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Biofumigation for crop protection: potential for adoption in Zimbabwe

Review Paper

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1 SUMMARY

Biofumigation is the practice of using volatile chemicals released from decomposing plant material to suppress soil pathogens, insects and germinating weed seeds. Brassicas are mainly used for biofumigation, but plants in the Moringaceae, Salvadoraceae and Tropaeolaceae families also have biofumigant properties. The decomposition of the plant tissues in these families releases isothiocyanates which are biocidal. Plants have different profiles of isothiocyanates, and stressing the plants increases the amount of isothiocyanates produced by plants. Biofumigation has been used as an alternative to methyl bromide and other synthetic pesticides in horticulture and agriculture in general. It has also been used to reclaim soils contaminated with heavy metals. It is eco-friendly and adds organic matter to the soil. There is potential for this technique to be adopted in Zimbabwe by tobacco and horticulture farmers involved in organic farming and as a stored pest management technique. However, there is need for local research into brassicas that can be used for biofumigation. There is need also to research on methods of incorporating the biofumigant plants into the soil. Breeding for brassicas with high isothiocyanates content also has to be done. There should also be effort to educate farmers about biofumigtion since most farmers are not aware of this technique.

2 INTRODUCTION

Biofumigation is the agronomic practice of using volatile chemicals (allelochemicals) released from decomposing plant tissues to suppress pests (Brown and Morra, 1997; Rosa *et al*., 1997). The range of pests suppressed includes germinating weed seeds, nematodes, bacteria, fungi, viruses and insects. The term biofumigation was coined by Australian scientists to describe the suppression of soil-borne pests by compounds released by brassica species (Kirkegaard *et al*., 1993). It is now known that besides the brassicas, plants in the Caricaceae, Moringaceae, Salvadoraceae and Tropaeolaceae families also have biofumigant properties (Gouws, 2004; van Dam *et al*., 2009). Biofumigation has been widely researched on in Australia, Italy, South Africa, New Zealand, the Netherlands and the USA. Asian countries like Cambodia, China, India, Thailand and the Philippines have also been involved in biofumigation trials (Kumar, 2005). Biofumigation holds a lot of potential in Asia because brassicas are widely grown and consumed. They are grown as oilseed crops, leafy vegetables and fodder crops. They are intercropped with legumes and wheat, two major crops grown in Asia. In African countries outside of South Africa, biofumigation is relatively unknown to farmers. However, brassicas are widely grown and consumed as relish. In Zimbabwe for example, cabbages (*Brassica oleracea capitata*), broccoli (*Brassica olearceae* var *italica*), rape (*Brassica napus*), cauliflower (*Brassica oleracea* var *botrytis*), choumollier (*Brassica oleracea*), kale (*Brassica oleracea* var *acephala*), turnip (*Brassica campestris* var *rapa*), mustard (*Brassica juncea*) and radish (*Raphanus sativus*) are some of the commonly grown brassicas (Godfrey-Sam-Aggrey and Tekie, 1990). Worldwide interest in biofumigation developed when it was hypothesized that the technique could be an effective alternative to the environmentally-damaging chemical fumigants and sterilants (Gouws, 2004). It was realized that there is potential to use biofumigation as an alternative to methyl bromide in horticulture and broad agriculture to manage pests (Brown and Morra, 1997). In most countries, methyl bromide and other synthetic pesticides perceived to be harmful to humans and the environment have been banned under the Montreal Protocol on Substances that Deplete the Ozone Layer, due to their negative effects on the environment (Ibekwe, 2004). Despite the ban, the demand for blemish-free produce is increasing. Biofumigation is a bio-pesticide that can be used to control soil-borne pests without causing harm to the environment.

This article reviews the science behind biofumigation. It looks at the plant species that can be used for biofumigation, instances where biofumigation has been successfully practiced and the factors for and against the adoption of biofumigation.It also highlights the areas that could embrace the biofumigation technology in Zimbabwe.

3 THE SCIENCE AND PRACTICE OF BIOFUMIGATION

Most studies on biofumigation have been done with brassicas (Kirkegaard *et al*., 1993; Gouws, 2004; Kumar, 2005; Ramirez *et al*., 2009; Szczyglowska *et al*., 2011), but as already noted, other families contain plants with biofumigant properties. The decomposition of biofumigant plant tissues mainly releases isothiocyanates (ITCs), in addition to thiocyanates, nitriles and oxazolidinethiones (Kirkegaard and Sawar, 1998; Fahey *et al*., 2001). The ITCs are related to the active ingredients of metham sodium and dazomet. They are released following tissue damage, when endogenous myrosinase enzymes hydrolyze glucosinolates (GCs). GCs are sulphur-containing chemicals that are produced by plants as secondary metabolites (Agrios, 2005). They are found in the vacuole. In the plant, GCs are relatively inactive against microbes. But when hydrolyzed, the ITCs in particular, are biocidal to nematodes, bacteria, fungi, insects and germinating seeds (Sarwar *et al*., 1998). There are over 120 ITCs (Fahey *et al*., 2001) that have been identified mainly from plants in the Brassicaceae family (van Dam *et al*., 2009) (Table 1).

Differences in structure of individual ITCs depend on their organic side-chain, which in turn, influence their biocidal activity (Rosa *et al*., 1997; Clark, 2010). The side chains may be aliphatic, aromatic or indole. Aromatic ITCs are mainly produced in roots and are very toxic (at least 50 times more toxic than metham sodium's methyl ITC) to a range of soil borne fungal pathogens (Vaughn *et al*., 1993). They have low volatility and long persistence in the soil.

Table 1: Plants with glucosinolates in their leaves and stems

Plant Species	Common Name	Family
Alliaria petiolata	Garlic mustard	Brassicaceae
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
Diplotaxis tenuifolia	Perennial wall-rocket	Brassicaceae
Eruca sativa	salad rocket	Brassicaceae
Lepidium sativa	garden cress	Brassicaceae
Moringa oleifera	Moringa	Moringaceae
Moringa stenopetala	cabbage tree	Moringaceae
Rhaphanus sativus	radish	Brassicaceae
Sinapis alba	white mustard	Brassicaceae
Thlaspi arvense	field pennycress	Brassicaceae
Tropaeolum majus	Indian cress	Tropaeolaceae

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This long persistence benefits crops grown after the GC-producing plants. Roots may release ITCs both during growth and decomposition. Aliphatic ITCs are more common in shoots. They are of higher volatility than root ITCs. Thus, shoots tend to have a lower concentration of ITCs than roots. Exposure of dry shoot residues to the surface after crop harvest, burning and grazing of residues reduce the amount of ITCs in shoots. The indole ITCs are found in both roots and shoots. In shoots, the predominant ITC is derived from the GC indol-3-ylmethylglucosinolate, while roots have 1-methoxyindol-3-ylmethylglucosinolate and 4-methoxyindol-3-ylmethylglucosinolate (van Dam *et al*., 2009).
The amount and profile of ITCs produced by brassicas vary with the species and with the soil conditions. Table 2 gives common sources of some ITCs. For example, the three major ITCs identified from *Brassica juncea* roots are 3-butenyl, 4-pentenyl and 2-phenyethyl, while from *Brassica campestris* and *Brassica napus*, the major ITCs are 3-butenyl, 4-pentenyl, 2-phenyethyl, 5-methylthiopentyl and benzyl.

Table 2: Common sources of ITCs

Isothiocyanates	Common Sources
Methyl	*Capparales*, metham sodium
2-Propenyl	*B juncea*, *B carinata*, *B nigra*
3-Butenyl	*B napus*, *B campestris*
4-Pentenyl	*B napus*, *B campestris*
Benzyl	*Sinapis* spp
2-Phenylethyl	*Brassica* roots

3.1 Growing and Formulating Brassicas for Biofumigation: Brassicas can be grown as cover crops or intercrops. These can then be slashed and ploughed under at flowering (McGuire, 2003). Tissue maceration of brassicas and adequate watering facilitate enzymatic hydrolysis of GCs to ITCs. Plants grown under stressful conditions e.g. high density, nutrient stress, disease and mechanical damage to roots and shoots will have elevated concentration of ITCs in their tissues. Growing plants in soils with high sulphur content also results in higher GCs content, hence more ITCs. In Australia, plant breeders have produced varieties with elevated levels of ITCs (Kirkegaard, 2001). Besides growing the brassicas as green manure crops, the brassicas can be formulated into either a brassica cake or powder which can be incorporated into the soil or may be used as mulch. Also, Volatile oil of Mustard (VOOM), a mixture of different edible oils of *Brassica napus* and *Brassica juncea*, can be applied preplanting (Kumar, 2005).

3.2 Success Stories of Biofumigation: Biofumigation has been used to suppress the root knot nematode (*Meloidogyne* spp) and some root rots. Bello *et al.* (2001) showed biofumigation to have the same effect as methyl bromide on *Meloidogyne javanica* in pepper. In Australia, it has been used to control take-all disease caused by *Gaeumannomyces graminis* var *tritici* (Bianco *et al*., not dated). It has also been used to suppress potato scab caused *Streptomyces scabies* in South Africa (Gouws and Mienie 2000). In field trials with selected brassicas (canola, rapeseed, radish, turnip, yellow mustard and Indian mustard), potato scab was reduced by 15-40% by Indian mustard, rapeseed, and canola. Black scurf was reduced by 70-80% by canola and rapeseed. *In vitro* assays with the above brassicas inhibited growth of *Rhizoctonia solani*, *Phytophtora* *erythroseptica*, *Pythium ultimum*, and *Sclerotinia sclerotiorum* by 80-100% (Larkin and Griffin, 2007). In Oman, Deadman *et al.* (2006) showed that solarization and biofumigation can reduce the population density of *Phytophthora aphanidermatum* in greenhouses that had been planted with cucumbers. They also observed improved vegetative growth in the cucumbers. Biofumigation enhanced soil saprophytic activity by microbes like *Streptomyces* which act as agents for the induction of plant resistance to diseases like those caused by *Rhizoctonia*. Solarization, on the other hand, improved plant growth and yield through release of nutrients induced by high temperature. Field experiments in which *Brassica juncea* and *B rapa* were grown as green manure crops resulted in 91-95% mortality of encysted eggs of *Globodera pallida*, a key pest of potatoes (Lord *et al.*, 2011). Studies by Bates and Rothrock (undated) in 2004 and 2005 showed that high glucosinolate brassicas like the Indian mustard have potential for providing season-long control of the reniform nematode in heavily infested cotton fields. GC-containing plants have been used to reduce insect pest populations. In New Zealand, the Australian soldier fly (*Inopus rubriceps*), a pest that can devastate grass pastures can be controlled by ITC isolates from kale (*B oleraceae*). The isolates are effective against the larvae (Lowe *et al.*, 1971). When grown in soils contaminated with heavy metals, brassicas tend to accumulate the metals in their tissues. This leads to increased biosynthesis of GCs. Metals like cadmium, zinc, and copper induce the absorption of sulphate to sustain greater sulphur demand during the biosynthesis of GCs (Schiavon and Malagoli, 2008). This has been used in reclaiming soils contaminated with heavy metals (Szczyglowska *et al.*, 2011).

4 FACTORS FOR THE ADOPTION OF BIOFUMIGATION

Biofumigation greatly reduces pesticide use. Pest control has largely been dependent on synthetic pesticide use. Some of the pesticides are highly persistent and poisonous to both plant and animal life. Others like the chlorofluorocarbons are ozone depleting. The adoption of biofumigation will replace the use of these and even the alternative, non-persistent chemicals. This will make farming cheaper as farmers do not have to spend money on buying chemicals. It will also make farming safer, as biofumigants are not persistent in the environment. The practice will also add organic matter to the soil. This will increase soil aeration, water infiltration rates and soil water holding capacity. It also increases soil porosity if used as a green manure. It adds more organic carbon to the soil (Balesh *et al.*, 2005) which is needed to increase the activity of soil fauna and flora. In particular, the activities of biological control agents like predaceous nematodes, protozoa, fungi and bacteria will be enhanced as the presence of organic carbon in the soil increases the saprophytic activities of microorganisms.

5 POTENTIAL FOR ADOPTION OF BIOFUMIGATION IN ZIMBABWE

A number of brassicas are grown in Zimbabwe. Cabbage, choumoellier, Indian mustard (Plates 1-3) and rape are widely grown at both subsistence and commercial levels. They are grown mainly as sole crops for relish. The peak season for production is between April and August, but all-year-round production is possible in high altitude areas. These brassicas are easy to produce. Seed is readily available in supermarkets and seed houses. During the peak season, not all the produced brassicas are utilized due to oversupply on the market. As a result, some brassicas end up being fed to livestock or just senescing in the field. In our opinion, such brassicas could be used for biofumigation.

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Plate 1: Choumoellier

Plate 2: Indian mustard

Plate 3: Cabbage

Brassicas are already known to be tolerant to root knot nematodes (Godfrey-Sam-Aggrey and Tekie, 1990; Page, 1997), and are included as rotational crops in cropping programmes that contain susceptible horticultural crops like tomatoes, paprika and peas. Where cabbage harvesting is delayed, people complain about the foul smell produced by rotting cabbages. This bad smell is due to ITCs released from the breakdown of GCs. Normally farmers deposit the rotting cabbages in dumpsites. There is potential to use these cabbages for biofumigation. In Zimbabwe, there are a number of areas where biofumigation could be applied. Some of these areas are discussed below:

5.1 Tobacco Production: Tobacco remains a key crop in Zimbabwe, earning the country over US$300 million in the 2010-11 farming season. This was by far the largest single contribution to the Gross Domestic Product from the agricultural sector. The tobacco industry is now dominated by resettled farmers, the majority of whom are on six hectare plots and are financially constrained. Prior to the phase-out of methyl bromide, tobacco seedbeds were either fumigated with methyl bromide or heat-treated with firewood. Currently, the float tray system is being used for raising seedlings. Adoption rates for the float tray system stand at between 30 and 40%. Farmers have complained about the "high" prices and inaccessibility of the float trays, and the technological advancement of the system. Biofumigation isBi a potential alternative to the traditional methods of raising seedlings and the float tray system. Zimbabweans have already embraced brassica production. It will be easy to teach them to this "new" technique so that even those without float trays can still raise their own seedlings. Unlike the traditional method that uses firewood to generate heat to sterilize the soil, this method is eco-friendly as no carbon dioxide is emitted into the atmosphere. However, research has to quantify how much nitrogen in added into the soil when brassica tissues decompose, and what effect this nitrogen might have on tobacco seedling development.

5.2 Organic Farming: The "Organic Movement" has been gaining momentum especially in the developed world. Goods that are organically produced are preferred to those that are not, and consumers are willing to pay high prices so long the product is certified organic. In Zimbabwe, there are a number of organizations involved in organic agriculture. For example, Fambidzanayi Permaculture Centre has been promoting organic fruit, vegetable and cotton production amongst farmers for over two decades. Biofumigation could actually be incorporated into their programmes. Farmers who have been trained in organic farming could readily adopt this technology because of its relevance to organic agriculture.

5.3 Storage pest management: In the developing world, post-harvest losses of cereals and other agricultural commodities due to storage pests range between 10 and 40% (Raja *et al*., 2001). Fumigation with methyl bromide and phosphine has been effective tools for stored-product pest management. However, methyl bromide has been phased out in most countries, and cases of resistance to phosphine have been reported. Thus, there is need for alternatives that are safe to the environment and humans. Traditionally, botanicals have been used in agriculture. Lately, there have been attempts to use phytochemicals for insect pest management. The mustards contain ITCs that are insecticidal. Seeds of *Eruca sativa*, *Sisymbrium arvensis* and *Diplotaxis tenufolia* contain methylthio-butyl ITC. This ITC is effective against adults of *Sitophilus*, *Rhyzopertha*, *Oryzaephilus* and *Tribolium* (Shaaya and Kostyukovsky, 2009). ITCs are particularly interesting as potential candidates for stored-products pest management because only very low concentrations are needed. The methylthio-butyl ITC in *Eruca sativa* has low mammalian toxicity, making it an interesting candidate for the disinfestations of grain and dry food products. Farmers in Zimbabwe could greatly benefit from the use of biofumigation for stored-products pest management. Cases of resistance to the locally available grain protectants like pirimiphos methyl and fenitrothion have been reported. In most instances, smallholder farmers do not usually have the money to buy the synthetic grain protectants. As a result, very high post harvest losses occur. While these mustards are not available in Zimbabwe, it will be interesting to test the locally available mustards for their efficacy as stored-product protectants. Another option would be to import and grow the mustards locally.

5.4 Research: Virtually nothing has been done with regards to research on biofumigation in Zimbabwe. While there are many brassicas grown in Zimbabwe, the amount and profile of GCs and ITCs in each of them has not yet been quantified. There is need to screen local brassicas so that those with high GCs can be recommended for use as biofumigants. No breeding is being done to increase the amount of ITCs in the brassicas. Neither is there any work on formulating the brassicas for incorporation into the soil. Higher education institutions, private and public research organizations should take interest in biofumigation and spearhead research in the above areas. The research findings have to be disseminated to farmers for implementation. In this regard, the Ministry of Agriculture's Department of Agritex, has to be involved. The Crop Science Department at Bindura University of Science Education has initiated some research on biofumigation. Local brassicas are being evaluated for their efficacy in controlling *Meloidogyne javanica* on tomatoes.

6 LIMITATIONS OF BIOFUMIGATION

While biofumigation holds a lot of promise as a crop protection tool, its broad spectrum toxicity might harm non-target beneficial soil biota such as biocontrol agents or other pest antagonists (Ramirez *et al.*, 2009). This means the switch to brassica biofumigants might not eliminate all the harmful non-target effects associated with synthetic chemicals, thus potentially complicating the integration of cultural and biological control. Henderson *et al.* (2009) reported that biofumigation interfered with the biological control of *Meloidogyne chitwoodi* by the entomopathogenic nematodes *Steinernema feltiae* and *Steinernema riobrave*. Biofumigants are also non-persistent. Thus, it does not provide a long term control option for pests. Farmers might have to complement biofumigation with other crop protection tools.

7 CONCLUDING REMARKS

Despite its limitations, biofumigation has many potential benefits that could be useful in agriculture. It could provide an alternative pest control technique in horticulture, storage pest management and tobacco production where the use of methyl bromide has been banned. It could also put to better use those excess brassicas farmers produce during peak vegetable production periods. It is also very interesting for researchers to work on given the benefits that have been ascribed to it.

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