REVIEW

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Maize is a major cereal crop worldwide and India is the world's fourth-largest producer of maize by area and seventh-largest producer by volume, accounting for 2% of worldwide production. Reduced crop performance, lower yield, and greater production costs are all challenges caused by soil borne pathogens in maize production around the world. Now a days the menace of soil borne pathogens, disease epidemics in agricultural production, high chemical fungicide costs, and fungicide resistance development in pathogens, climate change effect, new disease outbreaks, and growing environmental concerns, as well as soil health, are becoming more visible. For agricultural production, this necessitates the employment of integrated soil borne disease management systems. In a system-based approach, this article summarizes strategic methods such as resistant cultivars/varieties and grafting, cropping system, soil solarization, biofumigants, soil amendments, anaerobic soil disinfestation, soil steam sterilization, soil fertility and plant nutrients, soilless culture, chemical control and biological control methods for managing soil borne diseases of crops in general, and of maize in particular. These strategies are useful in a system-based approach for mitigation of soil borne diseases.

Key words: Maize, soil borne pathogens, disease management

INTRODUCTION

Maize (*Zea mays* L.) is an important cereal crop belongs to the tribe Maydeae, of the grass family Poaceae, grown in 166 countries across the globe (Anon., 2012). India ranks 4th in area and 7th in production, contributing around 2% of the global production (IIMR, 2021). Maize has got multifarious uses and is used as feed in India and the world. Whereas, the industrial use of maize in world is 22% as compared to 16% in India due to higher percentage of industrial use of maize for bio-fuels in the USA (Sai Kumar *et al*., 2012). Further, the continued growth in the poultry and starch industry will support the higher consumption of maize in India (Kumar and Jhariya, 2013). The crop is affected by many biotic and abiotic stresses. Usually, soil borne diseases are considered a major limitation to crop production which can cause 50-75% yield loss (Mihajlovic *et al*., 2017). Maize is attacked by several bacterial and fungal diseases which are soil borne in nature.

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18th S.R.Bose Memorial Award Lecture of Indian Mycological Society, Department of Botany, University of Calcutta delivered on 24th December 2021.

Bacteria causing rot (Fig. 1A), leaf spots, and seedling blight in maize and several fungal diseases include leaf blight, banded leaf and sheath blight (Fig. 1B), brown spot, Pythium stalk rot (Fig.1C), post flowering stalk rot or charcoal rot (Fig. 1D), brown leaf spot, downy mildews, rust, false smut, ear rot, cob rots etc. The fungal pathogens often survive for long periods in host plant debris, soil organic matter as free-living organisms or resistant structures like microsclerotia, sclerotia, chlamydospore or oospores (Baysal-Gurel *et al.* 2012). Accurate diagnosis of a particular soil borne disease is difficult due to the similarity in symptoms such as seedling damping-off, root blackening, root rot, stunting, wilting, yellowing, bark cracking and twig or branch dieback which in turn makes the disease harder to manage. Many conventional synthetic chemical fungicides and fumigants are usually applied at regular intervals throughout the growing season of the crop to suppress the disease incidence. However, frequent and indiscriminate use of chemical is harmful for the environment which poses ecological disturbance, human health hazards, damage to aquatic ecosystems, reduction of beneficial microorganisms in soil and even ozone layer depletion. This can also lead to the development of fungicide resistance (Bolwerk *et al*. 2005). Studies on harzadous effect of chemical led to the development and adoption of new approaches (Borneman and Becker, 2007; Gross *et al*. 2007; Baysal-Gurel *et al*. 2019a, b) such as the use of crop rotation, soil solarization, anaerobic soil disinfestation, soil steam sterilization, biofumigants, resistant cultivars/varieties or grafted plants and biocontrol products have been developed to control soil borne diseases (Han *et al*. 2000; Krause *et al*. 2003). These practices help in active management of soil microbial communities which helps in effective natural suppression of soil borne plant pathogens (Alfano *et al.* 2007). To achieve this, it is important to understand interactions between soil microbial communities to develop a soil health management strategy in a system-based approach instead of focusing on individual disease-causing species (Mazzola, 2004).

SOIL BORNE PATHOGENS AND METHODS OF DISEASE MANAGEMENT

Cultural practices

Cultural practice can be harnessed for the management of soil borne diseases by creating an environment which is favorable for the crop and unfavorable for the pathogen. For the management of soil borne diseases by using cultural practices (Katan, 2010) are determined by level of disease reduction, economic and technological feasibility of the method, conditions under which disease reduction occurs (epidemiological aspects), reproducibility of disease reduction, possible long-term effects, mechanisms of disease reduction, which should be investigated since they may provide tools for improving the method.

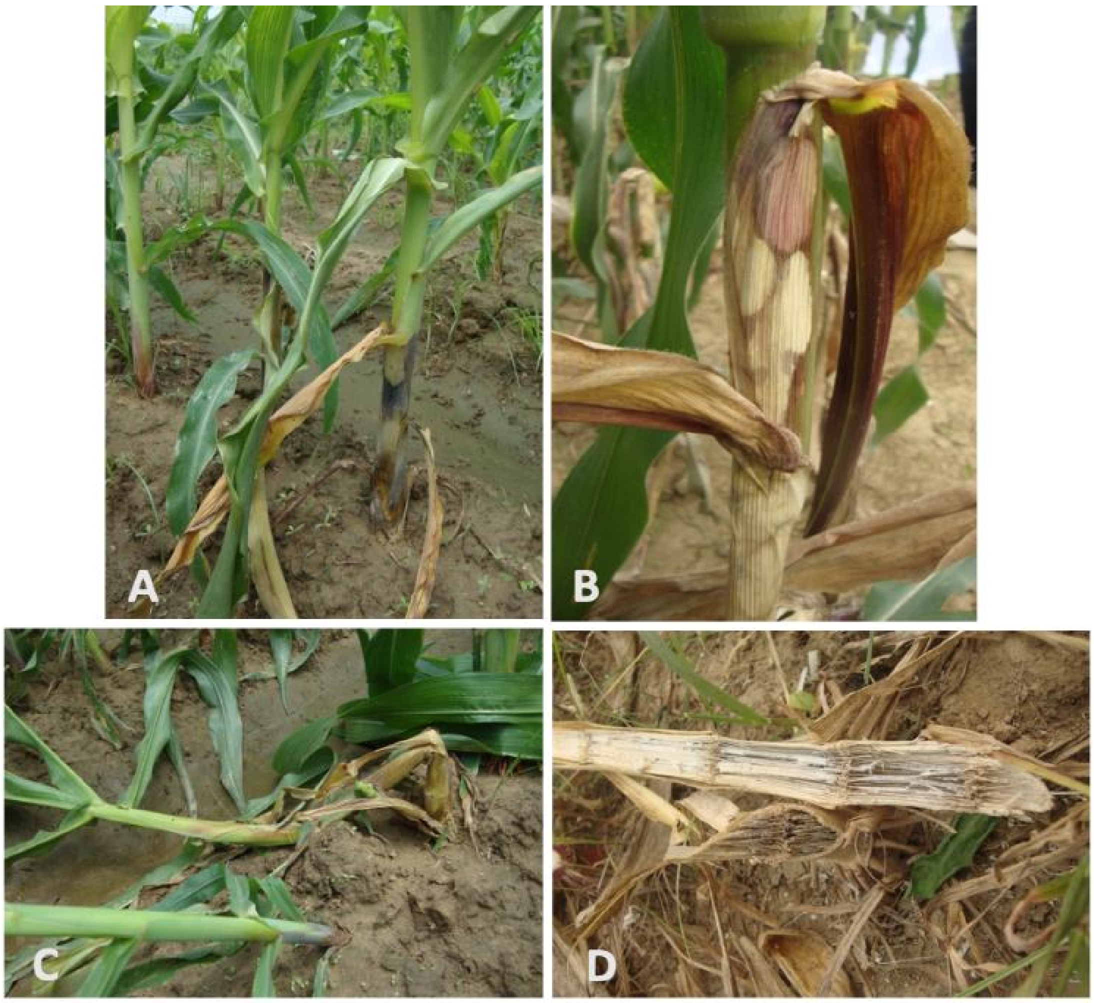

Fig. 1 : Four important soil borne diseases of maize (A) Bacterial stalk rot, (B) Banded leaf and sheath blight, (C): Pythium stalk rot, (D) Post flowering stalk rot (Charcoal rot)

Sanitation

Sanitation is the first step for the management of soil borne diseases in an integrated system. Sanitation includes any sort of activities which aimed to prevention of introduction of inoculum by any means and to reduce or eliminate the inoculum that is already present in the location (Katan, 2010). Soil borne plant pathogens can survive in soil with the help of resting structures like chlamydospores, microsclerotia, oospores or sclerotia and basic reproductive systems, for a very long time, even in the absence of a living host or plant debris and soil organic matter. Therefore, it becomes very important to remove the plant debris away from growing areas whenever possible or accelerate residue breakdown (Panth *et al.* 2020). This can be achieved by different means such as flooding, flaming, solarization, plowing, chemical treatments of resting structures, removal of residues, rouging, pruning and management of alternate hosts (Baysal-Gurel *et al.* 2012). Flooding is the technique helps in soil disinfestation by production of substances that are toxic to the pathogen in lack of oxygen conditions. This helps in control of *Fusarium oxysporum, F. verticillioides, Pseudomonas solanacearum, Verticillium dahliae, Macrophomina phaseolina* and many nematodes. Soil solarization is an environment-friendly, pre-planting, climate dependent method of using solar energy to control soil borne pathogens like *V. dahliae*, certain *Fusarium* spp., *Sclerotinia* spp., *Agrobacterium tumefaciens*, *Streptomyces scabies*, and nematodes, in addition to controlling many weeds (Mihajlovic *et al*. 2017; Panth *et al*. 2020). It can be performed by placing transparent plastic sheets over the production bed after sufficient irrigation. The plastic sheet then allows the solar radiation to be trapped inside to heat the upper layers of soil surface (Baysal-Gurel *et al*. 2012). Deep ploughing is also a good sanitization method which helps in exposure of propagules to elevated temperature which results in killing of the pathogen. This helps in reducing the incidence of southern blight disease and cyst nematode in maize.

Cropping system

Growing same crop year after year results in development and persistence of soil borne pathogens. Mixed cropping, intercropping and crop rotation are important practices which are widely used for the management of soil borne diseases. Managing cropping system helps in increasing soil fertility and destruction of survival structures present in soil which not only controls the specific disease but also helps in improving plant health (Katan, 2010). Although cropping system management is effective for plant disease management, but it is less effective against soil borne pathogens that have a wide host range or produce long-living survival structures or against the wind-blown or vectored or due to limited availability of crops for crop rotation, it is always difficult to control some of the diseases. Thus, it is recommended to use the combination of disease-free planting materials with cropping system (Panth *et al*. 2020) and rather than considering individual crops, plant family must be selected which is a better approach for many soil borne diseases. For example, tomato should be rotated with legumes, cole crops, or lettuce but not within the Solanaceae family (eggplant, chili, potato etc.) to reduce Fusarium wilt (*F. oxysporum*). 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, in comparison with the continuous potato (Larkin *et al*. 2010).

Soil amendments

Organic amendments to the soil are traditionally used for improving soil conditions and crop productivity as it not only improves soil structure and increase water holding capacity, they also support in increasing the beneficial microorganisms in soil. Organic amendments can also effective in management of plant diseases by suppressing soil-borne pathogens (Kirkegaard *et al*. 2000; Paret *et al*. 2010; El-Sharouny, 2015) as increase in activity of microorganisms in the soil creates competition to soil-borne plant pathogens. Organic manures made up of organic wastes, composts and peats, have been proposed to control soil borne diseases and pests such as *R. solani, Thielaviopsis basicola, V. dahliae, Fusarium* spp., *Phytophthora, Pythium* and *Sclerotium*, which may lead to effective suppression of harmful soil borne pathogens. The efficacy of these amendments widely depends upon the amount added, type of soil, physical properties like structure and chemical properties such as cation exchange

Table 1: Major roles of minerals in the management of maize diseases

Minerals	Diseases of maize	Deficiency symptoms	Role of minerals
Nitrogen (N)	Stalk rot and root rot in maize.	Stunted growth, excessive paleness, and upright light green/yellow leaves are all signs of deficiency. In severe insufficiency, it appears burned.	Application of nitrogen improves the plant health because play vital role in chlorophyll synthesis, nucleic acid synthesis.
Phosphorus (P)	Corn smut, downy mildews, Pythium root rot, leaf and sheath blight diseases	Lower leaves and stem turn purplish or reddish in colour. Plants become short and dark green, with a brown or black coloration under the leaf in extreme shortage.	Application of phosphorus Stimulates root growth, stalk and stem strength, flowering, crop maturity, crop quality, resistance against diseases. It affects overall life cycle of plants
Potassium (K) .	Northern leaf blight, root rot, post flowering stalk rot, Stewart's wilt	Tissue hardening, stomatal opening patterns, etc. further enhance infestation intensity. Deficiency appears as small spots on tips, edges of pale leaves. Spots turn rusty and fold at tips.	K+ acts as mobile regulator of enzyme activity. Involved in essentially all cellular functions. Excess K inhibits the uptake of Mg and Ca. K+ deficiency favours accumulation of nitrogen compounds, sugars, for conditioning of pathogen development
Calcium (Ca) .	Bacterial stalk rot and top rot diseases	Deficiency appears as plant appearing dark green, with tender and pale colored leaves, drying starts from tips and eventually leaves die.	Ca deficiency causes the plant cell walls to develop or function improperly, resulting in increased disease infection and spread inside the plants, therefore application of Ca improves plant health

Table 2: Few important maize pathogens/diseases managed using IDM

Maize pathogen/Diseases	IDM Component Applied	References
Fusarium sp.	Soil solarization, Sanitation	Baysal *et al.*, 2012
Macrophomina phaseolina	Soil amendments	Singh and Singh, 1981
Verticillium dahlia *Fusarium* sp. *Rhizoctonia* sp.	Sanitation, cropping system and chemical management	Tenuta, 2001
Corn smut, Pythium root rots and sheath blight of maize	Phosphorus based nutrient application	Singh *et al*., 2017

Note: All soil borne pathogens can be managed or minimized by biological control i.e. by bacteria *Pseudomonas fluorescence,* or fungi *Trichoderma viridae*

capacity, pH, electrical conductivity of the soil (Panth *et al*. 2020). The effectiveness of some organic amendments in decreasing the severity of stalk rot of maize in the field was also reported. Besides, the suppressive effect of organic amendment of soil on *Fusarium* spp. and *Macrophomina phaseolina* has also been demonstrated.

Soil fertility and plant nutrients

Mineral nutrients are components of plants which regulate metabolic activity which can make the plant more tolerant or resistant to diseases (Sullivan, 2001). Soil nutrition, along with the use of fertilizers and amendments, has been shown to

Table 3: Few important maize pathogens/ diseases managed using IDM

Disease and pathogen	Symptoms and predisposing factors	IDM
Banded leaf and sheath blight *Rhizoctonia solani*	Mature symptoms are characteristic cigar shaped lesions that are 3 to 15cm long. Lesions are elliptical and tan in color, developing distinct dark areas as they mature that are associated with fungal sporulation. Lesions typically first appear on lower leaves, spreading to upper leaves and the ear sheaths as the crop matures. Predisposing factors**:** Optimum temperature for the germination of conidia is 8 to 27°C provided with free water on the leaf, infection takes place early in the wet season.	Lower leaves and sheaths stripping (Kaur *et al*. 2020, Fig. 2), hybrids of resistant and tolerant variety planting. At 50 DAS or as soon as symptoms occur, foliar spray Azoxystrobin 18.2 percent + Difenconazole 11.4 percent w/w SC (Amistar Top 325 SC) 1ml/L of water Repeat the spray at a 15-day interval if necessary.
Fusarium stalk rot *Fusarium verticillioides*	Cause reduced growth, rotted leaf sheaths and internal stalk tissue and brown streaks in the lower internodes. Mature plants, it shows pink to salmon discoloration of the internal stalk pith tissues. Predisposing factors**:** High temperature low soil moisture. Presence of debris.	Sanitation in the field Complete elimination of previous crop detritus and extensive ploughing Crop rotation is a good option. Apply a well-balanced fertilizer dose (low nitrogen and high potassium). Harvesting early lowers ear loss if stalk rot is prevalent. Hybrids that are resistant and tolerant
Bacterial stalk rot *Dickeya zeae, Erwinia chrysanthemi*, *Erwinia dissolvens*	It causes decay of the first internode above the soil. The rind and the pith become soft, brown, and water-soaked. Affected plants have a foul odor. Predisposing factors**:** Wet conditions. Some hybrids are more susceptible than others.	Destroy plant debris, Maintain the proper drainage, Use of resistant/tolerant variety, drenching with bleaching powder Ca $(ClO)_2$ with 1.5g /15 l of water immediately after symptoms appear
Downy mildew *Pernosclespora sorghi*	Chlorotic streaks appear on the leaf, white fungus growth is seen on both the surfaces. Stunting of plant and bushy appearance due to shortening of internodes. proliferation of axillary buds on the stalk of the tassel are noticed. Predisposing factors**:** Low temperature (21-33°C), 90% relative humidity and drizzling young plants are highly susceptible.	Plant early and avoid staggered planting, Use of resistant/tolerant hybrids, Treat seeds with Metalaxyl with Mancozeb (WS) at the rate 3.0 g/kg seeds, Foliar spray Azoxystrobin 18.2%with Difenconazole 11.4% w/w SC (0.1%) after 20 days of sowing.

directly impact microbial communities (Table 1). Addition of high nitrogen organic amendments reduced the populations of plant pathogens such as verticillium wilt of tomato, common scab of potato, post flowering stalk rot of maize, root rot of maize and plant parasitic nematode populations (Conn and Lazarovits, 2001;Tenuta, 2001). Soil fertility and chemistry including soil pH, calcium, phosphorus and zinc levels and nitrogen form can all play a major role in the management of soil borne diseases. Calcium applications increases the structural integrity and resistance of middle lamella, components of cell wall, and cell membranes to the toxins produced by harmful pathogens and helps in management of *P. myriotylum, S. rolfsii, Cylindrocladium crotalariae, S. minor, R. solani* and *F. solani* (Huber and Haneklaus, 2007). The increase in pH helps in uptake of calcium control clubroot of crucifers (*Plasmodiophora brassicae*). The nitrate form of nitrogen makes the root zone less acidic, which results in better control of Fusarium wilt. The level of phosphate in the soil can also be critical to disease which helps in management of soil borne diseases such as Fusarium wilt in tomatoes, wilt in cotton (Sullivan, 2001), corn smut, Pythium root rots and sheath blight of maize (Singh *et al*. 2017). Systemic acquired resistance may be involved in disease suppression which is regulated by many micronutrients such as manganese, zinc, lithium, sodium, cadmium, aluminium and mercury may also have role in host plant relationship. Manganese inhibits the aminopeptidase induction which supplies essential amino acids for fungal growth (Dordas, 2008) and this helps in management of leaf spot, mildews and stalk rot of maize (Singh *et al*. 2017). Similarly, zinc can reduce disease severity caused by *P. dreschsleri* and is effective in management of fusarium stalk rot, Alternaria leaf spot, sheath blight and downy mildew of maize (Singh *et al*. 2017). Lower leaves stripping and clean cultivation for management of banded leaf and sheath blight disease of maize has been introduced (Fig 2).The stalk rot complex of maize caused by *M. phaseolina* and *F. verticillioides* could be well managed by application of increased dose of potash (80 kg K/ha) and by maintaining high soil moisture during flowering stage (Gogoi, 2020, unpublished). Although, resistance is primarily genetically controlled; however, it can be modulated by physiological and biochemical processes which are associated with nutrient level. Therefore, the proper management of nutrients, along with other integrated measures to control the diseases, aids in keeping the disease under the threshold level.

Resistant cultivars/ varieties

The use of resistant cultivars or varieties is one of the effective tools in disease management which involves the use of cultivars that are able to resist or tolerate pathogen attack (Legreve and Duveiller, 2010). This method of disease management is easy, cheap, environmentally sound and effective (Dodds and Rathjen, 2010), unless pathogens overcome the resistance. On the other hand, conventional breeding is used for the development of resistant cultivars/varieties time-consuming method (Katan, 2017) as there is not any one plant cultivar/variety that is completely resistant to all disease threats (Baysal *et al.* 2012).

Resistance is determined by the interaction between genetic factors in the pathogen and alteration of genetic material by biotechnology is more promising (Christou, 2013). Changes in atmospheric composition and climate may influence host–pathogen interactions and host resistance through numerous types of morphological and physiological alterations (Chakraborty *et al.* 2000, Lake and Wade, 2009, Eastburn *et al.*. 2010). A better understanding of host–microbe interaction for broad adaptation to multiple environments can play a very good role in the use of genetic engineering to create disease resistance. Breeding for resistance against several pathogens should be combined with breeding for tolerance to abiotic stresses such as drought and heat (Legreve and Duveiller, 2010; Tilman *et al.* 2002). Incorporation if resistant varieties in IDM are a double alternative for the management of many diseases such as stalk rot of maize (Hooda *et al.* 2017). The most effective control of late wilt is possible using resistant germplasm (Bisht *et al*. 2019)

Biological control

Chemical methods are easy, quick and effective; yet they are harmful for the environment and reduce populations of beneficial microorganisms in the soil. The application of biocontrol agents (BCA) to the soil is an alternate to suppress soil borne plant pathogens through parasitism, antagonism, competition, and induction of resistance in plants against pathogens (Shafique *et al.* 2016). In field conditions total crop losses

Fig. 2: Lower leaves stripping and clean cultivation for management of banded leaf and sheath blight disease of maize

are rarely due to the result of the activity of one pathogen, but of a combination. Because of the complexity of such a situation, biocontrol studies are difficult to implement and the results are not easy to evaluate. In general, their effectiveness of biological control agents requires specific, conducive environmental conditions; BCA populations may fail to reduce disease incidence and severity (Garrett *et al.* 2006). BCAs may be effective either upon introduction by application or through strengthening their natural occurrence. The efficacy of biological control method has been a long-term goal in sustainable agriculture. It is highly dependent on the integrated approaches for maintaining soil health and controlling soil borne pathogens. Various attempts at biological control by inoculating corn seed with competitive or antagonistic organisms *(Macrophomina phaseolina, Trichurus spiralis, Bacillus subtilis, Pseudomonas fluorescens, Verticillium tricorpus*) have been evaluated against soil borne diseases of maize (Mazzola and Freilich, 2017; Bisht *et al.* 2019). Seed treatment with *Streptomyces graminofaciens* significantly reduced the incidence of late wilt of maize (El-Mehalawy *et al.* 2004) and seed treatments with *T. harizianum* (4 g/kg seed)

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along with castor and neem cake also reduces the disease incidence (Degani and Weinberg, 2014; Elshahawy *et al.* 2018).

Chemical control

Chemical treatment of soil borne plant diseases is commonly used in big agricultural production areas because of its quick effect and ease of use. Certain dicarboximide, benzimidazole, and triazole fungicides have been shown to successfully suppress soil borne fungal disease. Growers are resorting to numerous recognized chemical alternatives to methyl bromide for soil fumigation because non-chemical alternatives can be time-consuming and ineffective against soil borne plant diseases (Budge *et al*., 2001; Matheron *et al*., 2004; Labrada *et al*., 2007).

Integrated disease management (IDM)

In view of environmental problems caused by massive use of chemical pesticides and inefficacy of other disease management practices, IDM has

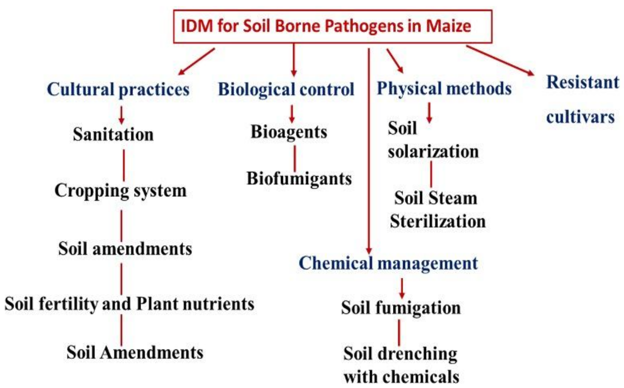

Fig. 3 : Schematic representation of integrated disease management of soil borne pathogen in maize

been accepted as an important principle of the overall crop protection programmes. In IDM, the economic threshold level (ETL) of important diseases is mostly emphasized. Thus, IDM comprising the best combinations of cultural, biological and chemical measures provides the most cost effective and environment safety methods of managing diseases and other pests (Fig. 3). Management of some of the important maize diseases by adopting IDM approaches have been cited in Tables 2 and 3.

CONCLUSION

Soil borne diseases are important to manage as they are considered as a major limitation to crop production. Similarities among the symptoms such as seedling damping off, root blackening, root rot, stunting, wilting, yellowing, bark cracking and twig or branch dieback among different disease make the accurate diagnosis of a particular disease difficult which in turn makes the disease harder to manage. Climate change probably influence the occurrence, prevalence and severity of soil borne diseases which will also affect disease management with regard to timing, preference and efficacy of chemical, physical and biological measures of control and their utilization within integrated pest management (IPM) strategies. For the management of these diseases, conventional synthetic chemical fungicides and fumigants are applied at regular intervals throughout the growing season of the crop. Although the use of fungicides against soil borne plant pathogens can help to manage some diseases but frequent and indiscriminate use of these chemicals are harmful for the environment and can also lead to development of fungicide resistance. With the increasing environmental and health concerns, alternative methods must be developed and put into use. Some environment-friendly approaches such as the use of crop rotation, soil solarization, anaerobic soil disinfestation, soil steam sterilization, biofumigants, resistant cultivars/varieties or grafted plants and biocontrol products have been developed to control soil borne diseases while maintaining the environment. However, these alternative disease-management methods either have inconsistent results or are less effective than chemical management.

A particular challenge is the effective dissemination and use of known but currently underutilized techniques. Like the use of plant disease resistance and tolerance are effective but they are genetically controlled, they are affected by the environment and especially by nutrient deficiencies and toxicities. As soil comprises a full ecosystem including many microbes, it is very important to understand those interactions to develop a soil health management strategy instead of focusing on individual disease causing species. Studies on disease suppressive soils have led to the development and adoption of new approaches for a better understanding of soil microbial community responses they could be use for an effective method for natural suppression of soil borne plant pathogens. There are many agronomic factors that affect the severity of plant disease viz., planting time, crop rotation, mulching and mineral nutrients, organic amendments (manures and green manures), liming for pH adjustment, tillage, seedbed preparation and irrigation. A balanced human intervention, replenishment of soil water storage and runoff to prevent risk of soil erosion and transfer of sediments to surface with proper regulation of the movement of nutrients, pollutants and sediments to surface- or groundwaters can be effective for maintaining soil health. It is further necessary that plant pathologists should identify and focus on management practices that promote soil health, have positive effects on the management of soil borne diseases.

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