Int. j. adv. multidisc. res. stud. 2024; 4(1):134-138

Received: 16-11-2023
Accepted: 26-12-2023

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Biofumigation-a Sustainable Alternative to Chemical Control of Soil Borne Pathogens: A Review

[1] Dr. Bijaylakhmi Goswami, [2] Biju Pariyar

[1] Co-Founder and Head, Research and Development, Agrithink Services LLP, Assam, India
[2] Additional Director, Department of Horticulture, Krishi Bhawan, Gangtok Sikkim, India

Corresponding Author: **Dr. Bijaylakhmi Goswami**

Abstract

The phytopathogenic bacterial and fungal microorganism species are among the most common soil-borne pathogens of plants. Soil-borne plant pathogenic fungi cause a plethora of diseases, such as root rot, stem rot, crown rot, damping-off vascular wilts etc., resulting in significant economic losses in the yield and quality of agricultural and horticultural crops worldwide. Conventionally the soil-borne pathogens and insects are kept in check by farm entrepreneurs by using soil fumigants as pre-planting treatment of soil. A fumigant is a chemical that, at a required temperature and pressure, can exist as a vapour or gas which when released penetrates objects or enclosed areas in concentrations. When applied at a high enough concentration for a long time, fumigants kill many kinds of soil organisms, thus disrupting plant growth and crop production. Concerns about the extensive use and negative environmental effects of chemical fumigants have led to the development of Biofumigation. The concept of Biofumigation is emerging as an increasingly feasible method of pest management practice in commercial agriculture because it can control agricultural crop pathogens and diseases without health and environmental risks. The process acts through the growth or incorporation of plant material into the soil which, throughout its degradation, releases glucosinolates that break down into nematotoxic isothiocyanates. Commonly used biofumigant plants include brown mustards, white mustards, radishes and rocket species. Also, sorghum (*Sorghum bicolor*) and sorghum-sudangrass (*S. bicolor* x, *S. sudanense*) cultivars with high content of dhurrin, a substance which is transformed into toxic hydrogen cyanide (also called prussic acid) are used as biofumigants.

Keywords: Soil Borne Pathogen, Soil Fumigation, Biofumigation, Biofumigants, Isothiocyanates, Glucosinolates, Dhurrin

Introduction

The phytopathogenic bacterial and fungal microorganism species are among the most common soil-borne pathogens of plants. Ongoing climatic changes have induced significant shifts in soil health, including alterations in texture, structure, and biochemical. Rengel (2011) [37] reported that a notable concern is the decline in soil pH, attributed to climate-induced factors such as rising temperatures and increased rainfall, leading to soil acidification by removing alkalinity from harvested produce. Acidic soils become breeding grounds for plant parasitic fungi, particularly thriving in low pH or slightly acidic, undisturbed soils (Hoorman, 2016) [13]. Pathogenic fungi, exemplified by Fusarium, significantly jeopardize plant roots, particularly under acidic conditions. Various plant pathogenic fungi, including *Colletotrichum gloesporiodis, Homa sp., Phaeodactylum spp, Pestalotiopsis royenae, Rhizoctonia solani* Khun, *Pythium vexans* de Barre, *and Fusarium oxysporum*, exert a substantial impact on global food supplies by causing widespread infections in plants. These pathogens can persist in the soil as saprophytes on plant residues or in spores or resting structures for extended periods, even under adverse conditions. They primarily target roots, causing diseases such as root rot, stem rot, crown rot, damping-off and vascular wilts, leading to significant economic losses in agricultural and horticultural crops worldwide (Sainz, 2020) [38].

Conventionally, soil-borne pathogens and insects have been controlled by farm entrepreneurs through the use of soil fumigants. A fumigant, as defined by the NSDA, is a chemical that, under specific temperature and pressure conditions, can exist as a vapour or gas. When released, it permeates objects or enclosed areas in concentrations. This application, when done at a sufficiently high concentration for an appropriate duration, effectively eliminates various soil-dwelling pests, thereby disrupting plant growth and impeding crop production.

Soil fumigants find extensive use in pre-plant pest control for a range of high-value crops, offering benefits to growers by effectively managing nematodes, fungi, bacteria, insects, and weeds. However, the effectiveness of fumigants is limited to the treated area and does not provide residual protection. These chemicals are intensively employed in annual crops such as potatoes, tomatoes, strawberries, peppers, and carrots, as well as in nurseries for fruit trees, nut trees, grapevines, and floriculture. The majority of fumigants are halogenated compounds, also referred to as halocarbons, where at least one hydrogen atom is replaced by a halogen.

The historical success of managing soil-borne pathogens and insects through chemical fumigation, particularly using methyl bromide (CH_3Br), has been notable over several decades. However, the use of synthetic fumigants, including methyl bromide, raises environmental and health concerns, as highlighted by Brennan *et al.* (2020) [36]. Methyl bromide, in particular, poses risks such as ozone layer depletion upon release into the atmosphere, toxicity, and significant health and safety hazards for agricultural workers and those exposed to these substances. Environmental risks stemming from misapplication, accidents, and other hazards further compound these concerns. It is noteworthy that all chemical fumigants indiscriminately kill soil microorganisms through direct contact (Boone, 1988) [2]. The susceptibility of microorganisms to fumigants varies, but all microorganisms are vulnerable at sufficiently high fumigant concentrations. The effectiveness of fumigant action is notably influenced by soil temperature, with most chemicals exhibiting higher efficacy at elevated temperatures (Gandy and Chanter, 1976) [9].

The phase-out of methyl bromide has led to an increased reliance on alternative fumigants, such as 1,3-dichloropropene, chloropicrin, paraformaldehyde (commonly known as Fogidesfarm), and formaldehyde (CH2O) as stated by Mahmoud Taleb Al-Khatib *et al*., 2017. [26] Owing to concerns about the extensive use and negative environmental effects of chemical fumigants, there has been a growing emphasis on research into biofumigation (Lazzeri *et al*., 2004) [23].

Biofumigation is gaining prominence as a viable pest management strategy in commercial agriculture, offering control over crop pathogens and diseases without the associated health and environmental risks linked to chemical fumigants (Brown and Morra 1997 [3]; Potgieter *et al*. 2013). The term "biofumigation" was coined by J. A. Kirkegaard (Kirkegaard *et al.,* 1993) [17] to describe the suppressive effects of plant species on noxious soil-borne organisms, particularly through the liberation of isothiocyanates from the hydrolysis of glucosinolates, characteristic of the Brassicaceae family. Similar to solarization, biofumigation also enhances nutrient uptake by plants (Kirkegaard and Matthiessen, 2006) [27]. This method involves incorporating plant material into the soil, with its subsequent degradation releasing glucosinolates that transform into nematotoxic isothiocyanates. Notably, plants from the Cruciferae family are considered ideal for biofumigation due to their substantial release of these toxic compounds in the soil (Brennan *et al*., 2020) [36]. The primary targets of biofumigants are active stages such as fungal mycelia, mobile nematodes, or germinated weeds. Compared to traditional soil fumigation, biofumigation proves to be an economical tool with additional benefits, including the reduction of subsequent weed issues, augmentation of soil organic matter, enhancement of nutrient availability, and mitigation of soil erosion. Numerous studies have affirmed the efficacy of natural toxins, particularly isothiocyanates (ITCs), as fungicidal, bactericidal, and/or nematicidal agents against various plant pests, including crown rot, wilt, and root-knot nematodes affecting corn and wheat crops (Brown and Morra, 1997; Kirkegaard and Mathiesen, 2004; Henderson *et al*., 2009; Matthiessen and Kirkegaard, 2006) [3, 18, 11, 27].

Brassica amendments, a notable source of biofumigants, have proved to be efficient in reducing root rot in peas caused by *Aphanomyces euteiches* (Papavizas and Lewis, 1971) [35]. Additionally, Soil amended with alfalfa hay, corn stover and cabbage tissue controlled red root rot of Sesame caused by *Thieleviopsis basicola* (Adams, 1971) [1]. Populations of soil-borne pathogens *like Fusarium oxysporum* f. sp. conglutinans were reduced by nine species of cruciferous crops (Villapudua and Munneke, 1988) [46]. *Verticillium dahlia* causing microsclerotia in soil and wilt of cauliflower was controlled by incorporation of broccoli (Subbarao *et al*.,1999) [43] while *Meloidogyne chitwoodi* infection in potato was controlled by rapeseed incorporation as green manure (Mojtahedi *et al*., 1993) [32]. Njoroge *et al*. (2008) [34] also established that incorporation of *Brassica* spp. residues on population densities of soilborn microorganisms and on damping-off and Fusarium wilt of watermelon.

Different ways for use of biofumigant crops for disease control

1. **Intercrops and Crop Rotation with Biofumigants:** Sootweg's (1956) [41] serendipitous discovery that *T. erecta* planted into soil subsequently provided control of the lesion nematode *Pratylenchus penetrans* in *Narcissus tazetta* opened the avenues for researches rotation based biofumigation researches. Various studies have highlighted the production of glucosinolates (GSLs) and isothiocyanates (ITCs) from the active rhizosphere, demonstrating their role in pest and pathogen suppression (Van Dam *et al*., 2009) [45]. Soil organisms with myrosinase activity have been identified as mediators in the conversion of GSLs to ITCs.
2. **Incorporation of Fresh Mass into the Soil:** The most widely recognized application of biofumigant plants involves growing a specific crop for incorporation into the soil to convert GSLs to ITCs. To achieve optimal ITC release, thorough maceration of plant tissue is essential, followed by rapid incorporation into the soil. Additionally, the addition of water may be necessary to ensure complete hydrolysis (Matthiessen & Kirkegaard, 2006; Kirkegaard, 2009) [27, 19]. The period when the plants are flowering (60-80% of the stand is in blossom) is considered ideal, as the glucosinolate concentration in the biomass is at its peak. Leaves and stem debris of the following plants *Salvia officinalis* L. (sage), *Rosmarinus officinalis* L. (rosemary), *Coriandrum sativum* L. (coriander), *Diplotaxis tenuifolia* (L.) DC. (wild rocket, WR), *Mentha piperita* L. (peppermint), *Brassica oleracea* L. var. italica (broccoli), *B. oleraceae* L. var. botrytis (cauliflower) and *Artemisia dracunculus* L. (tarragon) were used as amendments and incorporated in soi to test soil suppressiveness to

Fusarium disease in cucumber and to root knot nematodes by *M. javanica* and found encouraging results (Klein, 2011) [20].

Procedure

a) **Chaffing Above-Ground Growth:** To maximize glucosinolate release, above-ground growth must be finely chaffed to break down all plant cells. This can be directly done for on-site crops or when incorporating mass from elsewhere into the field. In the latter case, thorough soil preparation is essential before incorporation.
b) **Immediate Soil Incorporation:** The finely chopped plant material should be promptly worked into the soil at a depth of 15-20 cm, utilizing equipment such as a rotary cutter, disc harrow, or spading machine. Adequate soil preparation is crucial if incorporating mass from a different location.
c) **Irrigation at Field Capacity:** Maintaining the soil at its field capacity by irrigating appropriately is essential.
d) **Covering Soil Surface:** Wrapping the soil surface tightly with a transparent plastic film, similar to the one used for soil solarization is the next required step.
e) **Film Removal and Soil Aeration:** Removing the film 3-4 weeks later and slightly disturbing the soil will allow gases to escape.
f) **Planting of Interested Crop:** Planting can be done with the desired crop 24 hours after the film removal (FAO, 2022).

3. **Seed meals and other processed biofumigants:** Seed meal produced after the processing of brassica seeds for oil (e.g., in mustard crops) also offers a convenient source of high GSL material for soil amendment as the myrosinase required for hydrolysis to ITCs remains intact (Brown and Mazzola, 1997). These materials have shown promise against several soil-borne plant pathogens including *Rhizoctonia* spp. (Mazzola *et al*., 2007) [29] and *Meloidogne spp*. (Lazzeri *et al*., 2009) [24].

Crop plants/fungus suitable for biofumigation and their effect on pathogen

Commonly used biofumigant plants include *Brassica juncea, Sinapis Alba, Eruca sativa* or *Raphanus sativus* varieties. Indian mustard (*Brassica juncea*), which is rich in allyl glucosinolate, a precursor to allyl isothiocyanate, was most effective in bioassay screenings of Brassicaceae cultivars (Hanschen and Winkelmann, 2020) [12] but sorghum (*Sorghum bicolor*) and sorghum-sudangrass (*S. bicolor* x,*S. sudanense*) cultivars with high content of dhurrin, a substance which is transformed in toxic hydrogen cyanide, also called prussic acid (Nicola *et al*., 2011) [5]. The broader categories can be:

1. **Sorghum:** Sorghum produces Dhurrin, a cyanogenic glucoside that acts as a secondary defensive system, releasing toxic cyanide when plant tissue is damaged (Mojtahedi *et al*., 1993) [32].
2. **Mexican Marigold:** It is effective in controlling root-knot nematodes in roses and serves as a trap crop. Its root cells produce terthiophenes in response to damage, blocking the development and metabolism of plant pathogens (Kumar *et al*., 2018) [10].
3. ***Muscodor albus*:** *Muscodor albus*, an endophytic fungus, is used as a biofumigant for managing post-harvest diseases of fruits and vegetables. It controls a range of storage pathogens and fungal decay, including brown rot of peaches, gray mould, and blue mould of apples, and postharvest lemon diseases (Mercier and Smilanick, 2005) [30].
4. ***Brassica* spp:** These are widely used as biofumigants. They contain glucosinolates with varying profiles, concentrations, and distributions. Fumigation releases biocidal hydrolysis products, contributing to pest and pathogen control. Fumigation is crucial for sustaining agricultural production as the world's population grows, but it may affect non-targeted soil microorganisms (Mithen, 1992; Husein *et al*., 2010; Sennett, 2022) [31, 14, 25].

Among various Brassica species, macerated mustard plant parts have demonstrated efficacy in inhibiting the radial growth and sclerotia production of *Rhizoctonia solani* f. Sp Sasakii (Madhavi *et al.*, 2015) [7]. Notably, the suppression of *R. solani* was most pronounced at high rates of biofumigant material. At elevated doses of all tested plant parts, the volatiles emanating from the biofumigant crop proved lethal to *R. solani.*

Indian mustard tissues exhibited a more significant inhibitory effect against sclerotial formation compared to other Brassica crops. Studies by Walker *et al.* (1937) [47] and Mayton *et al.* (1996) [28] demonstrated that allyl isothiocyanate released from macerated *Brassica juncea* cv. Cutlass tissue completely suppressed the *in vitro* growth of five common plant pathogens, including *Pythium ultimum, Rhizoctonia solani, Verticillium dahliae, Verticillium alboatrum,* and *Colletotrichum coccodes* under *in vitro* conditions.

Kasuya *et al*. (2006) [16] found that dried Brassica Rapa plant residue exhibited suppressive effects on *R. solani* in pot assays and mycelial growth assays *in vitro*. Biofumigation with *Brassica oleracea* (Capitata group) reduced *Pythium aphanidermatum*-induced damping-off and enhanced vegetative growth of greenhouse cucumber in Oman (Deadman *et al*., 2006) [6]. Larkin and Griffin (2007) [22] reported that volatiles released from chopped leaf material of Brassica crops and barley inhibited the growth of *Rhizoctonia solani*, with Indian mustard resulting in nearly complete inhibition (80–100%) *in vitro* assays. Biofumigant crops serve as break crops, disrupting the lifecycle of pests and diseases. Suppression may occur through direct biocidal toxicity as well as indirect effects on the soil fauna and microbial community (Srivastava and Ghatak, 2017) [42].

Behaviour of Biofumigants and Effect on Earthworms and Microbes

Earthworms and soil microbial communities are integral components of terrestrial ecosystems, playing a crucial role in soil productivity (Brussaard, 2012) [4]. A study focused on crop residues of Brassica species, including mustard (*Brassica juncea*) and broccoli (*Brassica oleracea*), found no significant impact on earthworm survival or growth (Brown and Morra, 1997) [3]. The mustard treatment, however, led to lasting changes in the community structure, particularly affecting actinomycetes, after the 28-day test period. This study suggests that the use of multi-species cover crops as green manure in cropping systems might be more effective in suppressing soil-borne pathogens compared to single-species approaches (Fouché *et al*., 2016) [44].

The impact of biofumigants on the microbial community is most pronounced in the initial 14 days following application. Existing literature indicates that the majority of isothiocyanates (ITCs) are released within the first 4 to 10 days post-soil incorporation of plant material, after which ITC concentrations experience a rapid decline (Morra and Kirkegaard, 2002) [33].

Given that most fumigants exhibit non-selective actions, their use results in a soil habitat primarily colonized by the organisms reintroduced first after treatment. If these initial colonizers are beneficial fungi—competitive or antagonistic toward pathogens—pathogenic fungi introduced later may not proliferate, resulting in limited disease. Conversely, if pathogens are reintroduced first, such as on seeds, they can proliferate, potentially causing extensive disease losses. At the same time, Ziedan 2022 has mentioned biofumigants are selective for enhancing the growth and populations of beneficial soil microorganisms. A drawback of soil fumigation however is that, once implemented, it often needs repetition before each successive crop due to the disruption of the soil's biological balance of microorganisms (James, 1989).

Conclusion

In conclusion, the increasing challenges posed by soil-borne pathogens and the environmental concerns associated with chemical fumigation have led to the development and adoption of biofumigation as a sustainable alternative. Biofumigation, utilizing plants like *Brassica* species, sorghum, and fungi like *Muscodor albus*, harnesses natural compounds to control pests and diseases. This eco-friendly approach not only offers effective pathogen suppression but also enhances soil health and nutrient availability. As agriculture seeks more sustainable practices, biofumigation emerges as a promising strategy for safeguarding crop yields while minimizing environmental impacts.

References

1. Adams P. Effect of soil temperature and soil amendments on Thielaviopsis root rot of sesame. Phytopathology. 1971; 61:93-97.
2. Boone AJ. Soil fumigation in forest tree nurseries. In: Proceedings of the Southern Forest Nursery Association Meeting. USDA Forest Service, Southern Region, 1988, 33-38.
3. Brown PD, Morra MJ. Control of soilborne plant pests using glucosinolate-containing plants. In: Donald LS, ed. Advances in Agronomy. 1997; 61:167-231.
4. Brussaard L, Aanen DK, Briones MJI, Decaëns T, de Deyn GB, Fayle TM, *et al*. Biogeography and phylogenetic community structure of soil invertebrate ecosystem engineers, Global to Local Patterns, Implications for Ecosystem, Functioning and Services and Global, Environmental Change Impacts. In D. H. Wall (Ed.). Soil Ecology Ecosystems Services, 2012, 201-232.
5. De Nicola GR, Leoni O, Malaguti L, Bernardi R, Lazzeri LA. Simple analytical method for dhurrin content evaluation in cyanogenic plants for their utilization in fodder and biofumigation. J. Agric. Food Chem. 2011; 59: 8065-8069.
6. Deadman M, Al Hasani H, Al Sa'di A. Solarization and biofumigation reduce *Pythium aphanidermatum* induced damping-off and enhance vegetative growth of greenhouse cucumber in Oman. J. Plant Pathol. 2006; 88:335-337.
7. Bindu Madhavi, Uma Devi G, Vijay Krishna Kumar K, Ramesh Babu T, Naidu TCM. Evaluation of different brassica species and onion for their biofumigation effect against Rhizoctonia solani f. Sp. Sasakii *in vitro*. J.Res. Angrau. 2015; 43(3-4):22-28.
8. FAO, 2002. https://www.fao.org/agriculture/crops/thematicsitemap/theme/climatechange0/methyl-bromide/alt/biofum/en/
9. Gandy DG, Chanter DO. Some effects of time, temperature of treatment, and fumigant concentration on the fungicidal properties of methyl bromide. Annals of Applied Biology. 1976; 82:279-290.
10. Kiran Kumar GN, Jayasudha SM, Kiran kumar KC. Disease management by Biofumigation in organic farming system. Journal of Pharmacognosy and Phytochemistry. 2018; 7(4):676-679.
11. Henderson DR, Ekaterini Riga, Ricardo A Ramirez, John Wilson, William E Snyder. Mustard biofumigation disrupts biological control by Steinernema spp. nematodes in the soil. Biological Control. 2009; 48(3):316-322. Doi: https://doi.org/10.1016/j.biocontrol.2008.12.004
12. Hanschen FS. Winkelmann T. Biofumigation for Fighting Replant Disease- A Review. Agronomy. 2020; 10(3).
13. Hoorman James J. Role of Soil Fungus Ohioline. Ohio State University Extension, 2016. https://ohioline.osu.edu/factsheet/anr-37
14. Husein Ajwal William J. Ntow1RuijunQin1SuduanGao. Chapter 9 - Properties of Soil Fumigants and Their Fate in the Environment Hayes' Handbook of Pesticide Toxicology (Third Edition), 2010, 315-330.
15. James RL. Effects of Fumigation on Soil Pathogens and Beneficial Microorganisms. In: Landis, T.D., technical coordinator. Proceedings, Intermountain Forest Nursery Association; 1989, August, 14-18; Bismarck, ND. General Technical Report RM-184. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 29-33, 2016. Available at: http:www.fcnanet.org/proceedings/1989/james.pd
16. Kasuya M, Olivier AR, Ota Y Tojo M. Induction of soil suppressiveness against Rhizoctonia solani by incorporation of dried plant residues into soil. Phyto Pathology. 2006; 96:1372-1379.
17. Kirkegaard JA, Gardner PA, Desmarchelier JM, Angus JF. Biofumigation - using Brassica species to control pests and diseases horticulture and agriculture. IN: Wratten N., Mailer R. J. (eds.) Proceedings of the 9th Australian Research Assembly on Brassicas, 1993, 77-78.
18. Kirkegaard John, John Matthiessen. Developing and refining the biofumigation concept. AgroIndustria. 2004; 3(3):233-239.
19. Kirkegaard J. Biofumigation for plant disease control - from the fundamentals to the farming system. IN: Walters D. (ed.) Disease control in crops: Biological and environmentally friendly approaches. John Wiley & Sons Ltd, Chichester, UK, 2009, 172-195.
20. Klein Eyal. Suppression of soilborne plant pathogens following organic amendments and soil solarization. Thesis submitted for the degree of "Doctor of Philosophy". Submitted to the Senate of the Hebrew University, 2011.

21. Ziedan El-Sayed Hussein. A review of the efficacy of biofumigation agents in the control of soil-borne plant diseases. Journal of Plant Protection Research. 2022; 6(21):1-11. Doi: 10.24425/jppr.2022.140292
22. Larkin RP, Griffin TS. Control of Soilborne Potato Disease Using Brassica GreenManures. CropProtection. 2007; 26:1067-1077. Doi: http://dx.doi.org/10.1016/j.cropro.2006.10.004
23. Lazzeri L, Leoni O, Bernardi R, Malaguti L, Cinti S. Plants techniques and products for optimizing biofumigation in full field. Agroindustria. 2004; 3(3):281-288.
24. Lazzeri L, Curto G, Dallavalle E, D'Avino L, Malaguti L, Santi R, *et al*. Nematicidal Efficacy of Biofumigation by Defatted Brassicaceae Meal for Control of *Meloidogyne incognita* (Kofoid *et* White) Chitw. On a Full Field Zucchini Crop, Journal of Sustainable Agriculture. 2009; 33(3):349-358. Doi: 10.1080/10440040902773202
25. Louise B Sennett, Claudia Goyer, David L Burton, Bernie J Zebarth, Sean Whitney. Chemical fumigation and biofumigation alter soil bacterial community diversity and composition, FEMS Microbiology Ecology. 2022; 98 (40). Doi: https://doi.org/10.1093/femsec/fiac026
26. Mahmoud Taleb Al-Khatib, Maen Nimer Shequarah, Saeed Abdullah Alsmadi. Control of Soil-borne Pathogens by Soil Fumigation with Paraformaldehyde (Fogidesfarm) as an Alternative to Methyl Bromide. Asian Journal of Plant Pathology. 2017; 11(2):81-88.
27. Matthiessen JN, Kirkegaard JA. Biofumigation and Enhanced Biodegradation: Opportunity and Challenge in Soilborne Pest and Disease Management. Critical Reviews in Plant Science. 2006; 25:235-65.
28. Mayton SH, Olivier C, Vaughn FS, Loria R. Correlation of fungicidal activity of brassica species with allyl isothiocyanate production in macerated leaf tissue. The American Phytopathological Society. 1996; 86:267-271.
29. Mazzola M, Brown J, Izzo AD, Cohen MF. The mechanism of action and efficacy of seed meal-induced pathogen suppression differ in a Brassicaceae species and time-dependent manner. Phytopathology. 2007; 97:454-460.
30. Mercier Julien JL. Smilanick. Control of green mould and sour rot of stored lemon by biofumigation with Muscodor albus. Biological Control. 2005; 32(3):401-407.
31. Mithen R. Leaf glucosinolate profiles and their relationship to pest and disease resistance in oilseed rape. Euphytica. 1992; 63:71-83.
32. Mojtahedi H, Santo GS, Wilson JH, Hang AN. Managing Meloidogynechitwoodi on potato with rapeseed as green manure. Plant Disease. 1993; 77:42-48.
33. Morra MJ, Kirkegaard JA. Isothiocyanate release from soil-incorporated Brassica tissues. Soil Biology and Biochemistry. 2002; 34:1683-1690.
34. Njoroge SMC, Riley MB, Keinath AP. Effect of incorporation of Brassica spp. residues on population densities of soilborne microorganisms and damping-off and Fusarium wilt of watermelon. Plant Dis. 2008; 92:287-294.
35. Papavizas GC, Lewis JA. Effect of amendments and fun¬gicides on Aphanomyces root rot of peas. Phytopathology. 1971, 61:215-220.
36. Rebecca Jean Barnes Brennan, Samantha Glaze-Corcoran, Robert Wick, Masoud Hashemi. Biofumigation: An alternative strategy for the control of plant parasitic nematodes. Journal of Integrative Agriculture. 2020; 19(7):1680-1690.
37. Rengel Z. Soil pH, Soil Health and Climate Change. In: Singh, B., Cowie, A., Chan, K. (eds) Soil Health and Climate Change. Soil Biology. 2011; 29. Springer, Berlin, Heidelberg. Doi: https://doi.org/10.1007/978-3-642-20256-8_4
38. Sainz Dr. María J**.** Disease management by Biofumigation in the organic farming system, 2020. https://www.mdpi.com/journal/pathogens/special_issues/soilborne_plant_pathogenic_fungi
39. Scott D Cichowlaz. Fumigation the Use of Poisonous and Lethal Fumigants. Volume V (2004 - 2005). Version. Nevada State Department of Agriculture, 2005.
40. Smita Puri. Biofumigation: a new strategy for disease management in organic farming system. International Journal of Current Research. 2016; 8(1):25002-08.
41. Slootweg AFG. Rootrot of bulbs caused by Pratylenchus and Hoplolai-mus sp. Nematologica, 1956; 1:192-201.
42. Srivastava JN, Ghatak Abhijeet. Biofumigation: A control method for the soil-borne diseases. Internat. J. Plant Protec. 2017; 10(2):453-460. Doi: 10.15740/HAS/IJPP/10.2/453-460
43. Subbarao KV, Hubbard JC, Koike ST. Evaluation of broccoli residue incorporation into field soil for Verticillium wilt control in cauliflower. Plant Dis. 1999; 83:124-129.
44. Tanya Fouché, Mark Maboeta, Sarina. Claassens Effect of Biofumigants on Soil Microbial Communities and Ecotoxicology of Earthworms (Eisenia andrei) Water Air Soil Pollut. 2016; 227:256. Doi: 10.1007/s11270-016-2960-6)
45. Van Dam N, Tytgat TG, Kirkegaard J. Root and shoot glucosinolates: A comparison of their diversity, function and interactions in natural and managed ecosystems. Phytochemistry Reviews. 2009; 8:171-86.
46. Villapudua RJ, Munneke D. Effects of solar heating and soil amendments of cruciferous residues on Fusarium oxysporum fsp. Conglutinans and other organisms. Phytopathology. 1988; 3:289-295.
47. Walker CJ, Morell S, Foster HT. oxicity of mustard oils and related sulphur compounds to certain fungi.1937. American Journal of Botany. 1937; 24:241-536.
48. Yasmin S, D'Souza D. Effects of pesticides on the reproductive output of Eiseinia fetida. Bulletin of Environmental Contamination and Toxicology. 2007; 79:529-532.