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Original article

Beyond Chemicals: The Role of Biofumigation in Controlling Soil-Borne Pathogens, Insects, and Nematodes

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ABSTRACT

Biofumigation is a sustainable pest management approach that utilizes glucosinolate-rich plants, mainly from the Brassicaceae family, to control soil-borne pests, pathogens, and weeds. Upon incorporation into soil, enzymatic hydrolysis of plant tissues releases volatile isothiocyanates (ITCs), which disrupt the physiological functions of nematodes and insect pests, particularly during their below-ground life stages (eggs, larvae, pupae). These compounds inhibit respiration, enzymatic activity, and nervous system function, offering targeted pest suppression without harmful soil residues. Biofumigation is notably effective against root-knot and cyst nematodes, as well as fungal pathogens like Rhizoctonia solani and Phytophthora nicotianae. Beyond pest control, it enhances soil health by promoting beneficial microbes and nutrient availability, ultimately improving crop vigor and yield. Integrating biofumigant crops such as mustard, radish, or cabbage—especially in rotation or with plant growth-promoting rhizobacteria (PGPR)—offers a green, eco-friendly alternative to synthetic fumigants and supports sustainable, high-yield agricultural systems.

Keywords: Biocontrol, Glucosinolates, Isothiocyanates, Nematodes, PGPR

1. INTRODUCTION

Agriculture is one of the most vital industries for every country since it is where crops are grown and animals are produced. Climate change, biodiversity loss, natural hazards and disasters, health security, ageing farmers, energy supply, infrastructure security, limited resources, rising food demand due to population growth, market fluctuations, etc. are just a few of the threats and risks that agriculture has been and will continue to face under the changes and trends in global security. Agriculture is impacted by a nation's or region's safety and security, dangers resulting from globalisation, local and international policy contexts, and the need for sustainable development (Wu et al., 2022).

The growing human population is driving up demand for agricultural products worldwide. Various agricultural alternatives, including fertilisers, pesticides, and insecticides, have been used to produce crops with high yields in the shortest amount of time and to protect them from insects and pest attack during and after harvest in order to address the challenges of food scarcity brought on by population growth (Daniel et al., 2022).

Insect pests severely impair global food security by inflicting significant losses in vital food crops both before and after harvest. Along with secondary impacts on commerce, livelihoods, poverty, and ecosystems, these also involve direct economic consequences. Insect pests cause downstream effects on crop values, yields, and quality that destabilise trade and labour markets in addition to direct losses.

Crop pests lead to widespread insecticide use, which damages ecosystems by causing the loss of natural enemies and helpful pollinators due to chemical toxicity. Cutting off natural biocontrol services necessitates ongoing pesticide applications, which can lead to unintended consequences like insect resistance and toxic residues in food and water (Ali et al., 2023).

The goal of integrated pest management (IPM) is to reduce or eliminate the usage of synthetic pesticides by utilising a variety of pest control methods. It is a sustainable pest management technique that has been in use for a very long time. IPM keeps insect numbers below a threshold that prevents them from negatively impacting the economy. It entails choosing tactics that are realistic, reasonably priced, and reduce harm to the environment. IPM is the term for crop management that employs a range of techniques to maintain pest populations below a specific economic threshold. It is a systematic approach that combines numerous pest-control techniques into a single program. Reliance on pesticides is reduced by taking into account cultural, biological, genetic, physical, legal, and mechanical constraints (Angon et al., 2023).

Biofumigation is an environmentally friendly agricultural practice that utilizes the natural defense mechanisms of cruciferous and other plants to manage soil-borne pests, diseases, and weeds. J. A. Kirkegaard first offered this idea in 1993. He explained how to grow, break down, and use Brassica residues to help release volatile compounds by hydrolysing glucosinolates in plant tissues. Later, it was shown that Moringaceae and Capparaceae, two more plants in the Brassicales group, also possess biofumigant qualities (Batistič et al, 2025).

Growing, macerating, or introducing specific Brassica or similar species into the soil is known as biofumigation. This process causes the degradation of glucosinolate (GSL) molecules in the plant tissues, which releases isothiocyanate compounds (ITCs). Soil structure, microbial communities, parasite control, and soil quality are all impacted by biofumigation. Nematodes and pests are poisoned by natural isothiocyanates (Mossa, 2021).

2. Bio fumigation

Smallholder cultivators of vegetables must manage soil-borne maladies and pests. Vegetable crops are prone to a variety of pathogenic organisms that can either harm the product and render it unmarketable or kill the plant, reducing productivity. Nematodes, insects, Pests that target the roots of vegetable crops include bacteria and fungus (Shafique et al., 2016). These pests are hard to pin down or spot because they are concealed in the soil. This indicates that root pests and diseases cannot be controlled using the threshold-based prevention methods adopted in integrated pest management (IPM) programs for vegetable crops. Control of soil-borne diseases is challenging because even very small populations can cause substantial damage, the organisms are generally minute, and they are buried and dispersed unevenly in the soil. Consequently, farmers regularly employ preventative approaches of pesticides before planting in order to protect against crop damage and yield loss (Veena et al., 2014). In order to successfully manage soil-borne pest organisms during crop growth, pesticides usually have to be used too late and impractically. When addressing diseases and pests that are beneath the surface, horticulture faces an assortment of issues. Methyl bromide has been phased out under the Montreal Protocol, and residual pesticides are no longer permitted for the control of soil insects. On Ozone Layer Depleting Substances, to which the majority of nations have ratified, while the demand for goods free of flaws is rising (Protocol, 1987). For this reason, bio fumigation is currently being investigated to manage soil-borne illnesses in order to create bio-pesticides that could potentially be effective against a variety of root infections without harming the soil ecosystem.

A major hurdle to the sustainable growth of agriculture is the introduction of soil-borne illnesses. A build-up of harmful microorganisms in the soil is a result of facility agriculture's rapid expansion and the periodic manufacture of high-value crops. This build-up has caused substantial declines in harvests and, in extreme cases, succeed in crop loss (Cao et al., 2017). Currently, there are plenty of methods implemented for managing soil-borne diseases: physical methods like steam and solar disinfection; chemical treatments like dazomet and chloropicrin fumigation; biological techniques like bio fumigation and anaerobic disinfection; and agricultural practices like grafting and the use of disease-resistant varieties (Al-Shammary et al., 2020; Zhang et al., 2020). While chemical fumigation is favoured for its rapid action and broad-spectrum effectiveness, its high-cost limits widespread applications (Fang et al., 2018; Zhang et al., 2019). Bio fumigation, on the other present, is more economic yet offers added benefits like improving soil fertility and its number of beneficial bacteria (Tagele et al., 2021; Gao et al., 2022).

Using plant material for bio fumigation is an environmentally friendly method of soil fumigation. It uses biocidal agents produced by plant metabolism, fermentation, and decomposition to combat weeds, pests, and soil-borne illnesses (Szczygłowska et al., 2011). Plant materials should be quickly and evenly mixed into the soil upon be finely chopped to ensure effective field applications (Matthiessen, 2004; Gimsing, 2006). (Figure 1)

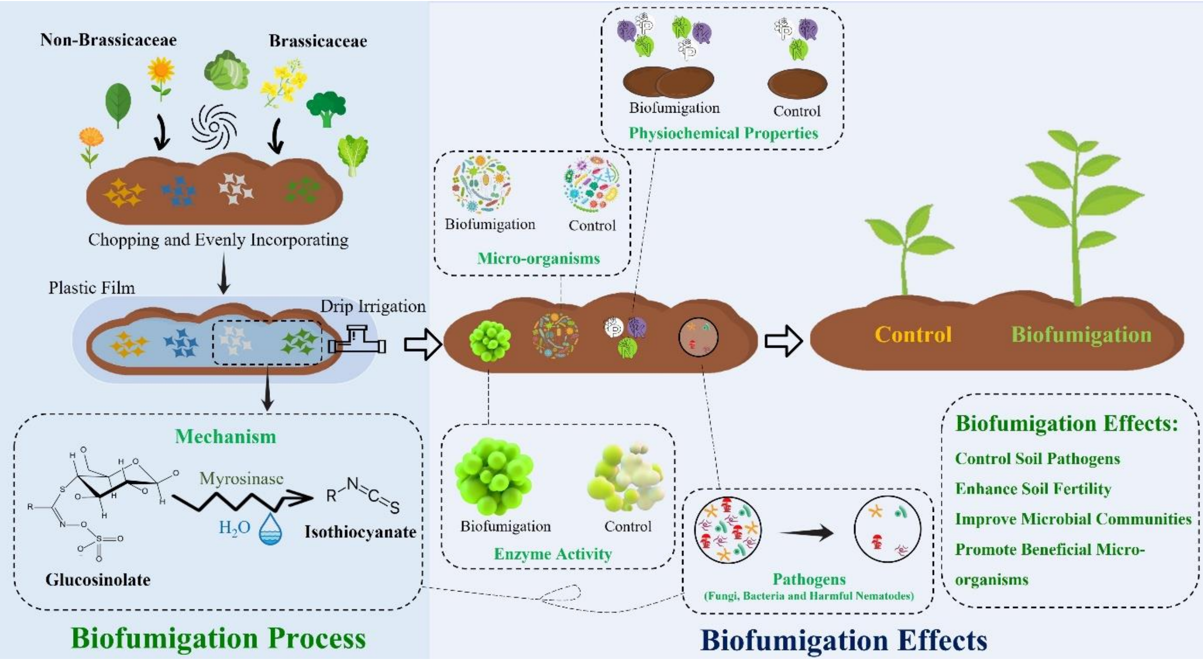

Figure 1: *Bio fumigation process and effects*

The agronomic strategy of bio fumigation uses volatile compounds (allelochemicals) derived from decaying Brassica tissues to inhibit infections and pests that the pass by the soil. When Brassicas break down, the most frequent volatiles that are created are (ITCs) isothiocyanates. The active ingredients of commercial fumigants metham sodium and dazomet are linked to ITCs, which are extremely harmful to diseases and pests. After tissue injury, they are produced when myrosinase enzymes hydrolyse glucosinolates (GSLs) at neutral pH in the presence of water. A good deal of experts thinks that GSLs, which are sulfur-containing compounds called thioglucosides that Brassicas make as secondary metabolites, have evolved to offer resistance to diseases and pests.

Many isothiocyanates (ITCs) generated by Brassica tissues have a well-established biocidal action (Brown and Morra 1997), and there is substantial empirical field data that Brassicas have the ability to inhibit a variety of soil-borne pests and illnesses (Matthiessen & Kirkegaard, 1998).

2.1 Key points of Bio fumigation

- **a)** Avoid soil-borne diseases and weed competition
- **b)** Altering the chemical composition of bacteria, post-harvest damaging fungus, and nematode populations in the soil
- **c)** Different rates of the nitrogen absorbing by plants are the result of altered belowground ecology.
- **d)** If used as green manure, increase soil porosity to improve the physical structure of the soil.
- **e)** Due to the high reactivity of ITCs, they target a broad spectrum of pathogens yet do not linger in the soil for extended periods of time.

2.2 Mechanism of Controlling Insect Pests

Incorporating certain plants, primarily from the Brassicaceae family, bio fumigation is a sustainable farming method that suppresses soil-borne pests, such as weeds, diseases, and insect pests. When plant tissues are injured, volatile biocidal chemicals, specifically isothiocyanates (ITCs), are naturally created and released as part of the bio fumigation mechanism.

In dicotyledonous angiosperms, glucosinolates (GS) belong to important chemical substances with sulphur and nitrogen, especially in the Brassicaceae family. Myrosinase, frequently referred to as thioglucoside glucohydrolase, uses the Epithiospecifier-modifier 1 protein to help catalysis the hydrolysis of GS. This enzyme is special because it may dissolve off glycosidic linkages that include sulphur (Koroleva et al., 2010; Peng et al., 2019). GS, which are not metabolically active, are kept in the vacuoles of plant cells. The enzyme myrosinase is found in myrosin cells found in various vegetable tissues (Hoglund et al., 1991; La and Fang, 2008).

Isothiocyanates (ITCs) and related compounds released during bio fumigation exert toxic effects on insects through multiple pathways. They disrupt cellular respiration and interfere with essential enzyme systems, impairing basic physiological processes. Additionally, these compounds can damage the insect nervous system, leading to disorientation, paralysis, or death. Feeding and reproductive behaviours are also inhibited, reducing pest populations over time. Insects may be affected either through direct contact with the toxic compounds or by inhalation of the volatile fumes. These effects are especially pronounced in soil-dwelling insect stages such as pupae, larvae, and eggs of pests like wireworms, root maggots, and various beetles, making bio fumigation particularly effective for managing subterranean pest threats.

Variables in the environment affect the GS hydrolysis products. GS first breaks down into the unstable intermediate thiohydroximate-O-sulphonate and glucose. ITCs are created when thiohydroximate-O-sulphonate goes through a lossen rearrangement at a pH of neutral. Nitriles and epithionitriles are formed in the presence of ferrous ions or under mildly acidic conditions (pH 2–5). Additionally, the formation of epithionitriles may be facilitated by the presence of epithio specifier proteins (Fahey et al., 2001; Zhang et al., 2017). (Figure 2)

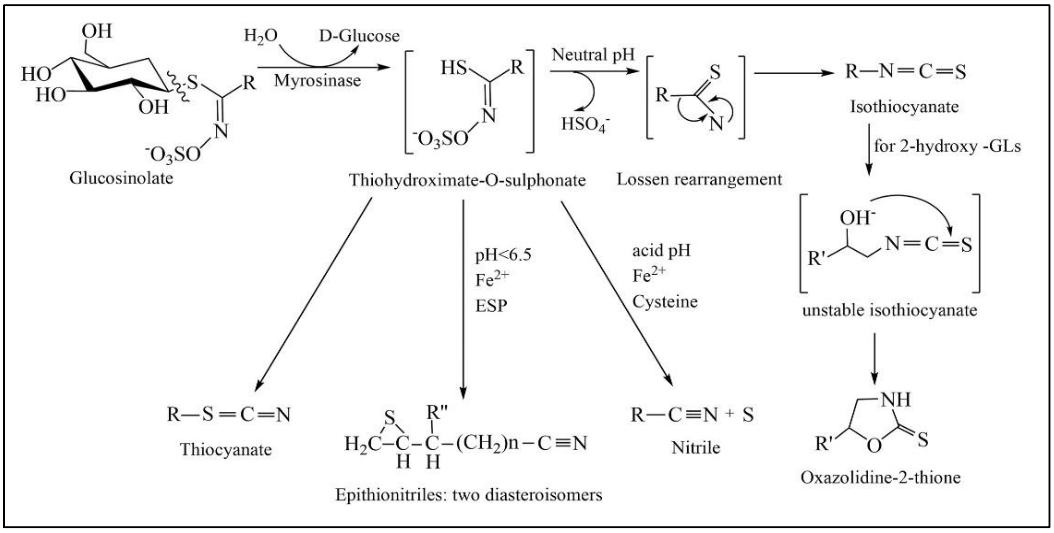

***Figure 2**: Enzymatic hydrolysis of glucosinolate*

3. Control effects on Pathogens

In 1994, researchers discovered that the inclusion of canola (Brassica napus) and Indian mustard (Brassica juncea) in soil could provide a reduction in the level of the wheat take-all fungus. The ITCs from the roots of these Brassicaceae plants were believed to be responsible for this effect (Angus et al., 1994).

There has been increasing interest in applying bio fumigation to manage disease since then. Plant debris of Indian mustard, brown mustard, turnip (B. rapa), and radish (Raphanus sativus), among others, have been shown to emit volatile sulphur compounds that suppress a variety of soil-borne pathogens of potatoes, including Phytophthora erythroseptica, P. nicotianae, Pythium ultimum, Sclerotinia sclerotiorum, and Rhizoctonia solani. For example, on a 25-mm high dextrose agar Petri plate infected with potato pathogens, 1 g of Indian mustard at 25°C produced an inhibition rate of 80% to 100% (Larkin and Griffin, 2007; Baysal-Gurel et al., 2020). In a similar vein, bio fumigation using 5% w/w black mustard (B. nigra) decreased the establishment rate of R. solani in soil to around 25% of its initial level in just one month, and this decrease sustained for six months (Yulianti et al., 2007). Plants such as B. integrifolia and B. oleracea var. gongylodes have been reported to exert serious inhibitory effects on P. aphanidermatum and Fusarium oxysporum under laboratory Petri dish bio fumigation experiments at 26°C (Fan et al., 2007). Fresh "Dilong 1" mustard plant material weighed 0.7 g effectively suppressed P. nicotianae at 25°C and reached a 100% inhibition rate (Sun et al., 2023).

The most effective use of biofumigation is on soilborne insect stages, including pupae, larvae, and eggs. The pests that are most at risk are wireworms, white grubs, and root maggots because they stay close to the treated soil that has the bioactive chemicals. Additionally, bio fumigation can lower pests over time by improving soil health and fostering beneficial microorganisms that either compete with or repel pests.

Generally speaking, bio fumigation presents a viable and safe approach to controlling insect pests, particularly when combined with other biological and cultural control techniques.

4. Control Effects on Nematodes

Bio fumigation is a safe and sustainable technique utilized for the control of plant-parasitic nematodes (PPNs), the leading agricultural insects responsible for vast crop devastation worldwide. In bio fumigation, some parts of the plants are placed in the soil, which results in the emission of bioactive compounds that suppress the population of nematodes.

4.1. Mechanism of Action

The primary mechanism by which bio fumigation functions is hydrolysis of glucosinolates (GSLs), found in Brassicaceae crops. Biocatalytic hydrolysis of GSLs into isothiocyanates (ITCs), with nonspecific biocidal action, occurs when plant tissue decomposes and becomes part of the soil. Due to their toxicity, the ITCs inhibit nematodes' survival and reproduction capabilities (Feyisa, 2022; Ji et al., 2024).

4.2. Efficacy Against Nematodes

Research has established the extent to which bio fumigation inhibits various nematode species:

a) **Root-Knot Nematodes (Meloidogyne spp.):** Meloidogyne incognita populations have been suppressed with the help of Brassica juncea residues in soil. For example, a recent study found that treatments with cabbage biofumigant reduced root-knot nematode populations by 69.5% (Habriantono et al., 2023).

b) **Cyst Nematodes (Globodera spp.):** Globodera pallida egg viability was suppressed more than 95% by biofumigation with high-GSL varieties like "Nemfix" and "Fumus." Also, in comparison to controls, cauliflower (Brassica oleracea var. botrytis) residues reduced new-cyst production in G. rostochiensis by 12% (Ji et al., 2024).

c) **Lesion Nematodes (Pratylenchus spp.):** While there have not been many studies on this topic, the general biocidal properties of ITCs suggests potential against lesion nematodes and warrants further research.

4.3. Factors that Have the Potential to Affect Biofumigation Success

There are a multitude of factors that have the potential to affect bio fumigation success:

a) **Plant Species and cultivar:** The amount and type of ITCs produced during hydrolysis are related to the GSL content and composition in different Brassicaceae species and cultivars (Tagele et al., 2021).

b) **Amount of Biomass and Timing of Incorporation:** In order to maximize the release of ITC and suppression of nematodes, the amount of plant material incorporated and the timing in association with planting the crop are very important.

c) **Soil Conditions:** Soil temperature, water content, and microbial activity can influence the biofumigation efficacy by affecting hydrolysis of GSL and dispersion of ITCs (Besri, 2021).

4.4. Integration into Pest Management Strategies

Bio fumigation can, in fact, be incorporated into pest management strategies more generally:

a) **Crop Rotation:** Rotation systems including crops with bio fumigant species can assist with improving soil health and reducing nematodes.

b) **Cover Cropping:** There are also two additional ways bio fumigant plants add value to using them as cover crops: provide organic matter and assist with weed suppression.

c) **Combined Methods:** By employing bio fumigation or bio fumigant species with other controls (resistant cultivars, biological control, etc.), nematode management as a whole can be improved.

5. Effects on Crop Growth

Research has shown that bio fumigation has a significant lessening effect on soil-borne diseases, higher soil fertility, and robustness of microbial community topologies which can greatly affect crop development. Collectively, these effects of bio fumigation ultimately contribute to higher yields and enhanced plant vigor in various crops.

Mustard (Brassica juncea) has been the subject of numerous studies that have involved biofumigation. When mustard was applied at a rate of 5 kg/m2 of fresh biomass, gerbera flower production increased by 39.5% compared with the untreated control. The applications of mustard at a rate of 7.5 kg/m2 increased eggplant production by 35.4%, and a single application of 3.5 kg/m2 of mustard significantly increased cucumber seedling vigor and productivity had nearly doubled (Ji et al., 2024). Mustard bio fumigation increased yield in spinach fields by 3.7 kg/m², and also created a residual effect of yield on the following crop of 0.8 kg/m² even without treatments applied again.

Other Brassicaceae crops bio fumigated also demonstrated quantifiable increases of growth. For example, applying 3.5 kilogram/m² of cabbage enhanced tomato yield by 0.4 kg per plant, and applying 0.4–0.8 kg/m² of radish bio fumigation raised eggplant yield by 30.4%. Similar to this, Ethiopian mustard increased strawberry fruit weight and leaf growth, whereas cauliflower bio fumigation increased red chilli pepper pod yields (Samtani et al., 2012; Song et al., 2020).

The effectiveness of processed Brassicaceae products has been comparable. The application of defatted black mustard seed meal nearly quadrupled the dry weight of melon stems, and rapeseed meal bio fumigation increased the production of chili peppers by 16.4% (Keinath and Hassell, 2014). Another study found that using Brassica residues for bio fumigation in continuous cropping systems improved plant nutrient uptake and physiological growth while also reducing pathogen stress (Tagele et al., 2022).

Moreover, there have been synergistic results from integration with biological amendments such plant growth-promoting rhizobacteria (PGPR). The joint application of PGPR and bio fumigation in eggplant created a better tolerance from nematode stress and expanded root and shoot biomass that helped improve the crop resilience (Ali et al 2024). However, crop species, bio fumigant application rate, and environmental conditions all contribute to the benefits of bio fumigation. Incorrect amounts or applications can disrupt the microbial balance or reduce effectiveness. Hence, improving treatment conditions is still highly important to maintain consistent yield response in crops.

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