# 19 Biofumigation in Crop Disease Management

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## 19.1 Introduction

Plant diseases have been associated with crop plants since agriculture began and, until recently, were routinely managed through application of synthetic fungicides. Among the plant diseases, soil-borne diseases are the important factor limiting the yield of crops resulting in serious economic losses in many countries. The major soil-borne pathogens include fungi (*Rhizoctonia solani*, *Sclerotium rolfsii*, *Fusarium* spp., *Pythium* spp. and *Phytophthora* spp.), bacteria (*Erwinia* spp., *Raltsonia* spp., *Rhizomonas* spp., *Agrobacterium* spp. and *Streptomyces* spp.) and nematodes belonging to the genera *Meloidogyne*, *Heterodera*, *Longidorus* and *Paratrichodorus*. In general, soil-borne diseases are difficult to control because the causal agents can survive in the soil for long periods in the absence of host. Effective management of soil-borne diseases is possible only through detailed study of their ways of survival and dissemination, effect of environmental conditions, role of cultural practices and host plant resistance. Fumigation and drenching of soil with synthetic chemicals has been practised in agriculture for many years to manage soil-borne diseases and pests of economically important crops. Some commonly used fumigants are methyl bromide, mefenoxam and 1,3-dichloropropene-chloropicrin. Dichloro-diphenyltrichloroethane (DDT), which was used as a chemical fumigant for the control of soil-borne pathogens, was later withdrawn from the market due to its adverse effect on the environment (Gamliel *et al*., 2000). Apart from DDT, methyl bromide and chloropicrin are also used to control fungal pathogens (Lazzeri *et al*., 2004), whereas metham sodium is specific against the fungi, *Verticillium* (Larkin and Griffin, 2007). Methyl bromide has been banned in developed countries since 2005 and will be banned in developing countries by 2015 because of its ozone depleting nature. These fumigants are highly volatile and non-specific, and their use leads to environmental pollution, ecological problems and destruction of beneficial microbial communities in the soil. Similarly, nematicides are highly toxic to humans, contaminate groundwater

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and can be absorbed by plants (Oka, 2010). Synthetic pesticides and fumigation chemicals like methyl bromide are able to cause damage to the ozone layer, are harmful to our environment and to humans as well, hence many developed and developing countries have banned the usage of these chemicals to reduce the risk.

Therefore, an alternative method is needed that can still control crop diseases without affecting human health and the environment. Attempts have been made to use non-chemical alternatives such as biofumigation, biocontrol and soil solarization in the place of pesticides. Brassicaceae plants contain glucosinolates and the products of these glucosinolates upon enzymatic hydrolysis exhibit fungicidal activity. Hence these plants may be used as an alternative approach for the management of soil-borne diseases (Walker *et al.*, 1937). Utilizing crop residues to reduce soil-borne pathogen populations has been examined many times over the years as a method to control these pathogens (Patrick *et al.*, 1964; Lewis and Papavizas, 1975). The value of this process is being re-examined mainly because of the deleterious environmental effects and costs of fumigants. Further, the rotation of crops with green manure crops as potential biofumigants has been widely explored in recent decades by many researchers.

## 19.2 Biofumigation

Biofumigation is a process, whereby volatile chemicals released from decomposing plant material are utilized for suppressing the growth of soil pathogens, nematodes, insects and germinating weed seeds. The term biofumigation was first coined by Kirkegaard *et al.* (1993), who specifically described using glucosinolate hydrolysis products, notably isothiocyanates. During decomposition, in addition to isothiocyanates, plant tissues release nitriles and oxazoldnethiones. Incorporation of glucosinolate-containing plants reduced the initial inoculum of certain soil-borne diseases according to Kirkegaard *et al.* (1993, 1998). Scientific studies have proved that volatiles released during the degradation of organic matter are responsible for the suppression of plant pathogens (Piedra Buena *et al.*, 2007; Clarke, 2010; Lord *et al.*, 2011).

## 19.3 Plant Species with Glucosinolates (GSLs)

Different plant species that contain glucosinolates and sulfur compounds have been reported to have biocidal activity. Glucosinolate-containing plants belong to the Brassicaceae, Capparidaceae, Tropaeolaceae, Moringaceae and Amaryllidaceae families. The family Brassicaceae (brassicas) contains more than 350 genera with 3000 species, of which many are known to contain GSLs. Other than brassica plants, about 500 species of non-brassica dicotyledonous plants also contain GSLs (Fahey *et al.*, 2001; Larkin and Griffin, 2007; Wang *et al.*, 2009) and these glucosinolates can be grouped into different classes, namely, aliphatic, aromatic and indolyl forms (Zasada and Ferris, 2004; Padilla *et al.*, 2007). Kruger *et al.* (2013) studied the biofumigation properties of *Eruca sativa* cv. Nemat, *Sinapis alba* cv. Braco, *Brassica juncea* cv. Caliente 199, and *Brassica napus* cv. AV Jade (canola) and suggested these species for suppression of soil-borne plant pathogens in South Africa.

In Brassicas, the most extensively produced GSLs are aliphatic (e.g. glucoraphenin, glucoerucin, glucocheirolin, glucosinigrin), ω-methylthioalkyl (e.g. glucobenzosisymbrin, glucomalcomiin), aromatic (e.g. glucotropaeolin, glucobarbarin, glucosinalbin) and heterocyclic or indole (e.g. glucobrassicin, neoglucobrassicin, 4-methoxyglucobrassicin) containing either straight or branched chain carbons (Fahey *et al.*, 2001). Allium species contain sulfur compounds known as disulfides (DS) and thiosulfinates (Ti), which have shown antimicrobial activity against plant pathogens (Auger and Thibout, 2004).

Plants contain GSLs that are hydrolysed by an enzyme, myrosinase, in the presence of water into various products upon tissue degradation. Generally GSLs are polar and highly water soluble (Gimsing *et al.*, 2005). The plant species used for soil fumigation are listed in Table 19.1.

## 19.4 Glucosinolates

Glucosinolates are stored in cell vacuoles (Rausch and Wachter, 2005), whereas myrosinase is accumulated in myrosin cells (Hoagland *et al.*, 1991). Glucosinolates consist of sulfur

**Table 19.1.** Plant species used for soil fumigation, as an alternative to chemical fumigation. (From: Lazzeri and Manici, 2001; Keusgen et al., 2002; Karavina and Mandumbu, 2012.)

| Plant species | Common name | Family |
|---|---|---|
| *Alliaria petiolata* | Garlic mustard | Brassicaceae |
| *Allium ursinum* | Bear's garlic | Amaryllidaceae |
| *Allium vineale* | Wild onion | Amaryllidaceae |
| *Arabidopsis thaliana* | Thale cress | Brassicaceae |
| *Azima tetracantha* | Needle bush | Salvadoraceae |
| *Brassica campestris rapa* | Turnip | Brassicaceae |
| *Brassica carinata* | Ethiopian mustard | Brassicaceae |
| *Brassica fruticulosa* | Mediterranean cabbage | Brassicaceae |
| *Brassica juncea* | Indian mustard | Brassicaceae |
| *Brassica napus* | Rape/canola | Brassicaceae |
| *Brassica nigra* | Black mustard | Brassicaceae |
| *Brassica oleraceae acephala* | Kale | Brassicaceae |
| *Brassica oleraceae* | Cabbage | Brassicaceae |
| *Cardamine cordifolia* | Heartleaf bittercress | Brassicaceae |
| *Cardamine diphylla* | Pepper root | Brassicaceae |
| *Carica papaya* | Pawpaw | Caricaceae |
| *Cleome hassleriana* | Spider flower | Capparidaceae |
| *Diplotaxis tenuifolia* | Perennial wall-rocket | Brassicaceae |
| *Eruca sativa* | Salad rocket | Brassicaceae |
| *Iberis amara* | Rocket candytuft | Brassicaceae |
| *Lepidium sativa* | Garden cress | Brassicaceae |
| *Moringa oleifera* | Moringa | Moringaceae |
| *Moringa stenopetala* | Cabbage tree | Moringaceae |
| *Rapistrum rugosum All.* | Common giant mustard | Brassicaceae |
| *Rhaphanus sativus* | Radish | Brassicaceae |
| *Sinapis alba* | White mustard | Brassicaceae |
| *Thlaspi arvense* | Field pennycress | Brassicaceae |
| *Tropaeolum maju* | Indian cress | Tropaeolaceae |

and nitrogen compounds and their quantity varies with plant species; for example, species such as Indian/brown mustard (*Brassica juncea*), black mustard (*Brassica nigra*) and white mustard (*Sinapis alba*) contain higher amounts of glucosinolates. The aliphatic group of glucosinolates is found in foliage of rapeseed (*Brassica napus*), and consists of 3-butenyl (gluconapin), R-2-hydroxy-3-bunenyl (progoitrin/glucorapiferin) and 4-pentenyl (glucobrassicanapin). Similarly, an aromatic glucosinolate found in the roots of rapeseed (*Brassica napus*) (Fig. 19.1) consists of 2-phenylethyl (gluconasturtiin). Earlier studies inferred that aliphatic GSLs degrade much more easily than aromatic GSLs.

### 19.4.1 Mode of action

Glucosinolates and the enzyme myrosinase are separated in living cells, and tissue degradation due to insect feeding, mechanical damage or infection helps to bring them together. At this point, glucosinolates are degraded by the myrosinase enzyme through the process of hydrolysis, thereby volatile products including isothiocyanates (ITCs), organic cyanides, ionic thiocynates and oxazolidinethiones are released. These volatile products are likely to have biological activity against plant pathogens. The enzymatic mechanism of myrosinase involves two steps: the glycosylation step, in which the glycosyl enzyme

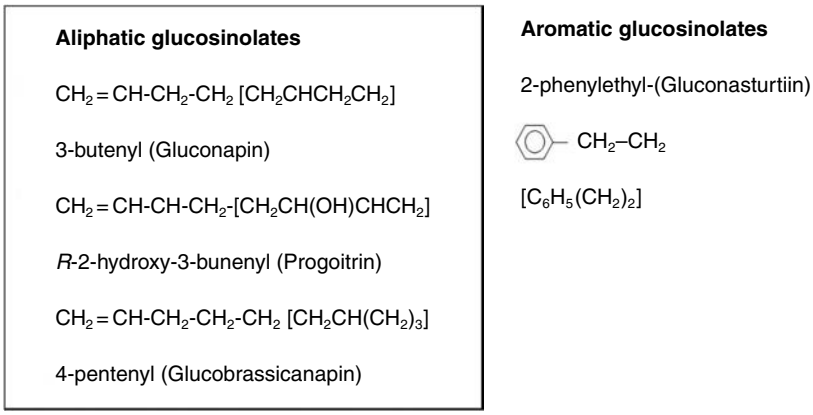


**Fig. 19.1.** Aliphatic and aromatic glucosinolates. (Courtesy of Matthew Back and Melvyn, Harper Adams University, Newport.)

is formed and subsequently the aglycone is released; followed by the deglycolyation step in which the glycosyl enzyme is hydrolysed by a water molecule (Burmeister *et al*., 1997).

These hydrolysis products, in particular the ITCs, are known to have broad biocidal activity including insecticidal, nematicidal, fungicidal, antibiotic and phytotoxic effects (Fenwick and Heaney, 1983; Chew, 1988; Brown and Morra, 1997; Rosa, 1997).

## 19.5 *Allium* Sp. for Biofumigation

Like *Brassica* spp., *Allium* spp. also have biofumigation properties because of their sulfur components, mainly three disulfides: dimethyl disulfide (DMDS), dipropyl disulfide (DPDS) and diallyl disulfide (DADS), with an efficacy superior to that of DMDS. Similar to enzyme myrosinase, alliinase is also stored in the vacuoles. Upon mechanical disruption or insect feeding, alliinase is released, which reacts with S-alk(en)yl-L-cysteine sulfoxides (RCSOs) (Lancaster *et al*., 1988) and releases sulfenic acids (Ferary and Auger, 1996). Many RCSOs (R= methyl, propyl, 1-propenyl) are present in onions, giving rise to DPDS (Arnault *et al*., 2004) as the end product of biosynthesis. In bear's garlic (*A. ursinum*), the major RCSO is methoinin (S-methyl-L-cysteine sulfoxide); it gives rise to dimethyl thiosulfinate (DMTi), which gets rearranged into DMDS. The biocidal activity of *Allium* has been proved and therefore it was suggested for soil fumigation (Auger and Thibout, 2004). GSLs are present in 16 families of dicotyledonous angiosperms including a large number of edible species, and at least 120 types of ITCs have been identified in these plants (Fahey *et al*., 2001).

## 19.6 Management of Soil-borne Diseases

*Brassica napus* contains several types of GSLs including but-3-enyl, benzyl, phenethyl and 2-hydroxy-but-3-enyl (Bjerg and Sorensen, 1987; Gardiner *et al*., 1999). Different stages of plant growth contain various glucosinolates, namely, glucoerucin, glucotropaeolin, glucoraphenin, glucobrassicin, and gluconasturtin. The roots contain mostly the GSL gluconasturtin, whereas the shoots have more aliphatic GSLs (Sarwar *et al*., 1998). It was confirmed that the root tissue of the *Brassicas*, canola and Indian mustard released volatile compounds, namely, methyl ITC and phenyl ethyl ITC, which inhibited the growth of pure cultures of the fungal pathogen that causes take-all of wheat, *Gaeumannomyces graminis* var. *tritici*, at low concentration

(Angus *et al.*, 1994). Higher fungitoxic activity of plants, namely, *Iberis amara* L. (selection ISCI14), *Rapistrum rugosum* All. (selection ISCI4) and *Cleome hassleriana* L. (selection ISCI2) was observed against *Pythium* sp. under *in vitro* conditions, and the activity was mainly due to the degradation products of glucosinolates (Lazzeri and Manici, 2001).

The effect of biofumigation on soil-borne fungal pathogens has been studied by many researchers, e.g. *Rhizoctonia* sp., *Verticillium* sp., *Sclerotinia* sp., *Colletotrichum* sp., *Fusarium* sp., *Pythium* sp., *Phytophthora* spp. (Steffek *et al.*, 2006; Zurera *et al.*, 2007; Mattner *et al.*, 2008; Friberg *et al.*, 2009; Omirou *et al.*, 2011). 2-propenyl ITC has been proved to be toxic to *Verticillium dahliae*, *Helminthosporium solani*, *Sclerotium rolfsii*, *Sclerotinia sclerotiorum* and *Phytophthora capsici* (Chung *et al.*, 2002). A higher percentage of fungal suppression was observed when both mustard roots and shoots were used for biofumigation (Snapp *et al.*, 2007). A reduced number of microsclerotia of *V. dahliae* in strawberry fields were observed as a result of biofumigation with different glucosinolate-containing *Brassica* spp. (Steffek *et al.*, 2006). The number of microsclerotia varied between 0% and 30% depending on the field characteristics and the biofumigant plant species used.

Incorporation of mustard (*Brassica juncea*) as a green manure decreased the inoculum density of *Rhizoctonia solani* (Friberg *et al.*, 2009). However, thick-walled hyphae (pseudosclerotia) of *R. solani* were less susceptible to GSL hydrolysis products than young hyphae (Yulianti *et al.*, 2006). Canola green manures are effective biofumigants against black scurf caused by *R. solani* (Larkin and Honeycutt, 2006; Larkin and Griffin, 2007). Wang *et al.* (2009) reported that production of methyl sulfide and dimethyl disulfide gases from white mustard (*Sinapis alba*) under natural field environments reduced soil-borne pathogens, namely, *V. dahliae*, *F. oxysporum* and *T. semipenetrans*. Taylor (2013) reported that benzyl ITC inhibited the growth of *R. solani* and *Helminthosporium solani* under *in vitro* conditions. Gas chromatography–mass spectrometry (GC-MS) studies confirmed that concentrations of specific ITCs produced during glucosinolate hydrolysis altered throughout the growth period. Hence, the efficacy of the method may depend on the specific biofumigant cultivar being grown and the time of incorporation of the plant material into the soil. Kirkegaard and Sarwar (1998) reported that aliphatic glucosinolates content was greater in shoots, while aromatic glucosinolates, particularly 2-phenylethyl glucosinolates, were dominant in the roots. The concentration of individual and total GSLs in both root and shoot tissues varied within the species. These findings help us to select or develop brassicas with enhanced biofumigation potential. The most significant pathogen suppression was observed with *R. solani* when it was exposed to benzyl or methyl ITC, and *H. solani* was sensitive to 2-phenylethyl ITC (Taylor, 2013).

Larkin and Griffin (2007) tested various *Brassica* crops, namely, canola, rapeseed, radish, turnip, yellow mustard and Indian mustard for the management of soil-borne potato pathogens. Volatiles released from leaf of *Brassica* species and barley were harmful to *R. solani*, *Phytophthora erythroseptica*, *Pythium ultimum*, *Sclerotinia sclerotiorum* and *Fusarium sambucinam* under *in vitro* conditions, whereas Indian mustard inhibited the growth completely up to 80–100%. These *Brassica* crops and barley under greenhouse conditions reduced the inoculum levels of *R. solani* (20–56% reduction); radish, rapeseed and Indian mustard reduced potato seedling disease by 40–83%. Canola and rapeseed grown as green manure rotation crops reduced black scurf by 70–80% in potato. Satisfactory results were obtained with Indian mustard against powdery scab and common scab diseases of potato, whereas *Rhizoctonia* diseases were reduced with rapeseed and canola treatment. The combination of mustard blend (mustards and rapeseed) grown as green manure was found to be the most effective in reducing potato scurf disease by up to 54% and increasing the yield by 25% compared with soybean cover crop (Larkin and Halloran, 2014).

The biofumigation process has been modified a little to increase the efficiency of the process. Blok *et al.* (2000) reported that *Brassica juncea* was decomposed anaerobically in field soil with temporary irrigation and covered with polythene sheets, and the technique, developed in the Netherlands and Japan, was named biological soil disinfestation (BSD). Model experiments of BSD with wheat bran or *Brassica juncea* and *Avena strigosa* plants as biomass sources successfully controlled the wilt pathogen populations of

tomato (*Fusarium oxysporum* f. sp. *lycopersici* and spinach (*F. oxysporum* f. sp. *spinacea*) when incorporated into soil (Mowlick *et al.*, 2013).

## 19.7 Seed Meal as a Source of Biofumigation

Seed meal, a by-product derivative of oil extraction of the seeds from the glusosinolate-containing plant species can also be used for soil-borne pathogen suppression, wherein it forms a source of nitrogen and other nutrients. Several reports have shown that amending the soil with *Brassica* sp. as seed meal suppressed many plant fungal pathogens (Lodha and Sharma, 2002; Kirkegaard and Matthiessen, 2004; Matthiessen and Kirkegaard, 2006). Mustard seed meal application significantly reduced the stem infection in lily caused by *Rhizoctonia solani* (Van Os *et al.*, 2004; Van Os and Lazzeri, 2006). Apple replant disease is commonly characterized as a pathogen complex involving the genera *Rhizoctonia*, *Cylindrocarpon*, *Pythium* and *Phytophthora* (*P. cactorum*) and lesion nematode *Pratylenchus penetrans* (Mazzola and Mullinix, 2005). The pathogen complex varies from site to site, even among orchards within close proximity (Traquair, 1984). The efficacy of brassicaceous seed meals (*Brassica juncea*, *Brassica napus* and *Sinapis alba*) for the management of apple replant disease was studied by Mazzola and Brown (2010). The study inferred that *B. juncea* and *S. alba* seed meal soil amendments were effective when it was combined with mefenoxam – a post plant fumigant – in terms of disease control, tree growth and overall fruit yields of Gala/M26 apple under a conventional production system. Similarly, a seed meal blend of *B. juncea*:*B. napus* (1:1 ratio) performed well in terms of disease control and vegetative growth of Gala/M26 under organic systems. Hence, the study results concluded that these amendments act as an alternative to soil fumigation for the control of apple replant disease in both conventional and organic systems.

Apple root infection by *R. solani* AG-5 was suppressed by allyl isothiocyanate (AITC), which was released from *B. juncea* seed meal amendments (Mazzola and Zhao, 2010). Seed meals of *B. juncea* and *B. napus* at a concentration of 0.5% significantly reduced the infection of *R. solani* AG 8 in wheat (*Triticum aestivum* L.) compared to the unamended control (Handiseni *et al.*, 2013). Radish (*Raphanus sativus* L.), mustard (*B. juncea* (L.) Czern) and winter rapeseed (*B. napus* L.) were evaluated for their biofumigant activity against *R. solani* in bell pepper. The crops were disked into the soil and immediately covered with virtually impermeable film (VIF) to reduce the escape of volatile pesticidal compounds. It was revealed that mustard followed by rapeseed and radish reduced populations of *R. solani*, and the concentration of ITCs was high in mustard followed by the other crops (Hansen and Keinath, 2013). *Fusarium oxysporium*, *R. solani*, *Macrophomina phaseolina* and *S. rolfsii* are the common fungal pathogens infecting soybean causing damping-off, root rot and wilt diseases resulting in serious economic losses. Management of these pathogens is difficult due to their broader host range and nature of survival mechanisms in the soil. Fayzalla *et al.* (2009) evaluated the effect of mustard seed meal as a biofumigant in lab, greenhouse and field conditions against the root rot and wilt pathogens infecting soybean. Mustard seed meal resulted in decreased linear growth of *R. solani* as compared with the control. In pot culture experiments, suppression of disease as well as increased plant growth were observed in mustard seed meal-treated pots compared to the untreated control. The sensitivity of the pathogen to seed meal differed at all levels and, among the pathogens, *R. solani* was the most sensitive. Under field conditions also, mustard seed meal was compared with Rhizolex® fungicide and both mustard seed meal and Rhizolex® reduced the disease incidence by 69.5% and 74.4%, respectively, 4 months after planting. Studies conducted by Handiseni *et al.* (2013) revealed that soils amended with *Sinapis alba* seed meal had the lowest severity of root rot caused by *R. solani* Kuhn anastomosis group (AG) 8 in wheat.

White lupine (*Lupinus albus*) mainly used as green manure, is infected by a wilt pathogen *F. oxysporum* f. sp. *lupine.* Shaban *et al.* (2011) studied the effect of mustard and canola seed meal against *F. oxysporum* f. sp. *lupine* as a biofumigant and compared it with Topsin M-70® fungicide under lab, greenhouse and field conditions. Under lab conditions, mustard seed meal decreased the growth of wilt pathogen of lupine and the growth decreased further with increasing concentrations

of seed meal, whereas canola seed meal reduced the growth of the pathogen only at high concentrations. In the pot culture studies, mustard seed meal treatment reduced the percentage of disease reduction up to 85.7%, followed by canola seed meal treatment (71.4%) and the fungicide Topsin M-70® treatment (64.3%), and the reduction in disease was reflected in increased growth parameters of lupine such as plant height, number of pods, weight of seeds and root length of plants grown. Field experiments with mustard seed meal treatment reduced the disease incidence by 83.6% at 30 and 90 days after planting for the first season (2008/2009) and 87.5% and 87.8% for the second season (2009/2010).

Fan *et al.* (2008) evaluated powdered tissues of *Brassica oleracea* var. *caulorapa* against 28 fungal isolates from 16 hosts under *in vitro* conditions. One gramme of powder of *B. oleracea* var. *caulorapa* could suppress the growth of *Ceratobasidium fimbriata* up to 68.6% and *V. dahliae* up to 68.7%. The findings also suggested that the amount of plant tissue should be standardized depending on target pathogen species for better results.

Other than *Brassica* plants, the alliaceous crops, namely, onion (*Allium cepa* L.) and garlic (*A. sativum* L.) also exhibited multiple bioactive properties against variety of soil microorganisms including fungi, bacteria and nematodes (Timonin and Thexton, 1950; Bianchi *et al.*, 1997). In *Allium* spp., suppression was due to the production of volatile sulfur compounds released via cleavage of certain S-alk(en)yl cysteine sulfoxides. The quality and quantity of volatile sulfur compounds varied among members of the Alliaceae (Jones *et al.*, 2004). In addition these bioactive compounds inhibited the germination of weed species like *Echinochloa crusgalli*, *Sisymbrium irio* and *Solanum oleraceus* in soil at ambient temperature (23°C) (Mallek *et al.*, 2007).

## 19.8 Management of Nematode Infection

Biofumigation has also been reported to reduce nematode populations (Henderson *et al.*, 2009; Zasada *et al.*, 2009). Green manures like *Brassica* sp. were more effective in suppressing nematodes under controlled conditions (Mojtahedi *et al.*, 1991; Mojtahedi *et al.*, 1993; Potter *et al.*, 1998). Rahman and Somers (2005) reported that when *B. juncea* cv. Nemfix (Indian mustard) was incorporated into the soil as a green manure, a suppressed population of *M. javanica* was observed. In addition to glucosinolate content of the brassica plants, secondary metabolites that are released during the biofumigation process might also play a role in the process of suppressing the nematode population (Piedra Buena *et al.*, 2006). Piedra Buena *et al.* (2006) reported that other than glucosinolates, secondary metabolites that are released during the biofumigation process also suppressed the nematode population. It was reported that root-knot nematode species can complete their life cycle on several *Brassica* spp., but their susceptibility varies with species (McLeod and Steel, 1999). The efficacy of biofumigation depends upon the selection of cover crop, because the selected crop should either be resistant or have a poor host status for the target pest (Vianene and Abawi, 1998). Melakeberhan *et al.* (2006) reported that *Eruca sativa* cv. Nemat was suitable trap crop for *Meloidogyne hapla* root-knot nematode wherein no eggs were produced in 80% of the plants. In addition to the selection of *Brassica* plants, soil temperature and duration of exposure of treatments played an important role in the efficacy of the biofumigation process. Ploeg and Stapleton (2001) tested the effect of time and temperature in combination with brassica soil residues on the suppression of *M. incognita* and *M. javanica*. It was found that in a temperature range of 30–35°C for 10 days, the treatment almost eliminated the galls on the roots. Methanol extracts of *Terminalia arjuna* (Combretaceae) bark, particularly 3,4-dihydroxybenzoic acid (3,4-DHBA) exhibited nematicidal activity against juveniles of *Meloidogyne incognita* collected from roots of infected cucumber plants (Nguyen *et al.*, 2013). Biofumigation with broccoli (*B. olerace* L. var. *italica* L.) plant parts efficiently controlled *M. incognita* and produced significantly higher yields in the organic tomato fields in Turkey to those found with treatment consisting of grafting the susceptible cultivars with resistant root stock (Kaskavalci *et al.*, 2009). Henderson *et al.* (2009) reported that in potato crop, both *Brassica carinata* seed meal and *Steinernema* spp. reduced root-knot nematode damage to potato tubers and increased marketable tuber yields.

## 19.9 Influence of Biofumigation on Soil

Application of crops as biofumigants also improves soil structure and physical properties, soil infiltration and nutrient values (Cherr *et al.*, 2006). Among the different crops tested, soil treated with canola had the highest dissolved carbon and cation concentration (K + sodium – Na). Solubility of Fe/Al phosphate increased the soil pH from 4.8 to 5.3–6.2 in the rhizosphere region (Wang *et al.*, 2007). In addition to improving soil structure, the added plant materials can also change the native microbial community with respect to competition, parasitism, antagonism and predation against the soil-borne pathogens (Raaijmakers *et al.*, 2009) due to the changes in plant root secretions (Xu *et al.*, 2009). *Brassica* sp. as plant material or its seed meal was found to influence microbial community structures (Vera *et al.*, 1987; Williams-Woodward *et al.*, 1997; Mazzola *et al.*, 2001; Cohen and Mazzola, 2006; Hoagland *et al.*, 2008; Friberg *et al.*, 2009; Omirou *et al.*, 2011). Incorporation of *Brassica* plant material for biofumigation altered the microbial community in the soil.

## 19.10 Compatability with Biocontrol Agents

The population of the rhizosphere microorganisms, namely, *Trichoderma* spp., *Pythium* spp., fluorescent *Pseudomonads*, *Streptomyces* spp., actinomycetes and other antagonists of soil-borne pathogens was either increased or decreased due to the effect of *Brassica napus* seed meal depending on the plant species and soil type (Mazzola *et al.*, 2001; Cohen and Mazzola, 2006; Mazzola and Zhao, 2010; Mazzola *et al.*, 2012). Wang *et al.* (2014) tested the compatibility of antagonistic *Bacillus amyloliquefaciens* strain BS211 along with biofumigation to control the pepper disease caused by *Phytophthora capsici* under controlled conditions. Application of the biofumigant along with the antagonistic bacteria reduced the disease incidence and increased soil bacterial diversity. Stefania Galletti *et al.* (2008) studied the compatibility of beneficial fungus *Trichoderma* with *Brassica carinata* seed meal (BCSM). Forty isolates of *Trichoderma* spp. were tested against seed meal and volatiles released by BCSM. *Trichoderma* spp. were found to be generally less sensitive than the tested fungal pathogens (*P. ultimum*, *R. solani* and *F. oxysporum*). In addition, the author also pointed out that there was a reduction in allyl-isothiocyanate concentration in the soil. This may be due to the activity of *Trichoderma* isolates which protected against the biocidal compounds.

## 19.11 Compatability with Other Techniques of Disease Management

The biofumigation process may not kill the pathogen completely, but the target pathogen group may be weakened so that it cannot survive in those environmental conditions. Hence, biofumigation can be combined with other techniques like soil solarization. Solarization, alone or combined with biofumigation or low doses of fumigants, has gained wider adoption as a methyl bromide alternative in areas with sunny climates and where it suits the cropping season and the pest and disease complex, especially countries like Morocco, Israel, Jordan and Brazil. Biofumigation is widely used at a commercial level in many developing and developed countries to control soil-borne pathogens (Zurera *et al.*, 2007; Fan *et al.*, 2008; Mattner *et al.*, 2008; Njoroge *et al.*, 2008; Bensen *et al.*, 2009). There are several patents for commercial manufacturing of biofumigants for pest control using *Brassica* seed products. Bello *et al.* (2003) reviewed the switching over of Spain to biofumigation and biosolarization as the main non-chemical alternatives, followed by soil-less cultivation, crop rotation, resistant varieties and grafting. These alternatives are more effective when combined in integrated crop management (ICM) systems.

The combination of biofumigation and soil solarization has been found to be synergistic in improving the efficacy of both procedures and thereby reducing the time required for solarization and the rates of amendment needed for biofumigation (Ndiaye *et al.*, 2007; Medina *et al.*, 2009; Porras *et al.*, 2009). Adoption of non-chemical alternatives such as substrates, grafting, resistant varieties, steam, solarization, biofumigation and biodisinfection has been

**Table 19.2.** Alternative soil technologies adopted in different countries instead of methyl bromide. (From: MBTOC 2010 Assessment Report.)

| Country | Soil technologies selected |
|---|---|
| Peru | Steam, floating trays, solarization, biocontrol agents and biofumigation |
| Uruguay | Solarization + chemicals (1,3-D/Pic, MI, MS, DMDS), biofumigation and steam |
| Egypt | Substrates, steam, biofumigation, grafting |
| Lebanon | 1,3-D, 1,3-D/Pic, metham sodium, solarization, solarization + reduced doses of chemicals, grafting, crop rotation, biofumigation and floating trays |
| Bosnia and Herzegovina | Floating trays, solarization and biofumigation |
| Macedonia | Floating trays and solarization + biofumigation |

increasing tremendously in recent years. In Europe, the non-chemical alternatives applied in commercial strawberry fruit production are crop rotation, which is widely used in Denmark, Germany, the Netherlands and Poland; steam, which is used to protect strawberry in Belgium, France and Germany; solarization, which is used in Cyprus; and mulches, which are used against weeds in countries like Estonia, Germany and Slovenia. These alternatives are used extensively as methyl bromide alternatives in *Solanaceous* crops in Mediterranean countries and other areas of the world (Besri, 2002; Fennimore *et al*., 2006). Solarization combined with biofumigation resulted in significant increase in tomato yields and decreased densities of certain pathogens and nematodes according to Iapichino *et al*. (2008). In Spain, biofumigation and biosolarization (biodisinfestation) are the main non-chemical alternatives that are increasingly used in pepper and tomato production.

## 19.12 Conclusion

Farmers have been accustomed to using very high levels of fungicide or fumigant for the management of soil-borne diseases. In recent years, public concern about the environment has increased the need to develop and implement effective non-chemical alternatives instead of chemical fumigants. The results of biofumigation studies have already shown its definite potential and good results for the management of nematodes, soil-borne diseases and weeds whenever its methodologies are applied correctly. Plants containing glucosinolates, especially *Brassica* spp., exhibit biocidal activity against soil-borne pathogens of various crops and can be exclusively used for the biofumigation process. Despite its limitations, biofumigation has many potential benefits that could be exploited in disease management very well in the future. Furthermore, it could act as a very good alternative technique to use of the chemical fumigant methyl bromide. Though few reports are available on the combination of cultural practices along with biofumigation processes, research has shown that the effects of biofumigation could be further strengthened alongside solarization and in combination with ITC -resistant biocontrol agents to achieve maximum benefit in management of soil-borne pathogens.

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