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RHIZOCTONIA SOLANI OF POTATO AND ITS MANAGEMENT: A REVIEW

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ABSTRACT

Potatoes are an annual and the most cultivated tuberous crop worldwide. Potatoes play an important role to fulfil the world's basic food requirements because of enriched nutrients and delicious taste. Rhizoctonia solani is the most virulent and widely distributed soil-borne fungus that causes severe yield losses of potatoes globally. Several management practices have been adopted to overcome the yield losses inflicted by this fungus. Biocontrol agents play a significant role as mycoparasites and activate defense mechanisms through disease resistance genes to suppress pathogens. Compost is also applied as a soil amendment that increases soil fertility through the addition of organic matter in soil and nutrients uptake in organic form. Besides, it is a rich source of carbon and nitrogen which can address soil erosion, nutrients and organic matter depletion issues and restores soil fertility by adding organic matter and reducing the incidence of soil-borne pathogens in the soil. Biochar utilization in the agriculture sector is increasing day by day because of its great potential for disease suppression. Both biochar and compost are used commercially to improve plant growth and suppress potato diseases caused by R. solani. Therefore, in this review, we discussed the symptoms on potatoes, epidemiology and biological characteristics of R. solani and summarized to date control strategies mainly focusing on biological, chemical, biochar

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and compost approaches.

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INTRODUCTION

Potato (*Solanum tuberosum* L.) is the most popular and consumed nutritious crop of the family *Solanaceae* all over the world (Abbas et al., 2012). Potato was first cultivated in Peru in 5000 BC and in Europe in 1567 (Juzepchuk and Bukasov, 1929). It has become an important part of daily food in most of the European and Asian countries because of high nutrient supply as starch, carbohydrates, proteins and vitamins. This tuberous crop contains 77.8% water, 2 g protein, 13 g calcium, 12 mg ascorbic acid, 0.06 g riboflavin and energy of 85% calories (Rauscher et al., 2006). In medical science, antioxidants from potato are quite helpful against cancer, high blood pressure and heart diseases (Al-Saikhan et al., 1995). Potato growth is strongly affected by temperature and soil moisture (Mittler, 2006). Potato production is affected by irrigation problems, poor seed quality, biotic and abiotic factors (Khan et al., 2016). Biotic factors may include fungi, viruses, bacteria, nematodes and insect pests which have a drastic effect on potato production by causing severe diseases (Ahmed et al., 2018; Haneef et al., 2021; Majeed et al., 2017). Fungi play a tremendous role in potato yield loss by causing foliar, tuber and soil-borne diseases. *Rhizoctonia solani* (Teleomorph*; Thanatephorus cucumeris*) is the most devastating pathogen of potato among all soil-borne fungi (Ahmad et al., 1995) which causes black scurf, root rot, stem canker and damping-off disease complexes of potato crop (Bains et al., 2002). Temperature and soil moisture play important role in disease development. The optimum temperature is 20-25°C and moisture is 20% for its growth. This pathogen produces symptoms on both above and below-ground plant parts of potato. The most obvious and characteristic symptoms are brown to black sclerotia on potato tubers known as black scurf of potato (Carling and Leiner, 1986). Sclerotia are black, irregular shaped resting spores of *R. solani* that tightly adheres to the tuber surface with the lump of soil. Black scurf has a negative impact on the market quality of potato and results in an economic loss (Carling and Leiner, 1990). Above ground symptoms include brown lesions on the collar region of the plant that leads to stem canker, stem girdling, yellowing, leaf curling, root detrition and falling off the plant (Baker, 2020).

Integrated disease management practices are adopted worldwide to manage this pathogen (Alptekin, 2011). The most commonly used methods are cultural and chemical control and the use of disease-free seed (Daami-Remadi et al., 2008; Larkin et al., 2017). Potato crop can be rotated with barley, beans and alfalfa. Moreover, crop rotation for 3-5 years also minimizes *R. solani* survival in soil (Larkin and Honeycutt, 2006). Biological control agents (BCAs) are capable of suppression of *R. solani* in soil. *Trichoderma* spp. is the most reliable BCAs to inhibit *R. solani* through hyperparasitism and production of lethal metabolites (Antal et al., 2000). Furthermore, many fungicides are used to overcome yield losses due to *R. solani.* The most commonly used fungicides are Dithane-M, Mancozeb and Captan which are used as seed treatments (Olaya et al., 1994). However, the use of fungicides to manage this pathogen is unsafe and costly (Wharton et al., 2007). Hence, certain ecofriendly approaches like nutrients, organic amendments, composts, biochar, plant extracts and oils are used as an alternative to chemical control against *R. solani* (Pawar and Thaker, 2006). Compost is a heterogeneous organic material prepared from animal manures, greenhouse waste, vegetable waste, bark solids and grape marcs and are strongly capable of inhibition of soil-borne pathogens (Hoitink et al., 1997). Compost is effective against many soils borne fungal pathogens like *Rhizoctonia* spp., *Pythium* spp., *Fusarium* spp., *Phytophthora* spp. and *Sclerotium* spp. (Noble and Coventry, 2005). It is enriched with carbon, nitrogen, and micronutrients which fulfill the nutrient deficiency of plants in soil (De Ceuster and Hoitink, 1999; Yogev et al., 2006). Besides, *biochar plays an important role to attain a sustainable environment because of the long term availability of carbon compounds to the soil that maintains soil fertility (Lehmann and Jospeh, 2009). Biochar improved the physicochemical and biological characteristics of soil like water holding capacity, cation exchange capacity, nutrients uptake and retention, maintain the pH level of acidic soils, soil microbial population that are the necessary elements for better* *plant growth and induced resistance in plants against pathogens (Bonanomi et al., 2014). Now a day biochar is a good organic source to manage yield losses and reduce disease incidence caused by soil-borne pathogens (Bonanomi et al., 2015). Biochar suppression mechanism is quite similar to compost (Kraus et al., 2003). It is proved that biochar induced resistance in plants through both salicylic acid and jasmonic acid pathways and enabled plant enzymatic activities quicker to produce antioxidants against fungi (Wang et al., 2014). In this review, we describe anastomosis groups (AGs), symptoms on potato caused by* R. solani*, epidemiology, disease control approaches including host resistance, cultural, chemical, biological, and recent disease control approaches such as* compost and biochar.

Anastomosis Groups (AGs)

To date, thirteen AGs designated as AG1–AG13 and AG-BI have been assigned based on hyphal anastomosis interaction. Among these AGs, AG-3, AG-5, AG-8, AG-4, and AG-2 have been reported to infect potato (Nejad et al., 2007). Pathogenicity test of these isolates performed on potato showed that isolates of AG-3 were found more virulent than others (Woodhall et al., 2007). They worked on the modification of a previously published primer to study anastomosis groups of *R. solani.* Anastomosis groups were assigned to the isolates through conventional PCR assays and the hyphal observations. Twenty isolates of *R. solani* AG-3 were isolated from diseased potato produced in lower Egyptian areas. The pathogenicity of these isolates was tested on nine potato varieties under greenhouse conditions. Symptoms of black scurf and stem canker confirmed the pathogenicity of *R. solani* AG-3 (Abd El-Aziz et al., 2013).

Symptomology

R. solani produced both above ground and below ground symptoms on potato. Above-ground symptoms include yellowing and necrotic lesions at the collar region of stem (Jeger et al., 1996). Below ground symptoms represent brown water-soaked lesions on roots and dark black colored sclerotia on potato tubers which may damage the economic value of potato (Kataria and Gisi, 1996). Symptoms were observed after four weeks of germination by uprooting plants. Symptoms of stem canker were observed at two weeks of germination while necrosis, yellowing, wilting and canker at collar region were observed at 3rd and 4th weeks of germination. The disease symptoms of leaf spot and root rot caused by *R. solani* appeared on tobacco. *R. solani* survived in the soil in form of black persistent sclerotia of diameter 8-10 mm. *R. solani* was responsible of causing root rot disease and produced symptoms of stem rot, damping off, target spots on stem, water-soaked lesions on leaves and stem, rotting of roots and wilting in tobacco (Gonzalez et al., 2011).

Epidemiology

Epidemiological factors such as temperature and soil moisture play an important role in mycelium growth of *R. solani* and disease development on potato. Black scurf and stem canker diseases are severe at 16-23°C. Environmental factors such as low temperature, humid soil, cool weather and high humidity were found responsible for disease occurrence (Das et al., 2014).

Management

R. solani is a destructive pathogen of potato crop and there is an urge to overcome potato yield losses by suppressing the pathogen. Many known methods such as agronomic or cultural practices, chemical control, biological control, nutrient application and organic amendments are used since many years against *R. solani*. Disease management strategies have been summarized in Table 1.

Table 1. Disease management strategies.

Disease Management									
Genetic Resistance		Cultural Practices			Chemical Control		Biological Control		
Resistant Varieties	Screening	Crop Rotation	Sowing Time	Mulching	Nutrient Application	Fungicide Application	Using Plant Extracts	Using Biochar	Using Compost

Host resistance

Rauf et al. (2007) carried out a greenhouse experiment to evaluate 15 potato varieties against *R. solani* (AG-3) isolate CL-58. Naz et al. (2008) evaluated the virulence of *R. solani* AG-3 isolate (CL-58) at 10, 15, and 20 inoculum levels on potato varieties (Cardinal, Desiree, SH-216-A, TPS-9813, CIP 393594-61). Screening of varieties showed that Desiree and SH-216-A were found susceptible and cardinal and CIP 393594-61 were found resistant against *R. solani* AG-3 (Mohsan et al., 2016).

Cultural approaches

Agronomic practices

Several agronomic practices like crop rotation, sowing date, sowing method and disease-free seed are adopted to avoid pathogenic problems in the field. The impact of agronomic practices (date of planting, irrigation, and size of seed tubers) was studied on soil-borne destructive pathogenic fungi *R. solani* of potato. The experiment was carried out and data were analyzed through linear contrast, quadratic contrast, and the area under disease progress or host growth curve. Results showed that late planting dates and pre-emergence irrigation decreased the disease incidence of stem canker while the size of seed tuber did not affect disease reduction (Simons and Gilligan, 1997). The use of fungicides and agronomic practices to inhibit the growth of *R. solani* on potato plants was also found effective (Bains et al., 2002). Agronomic practices included crop rotation of potato with *Beta vulgaris, Brassica campestris, Hordeum vulgare, Pisum sativum, Triticum aestivum, Zea mays* crops reduced the black scurf disease on potato. The impact of crop rotation and tillage practices to overcome disease losses of potato caused by soil borne pathogens is also well established. Crop rotation of 2 and 3 years was practiced with conventional or minimum tillage (Peters et al., 2004). Three-year crop rotation significantly reduced stem and stolon canker and black scurf symptoms caused by *R. solani* than two-year rotation. Crop rotation was the main factor to overcome *R. solani* diseases as compared to tillage practices. The sowing dates have an impact on the yield and growth parameters of the potato.

Three potato varieties (BARI Alu-35, BARI Alu-40, BARI Alu-41) were planted at three dates (November 20, December 5, and December 29). The sowing time of December 5 showed maximum plant height of 42.3 cm in variety BARI Alu-40, the highest number of tuber/plants 13 in variety BARI Alu-41, highest tuber weight/plant of 97.25 g in variety BARI Alu-35, and the maximum potato yield of 42.12 t/ha in variety BARI Alu-41. It can be recommended from the results that December 5 is the suitable sowing time for the potato with concerns to yield and physiological parameters (Ahmed et al., 2017). The microbial amendments, *T. virens* and *L. arvalis* reduced black scurf and stem canker in some rotations and increased tuber yield and quality (Larkin et al., 2017).

Nutrients application

Nutrient application is the safest way to reduce disease losses and improve plant growth (Jeger et al., 1996). Sulphur fertilizer was used to control *R. solani* and *S. scabies* infection on potato. Sulphur significantly improved plant health and increased tuber yield and reduced infection of *R. solani* on potato in both years at an increased dose of 50kg/ha of elemental S and K_2SO_4 while there was no impact of Sulphur on *S. scabies* reduction. It was concluded that Sulphur fertilizer was good for potato health as well as reduction of *R. solani* infection on potato. Silicon was used as a remedy to suppress fusarium crown and root rot disease of tomato caused by *F. oxysporum* f.sp. *radicis-lycopersici*. Silicon prolonged the initial infection and slows down the movement of pathogen from roots to upward parts of the plant. It was evident from the results that more silicon uptake by roots reduced the disease severity. Another nutritional management was performed by Ngadze (2018) on soft rot and black leg diseases of potato caused by *Pectobacteroum* spp. and *Dickeya dadantii*. Calcium nitrate reduced the disease incidence of black leg and soft rot up to 20%. Maximum yield 39.27 of tons/ha was reported in the block treated with compound S + ammonium nitrate. Calcium nitrate reduced postharvest losses and increased the shelf life of potato. They proved that calcium nitrate was efficient in defense mechanism of the plant by inducing resistance.

Chemical approaches

Synthetic fungicides

Fungicide application is the most common method to suppress plant diseases. The most commonly used fungicides are Azoxystrobin, Mancozeb and Imazalil to reduce disease incidence of black scurf and damping-off (Kataria and Gisi, 1996). Seed treatment with 3% boric acid and 3% Dithane M-45 gave significant results and reduced the disease incidence, whereas soil treatment of bleaching powder and Sulphur had no impact on disease incidence. Certain fungicides such as Strobilurin fungicides (Azoxystrobin and Pyraclostrobin) with two nitrogen levels (high and low) were applied to suppress *Alternaria solani* responsible for early blight disease in potato. Both fungicides had a significant effect on tuber yield and reduced disease severity by 3% than control 25-75% while low nitrogen had 12-25% of lesions on leaves as compared to high nitrogen reduced lesions up to 3-6%. There was no significant impact of nitrogen on tuber yield. Bokhari et al. (2008) checked the efficacy of

Trichoderma harzianum and fungicides (Topsin M, Alert plus, Reconil M) to suppress guava decline caused by soil borne pathogens (*Botryodiplodia theobromae, Fusarium oxysporum* f.sp. *Psidii, Phytophthora parasitica,* and *Fusarium solani* f. sp. *Psidii*). Results concluded that *T. harzianum* and Topsin M reduced the disease incidence up to 0.0 and 0.74% in sterilized and unsterilized soil respectively. Salicyclic acid (SA) affected black scurf disease and stem canker disease of potato caused by *R. solani*. All SA treatments with *R. solani* inoculation suppressed the symptoms of black scurf and stem canker as compared to control.

Disease severity was reduced by 89.6 and 88.8% through treatments of un inoculated seed tubers with SA foliar application and un inoculated tubers with SA soil drenching. SA treatments inoculated with *R. solani* increased tuber weight as compared to control. The SA has a significant effect on black scurf disease reduction (Al-Mughrabi, 2008). Different fungicides (azoxystrobin, prothioconazole, pyraclostrobin, difenoconazole, propiconazole, flutolanil, polyoxin D) were evaluated to suppress *Rhizoctonia* root and crown rot of sugar beet caused by *R. solani* AG-2-2. Among fungicides azoxystrobin, flutolanil and polyoxin D were found highly significant in disease suppression caused by AG-2-2 IIIB and AG-2-2 IV (Bolton et al., 2010).

Bio fungicides and phytochemicals approaches

Plant or botanical extract is a useful eco-friendly approach against phytopathogens. Tree seeds powder of *Azadirachta indica, Adenanthera pavonina* L.*, Leucaena leucocephala* and *Eucalyptus* spp. were evaluated against *R. solani, Fusarium* spp. and *Macrophomina phaseolina* to suppress root rot disease on mung bean and chick pea crops. *A. pavonina* at 1% w/w application showed maximum inhibition of *R. solani* and *Fusarium* spp. on mung bean plants. *A. pavonina* and *Eucalyptus spp.* suppressed the disease at 0.1 and 1% w/w amended with soil (Ahmed et al., 2009). Fermented onion extract proved effective against damping off disease caused by *R. solani* and *S. rolfsii* under lab conditions. Broth (B) and Sterilized Broth (SB) were prepared and incubated for 14 days at room temperature, with or without sterilization and mixed with PDA at concentrations of 1.7, 3.3, 8.3, 16.7 and 25%. Treatments 8.3, 16.7, 25% of Broth inhibited the growth of sclerotia for both tested pathogens. It is suggested from the results that unsterilized onion extract reduced the disease risk of damping off (Rivera et al., 2013). The antifungal ability of five plant extracts *Lantana camara, Salvadora persica, Thymus vulgaris, Zingiber officinale* and *Ziziphus spina-christi* and fungicide carbendazim against damping-off disease-causing organisms *F. oxysporum, P. aphanidermatum* and *R. solani* of tomato through *in-vitro* experiment of food poison technique. *T. vulgaris* and *Z. officinale* were found highly effective against these fungal pathogens with the concentration of 8 mg ml^{-1} and for *F. oxysporum* concentration of *Z. officinale* is 16 mg ml^{-1}. A moderate fungicidal ability was shown by *S. persica* while *Z. spina-christi* had no inhibitory effect on these fungi and *L. camara* had antifungal ability against *P. aphanidermatum* with 10 mg ml^{-1} concentration (Al-Rahmah et al., 2013). Carbendazim at 8 ppm was highly effective against these fungal pathogens. Chemical analysis of these plant extracts through Gas chromatography and Mass spectroscopy showed that *T. vulgaris* had 38.73% thymol, 19.31% carvacrol, 10.31% β-cimene and 5.94% α-terpinolene while *Z. officinale* was mainly consisted of 46.85% gingerol, 8.39% cedrene, 7.41% zingiberene, and 7.32% α-curcumene. The contribution of these plant extracts are the best alternate for fungicides. Hussain et al. (2014) used six plant extracts of *Cannabis sativa L.*, *Peganum harmala* L.*, Datura starmonium* L.*, Artemisia brevifolium* L.*, Capparis spinosa* L.*, Mentha royleana* L. and two bioagents; *T. harzianum* and *T. viride* for their antagonistic ability against *R. solani* under lab conditions through food poison and dual culture techniques. All plant extracts at 5-15% concentrations restricted the fungal growth. Khan et al. (2016) used three phytobiocides of turmeric, chilli, and pepper *in vitro* and two phytobiocides (turmeric and chilli) in screen house with bioagent *Paecilomyces* spp. to control *R. solani* on potato. All the three phytobiocides effectively inhibited the mycelium growth. In screen house test, two effective phytobiocides turmeric and chilli were used with bioagent *Paecilomyces* spp. Turmeric was found highly effective with the disease severity followed by *Paecilomyces* spp. Poisoned food technique performed for the evaluation of phytobiocides (Neem oil, garlic, ginger, pepper and turmeric) in PDA. Among phytobiocides garlic was found effective in reducing the colony diameter while others also have an inhibitory effect on *R. solani* except ginger. The antifungal ability of ethanol extract of *Silybum marianum* was evaluated against soil-borne pathogen *R. solani* through *in vitro* experiment by using different concentrations (5, 10, 15, and 20%) (Salim et al., 2017).

The 20% concentration was the best. Antifungal abilities of nine plant extracts; *Momordica charantia, Allium sativum, Eucalyptus globules, Azadirachta indica, Parthenium hysterophorus Calotropis procera*, *Aloe vera*, *Beta vulgari* and *Datura stramonium* assessed against three soilborne plant pathogens *R. solani, F. oxysporum* f.sp. *melongenae* and *M. phaseolina* through *in vitro* experiment (Cherkupally et al., 2017). The mycelial growth of *M. phaseolina* was completely suppressed by all concentrations of *A. sativum* extract. Plant extracts of *D. stramonium* and *E. globulus* at 20% suppressed *R. solani* by 72% and 70.7% respectively while *A. sativum, E. globulus* and *D. stramonium* were found suppressive against *F. oxysporum* f.sp. *melongenae* up to 60%.

Biological approaches

The use of biocontrol agents against phytopathogens is another environment-friendly and safe method. Certain fungi (*Trichoderma*, *Aspergillus*, *Verticillium*) and bacteria (*Bacillus*, *Pseudomonas*, *Actinomycetes*) are the most commonly used biocontrol agents and suppress soilborne diseases up to 78% (Escande and Echandi, 1991). *T. harzianum*, non-pathogenic *Rhizoctonia* and cattle manure compost were used to reduce black scurf disease of potato caused by *R. solani.* Treatments *T. harzianum,* non-pathogenic *Rhizoctonia* isolates (RS 521 and RU 56-8-AG-P), and compost were applied in furrows under field conditions. All treatments highly reduced the disease incidence on potato crops (Tsror et al., 2001). Biocontrol efficacy of *Trichoderma* isolates (*T. asperellum, T. harzianum* and *Trichoderma* spp.) was observed by Asad et al. (2014) in an aqueous and volatile form to suppress *R. solani* through *in vitro* and *in vivo* studies. *In vitro* observations revealed that aqueous treatments of *Trichoderma* isolates inhibited the fungal growth up to 74.4-67.8% on PDA as compared to volatile treatments 10.6-15.3%. A greenhouse study on bean plants revealed that *T. asperellum* was more effective with the disease incidence of 19.3-30.5% than the remaining isolates. The biological control as *T. harzianum*, effective microbe (EM) culture, biological potassium fertilizer (BPF) of *R. solani* on potato. Treatments were applied in the soil at interval of 20 days. *T. harzianum* was found best to minimize the disease incidence and improve tuber yield (Rauf et al., 2015). Antifungal ability of *Aspergillus* spp. tested isolated from soil and compost to suppress disease incidence of *Fusarium* dry rot and pink rot of potato caused by *Fusarium sambucinum* and *Phytophthora erythroseptica*. Nine isolates of *Aspergillus* spp. were analyzed through *in-vitro* and *in-vivo*. The dual culture showed that all *Aspergillus* isolates inhibited the mycelial growth of *F. sambucinum* and *P. erythroseptica* and the isolate CH12 of *A. niger* gave maximum inhibition. Bacteria are often used as a biocontrol against many diseases such as evaluated 10,000 bacteria against the black leg and soft rot diseases of potato caused by *Dickeya dianthicola* and *Pectobacterium* spp. Among them, 58 bacterial strains belonging to *Pseudomonas* and *Bacillus* species were found effective to inhibit pathogen growth. Management of potato common scab disease caused by *Streptomyces scabies* was carried through biocontrol agent *Bacillus* spp. under greenhouse and field conditions. *Bacillus* bacteria were isolated from the potato rhizosphere and their efficacy was studied against *S. scabies*. Among all the isolates, *Bacillus amyloliquefaciens* Ba01 was found effective to inhibit pathogen of potato common scab (Lin et al., 2018). The management of *R. solani* and *F. solani* of cucumber through bacterial antagonist *P. flourescens* and *B. subtilis* through *in vitro* and greenhouse experiments proved effectivd. It was obvious from *in vitro* and greenhouse experiment results that both bacteria *P. flourescens* and *B. subtilis* completely inhibited the growth of *R. solani* and *F. solani* (Al-Fadhal et al., 2019).

Biochar application

Biochar is a good organic amendment that has been used since ancient times to suppress pathogens and improve plant growth. Greenhouse experiments carried out to suppress gray mold and powdery mildew diseases on pepper and tomato caused by *Botrytis cinerea* and *Leveillula taurica* and insect pest *Polyphagotarsonemus latus* by using citrus wood biochar and coconut fibre potting mixture. The biochar significantly inhibited the diseases by inducing resistance in plants. Biochar at 5% concentration reduced the disease incidence of gray mold on pepper and tomato up to 58% and 75% respectively. While powdery mildew disease was suppressed by 3-5% biochar on pepper and tomato as compared to control (Elad et al., 2010). The hard wood dust biochar was used at 1.5 and 3% to suppress *Fusarium* crown and root rot diseases of asparagus caused by *F. oxysporum* f.sp. *asparagi* and *F. proliferatum* and checked the impact of biochar on root colonization of arbuscular mycorrhizal (AM) fungi on asparagus through allelopathic chemicals in greenhouse trail. It was clear that biochar reduced the disease symptoms and increased the root weight of asparagus plants. Biochar at 3% concentration increased root colonization of AM on asparagus roots. Allelopathic chemicals (cinnamic, coumaric, ferulic acid) harmed AM but in the presence of biochar, these chemicals have no harmful effect on root colonization of AM (Elmer and Pignatello, 2011). The suppression of stem canker disease of trees caused by *P. cinnamomi* through biochar is well proven. The experiment was performed with biochar prepared from pine trees at concentrations of 0, 5, 10 and 20% mixed in peat moss potting mixture and *P. cinnamomi* was inoculated through stem wound into seedlings of red oak and red maple. Disease suppression was recorded in horizontal and vertical means as vertical expansions include the total length of necrotic plant regions and the percentage of necrotic plant parts included were mentioned in horizontal assessment. The 5% biochar greatly reduced horizontal stem lesions in both plant hosts and vertical disease expression in red maple. Stem water potential in red oak and stem biomass of red maple was significantly influenced and increased by the addition of 5% biochar in the potting mixture (Zwart and Kim, 2012). The 20% compost alone or in combination with wood biochar (WB), garden waste residues biochar (GWB), and 3% arbuscular mycorrhizal fungi (AMF) used as soil substrates to change root exudates of tomato plant against *Fusarium oxysporum* f.sp. *lycopersici.* Soil substrate of GWB and AMF has a positive impact on tomato growth, while soil treatment with WB and AMF significantly reduced the microconidia produced by *F. oxysporum* f.sp. *lycopersici.* It is evident from the results that wood biochar (WB) with arbuscular mycorrhizal fungi (AMF) as a soil substrate changed the root exudates of the tomato plant and suppressed the production of microconidia in soil and reduce the disease assessment (Akhter et al., 2015). Efficacy of biochar against tomato wilt and root rot diseases caused by *F. oxysporum* and *R. solani* also proved good (Khalifa and Thabet, 2015). Salix wood chips biochar was applied as a potting mixture 5% of the weight. They revealed that without biochar, treatments had a high disease incidence of 86% in tomato wilt and 80% in root rot respectively. Wood or plant-based biochar is found very effective against many plant diseases such as used wood biochar as a remedy to control root-knot nematode (*Meloidogyne graminicola*) population in the rice field and observed molecular defense response of rice plants against root-knot nematode in a pot experiment. Biochar triggered plant defense mechanism and induced plant resistance through the accumulation of H_2O_2 as biochar primed and increase gene involvement in ethylene (ET) signaling pathway of plant resistance. Growth parameters plant length, root length, shoot length, shoot weight, root weight was also improved. Two types of biochar made from peanut shell (BC1) and wheat straw (BC2) are used as soil treatments against bacterial wilt disease of *Solanaceae* crops caused by *Ralstonia solanacearum.* Both biochars were found best to reduce disease incidence up to 28.6 and 65.7%. Biochar not only reduced the *R. solanacearum* in soil but also increased microbial population and nutrients phosphate and urea in soil (Lu et al., 2016).

Suppression of fusarium crown and root rot diseases of tomato caused by *Fusarium oxysporum* f.sp. *radices-lycopersici* through biochar. Two types of biochar; EUC-600 (eucalyptus wood chips biochar prepared at 600℃) and GHW-350 (greenhouse pepper plant wastes biochar prepared at 350^{0}C) at concentrations of 0, 0.5, 1 and 3% (w/w) were applied with potting mixture under greenhouse conditions (Jaiswal et al., 2014). Biochar combined with compost against plant diseases always showed better results such used vermicompost and two types of biochars based on sugarcane bagasse and rice husks at 1% to suppress root rot of common bean caused by soil-borne fungi (*F. oxysporum*, *F. solani*, *P. ultimum*, *R. solani*) in pot experiment under greenhouse conditions. Results stated that rice husk biochar with vermicompost increased shoot weight of plants up to 29% and sugarcane bagasse biochar with the combination of vermicompost increased root length up to 53% rather than the rest of treatments. Rice husk biochar with vermicompost had a significant impact on disease reduction and reduced the disease severity up to 33.3% (Were et al., 2019). The 2% wheat straw biochar under greenhouse is used for the management of bacterial wilt of tomato. Impact of biochar on soil properties and microbial community was observed. The biochar reduced the disease severity by up to 26-50%. Biochar improved soil chemical properties by increasing organic matter, C: N ratio, nitrogen, carbon, phosphorus, potash and electrical conductivity. Rhizosphere sequencing of 16S rRNA cleared that biochar increased beneficial Bacteriodetes and Proteobacteria in inoculated soil of *R. solanacearum* (Gao et al., 2019). The biochar and oil cakes (mustard cake, cotton cake, jasmine cake, sesame cake, and gooseberry cake) used to suppress the root-knot nematode (*Meliodogyne incognita)* population on lentils. The biochar (45 g) with oil cakes (15 g) had a significant impact on plant growth and nematode population reduction. The treatment combination of biochar and mustard cake suppressed nematode infestation in soil by reducing egg masses and eggs up to 56% and 52.7% and improved plant growth by increasing plant height and dry weight up to 74.1 and 63.8% respectively (Ansari et al., 2020).

Compost application

The first time in 1960, tree bark was used as an organic amendment by a nursery man who improved plant health. After that bark compost was often used to suppress *Phytophthora* root rots in horticultural plants. Nowadays compost is a good alternative to fungicides against plant pathogens (Hoitink et al., 1991). *In vitro* experiment was conducted to assess the antifungal potency of nine compost extracts with different animal manure proportions against plant pathogenic fungi (*Fusarium oxysporum* f. sp. *radicis-lycopersici*, *F. solani, F. graminearum, Fusicoccum amygdalis*, *Alternaria* sp., *Colletotrichum coccodes, Botrytis cinerea, Scelrotinia scelrotiorum, Aspergillus niger, Rhizoctonia solani, R. bataticola, Pythium* sp. and *Verticillium dahlia.* All treatments minimized the mycelial growth of these fungi but Compost extract C2 that was consisted of 60% cattle manure, 30% sheep manure, and 10% ground straw and Compost extract C7, composed of 40% cattle manure, 40% sheep manure, and 20% vegetable wastes, were suggested highly effective against the tested fungi. The management of *Pythium aphanidermatum* on tomato by using three composts Solid Olive Mill Wastes (SOMW), *Posidonia oceanica* (PO), and Chicken Manure (CM) at different concentrations through *in vitro* and *in vivo* experiments. *In vitro* results showed that compost extracts inhibited the growth of *P. aphanidermatum* on PDA. *In vivo* experiment was performed through drenching and dip root inoculation method and their results showed that root dip inoculated tomato seedlings with composts had better growth than drenching substrate with compost. Efficacy of chicken, pigeon, and cow manure used to manage stem canker and black scurf disease of *R. solani* on potato under *in vitro* and open greenhouse conditions. *In vitro* findings revealed that animal manure extracts at different concentrations (0-50) decreased the mycelial growth of targeted fungi but the highest reduction was due to pigeon manure extract at 50% concentration. In greenhouse trial cow manure highly suppressed the disease at all concentrations while pigeon and chicken manures suppressed the disease incidence at 1% (Abo-Elnaga et al., 2012). The mixture (70:30 v/v) of vegetable waste and *Posidonia oceanica* compost to manage *Fusarium* wilt of tomato caused by *F. oxysporum* f.sp. *lycopersici* through *in vitro* and greenhouse experiments showed good effect. There were nine treatments sterilized and unsterilized (0.5, 1, 2, 4, 6, 8, 10, 15, 20%) of compost extract. All unsterilized treatments inhibited mycelium growth on PDA as well in pots. Higher concentrations of 15 and 20% of sterilized compost extract were found significant in pathogen inhibition (Kouki et al., 2012). The field experiment was performed to suppress stem canker disease of potato caused by *R. solani* through ten treatments (Control, Ridomil fungicide, compost tea as foliar application, compost tea as soil application, poultry litter extract as soil application, compost, poultry litter, bio pesticide, BAU-biofungicide, mustard oil cake). Treatments were applied through the foliar spray and soil drenching. The foliar and soil treatments both reduced disease incidence than control and improved growth parameters and yield of potato. Benefit-cost analysis of the treatments had shown that foliar spray of compost tea gave best results with profit of 65.20% followed by soil application of BAU-biofungicides with 54.38%, Ridomil with 35.31% and foliar spray of BAU-biofungicides with 38.88% (Islam et al., 2013). The efficacy of three compost teas (pine bark, manure, and vermicasting), Root Rescue Landscape Powder, and a greenhouse nutrient solution against six pathogens *Fusarium foetens, Rhizoctonia solani, Sclerotinia sclerotiorum, Phytophthora cryptogea, Pythium intermedium, and P. ultimum* was performed *in vitro* experiment. All treatments had significant effect in reducing the fungal growth of these pathogens. Pine bark tea suppressed the growth of all six pathogens up to 50%; vermicasting tea suppressed *S. scelrotiorum* and *F. foetens* up to 40%; manure tea showed suppression of 42% against *F. foetens;* greenhouse nutrient solution suppressed *R. solani* 56.7% and *F. foetens* 43.4%; Root Rescue Landscape Powder showed 66% inhibitory effect against *P. intermedium* (Tian and Zheng, 2013). Five commercial composts were used to suppress root rot pathogens (*Fusarium solani, Pythium ultimum, Rhizoctonia solani*, and *Scelrotium rolfsii*) of cucumber plant through *in vitro* and greenhouse trails. *In vitro* results concluded that unautoclaved and unfiltered composts water extracts reduced the growth of all tested fungi as compared to autoclaved and filtered ones. Results of greenhouse trial in pots showed that composts are suitable treatments to reduce the disease incidence and tested fungi population in soil and helped to improve plant growth parameters like root length, shoot length, fresh weight and dry weight (Sabet et al., 2013). Fungi were isolated from the composts against *R. solani* on PDA through the dual culture method and observed under the microscope. Microscopic observations revealed that the mechanism involved in suppressing the pathogenic fungi are mycelia lyses and mycoparasitism. Unsterilized and unfiltered compost extracts were found best to control *R. solani* because composts lost their active agents through filtration and heating. Greenhouse trial results concluded that date palm compost with cattle manure (CMC) amended with peat-sand highly reduced the black scurf and stem canker disease incidence of potato than date palm compost with sheep manure (SMC). Compost enriched with biocontrol agents has been found very effective to manage soil-borne diseases such as using *Trichoderma* fortified compost against soil-borne fungi (*Fusarium oxysporum, Rhizoctonia solani* and *Scelrotium rolfsii*) on chickpea. Among these isolates' Co-7 was found effective in reducing the mycelial growth of pathogenic fungi. In field experiment *Trichoderma* compost with saw dust, cow dung, tea waste, water hyacinth and poultry manure were applied as treatments. *Trichoderma* supplemented with poultry manure gave effective results in reducing pre-and post-emergence seedling mortality disease. The efficacy of sterilized and unsterilized compost extracts against *F. oxysporum* f.sp. *albedinis* that causes vascular wilt disease of date palm. Results cleared that all concentrations of unsterilized compost extract inhibited the fungal growth from 20-97%. Concentrations 30 and 40% gave the highest suppression of 93%, while sterilized compost extract had the least effects in reducing the disease (Said et al., 2017). The suppression of *F. oxysporum* f.sp. *lupini* and *R. solani* by using compost and pomegranate peel extract as an alternative of chemicals under lab and field conditions. *In vitro* experiment was performed with different formulations of compost and pomegranate peel powder in simple water and alkaline water. Results showed that compost and pomegranate peel powder tea formulations in alkaline water suppressed the *F. oxysporum f. sp. lupini* and *R. solani* up to 60 and 70% respectively. All treatments combination of compost tea and pomegranate peel powder in the field gave significant results in minimizing the disease incidence of wilt and damping-off and improved the growth of lupine plants. Compost tea with pomegranate peel powder is highly recommended because of less cost and no side effects (Abou -El-Nour et al., 2020).

CONCLUSION

In conclusion, careful selection of crops in rotations with potato, and management of *R. solani* in an integrated approach using biological, chemical, cultural with compost and biochar, may reduce future incidence and severity of diseases caused by *R. solani*.

AUTHORS' CONTRIBUTION

All the authors equally participated in collecting, organizing, writing and editing the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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