szczech and Smolińska 2001; Borrero et al. 2004).

Biological control Biological control consists of minimizing plant diseases by the interaction of one or more live microorganisms with the pathogen or use of extract of plants. Some findings report the use of *Trichoderma* isolates (Yao et al. 2016), *Chaetomium globosum* (Shanthiyaa et al. 2013), *T. viride*, and *Penicillium viridicatum* (Gupta 2016) and bacteria from the genera *Bacillus*, *Pseudomonas*, *Rahnella*, and *Serratia* (Daayf et al. 2003) as biocontrol agents in the management of late blight disease in potato. In Ethiopia, Zegeye et al. (2011) evaluate the antagonistic activity of *T. viride* and *P. fluorescens* against *P. infestans* under in vitro and greenhouse conditions. The result revealed that both the antagonists have the potential to inhibit the mycelium growth of *P. infestans* in vitro; however, foliar spray of the *T. viride* suspensions was found to be more efficient than *P. fluorescens* and mixed culture. Integrated approaches using fungal and bacterial bioagents has been adopted for managing late blight disease (Lal et al. 2017). Use of biosurfactant from *P. aeruginosa* was found effective in minimizing late blight disease (Tomar et al. 2019a). Recently, in a field study of Lal et al. (2021), neem-based products were found effective for controlling the late blight as well as increase tuber yields. *Trichoderma viride* and *P. fluorescens* were also found effective. *Allium sativum* (garlic) has been suggested as a potential intercropping plant for the management of potato late blight disease under Ethiopian condition (Kassa and Sommartya 2006). Still, few biological control measures are used by nonorganic growers due to low efficacy and farmers' lack of knowledge about these options and access to the most efficient products. Leaf extracts of onions, garlic, *Malus toringo, Reynoutria japonica*, and *Rheum coreanum* inhibited mycelial growth of

P. infestans in vitro. Further, extracts of *Malus toringo* were found effective in controlling late blight under greenhouse experiments (Paik 1989).

19.4 Black Scurf and Stem Canker

19.4.1 Symptoms

Black scurf on potato tubers and stem canker are two distinct phases of the same disease. Black scurf, characterized by the presence of varying size of sclerotia on the surface of tuber, is the best-known symptom of *Rhizoctonia* disease in potato (Fig. 19.3). In addition, symptoms due to severe infection of the stolons and tubers include atypical cracks, corky lesion, malformation, pitting, and desquamation, and elephant hide may also be observed (Campion et al. 2003; Muzhinji et al. 2014). After planting, the fungus may attack young sprouts through the epidermis and produce dark brown lesions, thereby killing underground sprouts much before the plant emergence resulting germination reduction. On the newly developing sprouts reddish brown to gray sunken lesions can be observed. These lesions can girdle the young sprout completely causing the part above the lesion to die. As these lesions mature, they become cankers that are rough and brown and have craters, cracks, or both (Baker 1970; Banville 1978). Infection of the stem causes stunting and rosetting of plant tops resulting in curling the upper leaves which sometime turn red or yellow (Wharton et al. 2007). In a recent study, Ito et al. (2017) observed that leaf curling is not a direct symptom of *Rhizoctonia*, but prior infection of *Potato leafroll virus* enhanced the severity of *Rhizoctonia* diseases. Aerial tubers could be formed in the leaf axils of stems due to interference of carbohydrate movement (Beukema and van der Zang 1990).

Fig. 19.3 Black scurf on potato tubers and stem cankers

19.4.2 Causal Organism

The causal organism of black scurf and stem/stolon/root canker of potato is *Rhizoctonia solani* Kühn AG-3 (anamorph) and *Thanatephorus cucumeris* (Frank) Donk (teleomorph) (Virgen-Calleros et al. 2000). Stevens et al. (1993) differentiated AG-3 isolates from potato and tobacco on the basis of culture appearance, fatty acid profile, and pathogenicity. *Rhizoctonia solani* does not produce asexual spores and exists as mycelia (hyphal growth form), sclerotia (dense asexual hyphal resting structures), or basidiospores (sexual spores) (Keijer et al. 1996). Anamorphic classification of *Rhizoctonia* spp. is based on a characterization of the cell nuclear condition (multi,- bi-, or uninucleate) and the ability of hyphae to anastomose with tester isolates of designated anastomosis groups (AGs) (Sneh et al. 1991).

Occurrence of *R. solani* anastomosis group (AGs) in potato Among the AGs, AG-3 is the most prevalent AG infecting potato (Woodhall et al. 2007; Lehtonen et al. 2008). However, a range of other AGs at lower frequency have been found in potato fields around the world. AG2-1 has been found in potato fields in Alaska (Carling et al. 1986), France (Campion et al. 2003), Turkey (Yanar et al. 2005), the Great Britain (Woodhall et al. 2007), and Finland (Lehtonen et al. 2008). Black scurf caused by AG4 has been observed under warm conditions from Peru (Anquiz and Martin 1989), Australia (Balali et al. 1995), Canada (Bains and Bisht 1995), and Mexico (Virgen-Calleros et al. 2000). Isolates of AG4 HG-I and AG4 HG-III (Muzhinji et al. 2014, 2015) and AG4 HG-II (Woodhall et al. 2012) cause stem canker symptoms on potato plants, but sclerotia formation and blemishes were not observed on the progeny tubers. In Maine, USA, AG-5 was widespread in soil but infrequently found on the stem, stolon, and root of potato plants and not on the tubers (Bandy et al. 1988). In Canada, isolates of AG-5 were not restricted to any particular region (Bains and Bisht 1995), but in France it was found in geographically distinct locations. AG-5 and some AG-3 and AG2-1 isolates were recovered from superficial tuber alterations, such as deformations, or corky or scabby lesions (Campion et al. 2003). Isolates of AG-8 have been recovered from Australian potato field soil (Balali et al. 1995), and symptoms of canker on stems, stolons, and roots and decreased numbers of feeder roots were reported in glasshouse experiment but not sclerotia on tubers. *Rhizoctonia solani* AG-9 has been isolated from Alaskan (Carling et al. 1986) and Turkish (Yanar et al. 2005) potato fields. It causes slight to moderate tuber damage on susceptible cultivars in the field and in greenhouse experiments. Also, binucleate *Rhizoctonia* (BNR) isolates were obtained from potato plants (Carling et al. 1986). Farrokhi-Nejad et al. (2007) reported 12 BNR isolates (out of 58), and Lehtonen et al. (2008) found a single BNR isolate (out of 119) that causes mild symptoms on potato sprouts. However, BNR AG A and AG R causing stem canker, black scurf, and tuber defects on potato were reported from South Africa (Muzhinji et al. 2015; Zimudzi et al. 2017).

19.4.3 Epidemiology

Rhizoctonia solani overwinters as sclerotia on seed tubers or as mycelium in plant debris in soil or on alternate hosts. The pathogen has a wide host range including many solanaceous and non-solanaceous plants. But the main sources of inoculums are infested seed tubers and infected soil. At the end of growing season, sclerotia remaining in soil serve as primary inoculum for infection of plants in the next growing season (Keijer et al. 1996). Soil temperature plays critical role in the initiation of *Rhizoctonia* disease in potato, with severity of the disease being positively correlated with the temperature. Low temperature with high soil moisture, organic matter, and a neutral to acidic soil (pH 7 or less) are suitable conditions for the development of stem canker. Sclerotia start forming on daughter tubers late in the crop growing season, mainly after harms cutting, but sclerotia can also be seen at mid of the cropping season.

19.4.4 Economic Impact

In potato production, *Rhizoctonia* diseases are responsible for both quantitative and qualitative yield losses (Fiers et al. 2011; Das et al. 2014). Quantitative yield losses occur due to infection of the stems, stolon, and roots, which affect tuber size and numbers (Carling et al. 1989), whereas qualitative losses occur mainly by the production of misshapen tubers and the development of sclerotia on the tuber surface (James and McKenzie 1972). It is reported that *Rhizoctonia* disease was responsible for 10–25% yield loss in India (Sharma 2015), up to 30% in Canada, and up to 50% in other countries, thereby affecting potato production severely (Woodhall et al. 2008). The marketable yield losses caused by *Rhizoctonia* spp. on potato have been estimated to reach up to 30% (Platt et al. 1993; Tsror 2010). *Rhizoctonia* disease in potato is hard to control due to the wider host range of the pathogen and long survivability in the form of dormant sclerotia under unfavorable environmental conditions. Further, the pathogen evolves with time allowing the pathogen to overcome the resistance level that may have been serious problem of the potato producers and breeders.

19.4.5 Management

Cultural practices Agronomic practices such as disease-free planting material, soil disinfection, crop rotation, haulm destruction, harvest timing, soil management, irrigation, and plant residues all have an influence on the *Rhizoctonia* disease development and crop quality and quantity.

Disease-free planting material Since black surf is tuber- and soilborne disease, infested seed tubers play an important role in disease development. Disease can be managed to a large extent by the use of certified seed free from sclerotia or any type of *R. solani* inoculums; thus quarantine of potato seed tubers should be done before planting.

Disease free soil *Rhizoctonia solani* inoculum density level in soil can be used as criteria in a risk-prediction system to decide control measure of the disease. Solarized soils are frequently more suppressive and less conducive to certain soilborne pathogens than nonsolarized soils (Greenberger et al. 1987). Soil solarization also improves soil structure and increases the availability of essential plant nutrients for rapid growth and development of plants (Elmore et al. 1997). Soil solarization with transparent polyethylene mulching during hot summer months in Indian subtropical plains was found effective against black scurf (Arora et al. 1997).

Crop rotation Besides the advantages like maintenance of soil fertility, soil organic matter, reduction in soil erosion, etc., crop rotation specifically decreases the incidence of plant diseases caused by soilborne pathogens (Pedersen and Hughes 1992). Monocropping systems generally led to the increase of soil density of specific pathogens resulting in the decline of crop yield and quality (Honeycutt et al. 1996). An increased number of potato cropping cycles enhanced the incidence and severity of stem canker due to the increase in soilborne inoculum level (Scholte 1992; Honeycutt et al. 1996). Although 2-year rotations are found effective to reduce disease levels compared with continuous potato cultivation (Little et al. 2004; Manici and Caputo 2009), longer rotation lengths of 3 or 4 years between potato crops are known to be more effective in controlling soilborne diseases (Buyer et al. 1999; Little et al. 2004; Larkin et al. 2010). Rotations of 3–5 years are often recommended for effectively reducing the black scurf severity. The use of crops with known disease-suppressive capabilities, such as *Brassica* spp., cereals, millets, sunhemp, and non-solanaceous crops, may provide additional resources for reducing disease through improved cropping systems. Various other plant species (including weeds) have been shown to sustain *R. solani* (Jager et al. 1982; Carling et al. 1986) and should be considered in crop rotation and weed control. In three cropping sequences, viz., potato-wheat-paddy, potato-onion-maize, and potato-green gram-groundnut, highest incidence of black scurf was recorded in potato-onion-maize cropping sequence (Anonymous 2019).

Haulm destruction and harvest timing Potato crop may be harvested as soon as it is possible. The harvesting methods applied for potato production can affect the level of black scurf (Dijst et al. 1986). The incidence of infested tubers increased with the length of interval between haulm destruction and harvest. When the temperature and moisture conditions are favorable, the sclerotia keep on appearing and developing on the tubers in the soil. Sclerotial production was stimulated similarly with individual practices of cutting off shoots, chemical haulm destruction, and cutting off roots (Dijst 1985). Green-crop harvesting (harvesting the immature crop mechanically and replacing the tubers to the soil for a curing and final harvesting 2–4 weeks later) and immature-crop harvesting often result in a low level of black scurf (Mulder et al. 1992; Lootsma and Scholte 1996). Green-crop harvesting has the advantage of involving the application of fungicides or antagonistic organisms with the first lifting of the tubers, resulting in effective control of black scurf (Mulder et al. 1992).

Organic matter amendment Organic compost matter, such as cattle manure, is an essential component of organic crop management as it improves soil structure, water holding capacity, and cation exchange capacity and promotes plant growth. The organic amendments provide an effective measure for soilborne black scurf disease management, and it represents a substitute to reliance on fungicides. Tsror et al. (2001) reported that in a field experiment application of *Trichoderma harzianum*, nonpathogenic *Rhizoctonia* and cattle manure compost in furrow could reduce black scurf incidence. Kumar and Kumar (2018) found that the soil amendment with vermicompost reduced disease severity up to 50%, followed by neem cake and mustard cake. The highest reduction in disease severity was observed when farm yard manure was applied in combination with white mustard or when oats were grown as a green manure crop (Scholte and Lootsma 1998), whereas least reduction was reported when farmyard manure was applied alone (Kumar and Kumar 2018). *Brassica* spp. and barley reduced inoculums level of *R. solani* by 20–56% in greenhouse tests (Larkin and Griffin 2007). Green manuring of *Brassica* crops by biofumigation at flowering stage was found effective to minimize disease incidences of black scurf of potato (Anonymous 2017).

Plant extract Plant extract or phytobiocides may be an effective alternative to control *Rhizoctonia* diseases due to their rapid degradation, narrow range of activity, and nonhazardous effects. Earlier reports have shown antifungal potential of *Azadirachta indica*, *Eucalyptus camaldulensis*, *Allium cepa*, *Allium sativum*, *Lantana camara*, *Capparis decidua*, *Dodonaea viscosa*, and *Peganum harmala* extracts against *R. solani* (Atiq et al. 2014; Khan et al. 2016). The bulb extract of *Allium sativum* and rhizome extract of *Zingiber officinale* were found effective in suppressing the mycelial growth of *R. solani* in vitro (Kumar et al. 2017). Recently, Rafiq et al. (2021) reported the in vitro antifungal activity of methanolic leaf extract of *Carthamus oxyacantha* against *R. solani.*

Biological control PGPR strains that were found effective against *R. solani* included *Pseudomonas* spp., *Bacillus* spp., and *Enterobacter* spp. (Tabassum et al. 2017). Two strains of *Pseudomonas* spp. (StT2 and StS3) were found effective against potato black scurf which reduced disease severity up to 65.1% and 73.8%, respectively (Tariq et al. 2010). In a greenhouse experiment, interaction of potato seeds with *Bacillus* spp. showed 30–41.4% disease reduction of black scurf and 28.5–40.2% of stem canker (Kumar et al. 2012). In an in vitro study, *B. subtilis* (V26) strain was found effective against *R. solani* and reduced disease incidence up to 63% and 81% of root canker and black scurf, respectively, as well as enhanced plant growth in planta (Khedher et al. 2015). *Pseudomonas* sp. strain (S8.Fb11) reduced the proportion of infected tubers by *R. solani* to 40% for cv Spunta and to 74% for cv Nicola (Mrabet et al. 2013).

Trichoderma spp. and *Gliocladium* spp. reduce *R. solani* growth by competition for nutrients and space, antibiosis, and by mycoparasitism involving antifungal secondary metabolites (Harman 2007). Tsror et al. (2001) reported that application of *T. harzianum* to the soil surface had relatively small effect compared to the in-furrow treatments. Wilson et al. (2008) reported that application of *T. harzianum*, either in-furrow or in combination with flutolanil applied to seed tubers, increased marketable tuber yield (from 35% to 60%) and reduced black scurf incidence on progeny tubers from 31% to 11%, which could not be achieved using flutolanil alone. In another study, Hicks et al. (2014) reported that isolates of *Trichoderma* spp. (*T. virens*, *T. atroviride*, and *T. barbatum*) reduced percentage of diseased stolon by 41–46% *in planta*. Rahman et al. (2014) evaluated *Trichoderma* spp. against *R. solani* on potato and suggested that integrated or combination approaches could be effective for the management of black scurf. A combination of *B. subtilis* and *T. virens* demonstrated a better control of stem canker than each organism alone (Brewer and Larkin 2005). Arora (2008) reported the treatment of *T. viride* after seed dressing with boric acid (1.5%) significantly minimized the black scurf disease on potato tubers. In a field study, tuber treatment with 2% boric acid along with *T. viride* at 10 g/kg seed recorded the lowest disease incidence (15.33%) and index (0.38) with highest yield (324.68 q/ha) (Patel and Singh 2020). Less control percent ability of *P. aeruginosa* and its metabolites was found to manage black scurf of potato (Tomar et al. 2019b). Recently, Chaudhary et al. (2020a) reported antagonistic activity of native *T. harzianum* against *R. solani* in vitro and greenhouse experiments. Despite the promising results with bioagents, the introduction of new biocontrol agents involves various considerations such as the tedious work of selection and screening, optimization of mode of application to achieve best results (Tabassum et al. 2017), shelf life of the bioagents, efficacy in the field experiments, eco-friendly measures, and registration to be used as a PGPR (Etesami and Maheshari 2018).

19.5 *Sclerotinia* Stem Rot

19.5.1 Symptoms

The first visible symptom of stem rot appears as water-soaked spots usually at stem and branch axils or on branches or stems in contact with the soil. A cottony white mycelium growth develops around the lesion, and the infected tissue becomes soft and watery. Lesions often expand in size rapidly and may girdle the stem which causes foliage wilting. Lesions become dry and will turn beige, tan, or bleached white in color and show papery appearance (Fig. 19.4). Hard, irregularly shaped sclerotia develop in and on decaying plant tissues. Generally, sclerotia are few millimeters in diameter and up to 25 mm in length. Initially, white to cream in color but become black after maturity and are frequently found in the hollowed-out center of infected stems.

19.5.2 Causal Organism

Sclerotinia stem rot, white mold, or watery soft rot of potato is caused by the necrotrophic fungus *Sclerotinia sclerotiorum* (Lib.) de Bary (Ojaghian et al. 2016; Chaudhary et al. 2020b). Generally, *S. sclerotiorum* is more important pathogen of

Fig. 19.4 Symptoms of *Sclerotinia* rot of potato and formation of sclerotia on stems

vegetables in the field during transit and in store. The fungus is both soil- and airborne and geographically widespread in nature, but the disease occurs in relatively cool moist conditions areas.

19.5.3 Epidemiology

Sclerotinia sclerotiorum overwinters in the soil for long time periods under dry and high temperature conditions in the form of dormant structures called sclerotia. The sclerotia may germinate myceliogenically to produce hyphae that infect stems of host plants directly or germinate carpogenically to produce apothecia depending on environmental conditions (Bardin and Huang 2001). The apothecia release millions of airborne ascospores thereby initiating plant infection. Extensive foliage growth which increases humidity and extends leaf wetness within crop canopies promotes development and spread of disease. Increased disease incidence is associated with overhead sprinkler irrigation, a non-upright cultivar architecture, higher crop density, close row width, continuous wetness, and excess nitrogen fertilization in potato and other crops (Grogan and Abawi 1975; Grau and Radke 1984; Gutierrez and Shew 1998). Epidemics of potato stem rot are initiated when airborne ascospores land on open potato blossoms attached to the canopy (Atallah and Johnson 2004). Apothecia present in the potato field, in neighboring potato fields, or in fields of other crops in rotation with potatoes or crops susceptible to *S. sclerotiorum* are likely sources of ascospore inoculum. Ascospores originating external to a potato field appear to be an important and abundant source of inoculum (Johnson and Atallah 2014). Over the last decade, a wide adaptation of monocropping cultural practices and cultivation of susceptible varieties under irrigated conditions has increased *S. sclerotiorum* inoculum in the soil that has made stem rot a serious threat for potato production.

19.5.4 Economic Impact

The economic impact of *S. sclerotiorum* is more limited and varies among the host plant species. In potato crop, it is capable of reducing crop yields up to 60% in a large number of potato fields in India (Dutta et al. 2009). In Germany, *S. sclerotiorum* causes yield reduction up to 30% in potato crop in some areas of Niedersachsen (Quentin 2004). Recently, Alam et al. (2021) observed that about 23% potato plants were wilted and died before harvest in affected fields in Pakistan. The *Sclerotinia* stem rot is reemerging in Western Uttar Pradesh due to change in climatic condition.

19.5.5 Management

The control of stem rot diseases is difficult due to the pathogen's wider host range, long-term persistence of sclerotia in the soil, and the production of airborne ascospores. Management practices to control *S. sclerotiorum* can be developed at several growth stages of the potato crops. Effective disease management strategies usually require implementation and integration of multiple methods.

Cultural practices Traditional agricultural practices such as use of disease-free clean seed tubers, early planting, soil tillage, and adjustment of row width and density of plant population contribute to a reduction of stem rot severity, but the effectiveness of these measures can be very limited (Steadman 1979; Mueller et al. 2002). Irrigation practices that promote leaf wetness or develop high relative humidity within the crop canopy should be avoided. Irrigation should be restricted during rainy weather and on cool, cloudy days, whenever possible.

Crop rotation *Sclerotinia sclerotiorum* survives in soil as sclerotia for long time under adverse environmental conditions. When conditions become congenial for its growth, dormant sclerotia germinate and develop inoculum-laden apothecia (Bolton et al. 2006). The most effective way to reduce the number of sclerotia in the fields is crop rotation. By rotating potato with nonhost crops, the annual life cycle of pathogen can be disrupted, resulting in decreased annual number of sclerotia in the fields. For effective implication of crop rotation, it must be coupled with an efficient weed control program that minimizes the chances of establishing and allowing *S. sclerotiorum* to persist in fields (Derbyshire and Denton-Giles 2016).

Varietal resistance Disease-resistant varieties remain the most economical and long-term approach for controlling the potato stem rot disease. However, no potato cultivars are available with resistance to infection of *S. sclerotiorum.* Further, the expression of the field resistance may be influenced by inoculum potential and other environmental conditions (Mueller et al. 2002). Higher disease incidence was found in "Kufri Garima" and "Kufri Chipsona-1," and less incidence was in "Kufri Pushkar" and "Kufri Pukhraj" under Indian conditions.

Organic amendments Organic matters are rich sources of nutrients for soil microorganism causing quantitative and qualitative changes in bacterial and fungal communities (Emmerling et al. 2002) which improves soil properties, plant health, and yield. In a study, Huang et al. (2002) tested 87 organic residues for their potential of controlling carpogenic germination of sclerotia. Among them, 46 effectively inhibited the development of the fungus when the materials were applied to the soil at a dose of 3% w/w. However, only three kinds of residues were effective at 0.5% w/w. The most effective in preventing ascospore production were materials with elevated levels of nitrogen, e.g., fish meal. They concluded that the loss of viability of sclerotia in the soil was connected with the production of ammonia and ammonia-related compounds. The most promising method to decrease inoculum level of *Sclerotinia* from infested field soil and pathogen multiplication is the use of organic matters combined with bioagents. Huang et al. (2002) reported that soil amendment with organic residues infested with *Coniothyrium minitans* and *T. virens* decreased carpogenic germination of sclerotia by killing the sclerotia. Similarly, Smolinska et al. (2016) found that the application of some selected *Trichoderma* species multiplied on the organic carriers prepared from agro-industrial wastes allowed the complete eradication of sclerotia of *S. sclerotiorum*. After analysis of about 2432 experiments, Bonanomi et al. (2007) concluded that compost was the most suppressive material and showing more than 50% disease control. The conducive conditions for *Sclerotinia* and addition of plant residues to the soil infested with sclerotia significantly decreased the yield of lettuce plants (Smolinska et al. 2016).

Biological control Several bioagents have been studied and identified for controlling stem rot disease in different crops. *Trichoderma harzianum* parasitizes both the sclerotial and hyphal growth stages of *S. sclerotiorum* (Abdullah et al. 2008; Troian et al. 2014). The mycoparasitic properties of *Trichoderma* species play a crucial role in the antagonistic activity against *S. sclerotiorum*. Hydrolytic enzymes, viz., chitinases, glucanases, proteases, and cellulases, are secreted by *Trichoderma* that disintegrate the cell wall of the pathogens (Chet et al. 1998; Kaur et al. 2005; Lopez-Mondejar et al. 2011; Chaudhary et al. 2020c).

In a field experiment, Geraldine et al. (2013) observed reduction in *S. sclerotiorum* apothecia number and disease severity after application of *T. asperellum* spore suspension with common bean. Under field conditions, *T. hamatum* reduced *Sclerotinia* disease by 31–57%, showing that *T. hamatum*-colonized sclerotia had reduced apothecial production and a lower carpogenic infection of cabbage (Jones et al. 2015). The white mold of cucumber fruit and stems was reduced by 64 and 30–35%, respectively, after *T. harzianum* T39 application under commercial greenhouse conditions (Elad 2000). *Trichoderma harzianum* isolate T-22 was found effective against *S. sclerotiorum* and decreased the disease severity index (DSI) by 38.5% in a field-grown soya bean crop (Zeng et al. 2012a). *Coniothyrium minitans* is another parasitic fungus that has been used for the biocontrol of *S. sclerotiorum*. Like *Trichoderma* spp., *C. minitans* parasitizes the sclerotia and mycelia of *S. sclerotiorum* (McQuilken et al. 1995; McLaren et al. 1996). During the seedling stage of canola, active spreading of *C. minitans* can reduce the amount of carpogenic germination of *S. sclerotiorum* later in the growing season (Yang et al. 2009). Studies showed that parasitization of *S. sclerotiorum* by *C. minitans* probably involves the degradation of oxalic acid, a pathogenicity factor of *S. sclerotiorum* (Cessna et al. 2000).

Additionally, many diverse bacterial genera have been studied and found effective against stem rot pathogen, *S. sclerotiorum. Bacillus* species were most commonly used as biocontrol agents (Hou et al. 2006; Hu et al. 2011, 2013; Gao et al. 2014; Wu et al. 2014); other BCAs including *Streptomyces platensis* (Wan et al. 2008), *S. lydicus* (Zeng et al. 2012b), *P. fluorescens* (Aeron et al. 2011), *P. chlororaphis* (Fernando et al. 2007; Selin et al. 2010), and *Serratia plymuthica* (Thaning et al. 2001) were also found effective against *S. sclerotiorum.*

19.6 *Sclerotium* Wilt

19.6.1 Symptoms

The pathogen first attacks the collar region, and a grayish brown, slightly sunken lesion appears on the stem just below the soil surface. Stem lesions expand upward the stem and downwards to cover the entire underground part of the plant leading to yellowing and wilting of the foliage (Mullen 2001). The wilting plants show a white weft of course fungal threads which girdle the basal part of the stem with selerotial bodies resembling mustard seeds on the collar region and roots (Fig. 19.5). The pathogen also infects tubers which showed small sunken, tan-colored spots with brownish margin. The affected tissues are tough and become soft and watery due to secondary rot-causing organisms.

The internal tissue decays and collapses, and the skin becomes broken exposing sunken cavities in the flesh. The white mycelium of the pathogen grows rapidly over the tuber surface in a fan-shaped outline. Sclerotia are formed in abundance on the hyphae.

19.6.2 Causal Organism

Sclerotium rolfsii (teleomorph: *Athelia rolfsii*) is the causal organism of stem rot or southern blight of many plant species in warm temperate, subtropical, and tropical regions (Punja 1985). It is a soilborne phytopathogen, distributed worldwide, and infects a wide range of plant species. *Sclerotium rolfsii* is a polyphagous plant pathogen which infects more than 500 species of monocotyledonous and dicotyledonous plants but especially severe on legumes, solanaceous crops, cucurbits, and other vegetable crops.

19.6.3 Epidemiology

Sclerotium rolfsii overwinters as sclerotia on seed tubers and in the soil or as mycelium on plant debris or on alternate hosts. In dry conditions the sclerotia remain viable for more than 2 years. The mycelial strands from an affected plant grow over the soil and cause infection of the adjoining plants. In crop fields, the wilted plants

Fig. 19.5 Symptoms of *Sclerotium* rot of potato and formation of sclerotia on stem

may be seen in patches indicating the center of infection. On potatoes, it attains major importance only occasionally and in certain locations. In the United States, *S. rolfsii* is an important pathogen in the tropics and subtropics and in areas of the southern and southeastern regions where temperatures are sufficiently high to permit the growth and survival of the fungus (Punja 1985), therefore known as southern blight, southern wilt, and southern *Sclerotium* wilt.

19.6.4 Economic Impact

Sclerotium wilt or rot is a disease of the warmer regions and attacks on a wide range of vegetable and field crops causing considerable yield losses. During the early 1960s, the disease was of annual occurrence at Pune, Maharashtra, especially during *kharif* season, and yield loss of 1–3% was recorded. However, severely affected crops recorded more than 50% crop loss. Postharvest losses of potato to the extent of 15% have been recorded in West Bengal state of India (Dasgupta and Mandal 1989). In Karnataka (India), the wilt incidence up to 30% and tuber rot up to 43% were recorded by Baswaraj (2005). In Bangladesh, it is responsible for the potato tuber yield reduction up to 60% (Rubayet et al. 2017).

19.6.5 Management

Cultural practices Cultural practices such as use of healthy seed tubers, excluding the pathogen from an area, soil removal and replacement, and rouging of infected plants and weed plants might help decrease disease incidence. Deep plowing is another effective method for removal of primary inoculum sources, i.e., sclerotia and infested plant debris, and prevents from contacting with plant tissues (Mullen 2001). Irrigating the fields at regular intervals to avoid too much dry helps in reducing the disease incidence.

Crop rotation Planting rotational crops that are non-susceptible such as corn, sorghum, cotton, or switchgrass was reported to reduce *S. rolfsii* disease incidence (Rodriguez-Kabana et al. 1994).

Organic amendments Incorporating organic amendments such as compost, oat or corn straw, and cotton-gin trash reduced the incidence of southern blight and also enhanced populations of beneficial soil microbes (Bulluck and Ristaino 2002). Neem oil and pine bark extracts or pine bark powder also reduce the growth of *S. rolfsii* (Kokalis-Burelle and Rodriquez-Kabana 1994). Organic matters such as neem cake with and without oil were found effective in reducing the potato *Sclerotium* rot incidence under field conditions (Gurjar et al. 2004; Baswaraj 2005).

Soil treatments In temperate and humid regions, soil solarization has been found effective in control of *S. rolfsii* (Hagan 2004). Other cultural practices that suppress *S. rolfsii* growth include adjusting the soil pH to about 6.5 by adding lime (Bulluck and Ristaino 2002) and aerification of the soil (Mullen 2001). A combined application of soil solarization with biofumigation was found most effective method for the management of *Sclerotium* rot disease in potato (Rubayet et al. 2017).

Varietal resistance Planting the resistant varieties or cultivars is a potentially preferable management method of stem rot disease (Mullen 2001). Potato cultivars show variations in their reaction to *S. rolfsii*; however, to date no cultivars have been reported to show complete resistance. "Kufri Chandramukhi," "Kufri Sindhuri," and some hybrid varieties showed moderate resistance to *Sclerotium* rot. An early maturing cultivar "Kufri Jawahar" recorded least disease incidence against *S. rolfsii* (Baswaraj 2005).

Biological control Various studies have reported the inhibition of mycelial growth and sclerotial production of *S. rolfsii* by using PGPRs, actinomycetes, mycorrhizal fungus, and *Trichoderma* species (Punja 1985). However, most of the studies were conducted under controlled in vitro conditions, and only few reports have demonstrated the biocontrol efficacy of these bioagents for control of *S. rolfsii* in the field (Cattalan et al. 1999; Tsahouridou and Thanassoulopoulos 2002). Many

Trichoderma spp. have been reported to control seed, root, and stem rots in many crops including potato. Under field conditions, isolates of *T. harzianum* and *T. longibrachiatum* have reported about 35–50% reduction in *Sclerotium* rot (Sreenivasaprasad and Manibhusanrao 1990; Asghari and Mayee 1991). In a study, Anahosu (2001) recorded least wilting (10%) with *T. harzianum* followed by *T. viride* (14%) in reducing potato wilt caused by *S. rolfsii.* Isolates of *T. harzianum* and *T. viride* were also reported the best bioagents in reducing the disease incidence in potato *Sclerotium* wilt (Baswaraj 2005). A combination of *T. harzianum* and mycorrhizal fungus *Glomus clarum* was found effective in suppression of *Sclerotium* rot (Sennoi et al. 2013). In a field study, Meena et al. (2018) found that soil treatment with *T. harzianum* (Th-BKN) at 10 kg/ha was the most effective treatment against *Sclerotium* rot.

19.7 *Fusarium* Wilt and Dry Rot

A study on the problems caused by *Fusarium* began with an investigation on the rotting of potatoes by Martius in 1840–1841, who found the causal organism to be a fungus which he called *Fusisporium solani* that was later transferred to *Fusarium* as *Fusarium solani* (Mart.) Sacc (Saccardo 1882). In India, Ajrekar and Kamat (1923) reported that *Fusarium coeruleum* affects potato. Padwick (1943) isolated *Fusarium solani* from rotting tubers at Shimla. Afterwards, several species of *Fusarium* are known to cause dry rot of potato, nine of which were reported from different parts of India (Singh et al. 1987). In India, the first report of dry rot caused by *F. sambucinum* was documented by Sagar et al. (2011). *Fusarium* wilt and dry rot has been reported in China, Tunisia, Egypt, the Great Britain, South Africa, Canada, Australia, the USA, Iran, and Poland.

19.7.1 Symptoms

In dry rot, the skin of infected tubers first becomes brown, then turns darker, and develops wrinkles. These wrinkles are often irregular concentric circles. In later stage, a hole may be observed in the center of ring with whitish or pinkish growth with one or more cavities (Fig. 19.6). At wilting stage, lower leaves turn yellow and affected plant dried off of fungal mycelium. After cutting the affected tubers, whitish to brownish colored tissues are visible. Sometimes partial stem infection is also observed where leaf symptoms may appear only on one side of the infected plants. Both stems and tubers at stolon end show vascular browning. Moreover, internal flecking of stem extending to upper leaves is also observed. Sometimes, damping off seedling type symptoms are also observed when temperature is high at early planting stage. Other symptoms like stem rot, damping off of seedlings, spots and necrosis on tubers, and seed pieces decay are also reported due to different *Fusarium*.

Fig. 19.6 Symptoms of dry rot in potato tubers

19.7.2 Epidemiology

Fusarium spp. are considered as both seed- and soilborne phytopathogen. Infected tubers and field soil are the primary source of inoculum. In general, the fungus remains viable in soil for 9–12 months. However, its resting structure (chlamydospores) can survive in soil for several years. *Fusarium* spp. have good saprophytic ability to survive in soil. The fungus grows well between 15 °C and 28 °C, and high humidity favors infection of tubers, and also congenial for secondary organisms such as *Erwinia* spp. can invade the infected tubers and cause soft rot. Infection of tubers occurs through wounds produced during harvesting operations, and dry rot develops slowly in storage. Temperature $>$ 10 °C favors *Fusarium* growth, while temperature $<$ 5 °C inhibits fungal growth. The pathogenicity of

Fusarium species varies significantly (Peters et al. 2008) with the potato cultivar and temperature during inoculation (Esfahani 2005). *Fusarium* wilt of potato is mainly affected by soil temperature and relative humidity. High wilt incidence in early planted crop is mainly associated with high temperature (Singh et al. 1990). The production of fusaric acid is also correlated with virulence of different *Fusarium oxysporum* (Yenter Sonja and Steyn 1998). Positive correlation was reported among thumb nail injury, wet rot, and *Fusarium* dry rot (Kumar et al. 2021).

19.7.3 Economics

Fusarium wilt and dry rot are caused by *Fusarium* spp. The wilt is caused under field condition and dry rot mainly at postharvest stages. Dry rot of seed tubers can reduce crop establishment by affecting the development of potato sprouts, decaying seed pieces, and causing crop losses up to 25% and occasionally losses up to 60% during long-term storage (Desjardins 2006; Wharton and Kirk 2007). In Tunisia, *Fusarium* wilt was reported to cause losses estimated at 30–50% of potato yield and decreased tuber quality (Kerkeni et al. 2013). Dry rot mainly occurs in storage condition, which causes 5–23% storage loss in plains (Sharma and Lal 2015), whereas wilt disease causes up to 19% losses under field condition in Western India; however, it causes 25–35% yield loss in highly infested field (Singh 2002). Recently, wide variation (0–90%) of *Fusarium* rot was recorded in seed lots of potato in Punjab (Kumar et al. 2016).

19.7.4 Management

Sanitation Use only clean and healthy seed tubers for planting and storage. The tuber damage and injury must be avoided during harvest, grading, transport, storage, etc. Adhering of soil on tubers must be avoided during harvesting. Washing of tubers to remove contaminated soil which adhere to the surface, besides, dry in shade can reduce the risk of infection. Curing of the seed tubers for 7–12 days at warm condition with dry atmosphere is suitable for wound healing. As far as possible, avoid cut tubers for planting because such tubers may get infected under infested soil.

Shallow planting and adjustment date of planting Deep planting should be avoided because it may cause more damage of the seed tubers. By adjusting 1 month delaying date of planting, *Fusarium* wilt can be reduced up to 36% disease incidence (Singh et al. 1990).

Crop rotation and soil solarization It will be better to follow longer (more than 3 years) crop rotation. Because 1or 2 years rotation had not shown significant results in managing *Fusarium* diseases. Crop rotations with Italian ryegrass, red clover, barley, or Italian red clover did not show significant reduction of dry rot diseases (Carter et al. 2003). In another study also, 3-year rotations with red clover, barley, and potato did not reduce significantly the severity of dry rot in 2 of the 3 years observed (Peters et al. 2004).

Soil solarization can be utilized to reduce the inoculum of soilborne pathogens. This process harnesses solar energy to increase soil temperature of moistened soil by covering soil with plastic films. Soil solarization minimizes the inoculum level of *Fusarium* spp. after 6 weeks of treatment (Saremi et al. 2011).

Soil amendments and botanicals Immature crop plant amendments, viz., pearl millet, sesbania, sunhemp, maize, and eucalyptus leaves, are used against *Fusarium* wilt of potato. Among these, eucalyptus leaves and maize show maximum suppression, and least was for sesbania. The groundnut cake was most effective than mustard cake and cotton seed cake for reducing the buildup of *Fusarium* wilt (Singh et al. 1988). Methanolic extracts of different plant species (eucalyptus, datura, thyme, lavender) revealed higher efficacy against *F. solani*, whereas aqueous extracts of these plant species showed less efficacy under lab and storage condition (Zaker 2014). Garlic and clove extracts (10%) were highly effective against *F. solani* under laboratory conditions (Awad et al. 2020).

Hot water treatment Artificially, wounded potato tubers may be dipped into hot water at 45 °C for 10 min. It was observed that hot water dipping was effective for wound healing of these tubers, thereby reducing weight loss and minimizing dry rot losses (Yanga et al. 2020).

Biological control The combined effect of antagonists *(Trichoderma* and *Pseudomonas)* with modified montmorillonite particles (Mod- MMT) against *Fusarium oxysporum* f. sp. *tuberose* showed less disease incidence and also enhanced plant height, fresh and dry weight, number of tubers/plant, and weight of tubers (Abeer and Makhlouf 2015). Application of *T. koningii* and *B. megaterium* alone or in combination 7 days earlier than soil infestation with *F. oxysporum* and/or the mixed population of *Meloidogyne* spp. significantly reduced *Fusarium* wilt disease incidence and nematode infection on potato and improved plant growth components under greenhouse condition. Generally, the mixture of the two biocontrol agents was more effective in controlling the plant disease and improving plant growth components than either of the two organisms used singly (El-Shennawy et al. 2012). The fungi *Aspergillus*, *Penicillium*, *Trichoderma*, and *Colletotrichum* showed positive response under in vitro against *F. sambucinum* and *F. solani.* These bioagents were isolated from roots, stems, and tubers of healthy plants (Trabelsi et al. 2016).

Varietal resistance Varieties like Baraka, Asterix, Alaska, Safrane, and Timate have some resistance against *Fusarium oxysporum* f. sp. *tuberose* in Tunisia (Ayd et al. 2006). The cultivar “Owyhee Russet” showed significantly higher resistance to dry rot than “Russet Burbank.” The cultivar Saturna and Frontier Russet and clone B-7200-33 are also reported as resistant and immune against *Fusarium* spp., respectively (Angelique et al. 2013).

19.8 Potato Wart

Potato wart is caused by *Synchytrium endobioticum* (Schilb) Perc. Potato wart was first reported in Trentschen, Slovakia, in Czechoslovakia in 1895 (Schilberszky 1896). Then it was reported to other countries. In India, wart disease of potato was first reported by Ganguly and Paul (1952) from Darjeeling hills, and it continues to be endemic to that area. It is a quarantine disease. The disease is known to many common names as per appearance of the symptoms, black wart, black scab, canker and cancer, cauliflower disease, etc. It was reported in Africa, Asia, Europe, South and North Asia, and New Zealand.

19.8.1 Symptoms

The disease shows cauliflower-like warty growths on tubers, stolons, and stem bases but not roots. The warts on tuber initially appear as small white granular swelling on the eyes. These warts on potato tubers may remain minute or may become as large as tuber. It depends on level of infection, variety, and available soil moisture. Under wet conditions, it may be seen in the form of greenish-yellow excrescences on the stem and leaves at or near the soil level. It is not necessary that all tubers from a diseased plant show wartlike symptoms. Diseased tubers may show either one or more tumors but sometimes are completely transformed into warty mass. Size of warts on tuber may be minute at harvesting time, but it may enlarge in stores.

19.8.2 Epidemiology

Wart disease is seed- and soilborne in nature. The pathogen spreads from one locality to another through infected seed tubers, infested soil adhering tubers, machinery, and other carriers of contaminated soil. The wart is favored by periodic flooding followed by drainage and aeration since free water is required for germination of sporangia and dispersal of zoospores of the pathogen. The resting sporangia are thick walled and may remain viable in soil for almost three to four decades. The resting sporangia may germinate over a wide range of temperature, the optimum being between 14 °C and 24 °C. The optimum temperature for wart development is found to be from 16.7 °C to 17.8 °C (Dutt 1979).

19.8.3 Management

Resistant varieties Host resistance is the best option to manage this disease. Wart-immune varieties, viz., “Kufri Jyoti,” “Kufri Bahar,” “Kufri Sherpa,” “Kufri Kanchan,” “Pimpernel,” and “Aeckersegen,” should be grown.

Quarantine Introduction of the disease in a field or locality can be effectively checked by strict quarantine legislation. Many countries have made possible to confine the disease with strictly enforcing quarantine measures.

Crop rotation Disease is both soil- and tuber-borne in nature. Therefore, application of long-term crop rotation (5 years or more) with non-solanaceous crops preferably maize, radish, cabbage, and pea would be helpful in minimizing the disease.

Agronomics Diseased seed tubers should not be used for planting. Rogue out plant of susceptible varieties. Warted lumps and potato peelings should not be thrown in the field or in the manure pit but destroyed by burning.

Soil amendments Infested soil needs to be amended with crushed crab shell for minimizing wart severity.

19.9 Silver Scurf

Silver scurf disease was recorded in Europe in 1871 and in Ireland in 1903 (Mckay 1955). After that, it was reported in Denmark, England, Brazil, the USA, India, Canada and Australia. In India, it was reported since 1962 in Nilgiris and in Darjeeling district (Srivastva 1965).

19.9.1 Symptoms

This disease does not affect foliage of the potato plant except stolons and tubers. Lesions could be seen on stolons after tuber initiation. On tuber skin, blemishes appear which start as small, round, silvery patches on the skin. When moistened the tuber lesions often appear as very clear silvery patches. These patches expand and merge during storage. Silver scurf does not usually cause any yield losses at harvest, but it does increase the permeability of the tuber skin, which leads to water losses and shrinkage during storage leading to weight losses reaching up to 17% (Read and Hide 1984).

19.9.2 Causal Organism and Epidemiology

Silver scurf is caused by *Helminthosporium solani*. Both tubers and soil may serve as primary sources of inoculum. The disease is favored by 12–26 °C along with 95% humidity. Symptoms are not normally present at harvest, but the disease can develop rapidly in store under humid, warm (>3 °C) conditions. The infection can spread from diseased to healthy tubers under storage. The disease is more common in sandy soils and red color varieties.

19.9.3 Management

Biological Control The infection of *H. solani* was reduced by fungal bioagent, *Clonostachys rosea* (*Gliocladium rosea*). A combination of different mechanisms, i.e., mycoparasitism, biocontrol-activated stimulation of plant defense mechanisms, microbial competition for nutrients, space, and antibiosis, etc., is involved to minimize silver scurf disease (Lysøe et al. 2017). Phosphorus acid-based products are effective to manage silver scurf of potato when applied at low to medium level of infection at postharvest (Hamm et al. 2013).

Crop Rotation Three years rotation with nonhost crop will reduce inoculum in the soil; subsequently infection would be reduced (Hamm et al. 2013).

Sanitation Potato seeds should be free from infection. It is essential to maintain hygienic condition in storage and avoid condensation of tuber surface for longer period.

Agronomics After haulms cutting and maturing of the skin of the tubers, harvesting should be followed. Harvested tubers should be shade dried before storage to reduce chance of infection.

19.10 Powdery Scab

This disease is sometimes known as corky scab. It is found mainly in cool and wet climates. Powdery scab was first reported as a disease in Germany in 1841 (Harrison et al. 1997). In India, it is mainly found in the higher hills specially Kumaon, Himalayas, Darjeeling, and Nilgiri (Ootacamund). It is also reported in Australia, Africa, America, Columbia, Japan, New Zealand, Russia, the UK, Pakistan, and Korea.

19.10.1 Symptoms

This disease attacks only the underground parts of the potato plants and does not show any effect on the growth of the plant. The underground parts include roots, stolons, tubers, and newly emerged shoots. On roots and stolons, small gall formation takes place, which is confused sometimes with symptoms of root knot nematode. Pimple-like spots appears on the surface of young tubers. These spots are circular, smooth, and light brown which gradually increase in size and later turn to scab-like lesions. However, unlike common scab, the lesions of powdery scab are round, raised, filled with powdery mass of spores, and surrounded by ruptured remains of the epidermis. Under certain conditions, wartlike protuberances may develop. Sometimes canker-like symptoms are also observed; whenever the eyes of the tubers are infected by the zoospores, canker formation takes place.

19.10.2 Causal Organism and Epidemiology

Powdery scab caused by *Spongospora subterranea* f. sp. *subterranea.* It is soilborne and obligate biotrophic pathogen. *Spongospora subterranea* f. sp. *subterranea* has both diploid and haploid phase in life cycle. The spore balls of pathogen on the tubers as well as in the soil serve as a source of infection. It can also survive in soil up to 10 years. The temperature below 18 °C and high soil water content favor the development of the disease. The infected root/stolons galls, which contain sporosori, are released into the soil. The pathogen also acts as the vector of potato mop-top virus (Harrison et al. 1997). The disease is more severe in heavy soil than the light soils.

19.10.3 Management

Cultural management By manipulating soil temperature during tuber initiation using plant covering with nonwoven fabric minimizes powdery scab on potato tubers up to 93%. In this process an increased average minimum and maximum soil temperature of 1.8 °C and 4.2 °C was achieved during experimentation (Tsror et al. 2020). Generally, tuber initiation phase is considered as the susceptible phase.

Sanitary measures Farm implements and container should be avoided from disease-affected areas, because they are sources to spread of spore ball/contaminated soil. Moreover, rotted tubers should not be kept in the manure pit, and also manures from animal fed with affected tubers should be avoided.

Disease-free seed It is essential to use of healthy seeds for planting; otherwise after planting diseased tubers, the inoculum level in the soil will be increased.

Drainage of field The disease can be managed by proper drainage facility in the fields because high moisture is conducive for powdery scab disease.

Crop rotation It was reported that crop rotation with *Brassica* crops (Indian mustard and rye grass) has been effective for minimizing incidence and severity of powdery scab (O'Brien and Milroy 2017). Growing non-solanaceous hosts in longer crop rotation also minimizes the disease up to certain extent.

Biological management During 3 years experimentation in Hokkaido, a fungus (*Aspergillus versicolor* Im6-50) was found effective to suppress pathogen *Spongospora subterranea* f. sp. *subterranea* with a protection value of 54–70%, when mycelia were applied directly on seed tubers, compared with a protection value of 77–93% by fluazinam (Nakayama 2021).

19.11 Conclusion and Future Outlook

The potato crop is an important vegetable crop in India and the world. It is directly utilized in vegetables and other processing products. Therefore, it would be better if we can use minimum chemical-based management strategies for managing fungal diseases of potato crop. In above chapter a comprehensive bio-intensive integrated management strategy for potato fungal diseases has been discussed. Bio-intensive management strategies enable management of diseases, besides maintaining soil health and ecological balance of microbes, which is helpful in sustaining the better crop yields with nutritious food.

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