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Biofumigation for the Control of Vegetables Soilborne Pathogens in Some non-Temperate Climate Countries

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ABSTRACT

Soil-borne pathogens (SBPs) significantly reduce the yield and quality of crops worldwide. In the past, their control was principally accomplished by using soil fumigants such as methyl bromide (MB). However, this fumigant which is a powerful ozone-depleting substance, has completely been phased out under the Montreal Protocol (MP). New chemicals and non-chemical alternatives to MB, including biofumigation, have been actively researched, developed, and commercially adopted worldwide. This review seeks to provide the status of biofumigation for the control of SBPs in some non-temperate climate zones referred to in this paper as Article 5 countries or developing countries according to the Montreal Protocol (MP) classification. The review will first define "the non-temperate climate zone," list the countries belonging to this zone, focus on the role and importance of the MP in phasing-out MB, and in searching and commercially adopting alternatives including biofumigation to this fumigant. It also describes the biofumigation techniques reported and used, reports its efficacy/inefficacy to manage SBPs in some non-climate temperate countries, insists on the place it must have in an IPM program to increase its efficacy, and finally, lists the collaboration and the research needed to further develop and commercially adopt this technology in non-temperate climate countries.

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1. Introduction

Soil-borne pathogens (SBPs) and particularly plant-parasitic nematodes (PPNs) significantly reduce the yield and quality of crops worldwide. PPNs are considered one of the major limiting factors in vegetable production. They cause an estimated crop yield loss of 14.6% in non-temperate climate zones (tropical and sub-tropical countries) and losses of 8.8% in temperate zone countries [1].

In the past, control of soil-borne pathogens of vegetable crops was principally accomplished using soil fumigants such as methyl bromide (MB) [2]. Due in large part to its adverse effect on the Earth's ozone layer, MB has been phased out of agricultural uses [2,3]. Replacement fumigants such as 1,3-D, chloropicrin, dazomet, metam sodium, methyl iodide, fluensulfone, DMDS, and others are available. However, there are problems associated with their use [3]. The need to phase out MB fumigant under the Montreal Protocol, together with requirements from consumers, market chains as well as restrictions imposed on many chemicals around the world, encouraged the search for non-chemical options that may provide a longer-term and more sustainable approach to soil pest management [3]. One of these non-chemical alternatives which are becoming increasingly popular is biofumigation [1,4-6].

This review seeks to provide the status of biofumigation for the control of SBPs in some non-temperate climate countries referred to in this paper as developing or A5 countries according to the Montreal Protocol countries classification [7]. The review will 1) describe briefly the climate zones, 2) present the role of the Montreal Protocol (MP) in searching and implementing alternatives to MB, including biofumigation in non-temperate zone countries, 3) report its efficacy/inefficacy to manage SBPs in non-temperate zone countries 4) insist on the place it must have in an IPM program to increase its efficacy and finally, 5) report the research needed to develop further and commercially adopt this technology in non-temperate climate countries.

2. "Climate Zones": Definition

Climate zones are areas with distinct climates. They are belt-shaped and circular around the Earth and are classified using different climatic parameters such as temperature (diurnal and night, annual, mean), humidity, precipitation, wind direction, and speed etc. There are four major climate zones (Figure 1): Tropical from 0°C–23.5°C (between the tropics), Subtropical from 23.5°C–40°C, Temperate from 40°C–60°C and Cold from 60°C–90°C. The non-temperate climate zones are, therefore, tropical and subtropical [8].

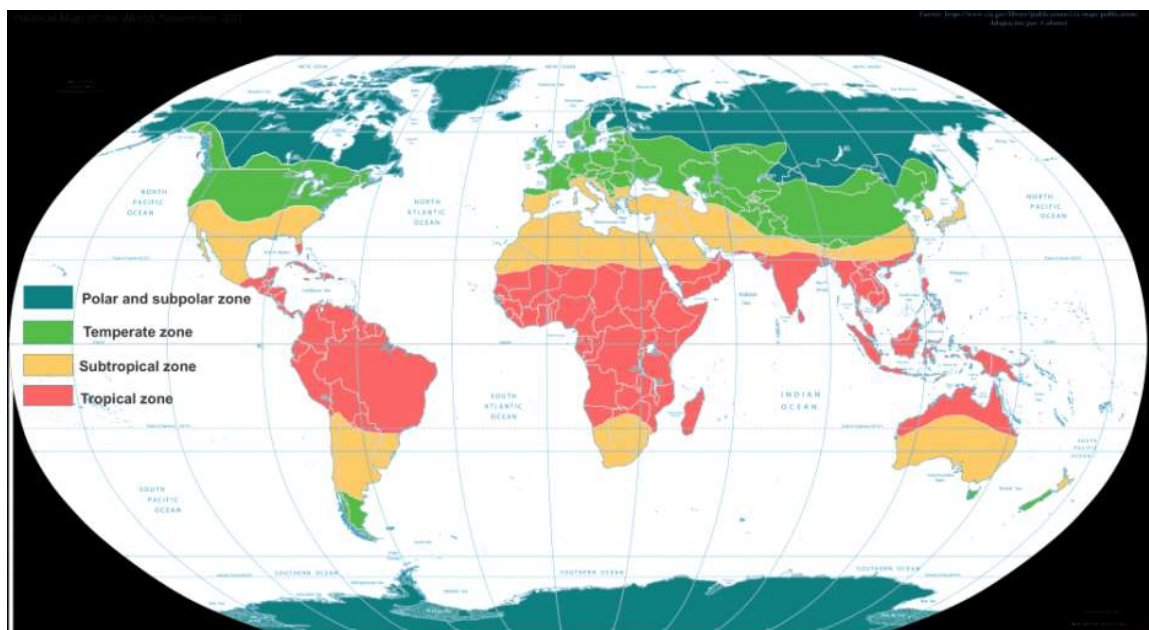


Figure 1: Major climate zones.

The solar radiation reaches the ground on different parts of the Earth at different angles. On the equator, the sunlight reaches the ground almost perpendicularly, whilst at the poles, the angle of the Sun is lower or even under the horizon during the polar night. That explains why, in general, climate areas tend to be warmer towards the equator (tropical and subtropical) and cooler towards the poles (temperate and cold). Therefore, the temperatures in the agricultural non-climate zone (tropical and subtropical) are higher than in the temperate and cold climate zones [8].

3. The Montreal Protocol and the Methyl Bromide Phase-Out

3.1. The Methyl Bromide and Its Uses

MB is a broad-spectrum pesticide used to control soil-borne pathogens, insects, nematodes, and weeds. MB is used in the following areas: 1) Pre-plant fumigation of soil to control soil-borne pests and diseases in the production of some high-value crops, e.g., vegetables, ornamentals, tobacco, and strawberries; 2) Fumigation of some commodities and structures to control damaging pests, and 3) Quarantine and pre-shipment fumigation to prevent the spread of pests and diseases (Phytosanitary measures) (Figure 2). About 50 to 95% of the MB bromide injected enters the atmosphere, contributing to the thinning of the ozone layer and allowing increased UV radiation to reach the Earth's surface, greatly impacting man and its environment [3].



Figure 2. Soil (A, B, C), commodities (D, E, F), and structures (G, H, I) fumigation with methyl bromide

3.2. The Montreal Protocol

In 1987, governments around the world agreed on the MP on substances that deplete the ozone layer (Chlorofluorocarbons (CFCs), Halons, Carbon tetrachloride, Hydrochlorofluorocarbons (HCFCs), Methyl chloroform, and Hydrobromofluorocarbons (HBFCs) to protect the man and its environment against depletion of the

stratospheric ozone layer resulting from human activities. MB was added to the Protocol as an ozone-depleting substance in 1992 through the Copenhagen Amendment to the Protocol [7].

In 1997, the Parties to the MP agreed to accelerate the reduction in the controlled production and consumption of MB. The parties called for an MB phaseout by the year 2005 for developed countries (non-article 5 countries) and 2015 for developing countries (Article 5 countries), among which most are located in the non-temperate climate zone (Table 1).

Table 1: Methyl bromide phaseout schedules agreed at the ninth Meeting of the Parties in 1997.

Year	Non-Article 5 Countries	Article 5 Countries
1991	Consumption/ production baseline	
1995	Freeze	
1995-98 average		Consumption / production baseline
1999	25% reduction	
2001	50% reduction	
2002		Freeze
2003	70% reduction	Review of reductions
2005	Phaseout with provision for CUEs	20% reduction
2015		Phaseout with provision for CUEs

Source: UNEP, Ozone Secretariat, 2020[9].

Non Article 5 countries; Developed countries.

Article 5 countries; Developing countries, most of them are in the non-temperate climate zone.

3.3. Implementation of alternatives to Methyl Bromide, including biofumigation, in *non-temperate* climate zone countries

In 1990, the international community established a financial mechanism called the Multilateral Fund (MLF) to support efforts in developing countries to phase out ozone-depleting substances under the Montreal Protocol [10]. Contributions from industrialized countries finance the MLF, and projects are implemented by four agencies: the United Nations Environment Program (UNEP), the United Nations Development Program (UNDP), the United Nations Industrial Development Organization (UNIDO), and the World Bank. In some cases, projects have also been funded directly by non-A5 countries through bilateral cooperation and by the non-A5 parties themselves (government, agricultural producers) [11].

The projects have identified many economically and technically non-chemical and chemical alternatives (Table 2), which have often proved to be as efficient as MB, particularly when they are used as components of IPMs programs. In many projects conducted in Article 5 countries, biofumigation has been considered as a key alternative to MB (Table 2). This has often implied that growers and other users change their approach to crop production and pest control, including investments and training. Early phaseout of MB has proven beneficial to A5 parties in many instances by improving production practices, increasing the competitiveness of certain agricultural products in international markets, and training large numbers of growers, technical staff, and other key stakeholders [11].

3.4. Biofumigation success stories in some *non-temperate* climate zone countries

Biofumigation is a sustainable agronomic practice using naturally produced plant compounds to manage soil pests, including PPNs. This practice primarily relies on volatile organic compounds (VOCs) when they, or their byproducts, are incorporated into the soil. Many plants produce VOCs. However, the biofumigation practice is dominated by the use of glucosinolates (GSLs) that are hydrolyzed into isothiocyanates (ITCs), which are capable of

killing or driving away PPNs [6]. In non-temperate zone countries, the biofumigant crop is grown as a cover crop and tilled into the soil at maturity, where it breaks down to release toxic compounds [4-6]. As previously reported, this SBPs control method is widely commercially used in many developing countries (Table 2 and Figure 3).

Table 2: Some multilateral funds projects considering biofumigation as an alternative to methyl bromide in non-temperate climate zone.

Region	Country	Selected Alternatives
Latin America and the Caribbean	Peru (Horticulture, tobacco)	<i>Biofumigation</i> , steam, solarisation, biological control, floating trays
	Uruguay (Tomato, ornamentals)	<i>Biofumigation</i> , soilless, steam, grafting
	Mexico (tomato, melon, strawberries, flowers)	<i>Biofumigation</i> , grafting, chemicals, IPM, steam, solarisation
	Argentina (tomato, tobacco, flowers, strawberries)	<i>Biofumigation</i> , chemicals (1, 3-D/Pic, MS, DMDS), steam, floating trays, grafting
	Costa Rica (Melon, cut flowers)	1, 3-D/pic, metam sodium, solarisation, biocontrols, steam
Africa	Morocco (vegetables, flowers, bananas, strawberries)	<i>Biofumigation</i> , grafting, solarisation, steam, soilless, chemicals
	Egypt (flowers, tomato, cucurbits)	<i>Biofumigation</i> , soilless, steam, grafting
	Kenya (flowers)	<i>Biofumigation</i> , metam sodium, substrates, steam, grafting, IPM
The Middle East and Asia	Lebanon (ornamentals, vegetables, tobacco, strawberries)	<i>Biofumigation</i> , fumigants, solarisation, grafting, floating trays
	Jordan (tomato, cucurbits)	<i>Biosolarisation</i> , grafted plants, chemicals, biocontrol, steam, soilless,
	Turkey (tomato, cucurbits, flowers, pepper, eggplant)	<i>Biofumigation</i> , grafting, metam sodium, 1, 3-D, 1, 3-D/Pic, dazomet, solarisation, substrates, grafting, resistant varieties, steam,
	China (tomato, cucurbits, strawberries, ginger)	<i>Biofumigation</i> , metam sodium, chloropicrin, 1, 3-D, grafting, biocontrol
Europa CEIT	Bosnia- Herzegovina (Tobacco, ornamentals)	<i>Biofumigation</i> , floating trays, solarisation
	Macedonia (Tobacco, vegetables)	<i>Biofumigation</i> , floating trays, solarisation, dazomet

CEIT: Countries whose economy is in transition.

Adapted from MBTOC [11].

3.5. The Montreal Protocol success in non-temperate and temperate zones countries

From 2005 to 2018 (Figure 4), MP has reduced the production and consumption of MB by more than 99 %. This reflects the successful adoption of alternatives in the vast majority of sectors where MB was once used, both as a soil fumigant and as a postharvest or structural treatment [14].

4. Success and Failure of Biofumigation in Managing Soil-Borne Pathogens in Some Non-Temperate Countries

4.1. Success of biofumigation

Biofumigation success is influenced by many factors such as the pest complex, soil characteristics, type and availability of the soil amendment, and climatic conditions. Acceptable levels of suppression in PPN populations *via* biofumigation with brassica and non-brassica plant tissues have been demonstrated worldwide (in the open field and protected cultivation). It has been observed that biofumigation has the following effects [1,4-6,15-20].

- Decreases in nematode population in host roots and soil and change in their sex ratio;
- Reduces the nematodes severity expressed as root galling;

- Increases the plant vigor, crop yield, and marketable production compared to fumigants treated plots (MB, 1, 3 D/Pic, Dazomet, MetamSodium, etc.);
- Increases of the beneficial microorganisms populations;
- Improves soil texture and structure and increases organic matter and water holding capacity;
- Is one of the least expensive alternatives to MB.

Argentina
Organic amendments



China
Chicken and straw



Lebanon
Lettuce and oil radish



Mexico
Crop residues



Morocco
Tagetes spp.



Spain
Crop residues and chicken manure



Picture Sources:

Argentina [12].

Picture 1: Control (left), biofumigation (right). Plants infected with *Nacobbus aberrans*, *Fusarium solani* and *Pyrenochaetalycopersici*. Biofumigants: organic amendments (chicken manure, tomato, and pepper crop debris)

Pictures 2 and 3: Weed control using cabbage in spring for open field tomatoes.

China: Cao Aocheng, personal communication.

Mexico: [13].

Morocco, Spain, Lebanon: Besri's pictures.

Figure 3. Biofumigation in some non-temperate countries.

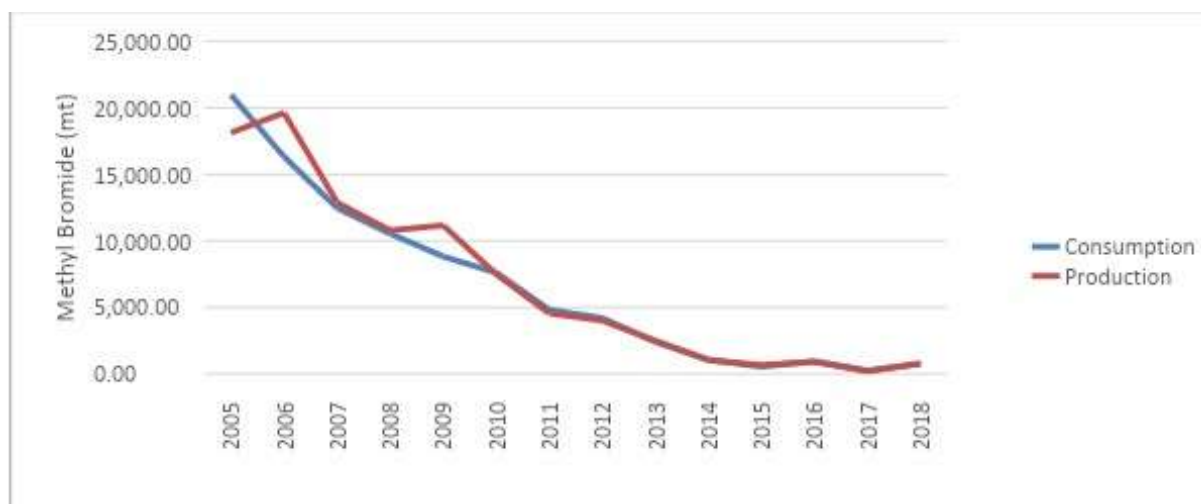


Figure 4. Controlled consumption vs. controlled production of MB (2005-2018).

4.2. Failure of Biofumigation

Reports on the inconsistency and inefficacy of biofumigation in suppressing SBPs under field and greenhouse conditions have also been reported. In some cases, insignificant or no reduction and instead increase in target SBPs level due to Brassica green manuring has been observed [1,6].

Most of the economically important PPNs are known to infect a broad spectrum of cruciferous plants. Therefore, Brassicaceous plants can also serve as hosts to PPNs. Nematode populations surviving in deeper soil layers are unaffected by biofumigation, and those may serve as the reservoir inoculum for the next cropping cycle. Biocidal isothiocyanates (ITCs) have a half-life of a maximum of 10 h in soil. After soil incorporation of the biofumigation material into the soil, poor irrigation will not allow the transportation to the deeper soil layers of the fumigant compound and consequently prevents the faster volatilization of ITC or other compounds. Some studies failed to show any biofumigation effect because the soil was too dry, and the degree of biomass disruption was insufficient to maximize the ITC release. Some biofumigant plant materials are more effective against J2s (second stage juveniles) than against the egg masses of *Meloidogyne* spp. The active nematode stages are more vulnerable to the toxic volatiles emanating from decomposing brassica biomass [1,6,21-23]. Failure of biofumigation could also be due to the quality of the plastic used to cover the soil. Trapping of ITCs by polyethylene mulching permeable to methyl ITC [24] do not retain biocidal compounds. On the other hand, virtually impermeable films increase the efficacy of biofumigation [25].

This technology also presents some disadvantages, such as nutrient eutrophication and greenhouse gas (GHG) emissions. Moreover, an organic amendment is pathogenic and site-specific. An organic amendment suppressive to one pathogen could be ineffective, or even conducive, to other pathogens [1,6,21,26,27].

5. Combination of biofumigation with other control methods in some non-temperate countries: IPM

Integrated Pests Management aims to reduce pest infestation by manipulating one or more of the biotic or abiotic components involved in the disease with minimal disturbance to the environment and natural resources [28,29].

In temperate and non-temperate climate zones, biofumigation alone may not be adequate to replace soil fumigants, particularly MB. Biofumigation controls many soil-borne pathogens but does not completely eradicate them. Therefore, this technology should be combined with other chemical and non-chemical control methods, e. g. resistant varieties and rootstocks, solarisation, steaming, hot water, anaerobic soil disinfestations, microwaves etc. [30-34].

5.1. Biofumigation and solarisation: Biosolarisation

Covering the soil during the hot months of the summer increases soil temperatures, particularly in the hot non-temperate climate zone (subtropical and tropical countries) [35-39]. The combined action of organic amendment and solarization (often referred to as “Biodisinfestation” or “biosolarization”) has shown its effectiveness to control PPN (*Meloidogyne* spp, *Nacobbus aberrans*, *Helycotylenchus* spp. *Criconebella* spp etc.) and fungal pathogens (*Pyrenochaeta lycopersici*, *Fusarium solani*, *Sclerotium rolfsii*, *Sclerotinia sclerotiorum* in many non-climate temperate [40-43].

Lacasa *et al.* [44], Bello *et al.* [45] reviewed how Spain switched to biofumigation and bio-solarization as the main non-chemical alternative, followed by soilless cultivation, crop rotation, resistant varieties, and grafting. Nunez-Zofio *et al.* [46] reported that applying sugar beet vinasse followed by solarization reduced the incidence of *Meloidogyne incognita* in pepper crops while improving soil quality. In Italy, Gilardi *et al.* [47] developed a strategy to control *Fusarium oxysporum* f. sp. *conglutinans* and *Fusarium oxysporum* f. sp. *raphani*, causal agents of Fusarium wilt of rocket and basil, by combining amendments and soil solarization. An IPM strategy combining grafting and bio-solarisation to control *Phytophthora capsici* on bell pepper has also been developed [48]. In Turkey, biofumigation was efficiently applied in conjunction with solarisation [49]. In Macedonia, solarisation + biofumigation reduced root-knot nematodes and *Fusarium* spp population and gave the best tomato and cucumber yields [50]. Mitidieri *et al.* [51] reduced the incidence and severity of *Nacobbus aberrans*, *Sclerotium rolfsii*, *Fusarium solani*, and *Pyrenochaeta lycopersici* on tomatoes by combining biofumigation (chicken manure+broccoli) and solarisation.

5.2. Biofumigation and antagonistic microorganisms

Zakaria *et al.* [52], Li *et al.* [53], Wang *et al.* [54], Garcia-Raya and Michel [55], Jin *et al.* [56] reported that integrating biofumigation with antagonistic endophytic bacteria controls SBPs by regulating soil bacterial community structure and that the combined application of these microorganisms and biofumigation had superior efficacy against the SBPs compared with each treatment alone.

In Jordan, Biofumigation combined with *Peacillomyces* and *Trichoderma* reduced the population of *Fusarium* spp and *Meloidogyne* spp. populations and soil-borne pathogens and increased the cucumber yields [57].

In Egypt, Ghoname *et al.* [18] reported that bio-compost fortified with *Trichoderma harzianum* and *Bacillus subtilis* (disease suppressive compost) increased the lettuce head length, diameter, fresh weight, dry weight, total and marketable yield.

In Argentina, Perniolal *et al.* [58] reported that the antagonist fungus *Trichoderma* spp. is compatible with biofumigation and with *Brassica juncea* and *Sinapis alba* and that *Azospirillum brasilense* is only compatible with *Sinapisalba* and with low doses of *Brassicajuncea*.

5.3. Biofumigation and grafting

Grafting is widely used to control a wide spectrum of vegetables fungal soil-borne fungal pathogens (*Fusarium*, *Verticillium*, *Pyrenochaeta*, *Monosporascus*, *Phytophthora*, *Pyrenochaeta*,) nematodes (*Meloidogyne* spp.), viruses (CMV, ZYMV, PRSV, WMV-II, TYLCV), and bacteria (*Ralstonia solanacearum*). In addition, grafting improves plant yield and promotes plant vigor [59-68].

In Brazil, Zeist *et al.* [69] reported a beneficial effect of combining biosolarization with the addition of chicken manure and grafting in the control of bacterial wilt (*Ralstonia solanacearum*).

5.4. Biofumigation and fumigants

In China, Cao *et al.* [70], Zhang *et al.* [71] developed a new rotation model to reduce the application of fumigants and phase out MB in Hebei Province. This model was chloropicrin treatment one year, followed by biofumigation application the next year. *Fusarium* spp. and *Phytophthora* spp. were significantly reduced, and the

yield significantly increased when rotating the two treatments.

In Lebanon, Haroutunian [72] evaluated the efficacy of two biofumigation crops, oil radish (*Raphanus sativus oleifera*) and arugula /rocket (*Eruca vesicaria sativa*), applied in combination with and without oxamyl in the management of the root-knot nematodes in greenhouse cucumber crops. The results have shown that incorporating oxamyl in the biofumigated soil does not increase the yield and does not reduce the nematode population. He concluded that oil radish and arugula as biofumigation crops with plastic cover could be considered an alternative management tool for the root-knot nematode in greenhouse cucumber production under Lebanese conditions.

5.5. Biofumigation and multiple control methods: IPM

In Mexico, Cristobal-Alejo *et al.* [73], Cid del Prado [13] and Franco Navarro *et al.* [74] developed an IPM program to control the false root nematode (*Nacobus aberrans*), including fertilization nematicide application (ethoprop), biological control, and biofumigation. It resulted in significant increases in plant height, dry foliage weight, stem diameter, and crop yield, as compared to other treatments. *Pochonia chlamyosporia* combined with nematicide application and environmentally friendly crop protection techniques that include incorporation of cabbage residues and composted manures has been recognised as a successful IPM tool for reducing *N. aberrans* populations.

In Morocco, *Tagetes* spp. is widely used as a component of an IPM program combining non-chemical (resistant cultivars and rootstocks), chemicals (metam sodium, 1, 3D/pic) to control SBPs attacking vegetable crops [30-32]. Integration of biofumigation with compost, solarisation, and grafting dramatically reduces the incidence of SBPs pathogens more than using each of these control methods used separately [75].

In Turkey, Ozturk *et al.* [49] reported that no single alternative (solarization, metam-sodium, 1,3 dichloropropene, dazomet, and biofumigation) could be recommended to replace MB. These control methods should be combined in an IPM program to manage soil-borne pests in Antalya conditions.

6. Conclusion

After phasing out of MB, biofumigation has gained increasing attention as an option in the sustainable management of soil borne-pathogens attacking many crops both in climate and non-climate temperate countries. However, in some particular environmental conditions, biofumigation does not significantly reduce the incidence and severity of SBPs. In addition, biofumigation has the major disadvantage of requesting a relatively longer period of application time (45 days) as compared to MB (10 days). This fact alone is a major handicap for the wide-scale adoption of this technique as a viable alternative to MB for most farmers. Therefore, many researchers are increasingly interested in biofumigation to improve its efficiency and to:

- Reduce the application period of biofumigation crops;
- Identify appropriate species and cultivars of plants having a high amount of GSLs in their tissue and short vegetative period;
- Research the optimal doses of biofumigants to be used;
- Improve the incorporation methods and timing;
- Improve biofumigation both in an open field and in protected cultivation;
- Identify the optimal cultural practices for each plant: soil preparation, sowing dates, plant density, irrigation, fertilization, mulches, incorporation in the soil, etc.
- Identify the target nematode(s) and their host status on candidate biofumigant crop;
- Combine the biofumigant crop with other chemical and non-chemical control methods in an IPM program;
- Produce high-quality compost by using the large amounts of organic waste generated by horticulture;

- Introduce the concept of biofumigation in the IPM training courses;
- Encourage MSC and PHDs research projects in biofumigation.

Research results will allow drafting regional practical guides on biofumigation, for non-temperate countries farmers, similar to the one edited by FAO to help Asian vegetable smallholders to adopt biofumigation as a soil-borne pathogens control method [76].

In addition, most of the countries in the non-temperate climate zone, which are mostly developing countries, need to strengthen their collaboration with the industrialized ones by participating in their research, increasing exchanges of researchers and students and to be part of networks such as the Best4soil network, which is currently open only to European countries.

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