Biofumigation: Prospects for control of soil borne plant diseases

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ABSTRACT

One of the biggest worries for farmers is the spread of pathogens through the soil. These diseases are difficult to control because they are often tiny in size, buried in the soil, and frequently highly harmful even in small numbers. The Montreal Protocol on Substances that Deplete the Ozone Layer, to which the majority of countries are signatories, has restricted the use of residual pesticides for the management of soil-borne infections, and the demand for food that is free of blemishes is rising. However, it has become urgently necessary to find suitable substitutes as a result of the phase-out of methyl bromide, a significant chemical. After introducing plants that contain glucosinolate, which is digested to produce isothiocyanates (ITC) in the soil, biofumigation has emerged as a crucial procedure to control plant diseases. The existence of glucosinolates and the byproducts of their hydrolysis in soil illustrate the effectiveness and environmental impact of biofumigation. The most significant producers of bioactive chemicals are Brassica species, which makes them suitable for biofumigation applications. This review focuses on the concept, the effective application of biofumigants against soil-borne diseases, and offers several case examples to highlight upcoming difficulties for the concept's continued advancement.

Keywords: Biofumigation, glucosinolates, hydrolysis, ITC

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INTRODUCTION

The biggest threat to agricultural productivity is thought to be soil-borne illnesses. Crop losses can be severe due to soilborne infections such *Phytophthora* spp., *Sclerotinia* spp., *Sclerotinia* spp., *Rhizoctonia* spp., and *Fusarium* spp. In soil organic matter, crop waste, free-living microorganisms, or dormant structures like oospores, microsclerotia, sclerotia, or chlamydospore, they typically live for a longer period of time. Due to the commonality of their symptoms, such as damping-off, root rot, root discoloration, dwarfing, wilting, chlorosis, bark cracking, and dieback, accurate disease identification is highly challenging, making it challenging to control the illness (Astrom *et al*., 1988). Agriculture has traditionally used soil fumigation, which involves adding toxic, volatile substances to the soil, to control soil-borne diseases. The recent methyl bromide prohibition has drawn attention to the need for substitute techniques to control soilborne pests (Ristaino and Thomas, 1997). In order to lessen the usage of synthetic chemicals and since natural goods are typically regarded as more environmentally friendly than synthetic chemicals, it is deemed desirable to employ natural materials for plant disease management in this way. An illustration of such a tactic is biofumigation, which discusses the utilisation of naturally occurring poisonous isothiocyanates (ITC) created by the hydrolysis of plants containing glucosinolates and integrated into the soil (Angus *et al*., 1994; Brown and Morra, 1997; Kirkegaard and Matthiessen, 2004; Matthiessen and Kirkegaard, 2006). A wide variety of pests, including weeds, nematodes, fungus, bacteria, viruses, and insect pests, are controlled by this strategy. Australian researchers coined the term "biofumigation" to describe the control of soilborne illnesses and pests by the release of various chemicals by brassica species (Kirkegaard *et al*., 1993). Additionally to brassicas, it has recently been discovered that plants from the Caricaceae, Salvadoraceae, Moringaceae, and Tropaeolaceae families also possess biofumigant capabilities (Gouws, 2004; Van Dam *et al*., 2009). It is crucial to have a basic understanding of the environmental chemistry of naturally occurring plant products like glucosinolates and the products of their hydrolysis in order to reduce the likelihood of unanticipated environmental effects from biofumigation. Additionally, in order to increase their effectiveness in preventing disease, it is crucial to comprehend the processes of loss and the significance of the compounds in soil. The significance of glucosinolates and the hydrolysis products they produce in soil is emphasised in this review.

Chemical fumigation on soil borne diseases

When agricultural crops are subjected to ongoing monocultures, fumigants are administered to the soil on a worldwide scale. The chemical components in the soil fumigants have high vapour pressure, a low boiling point, and are poisonous to a variety of microorganisms. The use of soil fumigants has been strictly regulated by the government due to the harm they cause to the environment and human health. It is the most effective and trustworthy technology currently being used in greenhouse crop production to control soilborne illnesses (Xie *et al.*, 2015). Prior to being outlawed globally by the Montreal Protocol due to its tendency to damage the ozone layer, methyl bromide (MB) was the most often used fumigant (Albritton and Kuijpers, 1999). According to Gilreath *et al.* (2004), chloropicrin (CP) and dazomet (DZ), which are now the most frequently employed fumigants worldwide for the production of cucumbers, have replaced methyl bromide. According to Blecker and Thomas (2012) and Noling (2013), these fumigants are restricted use chemical pesticides in the USA, with a few exceptions, and as such, they can only be employed by registered fumigant instruments.

Methyl bromide

At normal temperature and pressure, methyl bromide (CH_3Br) is an odourless, colourless gas. Hydrogen bromide and methanol (CH_3OH) are combined to create it (HBr). In addition to being produced commercially, methyl bromide can also be produced naturally by marine algae, other plants, or as a byproduct of the combustion of plant materials, such as in forest fires. It is a broad-spectrum chemical that was first employed for the fumigation of soil, the fumigation of buildings, and the quarantine of goods. It has been used as a very effective pre-plant soil fumigant against a variety of crop pests, including fungi, nematodes, insects, and over 100 different types of crops. It is strictly regulated by the U.S. Environmental Protection Agency (U.S. EPA) in accordance with the Federal Insecticide, Fungicide, and Rodenticide Act (Montreal Protocol, 2000). It is primarily used in many horticultural crops, such as *Fragaria ananassa*, *Lycopersicon esculentum*, *Nicotiana tabacum*, and *Vitis vinifera*, for the management of pathogens like *Verticillium*, *Pythium* spp., *Phytophthora* spp., *Cylindrocarpon*, and *Rhizoctonia* spp., due to its high volatility, which enables excellent penetration of the soil with (Wilhelm and Paulus, 1980; Ristaino and Thomas, 1997; Porter *et al.*, 1999; Duniway, 2002). However, because it easily contaminates the environment, particularly the Ozone layer, its usage has been prohibited (Duniway, 2002). The application of other fumigants like chemical pesticides with long histories of use, such as metam sodium, 1,3-dichloropropene (1,3-D), chloropicrin, or mixtures of these, and various biologically based options are among the most effective alternatives to control methods being recommended to replace methyl bromide (Desaeger *et al*., 2008).

Chemical fumigants: Alternative to methyl bromide

Chloropicrin

One of the first soil fumigants, it is used as a fungicide in the soil and also has herbicidal and nematicidal activity. Tricholoro (nitro) methane is the chemical name, and its chemical formula is CCl_3NO_2. Chloropicrin was used by Mathews (1920) to combat nematodes and fungus in England. Johnson and Godfrey evaluated the chemical's effectiveness in a pineapple field in 1932 and obtained excellent results against the root knot nematode. According to Cabrera *et al.* (2015), choropicrin has a beneficial effect on *Pythium* and *Verticillum* propagules but is less successful at controlling *Fuasrium* and *Phytophthora*. Similarly, when treated by drip technique, chloropicin was found to be quite efficient against *Sclerotinia sclerotiorum* (Gerik 2005). Chloropicrin and 1,3-dichloropropene can be used alone or in combination to effectively manage some crops that are afflicted by soil-borne plant infections such *Rhizoctonia solani*, *Phytophthora infestans*, and *Verticillium* spp. Methyl iodide and sodium azide are two alternatives to methyl bromide that work similarly well against soil-borne diseases. But more of these compounds must be used in the field. the application of fumigants via a shank or drip irrigation (Ajwa *et al.,* 2002). The use of non-permeable films like "completely impermeable film" gives each technique of fumigant application, such as chemigation or shank application, a benefit (TIF). Chloropicrin is the second-most often utilised fumigant in the field when MB is not present (Agrian, 2015a).

Dazomet is another powerful soil fumigant that can also be applied as a granular formulation to suppress pathogens that are found in soil, including fungi, bacteria, and nematodes (Anonymous, 1989; Harris, 1990). Additionally, it was pre-tested in horticultural nurseries and a playhouse for decorative plants cultivated in earthen pots before being transplanted (pre-planted) (Buczacki and White 1977; Ajwa *et al.* 2003; Fritz and Dimcock 2005 and Agrian 2015b). The effectiveness of dazomet (at rates of 100 & 250 kg per hectare) against the cauliflower disease clubroot was validated by Porter *et al.* in 1991. Another test was done to see how well the chemical dazomet worked against cabbage clubroot, and it dramatically decreased the amount of disease infection in the field (Buczacki and White 1979). Pathogens that affect canola yield and induce seedling blight, such as *Fusarium avenaceum*, *Pythium ultimum*, and *Rhizoctonia solani*, can be efficiently controlled with dazomet (Kaminski and Verma 1985; Sippell *et al.* 1985; Gugel *et al.*, 1987; Bailey *et al*., 2003; Soon *et al*., 2005; Hwang *et al.,* 2017).

DMDS (dimethyl disulfide): In a greenhouse setting, Coosemans (2005) examined the efficacy of DMDS (volatile sulphur compound) against numerous diseases, including the nematodes *Globodera* spp., *Meloidogyne* spp., and fungus *Fusarium*, *Pythium*, and *Phytophthora.* Additionally, *Pythium* spp. and *Fusarium* spp. were successfully eradicated by DMDS, according to Church *et al.* (2004).

Bio fumigation: Alternative to chemical fumigants

J.A. Kirkegaard coined the term "bio fumigation" to describe how adding certain brassicaceous varieties to the soil causes the glucosinolate (GSL), a sulphur compound present in plant tissues that has fungicidal, nematicidal, and insecticidal properties, to break down and produce isothiocyanate compounds (ITCs) (Kirkegarrd *et al*., 1993; Matthiessen and Kirkegaard, 2006; Morra, 2004). *Rhizoctonia solani* and *Phytophthora nicotianae* both responded favourably to this tactic (Larkin, 2006; Baysal-Gurel, 2018). Brassica root exudates' impact on *Globodera* spp. (a potato cyst nematode) has demonstrated the potential of GSL-containing plants for disease and pest management (Ellenby, 1945). Researchers Tsror *et al.* (2007) observed that bio fumigants can reduce the prevalence of fungi such *Pythium* spp., *Rhizoctonia solani*, *Verticillium dahliae*, and *Fusarium oxysporum*. Finely crushed *Brassica oleracea* var. *caulorapa* was used in lab tests by Fan *et al.* (2008) on an agar plate to stop the growth of *F. oxysporum* and *Pythium aphanidermatum* mycelium. Mustard's biocidal qualities decreased Verticillum's generation of microsclerotia by about 19–47%. (Michel *et al*., 2007). It has an impact on a variety of soil-borne illnesses and pests. Members of the Brassica family have emerged as one of the greatest sources for the treatment of soil-borne plant diseases in the hunt for an environmentally benign method of plant pathogen control.

Allyl Isothiocyanate

According to Kirkegaards *et al.* (1993) ruptured Brassica plants release a substance called ITCs that can be utilised as a bio fumigant to kill soil-borne diseases. *Sclerotium rolfsii*, a soil-borne disease, was controlled with allyl isothiocyanate, which had similar effects to methyl bromide (Rosskopf *et al*., 2014). Brown and Morra (1997); Rosa *et al.* (1997); Fenwick *et al.* (1983); Chew (1988); Mithen (2001); Matthiessen and Kirkegaard (2006); are just a few of the researchers who have examined and developed a highly sound method, known as bio fumigation, for controlling plant diseases. The increased interest in bio fumigation research from research groups throughout the world has led to the use of fresh cruciferous plant tissues to manage pests and diseases (Brown and Morra, 1997; Mathiessen and Kirkegaard). Hanschen and Winkelmann (2020) proved the abundance of ITC in *Brassica juncea* and found out the effectiveness of Brassicaceae cultivars in bioassay screening. Daneel *et al*. (2018) reported that Marigold, Mustard and cole crops produce nematotoxic chemicals such as GSLs and ITCs.

Economic Importance of bio fumigant crops

As soil-borne plant infections develop chemical resistance, it is more harder to control them. Several members of the Brassicaceae family of plants, such as cabbage, turnips, broccoli, kale, radish, and various mustard varieties, possess biocidal chemicals that can be utilised to successfully control soil-borne diseases.

Mustard as a bio fumigant

Several plants in the brassicaceae family, including mustard and several others, produce glucosinolate. Isothiocyanates and polyphenols, which are the biocidal chemicals of plant origin, are formed by glucosinolate hydrolysis, which is catalysed by the natural plant enzyme myrosinase (Matthiessen and Kirkegaard, 2006) (Fig. 1).

"Allyl isothiocynate" is another name for the isothiocynate that is produced by mustard (AITC). The substance in the industrial fumigant "Vapam," compound AITC, is remarkably similar to it. In laboratory trials, it has been found that isothiocyante (ITC) and nitriles are effective at controlling bacteria, fungus, insects, and nematodes as well as bacteria (Delaquis and Mazza, 1995; Sarwar *et al*., 1998; Noble *et al*., 1999). Abdallah and Kandil (2020) conducted few experiments to examine the effect of *Brassica juncea*, as a biofumigant . The best result was found in defetted seed meal against *Rhizoctonia solani.*

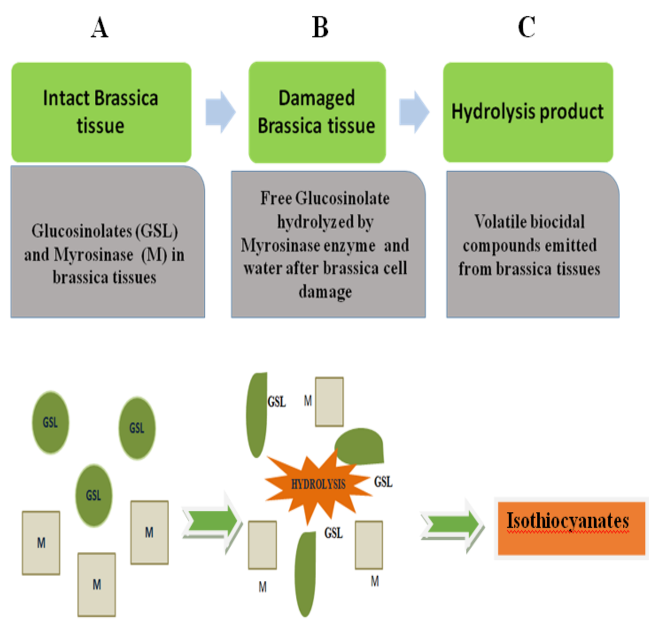

Fig.1. The biofumigation process

Onion, garlic and broccoli as bio fumigants

According to Auger *et al.* (2004), the plant *Allium* spp. contains sulphur compounds that were produced by the breakdown of Allium tissues. The study demonstrated the effectiveness of three disulfide compounds, namely dimethyl disulfide (DMDS), dipropyl disulfide (DPDS), and diallyl disulfide (DADS), against a number of soil-borne pathogens, including *Aphanomyces euteiches, Fusarium moniliforme, Colletotrichum coccodes, Phytophtora cinnamomi*, *Fusarium* Allium residue reportedly releases DMDS and DPDS into the soil, which has a major impact on the ability to combat soil-borne diseases, according to Arnault (2013). This attribute of Allium spp. makes it one of the best substitutes for methyl bromide in the treatment of plant diseases. By lowering the amount of sclerotia, the crop broccoli (*Brassica oleracea*) was proven to be beneficial against Sclerotinia minor (Baysal-Gurel, 2019; Arnault, 2013). By creating ITCs from the crop leftovers of the other Brassica crops, such as canola (*Brassica napus* L.) and Indian mustard (*Brassica juncea*), the soil-borne fungi pathogens were intended to be suppressed (Angus *et al.*, 1994; Kirkegaard *et al*., 1994). The toxicity of volatile chemicals emitted by *Brassica tissues* was proven by Angus *et al.*, 1994 and by Kirkegaard *et al.*, 1996. They also highlighted that it is crucial to create selection criteria for crops with high biofumigation capability.

Pathogen suppression through bio fumigation

Sclerotinia sclerotiorum, *Sclerotium rolfsii*, *Gaemannomyces graminis*, *Bipolaris sorokiniana*, *Rhizoctonia solani* (Kuhn), *Pythium irregulare*, and *Fusarium graminearum* are just a few of the soil-borne diseases that significantly reduce agricultural productivity globally. Biofumigants (ITCs) substances have different antifungal properties depending on their chemical structure (Drobnica *et al*., 1967). Various fungal infections have different ITC fungicidal concentrations (Brown and Morra, 1997). The list of significant biofumigants to inhibit the growth of soil-borne diseases is shown in Table 1.

Methods of application of bio fumigant

These crops can be used in different ways for controlling soil borne pathogens such fungi, bacteria and nematodes.

Green manure and cover crops

By preserving soil cover, increasing soil biomass, reducing soil erosion, increasing soil nutrients, organic matter, and soil structure, green manures crops help following crops and farming methods (Bailey and Lazarovts, 2003; Thorup-Kristensen *et al.*, 2003). For a variety of Brassica crops, brassicaceous green manures have been reported to improve soil structure (Chan and Heenan, 1996), prevent soil erosion (McGuire, 2004), and aid in nitrogen cycling (Thorup-Kristensen *et al*., 2003). Mcleod and Steel (1999) observed that all 15 Brassica cultivars have greatly reduced the population of Meloidogyne javanica when applied as green manure. Rapeseed was used as green manure on potato crops, which decreased the prevalence of *Meloidogyne chitwoodi* (Mojtahedi *et al.*, 1993). Chopped leaves of Brassica spp. and barley emitted volatiles that inhibited the growth of a number of soilborne potato diseases, according to Larkin and Graffin's (2007) research.

Intercropping and crop rotation with brassicaceous crops

Numerous studies have shown that adding Brassica crops as soil amendments significantly suppresses soil-borne diseases. Researchers have established that, in both controlled and uncontrolled environments, a sulphur component, glucosinolate, and ITCs present in the rhizosphere of the intact crop plant reduce soil-borne diseases. In order to effectively manage root-lesion nematodes, *Tagetes patula* was used in crop rotation in the potato (Ball-Coelho *et al*., 2003) and tobacco (Reynolds *et al*., 2000) crops. The generation of 2-phenylethyl ITC from the roots of Brassica rotation crops is thought to be associated with the rotation of Brassica break crops Indian mustard (*Brassica juncea*) and canola (*Brassica napus*) to succeeding cereals (Angus *et al*., 1994; Kirkegaard *et al*., 2000; Sarwar *et al*., 1998; Smith and Kirkegaard, 2002). According to Kirkegaard *et al*. (2000), the roots of canola cultivars with high 2-phenylethyl GSL concentrations reduced soil inoculum levels of the fungus *Gaeumannomyces graminins* var. *tritici* and prevented the occurrence of *Pratylenchus neglectus*, which readily multiplied to attack subsequent wheat crops (Potter *et al*., 1999).

Table 1. List of pathogens suppressed through biofumigation

Biofumigant crops/method of application	**Name of plant disease /pest**	**Causal agent**	**References**
Brassica residues	Common scab disease of potato	*Streptomyces scabies*	Reinette Gouws and Nico Mienie, 2000
Brassica nigra leaf extract	Stem canker and black scurf diseases of Potato	*Rhizoctonia solani PR2* isolate	Rubayet *et al*., 2018
Brassica juncea as cover crop	Root knot disease	*Meloidogyne*	Daneel *et al*., 2018
Brassica juncea as dry plants, seed meal, seed powder, methanol extract, and fresh plants	Damping off of vegetables	*Rhizoctonia solani*	Abdallah and Kandil, 2020
Brassica residues	Root-knot nematode in Pepper.	*Meloidogyne incognita*	Bello *et al*., 2001
B. napus as seed meal	suppressed apple root rot	*Rhizoctonia solani*	Mazzola *et al*., 2001
Mustard as cover crop	lettuce drop	*Sclerotinia minor*	Bensen *et al*., 2009
B. juncea and *B.napus* residues	Take all disease of wheat	*Gaeumannomyces graminis* var. *tritici*	Kirkegaard *et al*., 2000
B. oleracea residues	Damping off diseases in nurseries	*Pythium aphanidermatum*	Deadman *et al*., 2006
B. juncea as seed meal	Soil borne pathogenic fungi of Soyabean	*Fusarium oxysporum, R. solani, Macrophomina phaseolina, Sclerotium rolfsii*	Fayzalla *et al*., 2009
B.carinata as seed meal	Sugar beet damping off	*Pythium ultimum*	Galletti *et al*., 2008
B. oleracea residues	Cabbage yellows	*F. oxysporum f.sp. conglutinans*	Ramirez-Villapudua and Munnecke, 1988
Brassica as cover crop	Woody ornamentals	*R. solani* and *Phytophthora nicotianae*	Baysal-Gurel *et al*. , 2020
B. oleracea, B. napus residues	Wilt disease in herbaceous plants	*Verticillium dahliae*	Koike and Subbarao, 2000
Brassica spp. as green manure	Soil borne diseases of Potato	*Rhizoctonia solani, Phytophthora erythroseptica, Pythium ultimum, Sclerotinia sclerotiorum, and Fusarium sambucinam*	Larkin and Griffin, 2007
B. napus as green manure	*Root-knot* Nematode on *Potato*	*Meloidogyne chitwoodi*	Mojtahedi *et al*., 1993
B. napus as seed meals	Apple replant disease	*Cylindrocarpon,*	Mazzola, 1998

		Phytophthora, *Pythium* and *Rhizoctonia*	
B. juncea as green manure	Bacterial wilt of Tomato	*Ralstonia solanacearum*	Arthy *et al.*, 2005
B. juncea, *Raphanus sativus*, *B. rapa*, *Sinapsis alba*, *Vicia sativa* as cover crops	Late blight of potato	*Phytophthora infestans*	Sebastian Grabendorfer, 2014
B. oleracea residues and crop rotation	Gummy *stem blight* of Watermelon	*Didymella bryoniae*	Ke inath *et al.*, 1996
B. napus *B. juncea* as residues	Root rot of Grapevine	*Pythium* spp.	Stephens *et al.*, 1999
Sinapis alba as green manure	Root rot of Pea	*Aphanomyces euteiches*	Muehlchen *et al.*, 1990
B. oleracea as residues	*Verticillium* wilt of Cauliflower	*Verticillium dahliae*	Koike *et al.*, 1999
B. napus residues	*Phytophthora* blight of Pepper	*Phytophthora capsici*	Wang *et al.*, 2014
B. napus and *B.juncea* as residues	Soil borne diseases of Cereal crops (Wheat and Barley)	*Gaeumannomyces graminis* var. *tritici*, *R. solani*, *Fusarium graminearum*, *Pythium irregulare* and *Bipolaris sorokiniana*	Kirkegaard *et al.*, 1996
B. juncea as cover crop	Root rot of Pea	*Aphanomyces euteiches*	Hossain *et al.*, 2015
B. juncea leaf extracts and green manures	White Potato cyst nematode	*Globodera pallida*	Lord *et al.*, 2011
In vitro activity of *Brassica* spp.	Black spot of Crucifer	*Alternaria brassicicola* and *A. brassicae*	Sellam *et al.*, 2007
In vitro activity of *Brassica* spp.	Root rot and wilt of Conifer	*Fusarium oxysporum*	Smolinska *et al.*, 2003
In vitro activity of *B. napus*	Root rot of French bean, Take all of Wheat, Black root rot of Cotton	*Aphanomyces*, *Gaeumannomyces*, \and *Thielaviopsis*	Smith and Kirkegaard, 2002
In vitro activity *B. hirta*	Root knot of Tomato and Nematode on Olive	*Meloidogyne javanica* and *Tylenchulus semipenetrans*	Zasada and Ferris, 2003
Brassica spp. as seed meal	Fruit rot of Water melon	*Pythium aphanidermatum*	Chung *et al*., 2005
In vitro activity of *Brassica spp.*	Leaf spot of Tomato	*Alternaria alternate*	Troncoso *et al.*, 2005
In vitro activity of *Brassica* spp.	Stem rot of *Arabidopsis*	*Sclerotinia scleroturum*	Stotz *et al*., 2011
B. juncea as cover crop	Lettuce drop	*Sclerotinia minor*	Bensen *et al.*, 2009
Brassica spp. as intercrop	*Meloidogyne javanica*	Root knot of Grapevine	McLeod and Steel, 1999

Growing broccoli before cauliflower lowered the severity of verticillium because it created a particular GSL and supported the growth of myxobacteria, which decreased the survival of verticillium microsclerotia. When mustard (*Brassica juncea*) was cultivated in alternate rows with the potato crop (*Solanum tuberosum*), Akhtar and Alam (1991) discovered a decrease in the frequency of plant-parasitic nematodes. Additionally, several helpful fungi, such *Trichoderma* spp., demonstrated significant tolerance to ITCs (Galetti *et al*., 2008; Gimsing and Kirkegaard, 2009; Smith and Kirkegaard, 2002).

Seed meals and other processed bio fumigants

Brassica oil-processed seeds (such as those from mustard crops) are a suitable source of high GSL component for soil amendment because they retain the myrosinase enzyme necessary for ITC hydrolysis (Brown and Mazzola, 1997). These resources were discovered to be efficient against a variety of soil-borne microbial diseases, including *Rhizoctonia* spp. and *Meloidogne* spp. (Mazzola *et al*., 2007). (Lazzeri *et al*., 2009). Due to the production of 2-propenyl ITC from mustard (*Brassica juncea*), rapeseed meal and mustard decreased the activity of Pythium spp (Cohen and Mazzola, 2006). In the ground seeds of three Brassica species, Chung *et al*. (2002) discovered a fungicidal substance called Allyl isothiocyanate that was efficient in preventing Rhizoctonia damping-off of cabbage. *Meloidogyne incognita*'s activity was decreased by a liquid formulation of defatted *B. carinata* seed meal created by De Nicola *et al*. (2012). The nicest thing about this strategy is that the products may be used when biofumigant plant development is constrained (as in the winter), they are simple to include into crop rotations, and they are better suited to intensive production systems.

Maximising ITCs mediated suppression of plant diseases

According to Matthiessen and Kirkegaard (2006) and Kirkegaard (2009), there are a number of techniques or processes that can be used to make the best use of biofumigants. Several are briefly described below:

There are numerous productive brassicaceous plants that need to be investigated for their ability to suppress the target disease. It is possible to establish high-quality biofumigant for a specific soil-borne pathogen using in vitro techniques by evaluating the effect on the pathogen's resting structures, such as scleroitia, microsclerotia, and chlamydospores, primarily in soil-based medium under controlled conditions (Downie *et al*., 2012). According to Witzel *et al*. (2015), *Verticillium longisporum* growth was inhibited by high alkenyl-accumulating *Arabidopsis thaliana* accessions in a bioassay.

Selection of the best biofumigant

Brassicaceous plant species or crop types can be chosen based on a number of quantitative and qualitative factors, including growth rate, winter hardiness, and the production of compound glucosinolates at various periods of the year, which is intended to be taken into account. For the control of more resilient resting fungal structures, such as the micoscelerotia of *Verticillium dahlia*, seed meals and processed bio fumigants may be more effective (Neubauer *et al*., 2014). Information on the GSL compounds that the pathogen is most sensitive to is needed to choose the proper biofumigant. Because of the genetic diversity seen among Australian canola types, selection for increased root GSL levels is possible. The aromatic GSLs found in canola roots demonstrated high suppressiveness to the cereal fungal diseases (Kirkegaard and Sarwar 1999). **Optimization of Agronomic factors:** To increase the biomass of biofumigant crops and glucosinolate levels, several agronomical factors such crop seed rate, planting timing, and types of chemical fertilisers must be taken into consideration. Li *et al*. (2007) discovered that fertiliser application of sulphur and nitrogen might change the quantity of glucosinolates in plant tissues.

Limitations of bio fumigation

Bello *et al*. (2000) claim that not all cropping systems can be biofumigated, and that transferring plant residues to the fields for integration is either impractical or extremely expensive. Without the use of any synthetic nematicide, biofumigation has had uneven results (Oka *et al*., 2006). As a result, evaluating the effectiveness and economic significance of this method either by itself or in combination with chemical nematicides becomes a crucial research subject. According to Fourie *et al*. (2016), the majority of cruciferous plants are hosts to commercially significant PPNs. More research is needed to create and disseminate knowledge on alternate soil borne pathogen management tactics as frontline synthetic fumigants are gradually phased out of global markets and increasing trends toward biologically-based solutions. One of the best examples of such a tactic is the employment of biofumigation. Field effectiveness should be increased by choosing biofumigation plant kinds with strong fumigation capability along with integration techniques based on knowledge of GSL and ITC levels in soil. This information is crucial, especially when biofumigation is combined with other biologically based tactics, since this will encourage the use of synergistic methods rather than competing ones. So that it can continue to be a part of eco-friendly IDM alternatives to the use of synthetic fumigants, further advancements to increase the effectiveness of biofumigation should be taken into consideration.

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