REVIEW

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REVIEW

Biointensive approaches : an eco-dynamic strategy for sustainable management of soil borne plant pathogens

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The pathogens which survive within the soil or in the crop residues on the soil surface are called soilborne plant pathogens. The soilborne plant pathogens are considered as hidden or silent killers because mainly the cases infection initiates below the ground and it becomes very late to initiate any crop protection measures when visible symptoms or signs develop on the above ground plant parts. With the growing demand for higher crop production and consequent trend of accelerating cropping intensity under chemical input based intensive agricultural system, infestation of the soilborne plant pathogens are aggravating and will continue to rise in future, if effective, sustainable and eco-dynamic disease management strategies are not rightly taken up. Low inherent level of resistance of crop cultivars against such diseases, existence of high level genetic variability and wide host range of the pathogens, their ability to survive in soil for a long time, imbalanced application of plant nutrients make the disease management strategies more complicated. This review paper highlights the importance of soilborne pathogens, their biology, epidemiology and recent approaches of bio-intensive disease management strategies to mitigate the biotic stresses in crop plants caused by soilborne plant pathogens with special reference to *Sclerotium rolfsii*, *Rhizoctonia solani* and *Sclerotinia sclerotiorum*.

Key words: Bio-intensive management, plant diseases, soilborne plant pathogens

INTRODUCTION

Soil is a complex and bio-dynamic ecosystem where billions of macro and microorganisms inhabit. These are mostly beneficial in nature while few others are harmful to mankind. Some of the harmful microbes cause plant diseases. Plant diseases incited by soilborne pathogens are one of the major limiting factors in sustainable crop production. Soilborne pathogens include mostly fungi, oomycetes, bacteria, nematodes, viruses (carried by nematodes or other organisms) and parasitic plants (Gudmestad *et al.,*2007).

They cause heavy losses to many crop plants in different stages of crop growth by producing different types of symptoms like damping off, collar rot, stem rot, root rot and vascular wilts resulting in significant level of yield losses. Most common soilborne fungal pathogens such as *Rhizoctonia solani* (causing damping off, root rot, sheath blight and web blight), *Fusarium oxysporum* (causing vascular wilt), *Verticillium* spp. (inciting vascular wilt), *Sclerotinia sclerotiorum* (causing white rot or crown rot), *Sclerotium rolfsii* (causing collar rot, stem rot, southern blight), *Macrophomina phaseolina* (causing stem rot, charcoal rot), *Pythium* spp. (causing damping off, fruit rot) and *Phytophthora* spp. (causing leaf blight, crown rot, gummosis etc.) regularly incur considerable loss in crop production. For instance, sheath blight of rice leads to 40% yield losses under intensive cropping system, however, loss may increase up to 50% under heavy fertilizer application (Zheng *et al*., 2013; Nadarajah *et al*., 2014). Fusarium wilt of chickpea can cause 10%–90% annual yield losses (Sharma and Muehlbauer, 2007) and persist for years in soil even without host which makes it difficult to manage. *Sclerotinia sclerotiorum* attacks on more than 600 plant species and causes upto 90% yield losses in Indian mustard besides affecting soil quality (Sharma *et al*. 2018). *P.*

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aphanidermatum causes more than 60 per cent mortality of seedlings both in nursery and field condition and about 50-80% losses during storage (Rajalakshmi *et al*. 2016). Overall, soil borne plant pathogens can cause 50%–75% yield loss for many crops such as wheat, rice, cotton, maize, vegetables, fruits and ornamental crops (Katan, 2000; Panth *et al*. 2020). The crop losses due to soilborne diseases are presented in Table 1.

Although very diverse and being soilborne, these plant pathogens have common features related to survival in soil for at least a part of their life cycle. They survive in soil for long periods in host plant debris, soil organic matter as free living organisms or by producing resistant structures like resting sporangium, microsclerotia, sclerotia, chlamydospore or oospores etc. They can be ecologically either "soil inhabitants" (those are ubiquitous, mostly unspecialized parasites with a wide host range and able to survive in soil for relatively long time, if not indefinitely, in the soil as saprophytes) or "soil invaders" (those are found only locally and are more specialized parasites with host specificity to some extent that survive in soils in close association with their hosts and have very low or no competitive saprophytic survival ability or "soil transient"(those only able to survive in soil for relatively short time and incidentally appear as propagules (e.g. spores) to the soil from elsewhere or from the colonized above ground debris. A fourth group of soil microorganisms was also recognized that do not directly infect plants but can colonize rhizosphere and scavenge iron available to the plants resulted in yield depression in crops and denoted them as non-parasitic plant pathogens. There might have been a fifth group of plant pathogens those are not directly soil borne *per se* but depends on soil inhabitant micro-organism to reach the host plant. Plant pathogens, mainly phyto-viruses that are vectored by some soil inhabitant plant pathogens fall under this group.

In most of the cases, infection starts below the ground and primary symptoms remain invisible for a considerable period of crop growth. It often is very late to undertake any protection measure whilst any sign or visible symptoms develop above ground plant parts. Accurate diagnosis of a particular disease is difficult due to the similarity in symptoms produced by various pathogens or complex such as seedling damping off, root blackening, root rot etc.

Management of soilborne plant pathogens is difficult as these pathogens are hidden and their manifestation is often delayed resulting in delayed diagnosis. Hence, curative measures become non-economical. Simultaneous infection by multiple soilborne pathogens may result in disease complex which are difficult to predict, detect and diagnose, *e.g*., rhizome rot of zinger, Hooghly wilt of jute, etc. The low inherent level of resistance of crop cultivars against soilborne diseases, existence of high level genetic variability, wide host range of the pathogens and their prolong survival ability in soil due to production of resting sporangium, melanized sclerotia and mycelial production make the soilborne disease management strategy more complicated (Fig. 1).

To control these diseases outbreak, adoption of several cultural practices followed by application of chemical fungicides is used at regular intervals throughout the growing season to save the crop against such soilborne diseases. There are several issues with the use of synthetic fungicides which include ecological disturbance, human health hazards, damage to aquatic ecosystems, reduction of beneficial microorganisms in the soil and even ozone layer depletion. Methyl bromide was extensively used to control those pathogens in many parts of the world but implementation of the Montreal Protocol in 1986 leads to phase out of this chemical (Panth *et al*. 2020).

Some environment-friendly approaches such as the application of biocontrol agents, soil solarization, use of resistant varieties and more precisely bio-intensive disease management approaches have been adopted to control soilborne diseases while maintaining the environment safe. This review paper seeks to highlights the current approaches of bio intensive disease management strategies to mitigate the biotic stresses in crop plants caused by soilborne plant pathogens with special reference to *S. rolfsii*, *R. solani* and *S. sclerotiorum*.

IMPORTANCE OF SOILBORNE PLANT PATHOGENS

There are various soilborne plant pathogens which persist saprophytically for long time in soil; and in the availability of suitable hosts, incite various plant diseases in different plants parts of various crop plants and cause considerable losses in worldwide

Table 1: Estimated yield loss from various crop plans due to soil borne diseases

Crop	Name of the disease(s)	Causal pathogens	Country	Crop loss	References
Overall	Soil Borne Diseases	Various Soil Borne Plant Pathogens	World wide	10-20% US$80 billion per year	Yuliar *et al*. 2015 Price, 2000
Solanaceous crops	Bacterial wilt	*Ralstonia solanacearum*	Many countries	20-45%	Mansfied *et al*., 2012; Yuliar *et al*. 2015
Tomato	Wilt	*Fusarium oxysporum* f. sp. *lycopersici*	Indonasia	20-30%	Wibowo, 2005
Tomato	Sclerotinia rot	*Sclerotinia sclerotiorum*	Brazil	100%	Lobo *et al*. 2000
Pigeon pea	Wilt	*Fusarium oxysporum* f. sp. *udum*	India	30-99% depending on crop growth stages of wilting	
Chickpea	Wilt	*Fusarium oxysporum* f. sp. *ciceri*	India	24-94%	
Cowpea	Southern Blight	*Sclerotium rolfsii*	USA	50-60%	Fery and Duke, 2002
Potato	Black wart	*Synchytrium endobioticum*	Canada	50-100%	Obidiegwu *et al*. 2014
Rice	Sheath blight	*Rhizoctonia solani*	Malyasia	Upto 50%	Nadarajah *et.al*. 2014
Rice	Sheath blight	*Rhizoctonia solani*	China	Upto 50%	Zheng *et al*. 2013
Chickpea	Fusarium wilt	*Fusarium oxysporum* f. sp. *ciceri*	Southern Spain	Average 10%	
Chickpea	Fusarium wilt	*Fusarium oxysporum* f. sp. *ciceri*	India	Average 10%	
Indian mustard	Sclerotinia stem rot	*Sclerotinia sclerotiorum*	India	Upto 90%	Sharma *et al*., 2018
Turmeric	Rhizome rot	*Pythium aphanidermatum*	India	Upto 50%	Rajalakshmi *et al*., 2016

crop production. A systematic representation of disease cycle and other aspects related to crop diseases are described below.

Sclerotium rolfsii

Sclerotium rolfsii Sacc. [*Athelia rolfsii* (Curzi) Tu Kimbrough] is a notorious and cosmopolitan, Agaricomycetous soilborne plant pathogen causing southern blight, stem rot, collar rot diseases etc. on many dicotyledonous as well as several monocotyledonous plants (Yimer *et al*. 2018). It has wide geographic diversity and commonly found in the tropics, subtropics and other warm temperate regions especially the Southern United States, Central and South America, West Indies, India, Japan, Philippines etc. The fungus was first reported by P. H. Rolfs, an agronomist in Florida Agriculture Experiment Station, USA in 1892 as a cause of tomato blight in Florida and it was subsequently named as *S. rolfsii* by Saccardo. In India, an organism was isolated from rotted potatoes and identified as *Rhizoctonia destruens* Tassi and subsequently the fungus was placed into *S. rolfsii*. The fungus grows well on a wide range of culture media and is characterized by the presence fast growing, white coloured mycelium that tend to aggregate into rhizomorphic cords and produces tan to dark brown or black round shaped small hard sclerotia which plays a key role in the disease cycle and has the ability to survive in soil for long periods. The fungus does not produce any asexual spores. The wide host range, prolific growth and ability to produce persistent sclerotia contribute to the huge economic losses of many crops associated with this pathogen.

The teleomorphic stage as *Athelia rolfsii* (Curzi) Tu and Kimbrough is not so common on nutrient medium as well as in nature. When it does develop, *A. rolfsii* produces an exposed hymenium bearing clavate basidia and hyaline, pyriform basidiospores. Basidial production varies with the isolate, the nutrient composition of the medium, the light intensity, as well as the age of the culture. Basidia are generally produced in older cultures grown on media that are poor in nutrients at low-light intensities. The addition of activated charcoal also enhances fruiting in some isolates. Basidiospores can infect host tissue grown under greenhouse conditions by producing appressorium from the germinating spores. Symptoms of stem or collar rot diseases caused by *Sclerotium rolfsii* on various crops is given in Fig.2.

Rhizoctonia solani

The genus was first described by De Candolle and the genus *Rhizoctonia* and designated as *R. crocorum* (Pers.) DC as a type species. Following Irish famine in Europe, *Rhizoctonia solani,* a ubiquitous species of genus *Rhizoctonia* was described by Kuhn in 1858 from potato. The important characteristic features of this genus are (a) branching near the distal septum of the cell in young vegetative hypha (b) formation of septum in a branch near the point of origin and constriction of branch at the base (c) presence of dolipore septum in hypha with no clamp connection (d) no conidium production except monilioid cells and (e) sclerotium not differentiated into rind and medulla. The genus *Thanatephorus* was initially proposed by to designate teleomorphic phases of the *Rhizoctonia solani.* Different anastomosis groups (AG) of *R. solani* have been already reported from different parts of the world. Species complex of *R. solani* has also been divided into three categories based on cellular nuclear conditions as multinucleate, binucleate and uninucleate. Among multinucleate *R. solani*, AG-3, AG-4 and AG-5 are widely distributed whereas AG-K is dominant among the binucleate category.

The fungus is usually recovered from soils all over the world and is considered as a very destructive plant pathogen with a broad host range which causes diseases in a variety of crops belonging to different families like Solanaceae, Poaceae, Malvaceae, Leguminosae, Brassicaceae, Amaranthaceae, etc. under agricultural, ornamental and horticultural and forest ecosystems. It has been reported that *R. solani* has a wide host range infecting more than 27 families in both monocots and dicots. Important symptoms are damping off, sheath blight, brown patches, root rot, web blight etc. (Fig 3). Salazar *et al.* (2000) reported annual yield loss of up to 20% by this pathogen in over 200 economically important crops worldwide including large variety of vegetables and cereals. This necrotrophic pathogen can stay as saprophytic organism or form special survival structures *e.g.*, sclerotia to survive under soil in absence of host. *Rhizoctonia solani* is a global production constraint incurring grain losses of rice to an extent of 40% every year. Extent of yield losses imposed by *R. solani* varies from 5.9 to 69 per cent depending on age of the plant, time of infection etc. Reports from China revealed a range of 5.62-59.62% yield losses of rice positively correlated with severity of the disease. *Rhizoctonia solani* has immense impact on yield losses of soybean in the United States (Koenning and Wrather, 2010).

Sclerotinia sclerotiorum

The fungus *Sclerotinia sclerotiorum* was first described from Belgium as *Peziza sclerotiorum* by Madame M. A. Libert in 1837. Later it was included in the new genus *Sclerotinia* with the establishment of the genus and renamed as *Sclerotinia libertiana* and later changed into *S. sclerotiorum* by G. E. Massee in 1895, citing *S. sclerotiorum* (Lib.) Massee.

The fungus was generally considered to be more common in the cool and moist temperate under subtropical regions (Saharan and Mehta, 2008). Genetic diversity and greater adaptability of this fungus has endowed it to spread towards the hot and dry areas (Sharma *et al*. 2015). The pathogen affects more than 500 plant species at all stages of growth and harvest products (Sharma *et al*. 2015a). Wide host range of the pathogen poses difficulties in managing the disease. Limited source of resistance in host as well restricted number of non-host crops, management by crop rotation cannot be successful (Sharma *et al*. 2015). The new reports of the susceptible hosts have been increasing every year for *S. sclerotiorum*. Sharma *et al*. (2015) cited that Partyka and Mai in 1962 recorded 172 plant species from 118 genera in 37 families. The host index for *S. sclerotiorum* was further updated as 42 subspecies or varieties of plants from 408 species belonging to 278 genera under 75 families. In India, occurrence of Sclerotinia stem rot on several hosts including rapeseed-mustard was first recorded in 1915 by Shaw and Ajrekar at Pusa, Bihar (Sharma *et al*. 2015). The pathogen was first recorded on 'Motihari tobacco' from West Bengal in 1988 by Monga. However, more than twenty five hosts of *S. sclerotiorum* like French bean, potato, marigold, tulsi, kakuch, lankajaba, daisy, banana etc. were reported from West Bengal with the commencement of the new millennium (Dutta *et al*. 2009, 2016; Mondal *et al*. 2012, 2015). Symptoms of some diseases caused by *Sclerotinia sclerotiorum* on different hosts are given in Fig.4.

DISEASE CYCLE OF THE SOILBORNE PLANT PATHOGENS

Sclerotium rolfsii usually infects the collar region of the plant causing necrosis type of symptoms and often traverses towards the root system during severe infection (Sarma *et al*. 2002; Maurya *et al*. 2009). It establishes host parasitic relationship by a series of events that start with the adhesion of pathogen mycelium on plant surface at the collar region by secreting several cell wall degrading enzymes like polygalacturonases along with oxalic acid, which disturb the physiological integration of the cell and cell wall (Sarma *et al*. 2002). Oxalic acid sequesters calcium from the cell walls to form calcium oxalate and lowers the tissue pH to the optimum for endo-polygalacturonase and cellulase activities .

The infection of *S. rolfsii* initiates from hyphae which are closely oppressed to the surface of epidermal region and increases as the numerous hyphae that invades the host tissues inter and intracellularly into the cell lumen and across the cells etc. (Sarma *et al*. 2002). In the meantime, the collar region gets covered by a profuse growth of *S. rolfsii* and affected host stems show shredding symptom. The characteristic initial collar rot symptoms in legume include water-soaked lesions on lower stem tissue near the soil line followed by constricted dry rotting, wilting and blighting (Akram *et al*. 2008). Infected plants gradually wither and white mycelial mats and sclerotia appears on the surface of roots and stems at the soil line. Interestingly, the infection does not usually extend further up the stems and foliage of the plants. The disease is favoured by good soil moisture, high soil temperature (25-30ÚC) and low organic matter in the soil. Presence of susceptible hosts, enough inoculum of virulent isolates of the pathogen and favourable climatic conditions over a period of time play important role in disease outbreak.

R. solani survives in soil in the form of basidiospore, mycelium or sclerotium. Basidiospores which act as inoculum for leaf diseases are very fragile and are therefore, not suitable for long term survival. However, they are an important source of genetic variation and a means of long distance dispersal. Sclerotia are the primary survival structures and therefore an important source of inocula. On germination of both basidiospores and sclerotia, hyphae come in contact with the plant and starts to grow over the plant surface. After 10 to 12 hrs., hyphae gets flattened, become close and firmly attached to the plant surface and start to follow the epidermal cells. Like appressoria, complex infection structures are firmly attached to the epidermis by the hyphal branches and their swollen tips develop infection pegs to enter the epidermal cell causes different types of symptoms.

Hyphae of *Sclerotinia sclerotiorum* penetrate the host cuticle through mechanical pressure and enzymatic action following which the infection process initiates (Heller and Witt-Geiges, 2013). Plant parts close to soil are first affected when the initial inoculum is soil borne sclerotia while air borne ascospores initiate disease in any aerial plant parts including flower, fruits, leaf, young stem, branches etc. (Dutta *et al*. 2016). Thus, with myceliogenic germination of the scleortia, the type of diseases caused are root rot, basal stem rot and wilt while carpogenic germination leads to head rot, pod rot and blossom blight. The sclerotia, having long term survivability plays important role as primary source of inoculum. The fungus overwinters in sclerotial stage which can spend up to 90% of its lifecycle as sclerotia and thus, can able to remain viable up to eight years.

GERMINATION OF SCLEROTIA

Two forms of sclerotial germination, hyphal and eruptive are common in *S. rolfsii*. Hyphal germination is characterized by the growth of individual strands from the sclerotium surface but their growth is not extensive unless an external source of nutrients is available. In contrast, eruptive germination is characterized by plug(s) or aggregates of mycelium bursting through the sclerotial rind. Sclerotia can germinate eruptively only once, since internal stored materials are utilized during the growth of the mycelium.

The effects of pH on germination of sclerotia, hyphal growth and oxalic acid production in *S. rolfsii* have been reported. Sclerotia acidify their environment during germination and growth by excretion of oxalic acid which is often associated with the mechanism of attack on host plants . Moreover, there is evidence that during hyphal growth, oxalic acid is continually secreted until the environment reaches the pH preferred by the pathogen *S. rolfsii* (Zmora-Nahum *et al*. 2008).

Eruptive germination is induced by drying of sclerotia, exposure to volatile compounds (primarily alcohols and aldehydes) released from plant tissue and germinating seeds.

Sclerotia of *S. sclerotiorum* germinates by two ways *i.e.*, myceliogenic or carpogenic depending upon environmental conditions. Myceliogenic germination of sclerotia occurs with the emergence of hypahe or mycelium through the rind. Carpogenic germination of the sclerotium leads to formation of fruiting body apothecium (Fig. 5). The hymenium lined with asci that contain 8 hyaline ascospore. Majority of the infections caused by *Sclerotinia sclerotiorum* are initiated by airborne ascospores produced through carpogenic germination (Hao *et al*. 2003).

EPIDEMIOLOGY OF SOIL BORNE PLANT DISEASES

Microclimate in field favours hyphal growth and sclerotia production of the *S. rolfsii*. Being a warm loving pathogen, maximum growth and sclerotia formation occur at 27-30°. Linear growth rates of hyphae at 27°C on agar medium and in sterile soils range from 0.85-0.97 mm per hour. There is also a report that indicates the fluctuations of temperature may affect the shape and size of the sclerotia. Being strong aerobic in nature, linear mycelial extension of *S. rolfsii* is limited by low oxygen concentrations to a greater extent on non-sterile soil than on agar. High temperatures and moisture are associated with germination of the sclerotia of *S. rolfsii* while frequent irrigation and dense planting provoke disease spreading (Aycock, 1996). Soil temperature of 25-30 °C and soil moisture at 90% is suitable for *S. rolfsii* disease development (Gupta *et al*. 2002). Sharma and Ghosh (2017) reported 55–95 % mortality of chickpea seedlings under heavy rainfall and soil temperature range of 25–30 °C.

Rhizoctonia solani has wider adaptability under different ecological niche. Isolates and different anastomosis groups show variable temperature range for mycelia growth and sclerotia production. Same anastomosis group infecting different crops may not show similar mycelia growth under a fixed temperature. As for example, it has been mentioned that rice isolates of *R. solani* have wider adaptability under different temperatures as have been observed that isolates from higher temperature region grow well at 35°C, but not at 12°C and *vice versa*. The optimal temperature for growth of the fungus is 23-28°C, though there are reports that *R. solani* can grow well from 14-38ºC temperature.

The environmental conditions and the soil microbiota determine survivability of sclerotia of *S. sclerotiorum* in soil, which may be for 4-5 years (Niem *et al*. 2013). Several other factors such as soil type, previous crops, soil pH, soil temperature, soil moisture in the moderate range etc. also influenced survival of the sclerotia (Sharma *et al*. 2015). It has been found that less number of apothecia produced in sandy soil whereas maximum apothecia were formed in sandy loam soil. However, extremities in soil temperature and soil moisture for prolonged periods have adverse effect on sclerotial viability (Mehta *et al*. 2009). High soil temperature of >35ºC for a duration of 3 weeks or more have a negative influence on sclerotial survival. Again, high temperatures in wet summers were more detrimental for sclerotial survival than in dry summer.

Wu and Subbarao (2008) reported that the distribution of sclerotia and its number decrease in naturally infested fields before tillage while number becomes more or less uniform with increased soil depth from 0-10 cm after conventional tillage. Further, in undisturbed soils, sclerotia placed in depths of 10 cm and beyond 30 cm remain viable longer than those in upper 5 cm soil. (Cosic *et al*. 2012). The burial depth of sclerotia was also found to have negative influence on survivability- at 20 cm depth, sclerotia showed a rapid decline in viability and disintegrated within 5 months. However, sclerotia buried in river sand produced larger apothecia. Similarly, Mehta *et al.* (2009) found that least number of apothecia was formed in sandy soils whereas maximum apothecia were produced in sandy loam soil. Borah (2018) observed that soil temperature at (0-15 cm depth) was found to be the most important predictor for carpogenic type of sclerotia germination of *S. sclerotiorum*. Carpogenic type of sclerotial germination was more in sandy loam soil as compared to clay and clay loam soil. The texture of soil, moisture and temperature play an important role in the carpogenic germination of sclerotia of *Sclerotinia sclerotiorium* (Fig. 5). Borah (2018) also recorded highest carpogenic germination at 20ºC followed by 15°C but no carpogenic germination

Table 2: Epidemiological factors responsible for soilborne diseases

Epidemiological parameters	Pathogen	Disease	Effect on	Development	Reference
High soil temperature of >35 °C for 3 weeks or more	*S. sclerotiorum*	Sclerotinia diseases	Survival ability of sclerotium in soil	Negative influence on sclerotial survival	
Maximum relative humidity inside boroj (BRHmax.)	*Sclerotium rolfsii*	collar rot of betel vine	Disease incidence	Positively correlated with disease incidence	Garain *et al.* (2021b)
Optimum temperature of 30°C	*R. solani*	Soil borne diseases	Mycelial growth	Higher mycelia biomass production at optimum temperature	
Temperature of 35°C	*R. solani*	Soil borne diseases	Sclerotia production	Better for Sclerotia formation but rare or does not form any sclerotia at 20 °C and above 40 °C	Salunkhe *et al.* (2009)
Soil moisture and rainfall	*Sclerotium rolfsii*	collar rot of betel vine	Disease incidence	significantly and negatively correlated with disease incidence	Garain *et al.* (2021b)
The interaction of minimum temperature and relative humidity	*Sclerotinia sclerotiorum*	Sclerotinia rot incidence in mustard	Disease incidence	Onset of disease and forecasting	Sharma *et al.* (2015)
Soil water potential increased from -0.3 to –0.01 MPa;	*Sclerotinia sclerotiorum*	Soil borne diseases	Carpogenic germination	Increased germination	Wu and Subbarao (2008)
Increased burial depth from 0 to 10 cm before tillage	*Sclerotinia sclerotiorum* and *S. minor*	Soil borne diseases	Sclerotia production	Decreased with increase of soil depth, Apothecia of *S. minor* produced from sclerotia located at a shallower depth while those of *S. sclerotiorum* located as deep as 4 to 5 cm	Wu and Subbarao (2008)
Soils with low levels of organic carbon and higher sand percentage	*Sclerotinia sclerotiorum*	Soil borne diseases	Sclerotial germination	Increased carpogenic germination	
High ion-exchange capacity and soil nutrient availability like Ca^{2-}, Cl^{-} and $SO4^{2-}$	*Sclerotinia sclerotiorum*	Soil borne diseases	Germination of fruiting body	High apothecial germination	
The combination of soil moisture content at 60% of field capacity level and soil temperature at 30.C	*Sclerotinia sclerotiorum*	Soil borne diseases	Saprophytic colonizing ability	Increased saprophytic colonizing ability	Ray *et al.* (2019)

was observed at and below 10°C and at and above 25°C.

The congenial period for S. *rolfsii* infection was pre and post *Kharif* season and for *R. solani* it was monsoon season under West Bengal condition. However, disease conducive periods for *S. sclerotiorum* infection was in winter months (November-December to February) (Garain *et al*.,

2021a; Borah, 2018; Ray, 2019) (Fig. 6). Some of the Epidemiological factors responsible for soilborne diseases are enlisted in Table 2.

MANAGEMNET OF SOILBORNE PLANT PATHOGENS

Limiting the population of soilborne plant pathogens below threshold level is difficult task because of low inherent resistance among the cultivars against such diseases, existence of high level of genetic variability and wide host range of the pathogens and ability to survive in soil for long time etc. (Katan, 2000). Curative measures become non-economical in many cases as soilborne pathogens are hidden and their manifestation is often delayed to be diagnosed. Simultaneous infection by multiple soilborne pathogens may result in disease complex which is difficult to predict, detect and diagnose (Panth *et al*. 2020). In most of the cases soilborne pathogen survives in soil for many years in the absence of normal crop host through production of resting structure. Wide host range of soil borne pathogens gives them added benefit to remain in the soil in active state. This helps in horizontal distribution of soilborne pathogens. Biointensive disease management approach emphasises use of microbial pesticides or plant extracts or animal products or bio-fumigants, disease tolerant varieties and certain cultural practices that creates an adverse situation for the pathogen and modify the soil environment in favour of the crop growth and augmentation of the population of beneficial microbes. Bio-intensive disease management strategy is an ecology based dynamic management strategy that has the potential for enhancing ecological engineering service system of below ground rhizospheric region, thereby providing effective, environment benign and sustainable disease management with reduced on-farm and off-farm environmental impacts by declining the use of energy intensive inputs in disease management strategy (Fig. 7). The different bio-intensive disease management practices used for sustainable management of soil borne diseases are:

Sanitation

The aims of sanitation are to prevent the introduction of pathogen inoculums into the new field and to reduce the primary inoculum that is already present in the field. With production of different resting structures like chlamydospores, microsclerotia, oospores or sclerotia etc., soilborne plant pathogens survive in the soil for a very long time, even in the absence of a living host or plant debris and soil organic matter (Panth *et al*., 2020). Therefore, it becomes very important to remove the plant debris away from growing areas whenever possible or accelerate residue breakdown. Sanitation includes any sort of activities which are aimed to prevent the spread of pathogens by removing diseased and infected plant parts, decontamination of tools, equipment and washing hands. Severity of Fusarial wilt of cotton and Red gram, root rot of bean can be reduced to some extent by removal of diseased plant debris (Agrios, 2005). Similarly, removal of weed hosts is also important to break the disease cycle. (*e.g.*, *Rhizoctonia solani*).

Crop rotation

Crop rotation has been a part of Indian agricultural practices ever since the Vedic era (about 1500–500 BCE). According to the "Taittriya Samhita," rice is planted in the summer and pulses in the winter . Almost 2000 years ago, the Romans used crop rotation as a successful agronomic method, and it was first used in England in 1730. But crop rotation as management for soilborne root rot disease of cotton (Texas root rot) incited by *Phymatotricum omnivorum,* was first suggested by Pammel in 1881. Changing the crop rotationally reduces opportunities for root invasion by soilborne pathogens, exposes their resting bodies to extended periods of predation and enzymatic breakdown from antagonistic flora and fauna and to adverse physical and chemical environments.

Besides plant disease management, crop rotation has profound effect in enhancing soil fertility, improving soil physico-chemical properties and overall soil health. Generally, crops of the same family should not follow one another in the field and proper crop rotation can effectively control soil invaders. For example, tomato should be rotated with legumes, cole crops or lettuce but not crops within the Solanaceae family (eggplant, chili, potato etc.) to reduce Fusarium wilt (*F. oxysporum*) and bacterial wilt (*R. solanacearum*). However, it is less effective against soilborne pathogens that have wide host range and produces resistant structures like resting sporangium, sclerotia, oospores and chlamydospores that survive in soil

for long period of time. Rice- cole crops – maize rotation for 4-5 years effectively manage bacterial wilt of solanaceous vegetables. Growing marigold (*Tagetes* spp.) in rotation or as intercrop will suppress the pathogen in addition to its anti-nematode effect. Growing *Brassica* spp. and incorporating the plants into soil at flowering stage will reduce bacterial wilt incidence. Crop sequences like oat-potato, annual ryegrass-potato or clover-potato reduces *R. solani* inoculum levels in the soil and suppresses disease development. Larkin and his colleagues demonstrated reduction in Rhizoctonia canker and black scurf through the rotation cycles of barley and clover instead of growing continuous potato (Larkin *et al*. 2010).

Continuous cropping with the same crop for multiple times in a single year over a single land reduces the diversity of the microflora in the rhizosphere. This in turn reduces the population of beneficial microflora and increases the population of plant pathogens in rhizosphere. On the contrary, crop rotation with genetically diverse crops may increase, decrease or have negligible effect on diversification of soil microflora. The root exudates secreted into rhizosphere of crop rotation systems comprising of genetically diverse crops bring changes in soil microbial communities by differentially regulating species richness (Costa et al., 2006; Warde *et al*. 2004). This micro alternation of communities in rhizospheres additively changes the microbiome of the bulk soil (Kent and Triplett, 2002). Diversifications of soil microbial communities are studied in terms of species richness and species evenness using metagenomics. Meta-analysis based on literature review shows that on an average there is 15.11 per cent increase in soil microbial richness due to crop diversification in crop rotation (Venter *et al*. 2016). Species richness or introduction of new species is reported in crop rotational trials with at least 15 years of time period whereas species evenness has been reported to change in five years of crop rotation studies. Hence, increase in the number of beneficial microbes by species evenness and introduction of new species by species richness can be responsible for suppression of the soilborne plant pathogens. These beneficial activities of the microbes may include antagonism, higher saprophytic competitive ability, plant growth promotion and alleviation of the abiotic stress tolerance potential of the plants.

Crop rotation may cause the soil's microbial population to diversify because of changes in the soil's structure, water-holding capacity, water-use efficiency, and temperature. This occurs as a result of altered soil organic matter levels and ground cover during crop rotation. The increase in the diversity is also brought by chemical changes in soil due to diversity in ingredients of root exudates, which are deposited over the period of crop rotation. Plant root secretes various types of chemicals like sugars, amino acids, ethylene, vitamins, organic acids and enzymes. These root exudates may not be palatable for the target pathogen to use as source of energy for normal metabolism, which will reduce their population in the sick soil. These root exudates secreted from non-host crops may be used by beneficial microorganisms and may increase their population, which may suppress the population of the target pathogens. Recent studies have proved that microbial community of the rhizosphere has the relation to the crop type (Berg and Smalla, 2009) and crop developmental stage (Gyamfi *et al*. 2002). Again, the decomposed crop residues of the preceding crop provide a diversified residual carbon substrate, which in turn is the reason behind diversification of rhizospheric microbial communities. Some non-hosts are able to stimulate germination of resting pathogen structures, but the pathogen fails to survive on these plants.(Fig. 8).

Soil solarization

It is an eco-friendly method adopted prior to planting where solar energy is used by covering soil with transparent plastic sheet to control soil borne plant pathogens (Katan, 2015). Covering wet soil with transparent polythene sheet in warmer season increases soil temperature to the extent that can kill the soil pathogens. The plastic sheet allows the solar radiation to be trapped heat inside to the upper layer of soil surface (Katan and Gamliel 2010). Plant pathogens are more sensitive to high temperature, thus, the method of soil solarization selectively reduced the population of soilborne plant pathogens. Heating of sclerotia (*S. rolfsii*) in natural soil allowed organic substances to leak from the sclerotia and these substances apparently stimulated the colonization of the sclerotia by bacteria and streptomycetes and the formation of cracks. All of these developments apparently weakened the sclerotia and finally reduced the inoculum potential of soilborne plant pathogens. Soil solarization in nursery bed may

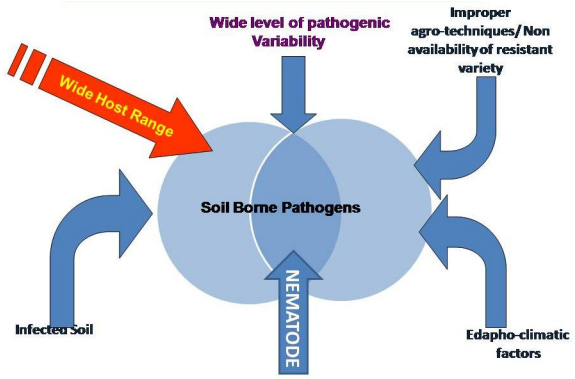

Fig. 1 : Complex interaction of edapho-climatic, biotic/abiotic and pathogenic factors in soil-pathogen-hostsystem

Fig. 2 : Stem/collar rot diseases caused by *Sclerotium rolfsii* on various crops A1-A3: Collar rot of cowpea B1-B2: Collar rot of betelvine C1-C2: Collar rot of groundnut D: Collar rot of cabbage E: Collar rot of lathyrus

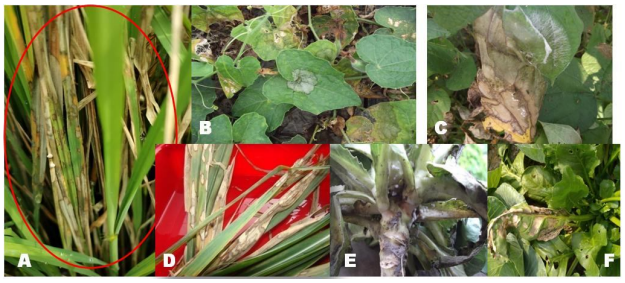

Fig. 3 : Different types of diseases caused by *Rhizoctonia solani* on various crops (A: Sheath blight of rice B: Net blight of pointed gourd C: Web blight of dolichos bean D: Blight of sugarcane E: Blight of cauliflower F: Blight of spinach

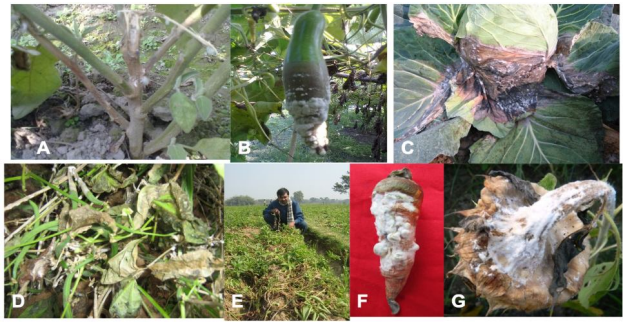

Fig. 4 : Diseases caused by *Sclerotinia sclerotiorum* on different hosts (A: Brinjal B: Bottle gourd C: Cabbage; D: French bean E: Potato F: Carrot G: Sunflower)

Fig. 5 : Carpogenic germination of *S. sclerotiorum* sclerotia in different soil types, soil moisture and temperature regimes

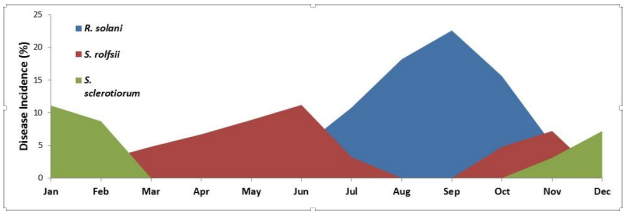

Fig. 6 : Disease risk periods of three different soilborne pathogens in New Alluvial Region of West Bengal

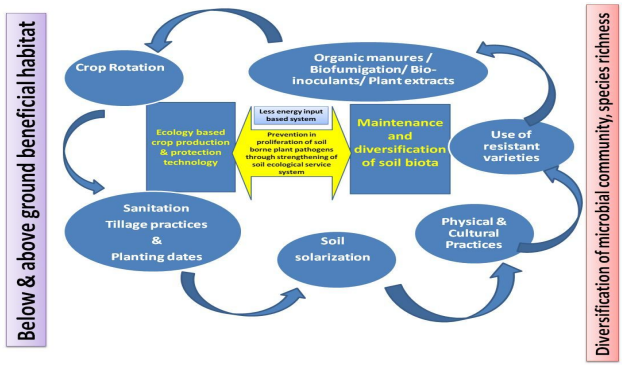

Fig. 7 : Various components of the bio-intensive disease management strategy

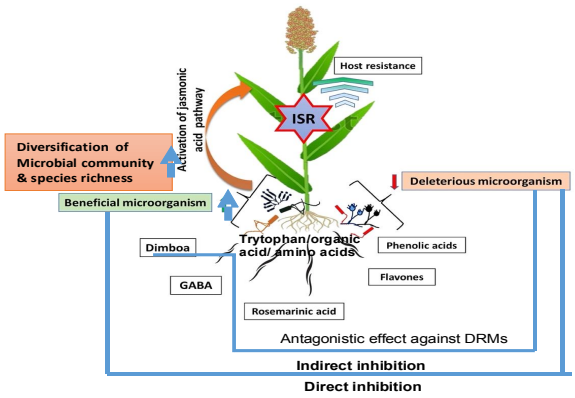

Fig. 8 : Effect of crop rotation on rhizomicrobiome diversity, plant health and pathogen suppressiveness

be an economic means for damping off and nematode management through reduction of the resting structures (primary inoculum) of soilborne pathogens. Solarization should be conducted for at least 6 weeks during the hottest part of the year (summer). The land to be solarized should be thoroughly ploughed, leveled and irrigation should be given prior to laying of the polythene sheeting. Clear, transparent (not black or of any other colour) polythene sheet of 25-100 µm thickness should be used. This process is highly effective against important soilborne pathogens like *V. dahliae*, certain *Fusarium* spp., *Sclerotinia* spp., *Agrobacterium tumefaciens*, *Streptomyces scabies* and nematodes in addition to controlling many weeds . Mulching with transparent polyethylene sheet (25µ) for 40 days was found to be effective for controlling *S. rolfsii* induced collar rot in strawberry (Bhardwaj and Raj, 2004). The influence of soil solarization for management of soilborne pathogens are enlisted in Table 3.

Flooding

Flooding operation before planting in infected soil creates unfavouarble condition to soilborne pathogens due to lack of O_2, increased CO_2 and production of toxic substances to the pathogens in the soil as a result of various microbial activities under anaerobic condition. Large scale control of Panama wilt disease of banana caused by *Fusarium oxysprum* f.sp. *cubense* can be achieved by flooding of the soil for 3-4 month with minimum of 30 cm of water. It also apparently destroys *Verticillium dahliae*, *Ralstonia solanacearum* and nematode *Radopholus similis*. Anaerobic conditions and low redox potential in flooded soil due to soil saturation may be important factor in killing *V. dahilae* (Katan, 2000).

Crop residue management

The rice-wheat system contributes nearly one-fourth of the total crop residues produced in India. These are good sources of plant nutrients, the primary source of organic matter (as C constitutes about 40% of the total dry biomass) added to the soil, and are important components for the stability of agricultural ecosystems (Singh and Sidhu , 2014). The presence of plant residues on the soil surface has frequently been associated with an increased incidence of crop diseases. The crop residue can also serve as an inoculums source and maintain favourable moisture and temperature conditions in the top 10-15 cm of soil where the pathogens are most active (Cook, 2001). Highest infection percentage of the brown foot rot disease has been observed when winter wheat was sown directly into the stubble. Short-term effects of cereal residues (wheat straw) decomposition in paddy field include stimulation of CH_4 emissions, immobilization of available N, suppression of rice growth and accumulation of toxic materials (Singh *et al*. 2005; Singh *et al*. 2008). Residue decomposition can vary with depth of placement in the soil, crop type and residue quantity, allelopathic interactions between existing soil biota and time (Bailey and Lazarovits, 2003).

Bio fumigation

Several plants belonging to the family Brassicaceae such as cabbage, broccoli, kale, turnip, radish, cauliflower, rapeseed and mustards are effectively used to control soilborne pathogens and pests due to the presence of sulfur containing compound glucosinolate which is released upon hydrolysis of biologically active volatile products such as isothiocyanates (ITC). This isothiocyanates (ITC) was found toxic to many soilborne plant pathogenic organisms such as *P. nicotianae, S. rolfsii, S. sclerotiorum* and *R. solani* (Panth *et al*. 2020; Garain *et al*. 2021a, 2022). Certain crops, like the *Brassicas* (Family: Brassicaceae) contain high quantities of glucosinolates (GSL) and Myrosinase enzyme (thioglucoside glucohydrolase) that are compartmentalized within different cells in their intact tissue. Cellular disruption either through maceration or decomposition of plant tissue brings these chemicals in contact, resulting in hydrolysis of the glucosinolates in presence of water and produces isothiocyanates (ITC), thiocyanates, nitriles and oxa-zolidinethiones . The toxicity of the isothiocyanates is due to non-specific and irreversible reaction with the sulphur containing groups in proteins of some organisms. Indian mustard (*Brassica juncea* L.) contains high level of glucosinolates, the most predominant being known as 2-Propenyl Glucosinolate or Allyl Glucosinolate or Sinigrin, which on hydrolysis produces high levels of Allyl Isothiocyanate (AITC) and hence could be successfully used as biofumigation crops. Harvey et al., (2002) reported that AITC, produced during cellular degradation of Indian mustard (*Brassica juncea*),

suppressed the mycelial growth of *S. rolfsii*. Relevante and Cumagun (2013) reported 100% reduction of *Fusarium* wilt incidence in bitter gourd and bottle gourd through biofumigation by incorporating macerated mustard leaves in the infested soil. Baysal-Gurel *et al*. (2019) reported the suppression of soil borne diseases (*Rhizoctonia solani* and *Phytophthora nicotianae*) in woody ornamentals by biofumigation with Brassica cover crops. Bio fumigation using fresh chicken manure for five consecutive years of treatment significantly increased the soil's NH_4^+, NO_3^- forms of N, available P, K and organic matter and increases the strawberry yield by suppressing the disease caused by *Fusarium* spp. and *Phytophthora* spp. (Zhang *et al*. 2020). Among various disease management modules studied by Garain (2021) for the management of collar rot disease in betelvine, the module with a combination of 'biofumigation (soil incorporation of shredded leaves of Indian mustard var. *Pusa Mahak* at pre-flowering stage @ 0.7 kg m^{-2})' + 'curing of soil (heaping of soil for 6 months followed by soil solarization for 30 days)' + 'application of native isolate of *Trichoderma* sp.T-Nam (twice @ 100g *Trichoderma,* mass multiplied on paddy grain, mixed with 10 kg vermicompost and applied to 100 vines per 9 m^2 area)' resulted in most economical and effective disease management option along with the highest leaf yield in the experimental plot. This module resulted in 76.82% reduction in collar rot incidence, 29.94% increase in leaf yield and 41.45% increase in net income (during March-July cycle) in farmers' field condition, compared to the Farmers' Practice (soil drench with 0.25% copper oxychloride 50WP @ 4L solution m^{-2} soil surface). The effect of biofumigation for management of soilborne pathogens are enlisted in table 4.

Application of organic amendments

Use of organic amendments like composts, manures, oil cake etc. in soil has been found to reduce incidence of many soilborne diseases including damping off and root rots caused by *Pythium ultimum*, *Rhizoctonia solani*, *Phytophthora* spp. and wilts caused by *Fusarium oxysporum* and *Verticillium dahliae* infecting wide range of crop plants (Lazarovits , 2001; Yogev *et al*. 2006; Van Elsas and Postma, 2007; Malandraki *et al*. 2008; Tamm *et al*. 2010; Yogev *et al*. 2010; Pane *et al*. 2011). Incorporation of organic matter enhances total microbial biomass as well as microbial activity in soil, leading to restriction of the pathogen population through competition for resources or by other direct forms of antagonism (Mazolla and Gu 2000). Several attributes of compost such as composition, age and quality etc. are the determining factors for suppressiveness (Termorshuizen *et al*. 2006; Bonanomi *et al*. 2010). Organic soil amendments impede population of pathogens by forming ammonia or nitrous acid which is lethal to pathogens or by forming volatile fatty acids in acidic soil (Lazarovits, 2001). The pathogen *Phytophthora cinnamomi* causing avocado root rots was suppressed by application of compost produced from vegetable waste (Downer *et al*. 2001). Several physico-chemical parameters like soil pH, N, C and organic C content and various cations are responsible for plant disease suppression (Bonilla *et al*. 2012). Soil microbes rapidly degrade high nitrogenous organic matter leading to production of N in its different forms. The excess amount of N is localized to soil solution as ammonium form (NH_4^+) that leads to formation of nitrite (NO_2^-) and subsequently nitrate (NO_3^-) by the bacterial nitrification (Lazarovits, 2001). The nitrification mechanisms lead to drastic reduction in the soil pH attaining 5.5 and under such reduced pH conditions, nontoxic NO_2^- is converted to HNO_2 which is highly toxic to soilborne pathogens (Lazarovits, 2001). Volatile fatty acids (VFAs) that can be injurious to some pathogens in low pH soils are produced by the decomposition of certain organic amendments such as liquid swine manure (Conn *et al*. 2005). Increasing the level of soil organic matter (SOM) is usually regarded as helpful for developing soil suppressiveness for soilborne diseases, which is known as organic matter mediated general suppressiveness. Two strategies are commonly used to increase SOM, *i.e*., reduced tillage which increases crop residues and organic matter additions such as manure or compost. Organic Matter (OM) was found significantly suppressive against 45% soilborne diseases, non-significant in 35% and conducive for 20% of the cases. Amendment with OM was observed highly suppressive under only in 12% of the cases (disease reduction >80%) (Bonanomi *et al.* 2010). Application of organic amendments like compost, saw dust, straw, oil cake etc. would effectively manage the diseases caused by *Pythium, Phytophthora, Verticillium, Macrophomina, Phymatotrichum* and *Aphanomyces*.

Adjustment of tillage operations

Deep ploughing of crop residues, harboring the pathogen is more effective in reducing important source of infection. Deep ploughing is generally done to reduce the contact between plant roots and pathogen structure to enhance killing of pathogens by burring them or by exposing the inoculums to natural heating and desiccation. It reduces incidence of southern blight of tomato caused by *S. rolfsii*. Taylor *et al*. (2005) demonstrated that a large proportion of *V. dahliae* inoculum restricted to the upper 10 cm of the soil profile and ploughing redistributed much of the inoculum in the lower soil layer where biological activity may contribute to lysis. Sub-soiling prior to planting was found to increase the green pea yields of root rot susceptible and tolerant cultivars planted in the soil infested with *F. solani* f.sp. *pisi* and *Pythium ultimum.*

Soil pH

Root rot diseases caused by *Phytophthora* are generally inhibited by lower soil pH. Low soil pH restricts sporangium formation, zoospore release and motility of the pathogen. Therefore, low pH sphagnum mosses are applied to reduce the populations of *Phytophthora* and *Pythium* spp. (Jambhulkar *et al*. 2015). On the other hand, high soil pH restricts Fusarium wilt occurrence by reducing the availability of soil nutrients to the pathogen .

Resistant cultivars

Use of resistant varieties is one of the practical ways to avoid soilborne diseases. However, searching resistant lines is not easy task and resistant cultivar become susceptible after few year of cultivation due to aggressiveness of pathogen that are present in soil for long time.

Grafting techniques

Grafting of susceptible scions on the compatible disease-resistant rootstocks is an important strategy for the management of soilborne plant pathogens. Some soilborne diseases such as bacterial wilt and root-knot nematode of solanaceous vegetables and Fusarium wilt of cucurbits are managed by grafting techniques (Bruton, 2005; Rivard and Louws, 2006). The rootstocks resistant to Fusarium are widely available and therefore the risk of Fusarium can be managed through grafting. Along with the achievement of disease resistance and tolerance, grafting may also increase tolerance to abiotic stresses, efficient water and nutrient utilization, better growth and development, improved crop yield, quality of the produce and yield stability (Lee and Oda, 2003; Cohen *et al*. 2007; Rouphael *et al*. 2018).

Biological management

Chemical methods are more popular among the farmer as these are easy to apply, response quickly and highly effective against wide spectrum of pathogens. However, they cause disturbance in the environment, adversely affect human health, disturb ecological balance, harm pollinators and reduce populations of beneficial microorganisms in the soils. The application of biocontrol agents into the soils is an alternative to suppress soilborne plant pathogens through parasitism, production of antagonistic chemicals, competition for the host and nutrients and induction of resistance in plants against disease-causing pathogens (Shafique *et al*. 2016). The exploitation of native plant growth promoting rhizomicrobia as biological control agents of diseases is one of the keys to crop production with less phytosanitary residues and greater food safety. Beside the mycorrhizal fungi, plant growth promoting rhizobacteria (PGPR), plant growth promoting fungi (PGPF) and endophytic fungi and bacteria are reported which improves the plant growth during the stress condition (Egamberdieva *et al*. 2011, 2013; Hameed *et al*. 2014; Ahmad *et al*. 2015). Several bacterial and fungal genera are commercially used as biological control agents against many soil borne plant pathogens. These include *Bacillus*, *Coniothyrium*, *Paecilomyces*, *Pseudomonas*, *Streptomyces* and *Trichoderma* etc. (Mazzola and Freilich., 2017). The application of biocontrol agents in soils such as *T. viride*, *T. harzianum*, Fluorescent Pseudomonads and *B. subtilis* have been found to be effective against root rot, wilt, collar rot, damping off, stem rot etc. caused by soilborne plant pathogens in a number of crops (Shafique *et al*. 2016). Among many bio control agents *Trichoderma* spp. are widely used bio fertilizers, bio stimulants and bio control agents for both abiotic and biotic stress management. (Brotman *et al*. 2010; Harman, 2011). *Trichoderma* can control a wide range of

Table 3: List of soilborne diseases managed by soil solarization

Disease	Pathogen	Soil solarization	Effects	Reference
Wilt of Watermelon	*F. oxysporum* f.sp. *niveum*	Temperature increased upto 60, 50, 42, 37 ºC at depth of 2, 10, 20 and 30 cm, respectively	Delayed the onset of wilt symptoms and reduced total disease incidence	Martyn and Hartz, 1986
Leather rot of strawberry	*Phytophthora cactorum*	50-µm low-density polyethylene mulch	Reduction of population of 100% in first year, 47% in second year , and 55% in third year	Porras et al., (2007)
Olive wilt	*Verticillium dahliae*	Solarization of two consecutive (double) years	Significantly reduced pathogen populations in the top 20 cm of soil for at least 3 years	López-Escudero and Blanco-López, (2001)
Soilborne diseases	*Sclerotinia sclerotiorum*	1 month solarization	Reduced the populations of sclerotia and ability of the surviving sclerotia to form apothecia at 5, 10 and 15 cm depth	Phillips (1990)
White root rot of avocado	*Dematophoranecatrix*	Maximal temperatures were 35 to 42°C, depending upon the year and soil depth (15 to 60 cm)	Low pathogen recovery and reduction of disease	López-Herrera et al.,(1998)
Wilt of lettuce	*Fusarium oxysporum* f. sp. *lactucae*	1 month summer soil solarization and flooding	42 to 91% reduction of wilt incidence	Matheron andPorchas (2010)
Wilt of eggplant	*Fusarium solani*	covered with transparent polyethylene sheet (25 µm thickness)	71% reduction of wilt	Chakraborty et al., (2009)

soil borne fungi through antibiotics, enzymes, volatile and non-volatile compounds or by triggering the systemic resistance in plant (Brunner *et al*. 2005). Various soil nutrient which are present in unavailable form are solubilized by *Trichoderma* spp and make it in available form such as solublization of complex Fe, Mn and Zn compounds and solublization of insoluble phosphorous (Kapri and Tewari, 2010). *Trichoderma* has been found effective against several soil borne pathogens as well as aerial pathogens (Chaube *et al*. 2002; Harman *et al*. 2004). The different microbial inoculants and their influence on soilborne disease management are presented in Table 5.

Agro-ecosystem based holistic exploitation of different eco-friendly bio-intensive approaches induce the enhancement of ecological engineering

Table 4. List of soil borne diseases disease managed by biofumigation

Disease	Pathogen	Material used	Effect of biofumigation	Reference
Tomato wilt	*F. oxysporum* f. sp. *lycoersici*	Indian Mustard *(Brassica juncea*) leaf	68.2% disease control	Ming-she *et al.* (2006)
Damping off	*P. aphanidermatum*	*B. oleracea*, Capitata group	20-50% disease control	Deadman *et al.* (2006)
Quercus ilex mortality	*Phytophthora cinnamomi*	*B. carinata* plant material	Inhibition of mycelial growth and chlamydospore and zoospore germination	Morales-Rodríguez *et al.* (2016)
Pepper blight	*P. capsici*	Rapeseed meal (*B. napus*)	Reduction of disease incidence and increased soil content of total N, NO_3^- –N, available P and available K.	Wang *et al.* (2014)
Soilborne diseases of Wood Ornamental	*R. solani* and *P. nicotianae*.	Turnip (*B. rapa*), Arugula (*Eruca vesicaria* ssp. *sativa*), Indian mustard (*B. juncea*), rape (*B. napus*) and Mustard green (*B. carinata*)	Significant disease reduction	Baysal-Gurel *et al.* (2020)
Vascular wilt	*Verticillium dahliae*	*B. juncea*, *Rhaphanus sativus* and *Sinapis alba*	69.3 to 81.3 % reduction of number of viable microsclerotia,	Neubauer *et al.* (2014)
Vascular wilt	*Fusarium oxysporum* f. sp. *conglutinans, F. oxysporum* f. sp. *raphani*	Brassica spp.	Reduction of pathogen inoculums	Lu *et al.* (2010)
Root rot of Oak	*Phytophthora cinnamomi*	Ground seed of *B. carinata* and *B. juncea*	Reduction of disease incidence	Rios *et al.* (2017)
Stem rot of potato	*Sclerotium rolfsii*	Mustard leaf	Inhibition of mycelia growth (78.79%) and sclerotia formation (83.13%) and 27.27% reduction of disease incidence	Rubayet *et al.* (2017)

service system of below ground rhizospheric region, enriching rhizo-microbiome diversity and richness in long run and thereby converting rhizosphere from playground to battle field for soilborne pathogens that leads to effective,

Table 5 : Managements of Soilborne Diseases by Bio control agents

Bio control agent	Mode of application	Target pathogen	Crop (Disease)	Mode of action	References
Serratia marcescens	Seed treatment and Soil application	*Erwinia tracheiphila*	Cucumber (wilt)	induced systemic resistance (ISR)	Zhender *et al.* (2001)
B. subtilis	Soil application	*P. aphanidermatum*	Lettuce (Root rot)	Antibiosis, plant growth promotion	Amer and Utkhede (2000)
P.putida	Seedling dip	*Verticillium dahliae*	Strawberry (Wilt)	Induced resistance	Berg *et al.* (2001)
Trichoderma atroviride	Foliar spray	*R. solani*	Bean	Induced resistance	Brunner *et al.* (2005)
Streptomyces (M2A2)	Seed treatment and Soil application (actinomycetes)	*Rhizoctonia solani*	Rice (sheath blight)	Induced systemic resistance and Antibiosis	Caviedes *et al.* (2021)
Bacillus velezensis D61-A	Foliar spray	*Rhizoctonia solani*	Rice sheath Blight	Induces resistance and antibiosis	Zheng *et al.* (2021)
Serratia marcescens	Seed treatment and Soil application	*Erwinia tracheiphila*	Cucumber (wilt)	induced systemic resistance (ISR)	Zhender *et al.* (2001)
B. subtilis	Soil application	*P. aphanidermatum*	Lettuce (Root rot)	Antibiosis, plant growth promotion	Amer and Utkhede (2000)
Bacillus subtilis (B4)	Seed treatment and soil application	*R.solani & S.rolfsii*	Damping off, Root and pod rot disease of peanut	Plant growth promotion and induced systemic resistance (ISR)	Ahmad *et al.* (2019)
Pseudomonas aeuginosa (GP-8), *Trichoderma asperellum* (SAG-17A) and *Bacillus subtilis* (B11)	Seed treatment and soil application	*Sclerotium rolfsii* *R. solani*	Collar rot of cowpea Web blight of cowpea	Plant growth promotion & ISR	Pati (2021), Patwari (2021)
B. pumilus (YSPMK11)	Foliar spray	*Sclerotinia sclerotiorum*	Sclerotinia stalk rot of cauliflower	Induces resistance and Plant growth promotion	Kaushal *et al.* (2017)
T. harzianum (Th-6) + mustard leaves (biofumigant for soil application)	Seed treatment	*S. rolfsii*	Southern blight of carrot	ISR and antibiosis	Rubayet *et al.* (2020)
Yeast (*Wickerhamomyces* sp.)	Foliar spray	*S.rolfsii*	Southern stem rot of peanut	ISR and antibiosis	Nurhalimah *et al.* (2022)
P. fluorescens (Pf1) in combination with either *T.asperellum* (TTH1) or *Bacillus subtilis* (EPCO-16)	Seed priming	*S. rolfsii*	Sugarbeet root rot	Induced resistance	Thilagavathi *et al.* (2012)
Trichoderma harzianum	Seed treatment	*S. rolfsii*	Collar rot of	Induced resistance and increase in plant	

environmental benign and sustainable disease management.

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