Alternatives to replace methyl bromide for soil-borne pest control in East and Central Europe

MANUAL

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Cover photos
Background image: Tomatoes grown in coconut fibre in Poland. Courtesy of S. Sluzarski.
Left inset: Solarized greenhouse in Bulgaria. Courtesy of G. Neshev and Stoika Masheva.
Right inset: Bucket used as a container in Hungary. Courtesy of Tompos Daniel.

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Edited by
R. Labrada

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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ALTERNATIVES TO REPLACE METHYL BROMIDE FOR SOIL-BORNE PEST CONTROL IN EAST AND CENTRAL EUROPE

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Abbreviations

CEITs	Countries with Economies in Transition
CGMMV	Cucumber Green Mottle Mosaic Virus
DTIE	Division of Technology, Industrey and Economics
EU	European Union
GEF	Global Environment Facility
IPM	Integrated Pest Management
MB	Methyl Bromide
MBTOC	Methyl Bromide Technical Options Committee
MITC	Methylisothiocyanateous
MS	Metam Sodium
TMV	Tobacco Mosaic Virus
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
VIF	Almost Impermeable Films

Preface

Elimination of production and consumption of Methyl Bromide (MB) would not only be important for protection of ozone layer, but it will contribute immensely to making present agriculture practices sustainable.

Soil-borne pests and diseases present major challenges to the production of vegetables, legumes, ornamentals and other crops grown in open fields as well as under greenhouses. Historically, the fumigant MB was applied to soils as it could effectively control a wide range of pests. As it is a broad spectrum fumigant, little effort was put into the analysis (evaluation) of the species, role and nature of soil pest organisms present before treatment.

Montreal Protocol now requires that MB be phased-out except for quarantine and pre-shipment uses. Most of the alternative technologies tested and validated in different countries have been effective to a large extent. For this reason the phase out of MB as a soil fumigant represents a real challenge for all, requiring not only changes in technologies, but also complementary techniques like pest and crop management systems, to ensure that alternatives are as effective as MB.

There is a need that agricultural researchers, extension workers and farmers work together in order to develop Integrated Pest Management (IPM), i.e. the combined use of two or more control strategies, which would provide the same level of effectiveness as MB, while enhancing the quality of soils in the long-term.

Within the framework of the project "Total Sector Methyl Bromide Phase out in Countries with Economies In Transition", the countries of Bulgaria, Hungary and Poland, gathered comprehensive data on MB use; raised awareness on MB alternatives; developed policy to support MB phase out; and identified and validated effective alternatives to replace its use in the soil sector.

The present manual - prepared under the technical guidance of the Food and Agriculture Organization (FAO) Plant Protection Service – demonstrates the alternatives that are already available in Bulgaria, Hungary and Poland, their advantages and limitations, as well as the need to further implement IPM to achieve the necessary results and to avoid crop losses due to the incidence of several noxious organisms in soil.

This compendium of useful technical information and expertise gained during the project can be consulted by scientists, extension workers, other agents working directly with farmers, and by farmers themselves, who often benefited in these countries from medium-to-high level education. Similarly, other countries of the Region or elsewhere with similar climate and crop conditions may use this information for its local validation and adoption if necessary.

We would like here to express our great appreciation towards Ms Erzsebet Dormannsne Simon from Hungary, Professor Georgi Neshev from Bulgaria and Dr Czeslaw Slusarski from Poland for their decisive contribution during the preparation of this excellent material on alternatives to MB for soil-borne pest control.

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Major soil-borne phytopathogens on tomato and cucumber in Bulgaria, and methods for their management

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I. Major soil-borne phytopathogens

In Bulgaria, basic greenhouses crops are tomato, cucumber and pepper. In recent years, the areas planted with flowers, especially in plastic greenhouses, have been increasing. Whenever there is no heating in greenhouses during winter, lettuce, spinach and other cold-resistant crops are grown. The perennial cultivation of these crops in the same plots is the reason for the build-up of soil-borne microorganisms, which cause several diseases and yield losses.

There are several different soil-borne phytopathogens prevailing in the production of vegetables in greenhouses and in the open field, which will be briefly described. The conditions for their appearance and development are variable and highly dependent on various factors such as air and soil temperature and humidity, cropping conditions and the preceding crop.

Fungal diseases of subterranean parts

Different Pythium species (*Pythium. ultimum, Pythium. debaryanum* and *Pythium. aphanidermatum*) and *Phytophthora spp.* (*Ph. cryptogea* and *Ph. drechsleri*) affect seedlings and cause damping off. In addition to affecting cucumber, they also affect tomato, pepper, aubergine, cabbage and other species. This is an “infant” plant disease. In typical cases, infection occurs at the soil line in the hypocotyl and results in softening and rotting at the base of the stem right on the soil surface. In other cases, the objects of the infection are the germs of the seeds, before their emergence on the surface of the soil. This kind of occurrence is called "pre-emergence damping off". The fungi can even attack the ageing seedlings. Their bark at the base of the stem mortifies without affecting the vascular system, which have already become wooden.

The agents of damping off are widely spread and their growth is especially facilitated by soil that is moist and rich with organic substances, comparatively high temperature and shortage of light. They grow very rapidly, especially under the conditions of sudden variations of the temperature and damages of nematodes. The thick and overgrown seedlings are more susceptible to damping off. The same happens with old plants after suffering climatic or other abiotic stress. Plants fertilized with nitrogen only, particularly those grown under light shortage conditions, have an increased susceptibility to this disease.

The damage caused to the seedlings and old plants is huge. The pathogens are able to survive in soil as saprophytes living at the expense of available organic substances. Their weak phylogenetic specialization also enables them to attack other plants and to survive better in the soil. They form solid forms of oospores and chlamydospores, which help them to remain viable in the soil for a 2–12 year period. At the highest density, they survive as mycelium. *Pythium* spp. grows at different soil depths, but their highest inoculum is found within the first 2–10 cm.

Rhizoctonia solani Kühn (*Perfect stage: Thanatephorus cucumeris (Frank) Donk*

This fungus also causes damping off. The fungus grows mainly in shallow soil layers, sometimes on the soil surface, which enables it to cause damage at the plant stem base. Sometimes, it also affects the leaves of the young plant. It survives in the soil as mycelium, while in the plant debris and in infected potatoes tubers, as sclerotium. The sclerotium sprouts as multicellular, cream-coloured turning to russet mycelium, which penetrates into the stem.

This pathogen is widely spread, affecting tomato, cucumber and other crops. It may be found in soil, compost and plant residues in form of sclerotium or mycelium, and grows in moist and heavy soils as well as in light and dry ones. The optimum temperature for its growth is 15–26^{0}C (Blancard, 1988; Blancard, Lecoq and Pitrat, 1991).

Fusarium solani f.sp. cucurbitae Snyder and Hansen (Perfect stage: Nectria haematococca Berk. & Broome (Fusarium root-rot)

This fungus causes basal and root decay on the cucumbers and, according to Paternotte, (2005) on the marrow as well. The first symptoms are associated with wilting during the hot hours of the day. Later, the lower leaves wilt, and the whole plant dies. Rotting tissues can be found at the stem base, which easily splits along the length of the stem. If high moisture prevails, the plant will hardly bloom. This pathogen can also be found in deeper soil layers. Increased soil moisture and temperature may enhance its growth. The optimum growth temperature is 28^0C. (Singh, 1985), remaining viable in soil and in the plant in the form of chlamydospores, persisting for a period of two years. Seeds can also be infected.

Pyrenochaeta lycopersici Gerlach & Schneider (Corky root)

This fungus, which is widely spread in greenhouses in Bulgaria, attacks various crops, such as tomato and cucumber.

The first symptoms can be observed on the lowest leaves. They begin to wilt and lose colour very rapidly. But the most typical symptom can be observed on the roots in the form of cork-brown zones. The fungus grows in the deeper soil layers. It lives for a long time in the form of chlamydospores. As a result of monocropping, the fungus population builds up in soil; for this reason, infected soils are called "exhausted". *Pyrenochaeta lycopersici* is easily spread by the agricultural implements.

The optimum growth temperatures of the fungus are 15–20^0C.

The agents of tracheomycosis/damage in the vascular system

Verticillium dahliae Kleb. and Verticillium albo-atrumReinke et Berth. (Verticillium wilt)

This is the causal agent of tracheomycosis. Initial symptoms include partial loss of crown leaves, the pathogen invades xylem vessels, impeding normal water flow in the plant, while the roots of the infected plants look fresh and unimpaired. When cutting the base of the stem, especially nodes transversely, tan to light brown coloration in the vascular system is observed. The infection penetrates into the roots through areas wounded by nematodes or mechanically during mechanical cultivation. These pathogens are widely spread and are hosted by a large number of plants. *Verticillium albo-atrum* is frequently found in high altitude areas; it forms dark mycelium and does not produce microsclerotia, while in *Verticillium dahliae*, this dark (black) mycelium is always associated with microsclerotia. The pathogens survive for a long period of time in the soil in the form of stable mycelium and microsclerotia. Cool weather is conductive to infection. Disease progression appears to be limited by high temperature, but infected plants do not recover. The plants are more susceptible in short days and faint light. The new areas are infected by infected seedlings or irrigated water, or in the process of applying compost that contains residues of sick plants. The seeds of the vegetable crops do not carry this disease.

Fusarium oxysporum f. sp.cucumerinum J.H.Owen (Fusarium wilt of cucumber)

This is a widespread and systemic disease of cucumbers grown in greenhouses, which also causes local damage along the stem. The fungus attacks cucumber at any stage of the plant cycle, including damping-off of seedlings. It penetrates the plant through the roots. At first, plants wilt and then die within 3–5 days. A transversal cut of the root and stem of the affected plants shows vascular discoloration. It survives in soil in the form of chlamydospores, saprophytically on plant debris and on plant seeds. Its spores are spread by air or by machinery for cultivation and irrigation. High soil moisture and temperatures enable the disease development.

Fusarium oxysporum f. sp.radicis-cucumerinum (Fusarium root and stem decay)

According to Vachev (2007, in press) this disease is widely spread in Bulgaria and is found in 21 greenhouses. The first symptoms are necrosis at the base of the stem, which later extends in the form of a pink-yellowish bloom brought by the fungal sporophores. The bark and the vascular bundles of the roots and the stem, especially at the nodes, turn a yellow-brown colour. At high air temperatures, the diseased plants wilt quickly, later dying. This disease is common in cucumbers cultivated in open fields as well as in hydroponics on coconut fibres substrate. In addition, the disease also affects pumpkins and other cucurbits, including *Cucurbita ficifolia*.

Fusarium oxysporum f.sp. lycopersici (Sacc.) Sn. E H. (Fusarium wilt) – the causal agent tomato tracheomycosis

This is a widespread disease of tomatoes grown in greenhouses. The first symptoms are observed on the leaves, which wilt, become yellow and die. The wilting also affects the leaves of the upper levels of the plant, which finally die. A transversal cut in the stem base shows brown-colour vascular bundles. Symptoms are not observed on the roots, but the roots soften, turning to pinky colour before they die. This pathogen forms chlamydospores on plant debris, which help it survive for a long time. It can be found deep enough in soil (up to 80 cm in depth) and is spread by machinery, soil particles and water. The optimal temperature for its growth is 28^0C. Its growth is also favoured by the light and well-drained soils. It grows poorly in soils with a pH of about 7 (Elenkov and Hristova, 1978). The fungus secretes pectolytic enzymes active in the tracheal wall of the plant, which diffuse themsevels through the xylem parenchyma walls. As a result, the water and nutrients movement in the plant is hindered.

Fungal diseases of aerial parts

Sclerotinia sclerotiorum (Lib.) de Bary (white mold)

This disease is mostly found in squash and pumpkin at the plant stem base or at the nodes of the stems. The symptom of rotting appears in the form of thick, cottony white mycelium. Affected fruits are rotted with symptoms of water-soaked spots, and cottony-white mycelium and sclerotia. The fruit dry may be occasionally affected and become mummified. The basic survival method of this fungus is by sclerotia and mycelium in the plant debris in the soil, where it remains viable for a long period of time, sometimes up to 20 years (Jarwis, 1992). *Sclerotinia sclerotiorum* forms hard black sclerotia in the pith cavity of the stem and on the fruit surface. Sclerotia are irregularly shaped and vary in diameter from a few mm to several cm. There are two sources of infection: by mycelium sprouted from the sclerotia and by ascospores from apothecium formed over the sclerotia. The growth of the pathogen is favoured by poor air circulation, high humidity and temperatures between 15 and 18^0C.

Didymella bryoniae (Auersw.) Rehm (syn. Mycosphaerella melonis (Pass.) Chiu & J.C.Walker) (gummy stem blight)

These are fungus that are widespread in warm and moist soils. It attacks leaves, stems and fruit of various species of Cucurbitaceae. Initially affected plants show watery spots on the upper leaves, which later become brown. The spots on the fruits are dark olive-green. The spots on the stem are round, light brown to dark. When the whole stem is damaged, the plant dies. Golden brown gum is seen in the affected areas. The pathogen may live in plant debris in the form of mycelium, pycnidia and perithecia, resistant to dry conditions, which enables it to prevail in greenhouses and in open-field crops. *Didymella bryoniae* is rarely found in plant seeds and is spread by the air in the form of pycnidiospores and ascospores. The risk of infection with ascospores in the greenhouses is permanent. The pathogen entered the leaves of the plant through the cuticle or intercellular spaces around the bases of trichomes, or through injured parts of the stem and fruits, either wounded or through flower scars at the time of pollination. The infection growth is favoured by temperatures of around 23^0C in cucumbers, but moisture is the most important factor for disease development. Infection clearly appears when air humidity is 60 percent; its fast growth takes place under 95 percent of air humidity and when water is available on the plant surface.

Phomopsis sclerotioides van Kesteren (black root-rot)

This soil fungus affects all Cucurbirtaceae species. Gray-black spots surrounded by a darker line of demarcation appear on the affected roots. If the pathogen girdles the root completely, the symptom turns brown and dies. The pseudosclerotia are formed on the affected root, which enables the fungus to remain viable for many years. When all roots are infected, the cortical tissues completely decay, leaving only vascular bundles. The fungus can cause black fruit rot. It is a saprophyte and has a big potential for quick reinfection in the soil. The main sources of this pathogen are infected plants and machinery parts. Low temperatures of around 10^0C favour the growth of *Phomopsis sclerotioides*, while at 20^0C the fungus begins to form pseudosclerotia (Jarwis, 1992).

Botrytis cinerea Pers. (gray mold)

This is a widespread fungus with a large number of hosts. It attacks all parts of the plant, but especially dead or dying tissues, and parts of stalks, flowers, etc. From these affected organs, the infection enters into the still unaffected tissues. The infected parts are covered with grey mycelium and spores. *Botrytis cynerea* remains viable as sclerotia in the plant debris and in the form of conidia or sclerotia in soil. The pathogen is spread by air, rainwater drops or from sprinkler irrigation. The main limiting factor for its growth is relative air humidity, adequate being over 95 percent, or when the plant leaves are covered by a water film. The main factor governing fungus development in greenhouses is the presence of condensed water over the greenhouse construction. Although the fungus can also infect plants at lower or higher temperatures, the optimum temperatures for plant infection are 17–23^{0}C.

Cucumber green mottle mosaic virus (CGMMV) (Tobamovirus group)

This virus affects only cucumbers that are mainly grown in greenhouses. The leaves of the infected plants become wilted, with dark, bubble-like swellings. Similar symptoms of this disease appear on the fruits of the plant.

This is one of the few viruses able to inhabit and remain viable in plant debris in the soil. The leaves of the affected cucumber plants are wrinkled, with dark bubble-like swellings. Similar symptoms can also be found on the fruit. The virus is temperature-resistant. It cannot be carried by greenflies, other sucking insects or mites. The infection enters into the plant via the roots from the infected plant residues left on soil by the preceding crop. It can also come from reused, growing substrate or via irrigation water. During the crop cycle, it can also be transmitted by human contact with plants or as a result of the friction between impaired and unimpaired leaves. However, the pathogen is mainly preserved in infected seeds.

Tobacco mosaic virus (TMV).

This widespread and highly variable virus affects a large number of plants (Kovachevsky *et al*., 1995). The virus has many varieties and strains, and as a result, a variety of symptoms, such as mosaic in tomatoes, fern-like and threaded leaves, yellow (aucuba) mosaic, streak and internal browning in the fruit (Kovachevsky *et al*., 1995). The virus is transmitted by human contact, in the process of plant cultivation such as transplanting, pruning and picking, by used machinery parts, clothes, and water used for hydroponics. It remains viable in the seeds, plant residues and in soil (Blancard, 1988).

II. Available alternatives to methyl bromide (MB)

Non-chemical alternatives

Nowadays, there is a global attempt to minimize the use of harmful substances, particularly pesticides in agriculture, in order to reduce the actual levels of pollution in the environment. In addition, customers worldwide demand produce for consumption that is free of pesticide residues. It is for this reason that non-chemical methods are welcome in the context of the agricultural production as one of the ways to reduce the use of substances of different levels of toxicity. MB has been the main fumigant used throughout the world for controlling soil-borne pests. Its ozone-depleting attributes have recently been discovered, forcing the world community to phase it out and use less environmentally risky methods.

Cultural methods

One of the major limiting factors in growing crops is soil degradation, which occurs after several years of monocropping, which is common in intensive greenhouse cropping of tomatoes, cucumbers, flowers, and other crops. Soil-borne pests are a major constraint to the production of these crops.

Experience has shown that correct implementation of cultural methods separately or combined with other methods may improve soil structure and may decrease the problem of soil-borne pests.

Crop rotation is the oldest and most popular method for control of plant diseases caused by soil-borne pathogens. Unfortunately, this cultural method is used a limited manner in greenhouses due to the intensive nature of production. This is due to the fact that full elimination of pathogens from soil is only achieved when they die together with the decomposing plant residues in the soil. When the pathogen survives as a saprophyte in soil or remains in plant residue, it can still be viable for over 5–6 years; crop rotation would be ineffective in these circumstances. Crop rotation may only reduce but not eliminate pathogens in soils. Therefore, it has a preventive rather than curing effect and cannot be considered an alternative to MB in intensive greenhouse production. Yet, it is suitable for establishing certain crop rotation in greenhouses, for example, to rotate tomatoes with lettuce, tomatoes with cucumbers, and cucumbers with lettuce or tomatoes.

Contrary to crop rotation, monocropping is common in greenhouses and brings about a heavy selection pressure of highly persistent and aggressive pathogens, which results in increased yield losses and the appearance of new pathotypes.

Selection of healthy planting material. The main sources of several pathogens are planting materials, such as seeds, seedlings and bulbs. For instance, seeds are the main source of agents of bacterial diseases on tomatoes, peppers and cucumbers, TMV in tomatoes and the CGMMV in cucumbers. This implies that the use of clean, pathogen-free seeds is a guarantee to reduce the incidence of several aggressive diseases.

Drainage and irrigation. Soil drainage can eliminate or reduce the factors that favour the development of several diseases, especially those caused by the parasitic fungi *oomycetes*. In many countries, root decay and self-cutting of plants is controlled through appropriate soil drainage. Abundant irrigation of poorly drained soils results in water saturation of soils for a long period of time, which increases the incidence of root decay caused by parasitic fungi such as Fusarium, Pythium and other soil pathogens. The amount of irrigating water may also have a strong impact on the incidence and development of various plant diseases. Frequent and profuse watering affects normal plant growth and, as a result, such disturbances make the plants susceptible to diseases. From a phytopathological point of view, drip irrigation is the most appropriate.

Use of resistant varieties. This is the cheapest, easiest, safest and the most efficient method of plant disease control. Growing resistant varieties eliminates both losses from diseases and expenses related to spraying or applying other methods for disease control. At the same time, this method prevents environmental pollution by toxic chemicals currently used for plant disease control. Furthermore, against diseases such as tracheobacteriosis, tracheomycosis and virosis, the use of resistant varieties is the main and probably the only feasible control method. Growing crop varieties resistant to root decay and other soil-borne pathogens plays a major role in organic agriculture. The main disadvantage here is the long periods required to grow high-quality and high-yielding varieties, as well as the high cost for hybrid production.

Soil cultivation. Correct soil cultivation improves the soil structure and also creates a good environment for moisture and temperature, which in turn makes plants less susceptible to diseases. In conventional cultivation, the soil layer is ploughed at 15–20 cm with a mouldboard, and afterwards it is again cultivated once or twice with a disc or cogged harrow. One of the objectives is to speed up the decay of plant residues, inactivating the inoculum available in soil.

Fertilizer application. The incidence and development of diseases can also be influenced by the type and quantity of the applied fertilizers that may affect, in various ways, the relationship between the crop grown and the pathogen. It has been proven, for example, that one-sided nitrogen fertilization prolongs plant vegetation; as a result, lush green mass develops and the plants, subsequently, grow mechanical tissues characterized by etiolated thin-walled cells, highly susceptible to diseases. It is for this reason that nitrogen fertilizers have always to be applied at the right rates combined with potassium and phosphorus. As a whole, potassium and phosphorus fertilizers increase the disease resistance of plants by thickening the cuticle and slowing down transpiration.

Green fertilizers or the addition of other organic substances improves soil structure and inhibits the development of certain pathogens. Leguminous crops, such as peas, beans, soya and clover, are suitable for this purpose; they enable the development of microorganisms – antagonists to soil-borne phytopathogens.

Planting method. Planting density is vital in preventing crop diseases. In general, low densities decrease the intensity of leaf diseases and vice versa. In addition, a well-arranged planting scheme may decrease losses caused by several soil-borne pathogens. Most diseases caused by soil pathogens are monocyclic and their intensity depends on the level of the primary infection. Since there is only one cycle of infection per season, the uninfected plants remain healthy until the end of their vegetation period.

Hydroponics. This technology used in greenhouses has been revived in Bulgaria. Nowadays, hydroponics is applied in an insignificant planting area, but its use is expected to reach 30-40 percent of greenhouse production in the near future. Hydroponics is more widely used in countries with developed greenhouse soilless production. It is an effective and environmentally friendly alternative to replace MB for soil-borne pest control.

Hydroponics can be used effectively for growing several vegetables and other crops, such as tomato, cucumber, pepper, lettuce, gerbera, basil, carnation and rose. This technology is highly productive, provides good quality produce and improved phytosanitary control, and is easy to implement. Obviously, there are some disadvantages, such as high initial investments, difficult fumigation of the used substrate, and difficulties in recycling the nutritious solutions of the substrates. In addition, there is a risk of asphyxia for the root system and/or of excess of salts in case of improper nutritional management. If practised in the open field, new diseases may quickly emerge.

Physical methods for soil disinfection

Steaming the soil (disinfecting the soil with steam) is the most effective soil pest control method. For over a hundred years, this has been the most efficient method for disinfecting soils. In Bulgaria, it has been known and used in greenhouses for a long time. For economic reasons, however, its application has been greatly reduced in the last 10–15 years. When applied, it must be considered that nematodes and oomycetes die at temperatures above 500^{0}C; bacteria and many fungi die at temperatures above $600–700^{0}$C; weeds, bacteria, viruses and insects, at above 820^{0}C; and TMV, CGMMV and some other thermo-resistant weed seeds, at above 930^{0}C. Since steaming is the most expensive method of soil disinfection, it is applied where soil is strongly infected by *Verticillium, Fusarium*, or when there is debris of cucumber plants with green mosaic or tomatoes with TMV. In addition to its total impact on disease agents, pathogens, pests and weeds, steaming has other advantages over soil fumigants: it does not leave any harmful residues and there is no need for a waiting period before planting.

In order to distribute steam evenly to enable it to penetrate into the soil at a certain depth and to exert its disinfecting effect, the soil in greenhouses must be very well prepared in advance, and its moisture should be about 60 percent of top soil field capacity. The most productive method, which is relatively easy, is to steam the soil in large greenhouses is through supercharging steam under thermostable sheets. The steaming should last eight hours.

It must be pointed out, however, that excessive and continuous high temperature has a negative effect, because it may kill the beneficial saprophyte microflora in the soil, creating an “ecological vacuum”. Such a condition makes it easy for pathogens to re-colonize the soil, causing a “boomerang effect”. Toxic substances from certain salts may also increase. Manganese, for instance, and toxic quantities of ammonia N and nitrites accumulate from the decay of nitrifying bacteria before the thermo-resistant ammonifying bacteria die. In addition, this method is labour- and energy-consuming and expensive to implement.

Solarization

Soil solarization is a relatively new method for soil disinfection. In Bulgaria, it has been used during the last 5–6 years. It is a hydro-thermal process that takes place in moist soils covered with transparent foil and exposed to sunshine in the warm summer months. During solarization, soil temperature reaches levels that prove lethal to many pests and pathogens. The success of soil solarization is due to the fact that most soil pathogens and pests are mesophyllic, i.e. they cannot survive at temperatures higher than 31–32^{0}C. Thermotolerant and thermophyllic soil-borne microorganisms usually survive solarization, but become weaker and more sensitive than other microorganisms-antagonists (Stapleton and De Vay, 1984). In addition, considerable biological, physical and chemical changes take place in the soil, which facilitate the growth and development of plants. This method is effective for the control of soil-borne pathogens (*Verticillium dahliae, Rhizoctonia solani, Fusarium* sp., *Pythium* sp. and others), nematodes and weeds. Transparent polyethylene is the ideal film for soil heating since it allows solar radiation to penetrate moist soil. Thicker polyethylene (50.100 and 150 microns) can also be used, but thinner polyethylene (25 and 40 microns) is more effective for soil heating and more cost-efficient per unit area (Stapleton and De Vay, 1986).

Black polyethylene, containing black carbon, absorbs solar radiation thus reducing soil warming by several degrees, but it is more stable and more durable when used in the open field (Dubois, 1978).

Soil moisture is essential to favour good soil solarization performance. Heat transferred by sun rays is well trapped by the soil, while soil-borne pests are well controlled. The higher the soil moisture, the higher the temperature maximum (Mahrer *et al*., 1984).

The intensity of solar radiation is also vital for solarization. It depends entirely on the geographic location of the region and cannot be altered directly. In Bulgaria, the most suitable months for solarization are July and August, during which the percentage of sunshine is 69.4 and 69.1 percent, respectively, and the average monthly hours of sunshine between 317.8 and 293.8.

Solarization has some important advantages: it is not harmful to the crop, has no impact on the environment, and increases yield and the quality of the produce. Further, no biological vacuum is created and therefore no "boomerang effect" is observed. In addition, it is more cost-effective than steaming. Solarization is a type of soil pasteurization, which preserves the beneficial soil flora and fauna. Its disadvantages are: the solarized area is not used for 4–6 weeks during the warmest period of the year; its effectiveness can be uncertain when variable climatic and meteorological conditions prevail; disposal of polyethylene film poses an environmental problem; and the method has a more limited range of effectiveness compared with MB and steaming, particularly with regard to the nematode control.

Biological method. This method consists of the use of microorganisms or derived products from living organisms, aiming at total or partial suppression of soil phytopathogens. Biological protection is based on the phenomenon of antagonism, which is widely spread among the various groups of microorganisms. The mechanism of the functioning of the microbiological agent is different, however. Once introduced in the soil, the microorganism-antagonist begins to multiply, covering the rhizosphere of plants and colonizing it before the pathogen has come into contact with the roots. By secreting substances with an antibiotic effect, the antagonist suppresses the development of pathogens or significantly competes with them for food and space. It may also exert its activity through proteolytic enzymes, which cause decay of pathogen cells. Microorganisms as *Trichoderma* spp., *Streptomyces griseoviridis* may also induce resistance of plants to diseases. In several cases, biological agents stimulate plant growth and development, and increase crop yields. Some agents behave as hyperparasites (*Coniothyrium minitans*). There are also the “fungi-hunters” (*Arthrobotrys oligospora*), which are able to catch the larvae of nematodes with their hyphae and decompose them chemically.

Biological agents, as living organisms, are much more sensitive to various external conditions than chemicals. The effect and duration of a biopreparation may be significantly influenced by several factors, such as soil reaction (pH), aerobic or anaerobic conditions, nutrient demands, temperature, moisture and others. It is important to point out that microbiological protection never reaches 100 percent effectiveness. It can reduce the harmful effect of some pathogens below a certain threshold with no substantial changes of the soil microbiological balance, something that does not occur when chemicals are applied.

As a result of several research studies, a biological product Trichodermin has been developed on the basis of *Trichoderma viridis* str.6, registered in Bulgaria in 2004 and applied against soil-borne fungi in greenhouses.

At present, one of the best alternatives of MB for Bulgarian climatic conditions is solarization combined with the application of biological products. Such a combined application started in 1999 and is used at present (Figure 1).

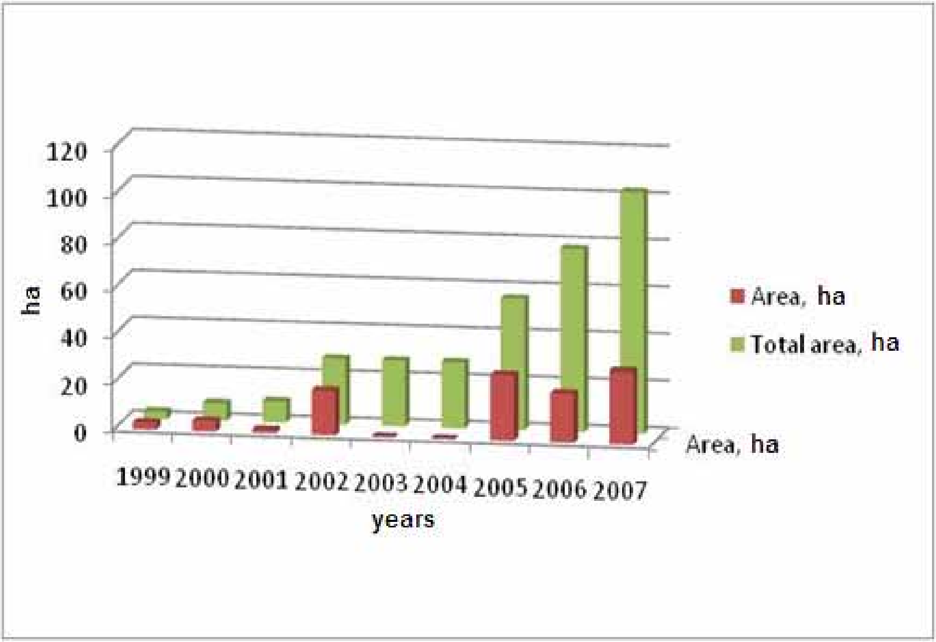

Figure 1: Areas treated with MB, Bulgaria, 1999–2007

Biofumigation is another method for sterilizing the soil in greenhouses and in the open field. It consists of the use of plant residues, living mass from certain crops, or different organic derivatives, e.g. cattle or poultry manure, which, after decomposition, deliver biologically active compounds called glucosinolates. These volatile toxic substances control diseases, nematodes and weeds in the soil. The term "biofumigation" was introduced by Kirkegaard to describe the effect of chemical substances produced by green vegetable residues from various species of Brassicaceae, such as coleseed, broccoli, cabbage and mustard. Such an effect can be defined as allelopathic, i.e. the chemical inhibition of one species by another. It is for this reason that research has mainly focused on the use of Brassicaceae plants, since they currently release toxic isothiocyanate compounds, similar to methyl isothiocyanate released by the methylisothiocyanateous (MITC) fumigants.

The chemical analyses performed to date have established that different types of glucosinolates are found in different plants. Isothiocyanates derived from glucosinolates differ in their activity according to the species, organs and tissues of the plant where they are delivered from. Some of these substances are more volatile than others, and their effect is higher when applied combined with other compounds than when used separately. It is established that some root-isolated isothiocyanates have an effect 50 times stronger than metam sodium (MS), but since they are volatile, the likelihood of contact with harmful organisms is much reduced. Glucosinolate concentration is higher in tissues of actively growing plants and gradually decreases with plant age. The maximum glucosinolate content is observed at the time of plant budding, and subsequently, it rapidly decreases. The incorporation of plant mass in the soil at the early stage of blooming ensures a better effect of fumigation. There is a positive relationship between the delivery of root glucosinolates and the effect on pests and pathogens. For example, roots can produce isothiocyanates equally well while growing or decaying. Consequently, the biofumigating potential of the roots can be higher when the root biomass remains in the soil.

Biofumigation can be deemed an alternative for suppressing soil-borne pests and pathogens. While alone it hardly provides the expected high control, its effectiveness can be enhanced when combined with solarization. To this end, plant residues should be soil-incorporated before placing the polyethylene sheet for solarization.

Chemical alternatives

In the last 15–20 years, MB has been widely applied for soil disinfection in greenhouses in Bulgaria. Pursuant to the Montreal Protocol, the use of MB was completely phased out in the country in 2005. In addition to MB, several other chemical fumigants are used in Bulgaria – dazomet, metam-sodium, formaldehyde and others.

Dazomet has proved to be the main alternative to MB for soil-borne pest control in greenhouses and substrate. Its use in Bulgaria is authorized and is effective against soil-borne phytopathogens as fungi of the genera *Pythium, Phytophthora, Rhizoctonia, Verticillium, Fusarium, Phoma, Didymella* and others, including nematodes *Pratylenchus* sp., *Rotylenchus* sp., *Meloidogyne* sp. and other species of the genus *Heterodera*; and other pests (cable-worms, Melolontha melolontha and others) and weeds (monocotyledonous, dicotyledonous, including *Orobanche* parasitic weeds).

Dazomet is relatively easy to apply. It is spread evenly and mechanically on the soil surface. When it gets in contact with the moist surface, the active substance breaks down into methylisothiocyanate, formaldehyde, methylamine and hydrogen sulphide. To achieve the maximum effect from the application of this chemical, the soil has to be well-moistened 8–14 days before application. The temperature range of 12–150 C^0 is optimal for the effect of the chemical. At temperatures below 60 C^0, toxic gases penetrate deeply into the soil and cannot therefore volatilize. These gases may cause damage to the subsequent crops if present in soil. If the temperature is too high, the gases volatilize too quickly without exerting their complete effect. This process occurs at temperatures above 200 C^0. To favour the penetration of gases, the soil has to be well tilled, with no application of any amendment or potassium, since this may inactivate the effect of the fumigant. After its application, delivered gases penetrate into the soil up to 20–30 cm depth. The rate of application will depend on the type of prevailing pests; it is usually 400–600 kg/ha, although in some cases, it may reach 800 kg/ha.

Afterwards, the chemical is soil-incorporated, either with 5 mm water irrigated to seal the soil or covered with polyethylene film. Under optimal conditions, not earlier than 6–7 days after the application of the granules, the treated soil surface is removed shallowly to enable the remaining gases to escape. The waiting period between the treatment and planting will depend on soil temperature, moisture, type and structure. At temperatures above 180 C^0 in the upper 10 cm layer, the waiting period should be 10–12 days; at temperatures of 6–80 C^0 and soil moisture of 70–80 percent, up to 45–50 days. Before the next crop is planted, the presence of remaining gases in the soil should be verified.

Metam sodium is the active substance of chemicals with trade marks Nemasol 510 and Raysan, which are approved and registered in Bulgaria for the control of gall nematodes (*Meloidogyne* sp.). Nemasol 510 is also used against soil pathogens (*Fusarium* sp., *Verticillium dahliae, Pyrenochaeta lycopersici, Pythium* sp., *Rhizoctonia solani, Sclerotinia sclerotiorum*). Before application, the soil is well tilled and moistened up to the desired depth to 75–80 percent field capacity. The temperature of the soil must be above 100 C^0 at 15 cm depth. The chemical can be applied through drip-irrigation systems, or by injection and incorporation by a rotary machine. When the chemical comes in contact with the moist soil, it decomposes to methyl isothiocyanate. Soil should be sealed by passing rolling machines or be covered with polyethylene sheets. A week after the application of the chemical, the ventilating shafts of the greenhouse are opened, and one week later, the soil is removed shallowly to enable the remaining gases to escape. New crops can be planted after a germination test has been performed to verify that no gas present in the soil.

Formalin is a widely used chemical for soil and compost disinfection. It is normally diluted with water 1:50–100, at a rate of 10 litres/m^2 for the control of bacteria and fungi. After watering, the soil is covered with polyethylene films for a day or two in such a way that formalin vapours may be retained in the soil. The new crop is planted 10–15 days after its application. An important condition to be observed when applying formalin is that soil temperature should not be below 10^0 C.

Enzon SL is a new product for pest control with fungicide, insecticide and nematocide effect. The active substance is sodium tetra-thiocarbonate – 400 g/litres. When in contact with water, a toxic gas is released, which penetrates deeply in the soil and expands, exerting its high biocidal effect. In greenhouses, it is used mainly for the control of gall nematodes (*Meloidogyne* spp.) and soil pathogens, such as fusarium (*Fusarium* spp.), verticillium (*Verticillium dahliae*), phytophthora (*Phytophthora* spp.), corky root (*Pyrenochaeta lycoprsici*), rhizoctonia (*Rhizoctonia solani*) and others. The application can be carried out through a drip-irrigation system equipped with a Dozatrone pump at a dosage rate of 600 litres/ha. When the chemical is applied to the soil, the moisture should be 50–70 percent of the field capacity, and the temperature no lower than 12^0C.

Combined alternatives

There is no single alternative that can effectively replace MB. The alternatives specified above provide partial effect, i.e. effectiveness can be expected under specific conditions over a limited number of pests and pathogens. A more integrated effect can be obtained when more than one method is applied in combination. This approach is known as IPM. By combining a fumigant with appropriate plant protection methods, a wide range of pathogens can be controlled. In some cases, the combination of various strategies with traditional fumigants provides an improved effect. For instance, according to Loginova and Boev (2001), the combination of 300 kg/ha of dazomet with irrigation after planting with 0.1 percent Topsin M provides good control of soil fungi.

Pesticides based on oxamyl, such as Vidate 10 G applied at 10 kg/ha, provide good control of the gall nematodes Meloidogyne. A new formulation with the same active ingredient is registered in Bulgaria – Vidate 10 L, which is effective against a complex of rodents and sucking pests such as Trialeurodes vaporariorium, gall nematodes (*Meloidogyne* spp.), cotton plant louse (*Aphis gossypii*) and mining flies (*Liriomyza* spp.). This chemical is applied through a drip-irrigation system at a rate of 10 litres/ha.

Nematorin 10 G, containing the active substance of phostiazate, is also effective for the control of gall nematodes. It is applied at a rate of 30 kg/ha and soil-incorporated at a depth of 10–15 cm. According to Katan and De Vay (1991), the combination of solarization with a half rate of the fumigant is effective in most cases and enables the farmers to reduce the period of exposure to two weeks. The possibility for combining solarization with reduced rates of fumigants has increased the number of growers using soil solarization as a method of control of soil-borne pests, with a subsequent reduction of the used chemical or fumigant.

It has been established that good results are also achieved when the microbial bioagents are applied right after the soil has been treated chemically or physically. Solarization combined with the application of appropriate bioagents, such as Trichodermin or bio-insecticides as BioAct VG, provides satisfactory results of soil-borne pest control. When this method is used, it is absolutely necessary to conduct a preliminary phytosanitary analysis of the soil to determine soil pathogens and to predict the effect of the treatment over the prevailing microorganisms. All this enables the selection of a suitable treatment, e.g. solarization, and the necessary bioantagonist for complementing the soil disinfection effect (Neshev and Naydenov, 2000).

Grafting of tomatoes, cucumbers and peppers on rootstocks that are resistant to various pests and pathogens is also an alternative method. Technologies and methods for manual, semi-automated and automated grafting have been developed. Its advantages include the reduction of soil pathogens and the increase of crop tolerance to low temperatures and soil salinity. This method is well known and has been widely applied in Bulgaria in recent years. KNVF and KNVFFr are appropriate rootstocks for grafting tomato, while *Cucurbita ficifolia, C.maxima, C. mocsha* and *Lagenaria sinceraria* are recommended for grafting cucumber (Loginova, 2005).

Many of the already-described methods can be used in combinations as successful alternatives to MB use as a soil fumigant. Most of the specialists envisage good opportunities for a sound IPM of soil-borne pests based on more than one control strategy.

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Cultivation in Hungary without methyl bromide (MB)

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I. Historical consumption of MBe as a soil fumigant in Hungary

MB was registered in 1984 as Metabrom 980 (98 percent MB + 2 percent chlorpichrin) for soil fumigation in 50 g/m2 rate.

When scientific studies revealed that MB was harmful for the ozone layer protecting the earth, Hungary supported international efforts to ban the application of this fumigant. Subsequently, the government asked for phase-out implementation, and from 2005, total abolition of its use in the country.

In Hungary, MB was used almost only for soil fumigation in greenhouses – there was also minor use by the tobacco industry, but it was insignificant compared with the amount used in greenhouses: 53 tonnes in 1991; 72 tonnes in 1993; 40 tonnes in 2000; and 6.5 tonnes in 2004. From 2005, there has been no application of Metabrom 980 as a soil fumigant. MB has never been registered and used for fumigation of stored products. Also, it has never been registered for usage in the open field.

Hungary's greenhouse area is about 4 000–5 000 ha (including glasshouses and plastic foil tunnels), mainly for horticultural production. Recently, the area decreased, but not the importance of this sector.

The overwhelming majority of greenhouse production is devoted to vegetable growing. The largest extension belongs to the most popular vegetable, white pepper (about 2 000 ha), followed by tomato and cucumber. Chinese cabbage, lettuce, radish, root vegetables such as carrots, parsley, celery and early potatoes, and early melons are grown on smaller surfaces.

Ornamentals are grown in 150–200 ha in greenhouses. Cultivation of some flowers – mainly carnation, gerbera and roses – is the most significant. Pot flowers and leaf ornamentals have much less importance, although their area may increase in the coming future. The territorial structure of main crops grown in Hungarian greenhouses is given in Table 1.

Table 1: Structure of Hungarian greenhouse vegetable production, 1995–98

Crops	**Area (ha)**			
	1995	**1996**	**1997**	**1998**
Pepper	2 050	2 100	2 200	2 250
Tomato	1 040	1 080	1 150	1 180
Cucumber	720	650	680	640
Cabbages	600	550	650	500
Root vegetables	400	430	400	500
Others	635	690	370	330
Total	5 445	5 500	5 450	5 400

Experiments with the use of artificial growing substrates began in the 1980s at Kecskemet Horticultural College, but large-scale application was introduced for gerbera in the country at the beginning of the 1990s at Floratom Co. in Szeged. Soon, the biggest vegetable- growing greenhouse farm, Arpad Co. in Szentes, also adopted the new technology, followed by others. Large farms, able to invest into technology, use mainly rockwool – in glasshouses. Off-soil techniques in different kinds of substrates – in buckets or containers – are used in smaller farms, under glass or plastic foil.

Still, growing in artificial substrates does not have a long tradition in Hungary, and although continuously growing, it takes only a very minor fraction of greenhouse surface. The overwhelming majority of greenhouse production takes place in natural soil. Farmers use the same soil year after year for cultivation of the same few crops. They are not able to keep the proper crop rotation that would help them to reduce the damage caused by the diseases and pests.

Most soil-borne pests and diseases find good conditions in the monocropping system, which is generally used in most plastic tunnels. The quantity of pests in soils used by the same crops constantly accumulates in the soil, and eventually, makes crop cultivation impossible. It is for this reason that in Hungary those farmers still growing their crops in natural soil need to find a way to reduce the pest population or disease inoculums in the soil.

Hungarian greenhouse production has two seasons: the spring-summer season that begins in February and ends in the middle of summer, and the autumn-winter season that begins at the end of August and ends in December or January, depending on the crop.

Real area of glasshouses occupies only some hundred hectares in the country. They are usually heated. Most greenhouses are plastic foil tunnels. Where heating is economical, for example, in southeast of Hungary where thermal water is used – a large part of plastic tunnels are also heated, but parts of them are not. Low glass or plastic foil tunnels are used mainly for seedling growing.

MB was used for soil fumigation in glasshouses before the introduction of artificial substrates and in some plastic tunnels mainly against root-knot nematodes. Greenhouse cucumber is the most sensitive crop for root-knot nematode infestation – total losses can occur. Tomato crop also suffers high damage by root-knot nematodes (30-40 percent), and resistant varieties are the only feasible protection strategy. This pest is more harmful in light, sandy soils than in more solid soils. In some areas, it makes cucumber growing, and sometimes tomato growing, almost impossible. The same can be true for pepper, although grafting has been introduced and spreads fast in the crop. Some root vegetables (carrots, parsley, celery) grown mainly in plastic foil tunnels also suffer from root-knot nematodes, especially in light soils, and, in rare occasions, from wireworms or other larvae. Lettuce is grown mainly in the autumn growing season and does not suffer from the nematodes due to the low soil temperature. Cabbages (white cabbage, cauliflower, Chinese cabbage) and radish are usually not attacked by root-knot nematodes.

Fungal diseases cause substantial damage in several greenhouse crops, especially in plastic foil tunnels.

Seedling growing stages of all crops suffer from damping-off disease. It is more dangerous for seedlings sown in seedbeds than for seedlings grown in seedling cubes, because in seedbeds, pathogens can spread fast. Damping-off can usually be prevented by the application of fungicides; the utilization of a fumigant such as MB was rarely necessary.

At the end of spring, especially at the beginning of summer when hot weather begins, in the traditional long plastic tunnels that are impossible to aerate properly, the heat – together with high humidity and the presence of condensation water – is favourable for soil-borne diseases as grey and white mould in vegetables such as pepper, tomato, cucumber, and to a rare extent, in Chinese cabbage. Such good conditions able to induce very high infection rates can be devastating, especially in the case of thick vegetation (even more in neglected cultivations with high weed infestation) when good aeration is lacking.

Lettuce crops suffer from white mould mainly in the autumn season and especially at the beginning of winter when the crop is at the end of vegetation. The lower leaves cover the soil and the condensed water under them creates favourable conditions for the pathogenic fungi to develop. At the same time, the temperatures outside the greenhouses are low, and intensive aeration is not possible since the plants may freeze, which often happens.

Wilt disease caused by *Fusarium* fungi can be very harmful for the carnation crop and sometimes for gerbera. It occurs less in vegetables, but can be very harmful in melons.

Root-rot diseases may be substantial in ornamentals, for example, *Pythium* or *Phytophthora* disease in gerbera.

There are other important diseases in various crops grown in different conditions. A detailed description of the most important pests and diseases are described in the following paragraphs.

II. Major soil-borne pests and diseases

Crops grown in the open field

In Hungary, MB was never used in open-field crops; nevertheless, there are soil-borne pests that have the same importance in crops grown in the open field as in greenhouse crops. Most of the procedures used in the open field can also be applicable for pest control in greenhouses.

Root-knot nematodes *(Meloidogyne spp.)*

Root-knot nematodes cause serious damage on warm sandy soils in southeast Hungary. Spice pepper and other field vegetables grown in monoculture are favourable for the spreading and multiplication of *Meloidogyne hapla*. The infestation level is usually uneven on the growing area. In addition to spice pepper, root-knot nematodes also cause serious damage in tomato and root vegetables (carrot, parsley, celery, dill and others).

In addition to agricultural crops, a vast number of weed species currently hosts root-knot nematodes. On the basis of various weed surveys carried out for several years in southeast Hungary, *Meloidogyne. incognita*, *Meloidogyne acrita, Meloidogyne arenaria* and *Meloidogyne thamesi* nematode species can be found hosted by several weed species. These nematodes develop well in heavy and light soils.

Root-knot nematodes are usually found in the upper 20–30 cm layer of soil. Young “invasion larvae” are attracted by the effect of plant root enzymes. The larvae invade the plant through the root tip and continue their life as internal parasites. High soil temperature is favourable for the development of the nematode and contributes to development of several generations (up to 10–12) that further build up the nematode infestation in soil. The nematodes remain alive and keep their ability to invade plants even if host plants are missing for 3–5 years.

Stem and bulb nematodes (*Ditylenchus dipsaci, Ditylenchus destructor*)

The stem nematodes cause considerable damage in onion and garlic crops, depending on weather conditions. Stem nematodes can mainly be found in dense soils, usually in the first 10–15 cm of soil depth. These nematodes can cause huge damage to garlic, which can reduce yields by 20–30 percent. Irrigation and early planting favour to higher nematode infections. Onions are also attacked, but much less. Open field bulbous ornamental crops, especially hyacinth grown in the Makó region, suffer great damage from stem nematodes. *Ditylenchus destructor* is harmful to potato but practical damage rarely found in field vegetation – it usually appears in storage rooms.

Insects (*Melolontha* spp., *Agriotes* spp. *Gryllotalpidae*, etc.)

These pests are common in crops grown in open field, although they may also cause damage in greenhouses, especially during the first years of establishing the crops in greenhouses. Therefore, they are not relevant to discussions on methods of control, since they are unrelated to MB phase-out.

Wilt diseases (*Fusarium* spp., *Verticillium* spp.)

Fusarium wilt is more important and more common in crops cultivated in Hungary than *Verticillium* wilt.

Fusarium wilt causes substantial damage in spice pepper in southeast Hungary at the end of summer, when hot weather and drought cause considerable stress for the plants. This disease appears on the territory in spots and spreads to other areas. It also occurs in melons and, to a less extent, in squash and cucumbers grown in the open field. This disease is very important in several greenhouse crops and a biological control agent can be used for spot treatments.

Other soil-borne diseases (grey mould, white mould, root-rots, and others)

These diseases are not as important in open-field crops since they are in greenhouses, mainly because of hot and dry summers prevailing in Hungary. They are also important, even in irrigated field crops. Sometimes *Rhizoctonia* rot can cause a problem in cool days of May and June.

Crops grown in green- and glasshouses

Root-knot nematodes (*Meloidogyne* spp.)

In Hungarian greenhouses, five species of *Meloidogynae* (root-knot nematodes) are known to cause serious damage, i.e. *Meloidogyne incognita, Meloidogyne arenaria, Meloidogyne javanica, Meloidogyne thameesi* and *Meloidogyne. hapla*. *Meloidogyne hapla* is the dominant species in areas on sandy soils. The conditions of soil-heated greenhouses favour the reproduction of nematodes. The same occurs in air-heated facilities (18-21 C^{o}) with constant temperature, where several nematode generations occur during the year. In cucumber, which is the most nematode-sensitive crop, the injury can lead to the total destruction of the plants. In infected crops of tomato and sweet peppers, yield losses can be greater than 30–40 percent.

After the invasion larvae invade the plants from the soil through the root tip, the nematode develops inside the plant and blocks the uptake of water and nutrients. Giant cells form in the roots that are unable to function. The roots thicken, forming “root knots” (Figure 2).

Tomato cultivars without any degree of resistance against nematodes (especially the half-determined varieties) may suffer considerable losses. The first fruit settings can be normal, but further on, fruit formation is missing and the yield loss could be up to 30–40 percent.

The shallow root system makes cucumber a susceptible crop, which also requires high temperature for its cropping, conditions all favourable for the population build-up of nematodes in soil. High nematode infestation causes wilting and early death of cucumber plants and even the total loss of the crop.

Long-cycle pepper cultivars (including the most popular in Hungary, the HFR cultivar) normally suffer from nematode infestation. Root-knots form, the plants unevenly develop and the top shoots of particular plants show a yellowish colour that could be easily confused with the symptoms of iron deficiency.

Nematode infestation in light soils could be an obstacle for growing root vegetables. Carrot and parsley roots become distorted with hairy root symptom and non-marketable.

Root-knot nematodes basically do not cause damage to lettuce, because it is grown mainly in the autumn-winter growing season, when the soil temperature is low and unfavourable for nematodes.

Figure 2: Symptoms of root-knot nematode infection on tomato

(Photo courtesy of C. Budai)

The same is valid for cabbages (white cabbage, cauliflower, Chinese cabbage) that are also cultivated in cooler conditions.

Several weed species may host nematode infestation. In greenhouse conditions, this is not a problem unless the farmer does not properly control the weeds.

Stem and bulb nematodes (*Ditylenchus dipsaci, Ditylenchus destructor)*

Onion and garlic are not grown in greenhouses, except early onions in very early springtime. These crops are not infested by the nematodes because of the low temperature in soil and short vegetation period. The same is valid for greenhouse grown bulbous ornamentals, except for susceptible hyacinths. Early potatoes are not attacked by bulb nematode (*Ditylenchus destructor*).

Insects (*Melolontha* spp., *Agriotes* spp. *Gryllotalpidae*, etc.)

These pests may cause damage in greenhouses only during the first few years of the establishment of the greenhouse; later, they usually disappear from soil.

Snails *(Mollusca)*

Snails are harmful to crops grown under plastic foil tunnels, but they can be well controlled without using any fumigant.

Soil-borne diseases

Soil-borne diseases are able to considerably decrease the quantity and quality of the yield of greenhouse crops. The pathogens remain and multiply in the soil, and represent an important challenge for the farmer because many of them are able to infect almost all vegetable crops and even the ornamentals. The pathogens can attack the plants simultaneously, which further decreases the chances for successful control. The monitoring and forecasting of diseases caused by soil-borne pathogens is difficult in the same way as their detection.

Soil is a very complex substrate from physiological, physical, environmental and biological points of view; knowledge and up-to-date information (soil analysis data) are thus necessary to design good plant protection against soil-borne diseases, without damaging the soil structure and the soil beneficial organisms.

According to their behaviour in the soil, it is advised to divide the pathogens into two groups: soil inhabitants, which are able to survive in soil for long time, and transitory soil inhabitants or transients, which live in the soil only for short periods of time. Several soil-borne pathogens are able to endure in the soil even without their plant hosts – if the conditions are otherwise favourable. Such pathogens enter into contact with dead or rotting plant tissues and live on them as saprophytes.

There are very few real soil inhabitants among plant pathogen bacteria – most of them subsist in the soil on plant residues, roots, or as free-living organisms. They do not form special cells that could remain in the soil for long time – normal vegetative cells cannot endure the enemy surroundings. At the same time, some bacteria species secrete special slimy substances that, when dry, form a protective layer around cells, preventing them from surviving.

Fungi can also survive in the soil on residues of the host plant, on other organic materials or as free-living organisms. Most of these fungi form chlamydospores, or sclerotia that penetrate the soil favoured by soil cultivation or by the presence of residues of the dead, infected plants. These spores can tolerate extreme low or high temperatures, dry conditions and the lack of the host plant, although in some circumstances, these long-living spores may also be damaged.

Vertical and horizontal spreading of pathogens in the soil depends on the methods of soil cultivation, on crop rotation and on many other factors. Most pathogens can be found in the upper 30-40 cm layer of the soil where the roots and tissues of the host plants and other organic materials are located. Horizontal spreading is influenced mainly by the presence of the host plant. Soil cultivation contributes to both vertical and horizontal spreading of the pathogen inocula. In this way, pathogens reaching the soil surface from deeper layers may dry out and die, while pathogens dwelling originally in limited space could easily be spread by soil cultivation horizontally on the whole territory; they could therefore find new uninfected host plants.

Activity of soil-borne pathogens is influenced by several factors, such as soil type, structure, pH, moisture content and nutrient content. Soil is a complex of inorganic particles, organic matter, air and water.

Soil structure may favour the appearance of root diseases. Well-aerated soils with good water runoff properties do not favour root diseases, while soils with bad aeration and stagnant water favour pathogens such as *Pythium, Phytophthora* and *Aphanomyces*, which cause damping-off and foot-rot diseases. There are only very few pathogens able to develop and survive in dry soils.

The effect of soil pH can also be considerable: cabbage disease *Plasmodiophora brassicae* can be active only in acid soils (below pH

5.7), while potato disease *Streptomyces scabies* is active only at the 5.2–8.0 pH range.

Nitrogen is the most striking macronutrient for pathogen development. High nitrogen level favours plant development, but its tissues may be loose and more susceptible to diseases. At the same time, if the nitrogen level in the soil is too low, the plants are weakened and become susceptible. From nitrogen fertilizers, high level of nitrates may increase the susceptibility to *Verticillium* wilt, while a high level of ammonia may increase the probability of the occurrence of *Fusarium* wilt.

Diseases caused by fungi

Damping-off disease

This disease occurs in the seedling stage of almost all greenhouse crops. It is caused by the pathogens such as *Pythium* spp., *Aphanomyces* spp., *Rhizoctonia solani*, *Fusarium* spp., *Alternaria alternata*, *Alternaria solani* and some *Phytophthora* spp. Pathogens causing damping-off may attack the plant simultaneously, which increases the harmful effect. Damping-off disease affects more seedlings sown in seedbeds where pathogens can spread quickly. Usually, the disease appears in spots and spreading in various directions. Seedlings grown in seedling cubes or pots are isolated from each other, thus limiting the spreading of the disease.

In such cases, the disease can only be spread by irrigation water.

Pythium, Rhizoctonia and *Fusarium* species are soil-inhabitant fungi, which are able to survive in the soil for several years, even in unfavourable conditions.

Some of the above-listed pathogens also cause other diseases. For example, *Phytophthora* spp. are the causal agents of foot rot and late blight, and in some cases, *Fusarium* spp. also cause wilt.

Seedlings are especially endangered by damping-off in cool, gloomy weather, and in the presence of high humidity. Thick plant stand, overirrigation, poorly aerated soil, low soil pH and lack of nutrients favour the development of these diseases.

The symptoms depend on the time of infection and on the pathogen. In case of a germ infection, plants die immediately in the soil and do not emerge or emerge distorted. In case of later infection, at first, one plant gets wilted and lays on the soil. Leaves usually remain green, but the foot part of the stem gets glassy, then becomes thin and falls (Figures 3 and 4). First, the foot part, then the whole plant, becomes brown. *Rhizoctonia* can attack plants even older than the 4–6 leaves stage.

Figure 3: Thinning of foot part of the stem typical for damping-off disease

(Photo: E. Dormannsne Simon)

Figure 4: Typical damping-off symptom of paprika seedlings grown in peat cube

(Photo: E. Dormannsne Simon)

Grey mould disease

Pathogen: *Botrytis cinerea.*

Grey mould disease infects most of the greenhouse crops – vegetables and ornamentals. It can access all parts of plants, spreading fast and can cause considerable damage. When the pathogen attacks the stem and side shoots of the plant, it gets wilted and depending on the humidity gets covered by grey mould. In the last stage, the plants die.

The pathogen can survive for long time in the soil and on plant residues in the form of sclerotia. It starts the primary infection, and then can spread very quickly by spores (conidia). Moisture is necessary for the germination of conidia. The pathogen invades the plants mainly through injuries, but it is able to start the infection through healthy epidermis as well.

In the case of cucumbers, the infection of fruits is favoured by wet flowers residues, which serve as a growing medium for the pathogen. In lettuce, the pathogen attacks the lower leaves that are in contact with the soil. The optimal temperature for the disease is around 25 C^0, but the conidia are able to germinate in the 5–40 C^0 temperature range, and infection can take place generally in any time. The fungus penetrating into the plant tissues by enzymes can also cause symptoms recalling soft rot.

Stem infection of tomato, cucumber and paprika are initiated usually through injuries caused by removal of side-shoots. At first, greyish-brown spot-like symptoms appear and when they encompass the stem, the branch or the stem dies. This is the most common in the autumn-winter growing season. Loose, grey mould always appears. In tomatoes, the pathogen remains alive in the stalks after the removal of the fruits, representing potential danger later on.

Fruit infection usually takes place through injuries or after flower infection. In cucumber, at first, soft rot symptoms appear, while in paprika or tomato, there is no soft rot. On pepper fruits, watery brown necrosis first appears and on tomato fruits, small, ring-like pattern appears at first, then the characteristic grey, loose, powdery mould always appears.

Leaf infection is very rare; it only appears under very moist conditions, usually in plastic folia tunnels, which cannot be aerated properly. At first, shapeless brown spots are formed starting from the edge of the leaves and then the characteristic grey mould appears. The loss of leaves could be substantial.

Grey mould is the most harmful disease in lettuce. The heads show brown-rotting and die. The symptoms make the produce totally unmarketable. Grey mould normally appears at the foot of the dying plants.

White mould disease

Pathogens: *Sclerotinia sclerotiorum* and *Sclerotinia minor*

White mould disease (Sclerotinia disease) causes similar symptoms to those of grey mould rot, except that in this case, the mould is thick and white and the black surviving sclerotia can be found throughout the stem and on other parts of the infected plants. Sclerotia remain alive in the soil for long time. The pathogen, similarly to the one causing grey mould, is polyphagous, and can infect several crops.

Primary infection initiates through the sclerotia. Secondary infection is initiated through the mycelia of the fungus and plays an important role in the incidence of the disease in greenhouse conditions.

If the soil is wet, then the sclerotia situated a few centimeters below the soil level will develop a funnel-like sexual propagating organ with a 5-10 mm upper diameter, called the apotecia. Spores responsible for the primary infection are situated on the surface of apotecia. Spores infect the plant at its wet parts: at branches, joints, stubs and other parts. Primary infection is promoted from outside, for example, from sunflower plantations.

The disease starts with typical drab coloured, oval or ring-like, watery necrotic spots. In humid conditions, snow-white, cotton-like mould appears on the infected plants. Sclerotia form on the mould; sometimes drops of water can also be observed. At lower levels of humidity, there is no mould and sclerotia are formed in the internal tissues of plants, mainly in the stem.

The disease causes partial dieback or total death of plants. In lettuce initially the plants are wilting, then begins light-brown rotting with appearance of white mould. Sclerotia appear on dead plants.

Wilt diseases

Pathogens causing wilt diseases may infect from the soil, fallen plant or soil-incorporated plant residues in the process of decomposition. The most important pathogens are *Fusarium* spp. (most often *Fusarium oxysporum*), *Verticillium albo-atrum* and *Verticillium dahliae*.

Symptoms of Fusarium and Verticillium wilts are the same: the vascular tissues in the stem turn brown and the plants wither, wilting, and often yellow. Symptom of mould can be seen from cross-cutting the stem and revealing the brown or black discoloration of cambium or phloem tissue. In pepper, an outside visible black stripe may appear on the stem. In tomato, a very aggressive race of *Fusarium* disease that has recently appeared in the country could cause substantial damage. Wilt diseases also attack the most important ornamental plants (Figure 5).

Figure 5: Beginning stage of Fusarium wilt, withering of youngest leaves of gerbera

(Photo: E. Dormannsne Simon)

Typical wilt pathogens attack the plants mainly through root injuries, but they can also infect healthy roots. Injuries are caused by soil-borne pests or cultivation tools. Dead Roots in badly aerated, dense soil can also represent a source for future reinfection. Plants die either from fungal toxin or lack of water and nutrients due to the blocked vascular tissues. The disease development can be very slow. The plants may be languid at noon and revive in the next morning. The plant then stops developing, wilts and slowly dies. Yield losses might be severe.

Foot- and root-rot diseases, blight disease

The most important pathogens are: *Phytophthora* spp., *Pythium* spp., *Thielaviopsis basicola* and *Pyrenochaeta lycopersici*.

Phytophthora foot rot most often occurs in melons and squash, which are rarely grown in greenhouses. *Phytophthora* blight, a well-known pathogen of crops grown in the open field (mainly *Phytophthora infestans*), also occurs in greenhouses and may appear with different symptoms. *Phytophthora infestans* may have different phenotypes, but it can also be *Phytophthora nicotiana* var. *Parasitica,*the least known in Hungary. *P. infestans* can cause heavy losses in unheated greenhouses. Large, light or dark brown spots with bright edges form on the leaves. The spots quickly grow, and eventually, the whole leaf dies. On the backside, whitish cover can be observed. Dark stripes appear on the stem. Fruits are non-marketable. On green fruits, large, light-coloured, yellowish hard spots appear and grow, and ultimately consume the whole fruit. This pathogen not only can originate from the soil, but can also be brought by wind from the open field.

Other *Phytophthora* species – the same pathogen also causing damping-off disease – show different symptoms. These are typically soil-borne organisms and can also cause typical foot rot on older plants. The infection is carried by the irrigation water splashing soil on the plants. The symptoms can be very typical on tomato fruits: greyish-brown large lesions are formed, with lighter centre surrounded by brown concentric rings. The infected fruits usually fall off. In cool and wet conditions, white sporulation can appear on the diseased fruits (Figure 6).

Figure 6: Unusually strong symptoms of *Phytophthora* sp. infection on greenhouse tomato

(Photo courtesy of C. Budai)

Thelaviopsis basicola causes black foot rot mainly on ornamentals, but has a wide host range. The lower part of the plant stem and the root show dark brown or black rotting. The diseases can spread by cuttings, but the main source of infection is the soil.

Pyrenochaeta lycopersici occurs on tomato, causing cork root disease and root-rot. The roots become brown in spots and corky texture; the epidermis gets swollen, tearing off in shreds; and the roots die, which may ultimately cause the death of the whole plant. The pathogen penetrates into the soil through plant residues and very slowly multiplies. Years can pass before the appearance of first symptoms.

Bacterial diseases

Plant pathogen bacteria are not real soil inhabitants; when they get incorporated into the soil they can survive on plant residues. Since soil fumigation is not useful for their control, their description here is irrelevant.

The most important bacterial disease is the Clavibacter disease of tomato, caused by *Clavibacter michiganensis* subsp. *michiganense.* The disease, however, can also be carried by seeds infected from plant residues.

III. Available alternatives for the replacement of methyl bromide in different crops

Most crop losses in greenhouses are caused by soil-borne pests and diseases. The reason for this is continuous crop growth with a subsequent build-up of the pest population, including weed seeds mainly placed in the upper 30–40 cm layer of the soil, which cause serious problems to the crops. Since soil change is not always possible, there is increased need for soil disinfection, especially in heated greenhouses. In 2005, in Hungary, new alternatives were implemented to replace MB as a soil fumigant.

Chemical alternatives

Development of greenhouse pest management began in Hungary in first half of 1970s, mainly in Csongrad County Plant Protection Station, where an intensive trial programme for the registration of new chemical agents for soil disinfection was implemented. Parts of the trials were directed to the control of root-rot nematodes, while other parts aimed at testing broad-spectrum chemicals, effective against soil-borne nematodes, insects, pathogens and weeds.

There was a wide choice of registered chemicals at the beginning of 1990s. At that time, licences for formulations of Dazomet 90 G, Di-Trapex, Shell DD and Telone II were withdrawn.

Trials for the registration of MB began in 1978. In 1982, the issued licences only allowed application of this fumigant by highly qualified plant protection specialists assisted by application specialists. The trade name of MB preparation was Metabrom 980, containing 98 percent of MB and 2 percent chlorpichrin, which fell into the “very toxic” category. Chlorpichrin served as a signalling gas of the presence of MB in the air.

MB was used only on 60–80 ha of greenhouses in Hungary. The main users were the Arpad Agrarian Co. in Szentes and the Zephyr Trading Service Co. in Kecskemét. In 2005, the Hungarian Government gave instructions to legally phase out the use of MB in the country.

In fact, MB was no longer used after the implementation of legal measures banning its use.

The choice of known chemical alternatives is not simple, because it depends on many factors, including: the temperature at the time of the application, soil conditions, the crops, the prevailing pests, their population level, cropping size, planning and the costs-profit ratio.

For soil treatments, broad-spectrum pesticides can be used, which are generally effective against various pests, diseases and weeds, or the pesticides that are effective only against nematodes, i.e. nematicides. The list of registered in 2006 pesticides are shown in Table 2.

Table 2: Registered pesticides for soil treatment in Hungary, 2006

Names of pesticides	Active ingredient	Rate
Pesticides with general effect		
Basamid G	98% dazomet	500–600 kg/ha
Nemasol 510	10% metam sodium	1 200 litres/ha
Ipam 40	40% metam ammonium	350-800 litres/ha
Nematicides		
Vydate 10 G	10% oxamil	30 kg/ha
Nemathorin 10 G	10% phostiasate	30 kg/ha
Vydate 10 L	10% oxamil	12–16 litres/ha

Preparations releasing gas in the soil (Basamid G, Nemasol 510, Ipam 40) are usually applied in the summertime, when the greenhouses have no crops, thus avoiding any phytotoxic effect from the fumigant applied. The duration of soil treatment is a minimum of 3–4 weeks. During this period, the volatile gases are released in the soil, exerting their toxic effect over the soil-borne pests. These fumigants evaporate upward from 20–30 cm depth, killing most of the living organisms there.

The soil should be carefully prepared before treatments in order to allow for a uniform application of the fumigant.

Most of soil fumigants, except Basamid G, are formulated as liquids and applied through injection into the soil. Basamid G is a granular formulation applied by spreading equipment.

All these chemicals are soil-incorporated to a depth of 15–20 cm using a rotating hoe.

After the treatment, it is very important to seal the soil surface well. This is usually done using a plastic foil cover; where unavailable, irrigation equivalent to 20 mm of water is necessary to delay the evaporation of gases released by the applied chemicals. To be effective, depending on the soil temperature, soil disinfectants need a duration of 7 days (at 18 C^0) to 30 days (at 5 C^0). After this period, the soil should be loosened by rotating the hoe once or twice to help the aeration and disappearance of gases from soil.

For up-to-date application of liquid soil disinfectants (fumigants) and of Basamid G, six pieces of special soil fumigation equipment were purchased and given to Arpad Agrarian Co. and Zephyr Trading Service Co., within the framework of the United Nations Environment Programme (UNEP)/United Nations Development Programme (UNDP) project aimed at replacing MB. The main characteristics of the alternative chemicals are given below.

Basamid G or dazomet is a granular pesticide with broad-spectrum effect in soil. It should be applied in greenhouses free of vegetation before planting. The treatment is usually carried out in the summertime, before the autumn-winter growing season. This chemical is the most commonly used for soil disinfection in Hungary, which is also used in tree and grapevine nurseries. It is particularly effective against several fungi.

Nemasol 510 is a liquid pesticide with broad-spectrum effect in soil of recent registration in the country. Only Zephyr Co. has the rights to use it in Hungary. The chemical is highly effective in sandy soils.

Vydate 10 G, or oxamyl, is a granular pesticide, effective against nematodes and other soil-borne pests. It is highly toxic and thus has a provisory licence for application. Oxamyl is spread on the surface of the soil and then incorporated. It is also used for soil treatment in the open field, in root vegetables and onion.

Nemathorin 10 G is registered for use in greenhouses, in tomato, pepper and cucumber. It has a contact and systemic effect, and is less toxic than Vydate 10 G. The efficacy of this preparation against nematodes is similar to that of Vydate 10 G.

Vydate L is licensed for use in greenhouse paprika and cucumber. It is applied using drip-irrigation equipment, in a closed system. The rate of application is 10–16 litres/ha. Three to five treatments are permitted in one crop, at two-week intervals. It should be handled carefully since it is very poisonous. The active ingredient comes into contact with the plants through the roots and is effective even against foliage pests such as whiteflies, aphids and thrips.

Non-chemical alternatives

Application of non-chemical alternatives is supported in Hungary. Nevertheless, these alternatives are not yet widely used by farmers, possibly due to the traditional conservative approach to this problem. In Hungary, pesticide use has been popular among farmers: since these chemicals are able to kill a certain level of pest population in a short period of time, when they compare this method with others, they normally choose a chemical approach. Their point of view is that those non-chemical methods will never reach the high efficacy given by the pesticides.

At present, there is worldwide concern about the environmental problems posed by the use of pesticides. However, it is difficult to change farmers' views when their crop yields are at the stake.

Most non-chemical alternatives used separately have lower efficacy than pesticides. The main ones applied to some extent in Hungary are explained below.

Resistant cultivars

Breeding of crop cultivars for resistance against pests is important in the context of IPM. Presently, there are crop varieties resistant to *Fusarium, Verticillium, Pyrenochaeta*, viruses and nematode diseases. These characteristics are indicated on the labels of sowing seeds. Growing varieties resistant to nematodes have the advantage of not disinfesting soils.

Tomato is the crop with more resistant varieties than any other, which does not always mean that there are no problems of root-knots. Pepper breeding also shows encouraging results, while in the case of cucumber, no nematode-resistant cultivars are yet available.

Grafted seedlings

Cultivation of grafted seedlings could provide a solution for the control of soil-borne pests and diseases. The desired cultivar is grafted on a rootstock resistant against certain diseases or nematodes. The procedure eliminates the need of soil fumigation in areas where there is no high pest-disease infestations. A further advantage of using grafted seedlings is that the plants develop well at less favourable conditions (cold or bad soil structure), since the rootstocks are able to uptake water and nutrients even under unfavourable conditions.

Increased use of grafted seedlings is expected for several greenhouse crops and even for those transplanted in the open field (pepper, tomato, cucumber, eggplant, watermelon and melon). Nevertheless, the fast spreading of grafting is hindered by several obstacles, especially lack of knowledge. In several farms, there were trials with this method, but only some large farms could afford the implementation of such a difficult procedure, which demands high concentration, special knowledge and expensive technical equipment. The other obstacle is the considerably higher costs and prices of the produced seedlings.

There are already some large seedling producing farms in Hungary that have adopted grafting and also import grafted seedlings, including KITE Co. Nádudvar, Grow Group Felgyő, Palántakert Co. and Palánta Co., among others.

The handling, transporting and planting of high-value seedlings need considerably more specialization by the farms using such planting material, many of which are not yet prepared to do so.

Soilless cultivation (separated from, or not in, the soil)

Soilless cultivation is a good alternative for preventing soil fumigation. A real possibility is cultivation on artificial substrates (hydroculture), which has developed substantially in the recent past. Greenhouse area on artificial substrates increases around 10–20 ha every year.

The two main methods that have become widespread in Hungary are: growing in rockwool and growing in buckets (containers). Unfortunately, the circle of consultants as a support to this type of cultivation is still to be established in Hungary. Nevertheless, soilless cultivation has the best outlook for greenhouse production at present.

Growing in rockwool

Although this method is a breakthrough in horticulture, it is not yet widely used. The main reason is its high initial costs; the necessary capital investment takes 30–40 million forints (about €140 000)/ha. It is hoped that the method will bring up to a 40–50 percent of yield increase, so that, together with the high quality of the obtained produce, investment could be returned in 2–3 years. Rock-wool is currently used in an area of 100–200 ha in the country.

Growing in buckets (containers)

This method needs much less investment than for rock-wool growing. It is currently applied on about 120–130 ha in the country. The most important factor is the selection of the growing medium, either coconut fibre, burned clay granules, mushroom compost, peat, and others. Introduction of this method must be preceded by careful planning. Companies selling seeds and horticultural equipments offer assistance for its implementation.

Biological control methods

Soil-borne pest control is made possible by the use of microbiological agents. Biological control should be based on a particular biological mechanism, which could be the use of microorganisms antagonists or hyperparasites of target pathogen. Such agents can also be found naturally in soil.

Soil-borne pathogens share their environment with many other organisms competing for the limited quantity of nutrients. At the same time, the natural agents or antagonists can also be found among microorganisms living in the soil. There are the “suppressive” soils, where several antagonists fully suppress the development and activity of plant pathogens.

Microbiological control is based on artificially reproducing the same conditions occurring in suppressive soils by inoculating the antagonists or incorporating plant residues or composts that may increase the population of beneficial microorganisms.

Antagonists – in the same way as pathogens, behave differently. In order to apply them successfully, their mechanism of action must be known.

The most important mechanisms are:

- penetration into the rhizosphere of the treated plant and colonize it before the pathogen can reach it;
- if there are good conditions of soil moisture, the antagonist or hyperparasite begins to reproduce on the plant (root) surface. In addition, it either: (i) delivers substances with an antibiotic effect that inhibit the development of the pathogen without actually killing it; (ii) successfully competes with the pathogen for the available nutrients and life space, suppressing the development of the pathogen; (iii) delivers enzymes able to kill the cells of the pathogen;
- or (iv) eventually, the antagonist induces an acquired resistance in the plant against the pathogen.

In many cases, antagonists stimulate crop development. Microbiological pest control has several advantages and disadvantages compared with chemical control methods.

The advantages are:

- the control effect is based on a microorganism occurring in nature (if natural), which is non-toxic to humans, animals and useful organisms, although it needs to pass registration tests;

- the target organism does not develop resistance against these agents;
- microbiological control can be used as another tool of IPM;
- after application, there is only a brief or no waiting period.

The disadvantages are:

- in most cases, microbiological control is less effective than chemical control; its effect rarely reaches levels close to 100 percent;
- manufacturing, formulation and registration of these agents are expensive, and their prices are high. Unfortunately, application of microbiological control is only affordable in special cases;
- the registration procedure of active ingredients and formulated products is long, complicated and costly;
- microbiological agents can be applied efficiently and economically only in protected areas where life conditions for the applied agents are ensured.

Trials with microbiological control methods in Hungary began in the early 1980s at the Csongrád County Plant Protection Station. Trials with several more agents had been carried out for about 20 years. Antagonists tested in Hódmezővásárhely are listed in Table 3.

Table 3: Antagonistic micro-organisms tested in Hungary, 1983–2004

Antagonists tested in Hungarian greenhouses	**Against pathogens and pests**	**Microbiological preparates registered in Hungary for greenhouses**	**Remark: the active ingredient is included in Annex 1. of 91/414 EEC dir.)**
Arthrobotrys oligospora	*Meloidogyne* spp.		–
Bacillus subtilis	Soil-borne pathogens		Inclusion in process
Coniothyrium minitans	*Sclerotinia* spp.	KONI	X (other strain)
Gliocladium catenulatum	Soil-borne pathogens		X
Streptomyces griseoviridis	Soil-borne pathogens	MYCOSTOP	X (notified as “existing old preparate”)
Trichoderma spp.	Soil-borne pathogens	TRICHODEX 50 WP (T. harzianum)	X (several *Trichoderma* spp. are notified as “existing old preparates”)
Pythium oligandrum	*Pythium* spp.		X (notified as “existing old preparate”)

Trichoderma strains (*Trichoderma* spp.) were isolated and tested at first in the laboratory, then in greenhouse trials in cooperation with the Plant Protection Centre and the Plant Protection Research Institute. The trials included many strains of several local *Trichoderma* species. Some of the results are shown in Table 4.

Table 4: Effect of treatments by Trichoderma strains on diseases of greenhouse paprika, Fábiánsebestyén, Hungary, 1987

Treatments (names of different strains)	**Rates, mode of application**	**Plants infected by soil-borne diseases (%)**		**Increase in income (%) compared with the standard**
		Fusarium sp.	*Sclerotinia* sp.	
TS-2	Application of 108 cfu/m^2 at planting + drenching monthly (6 x)	1.20	8.70	23.8
T-14	Application of 108 cfu/ m^2 at planting + drenching monthly (6 x)	5.87	8.53	24.7
Standard chemical control	Ronilan WP 0.1%, Sumilex WP 0.1%, Orthocid 50 WP 0.2% (a total of 8 treatments)	5.87	15.60	-

The trials aimed at finding the most effective strains feasible for manufacturing, i.e. with good chlamydospore production. The most effective strain, T-14, and the strain with best storage properties, Tv-5, were determined. The mechanism of action of Trichoderma formulations is their successful competition. It overgrows the pathogen and effectively competes for water and nutrients.

After the greenhouse trials, pilot manufacturing began in the Hódmezővásárhely laboratory with the dry fermentation method. This successful process was to be followed by large-scale industrial production. Unfortunately, the whole manufacturing process and the long registration procedure were highly expensive, which prevented any local production of Trichoderma preparation in the country.

After this experience, registration trials of several foreign-made microbiological agents were carried out, including the Finnish *Streptomyces griseoviridis* preparation of Kemira Oy (later Verdera Oy), called Mycostop. Except for registration trials, the Biological Control Laboratory in Hódmezővásárhely also took part in the preparation in Finland and Hungary.

Mycostop is active against almost all soil-borne fungi and proved to be the most effective against *Fusarium*. The mechanism of action of the *Streptomyces griseoviridis* active ingredient, originally from Finnish suppressive *Sphagnum* peat, is strong antibiotic, inhibiting the growth of most soil-borne fungi. Mycostop was registered in Hungary in 1992. Its use is described in Table 5.

Table 5: Mycostop – the Hungarian registration active ingredient: Streptomyces griseoviridis K61, Manufacturer: Verdera Oy (Kemira Oy) (SF)

Crops	Diseases	Rates, application
Carnation, Gerbera	Fusarium wilt	0.5–2.5 kg/ha 1.0–2.5 kg/ha
Potted and cut flowers	Root and foot rots, wilt diseases	0.1 kg/ha/1 000 l of spray volume (drenching)
Bedding flowers	Damping-off	5-10 g/kg seeds (seed treatment)
Vegetables, ornamentals, pepper (in seedling production and at transplanting)	Damping-off, Fusarium wilt	1 kg/ha (0.1 g/m2) sprayed on the soil or seedling cube in 3 000 litres/ha of spray volume (drenching), or in case of seed treatment, 1 kg/tonnes applied on seeds with 25 litres/tonnes of water
Melons	Damping-off, Fusarium wilt	1 kg/ha (0.1 g/m2) sprayed on the soil or seedling cube in 3 000–5 000 litres/ha of spray volume (drenching)

Although Mycostop is already available on the market in Hungary, it is not often used by farmers. This is due to its initial high price, which, although now reduced, continues to be unaffordable for them. The preparation should be kept in refrigeration; further, it has a limited storage period.

Mycostop, like other microbiological agents, should be used for the prevention of disease infection. Presently, the preparation Mycostop is used mainly in carnation and gerbera against *Fusarium disease* for spot treatment, by melon growers against *Fusarium* in seedling growing, and in vegetation for spot treatment.

The second microbiological preparation registered in Hungary is Trichodex WP (Table 6).

Table 6: Trichodex WP – Hungarian registration Active ingredient: Trichoderma harzianum T-39 Manufacturer: Makteshim (IL)

Crop	Disease	Rates, application
Strawberry, raspberry, grapevines, tomato, cucumber, lettuce, (greenhouse) ornamentals	Botrytis rot	2.0 kg/ha

Trichodex WP is, unfortunately, no longer available on the market in Hungary; although the manufacturer did not withdraw the registration, it no longer sells it.

The third microbiological agent registered in Hungary is KONI, based on *Coniothyrium minitans* strain K1, which has been isolated in the country." It is effective against white mould disease *Sclerotinia* spp (Table 7).

Table 7: KONI WG – Hungarian registration Active ingredient: Coniothyrium minitans K1 Manufacturer: Biovéd Bt. (HU)

Crop	Disease	Rates
Cucumber, tomato, lettuce, pepper, carrot, parsley, protected ornamentals, annual flowers	Sclerotinia rot	5–8 kg/ha
Sunflower, rape, soybean	Sclerotinia rot	2 kg/ha

Coniothyrium minitans is a hyperparasitic fungus, which invades the pathogen and consumes it. KONI is widely used for the protection of ornamentals in public parks, where no pesticides are accepted, and is also used in greenhouses. Recently, it has also been registered in sunflower for the control of white mould disease.

Trials with another Finnish-made micro-biological preparation, Prestop WP, based on *Gliocladium catenulatum,* have been carried out in Hódmezővásárhely, Hungary for approximately seven years. The first trials included the original strain J 1446. Some of the results are shown in Figure 7.

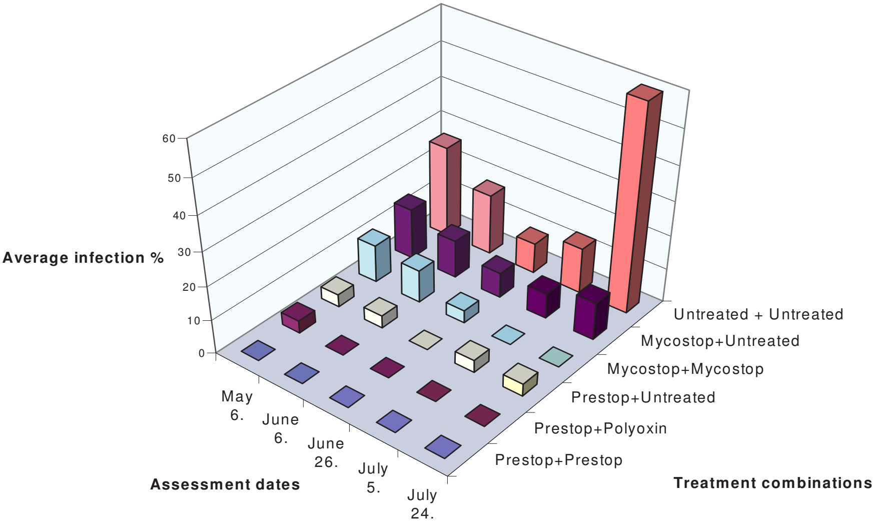

Figure 7: The effect of Prestop WP against soil-borne diseases of greenhouse tomato

Szentes, Hungary, 2001

Prestop WP proved very effective against almost all soil-borne diseases. The mechanism of action of *Gliocladium catenulatum* is due to hyperparasitism as in the case of *Coniothyrium*, as well as to successful competition, as in the case of *Trichoderma.*

Prestop WP has been registered in Europe, but not yet in Hungary, although there have been many trials. Only one application for registration is necessary.

On 1 May 2004, Hungary joined the European Union (EU). Since then, registration of active ingredients has taken place in Brussels, Belgium according to 91/414 EEC Directive and its modifications, while registration of formulated products remains the task of national authorities. Active ingredients registered in Europe are published in the ever-changing Annex 1 of the above Directive.

In order for preparations to be approved, the EU had to be informed of the "existing old preparations" that were registered prior to Hungary's membership in the EU. Review of these "old agents" is ongoing. New preparations should be registered according to EU rules.

Since microbiological control agents are based on a living organism, quality control is important. The active agent should be in concentrations as marked on the label.

Storage and application should be done with special care.

Application of bio-fumigants

There is growing interest worldwide for growing crops that can be used for biofumigation; these mainly belong to family of Brassicaceae. The roots deliver substances able to kill the pests and/or pathogens in soil.

In Hungary, trials began with *Phacelia tanacetifolia, Raphanus sativus* and *Sinapis alba* with promising results. They can also be applied as green manure, useful for soil fertility improvement.

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Alternatives for the replacement of methyl bromide as a soil fumigant in Poland

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I. Introduction

Among eight Countries with Economies In Transition (CEITs) in Central and Eastern Europe, surveyed on MB consumption from 1991 to 1999, Poland was the largest user of MB in 1999, consuming 50 percent of total MB in the region (Porter, 2001). In 2006, the total area of glasshouses and plastic tunnels totalled about 6200 ha, with the following crop structure: tomato, 39.8 percent; cucumber, 21.1 percent; pepper, 20.1 percent; other vegetables, 7.7 percent; and ornamental plants, 11.3 percent. Nevertheless, Polish greenhouse growers historically relied on MB to a much lesser extent than their colleagues from some Western European countries, such as Belgium, Italy, France, Spain or United Kingdom.

In Poland, from 2000 to 2002, within the framework of the UNEP Regional Demonstration Project, the identification and evaluation of environmentally sustainable alternatives for MB used on horticultural crops for Eastern and Central Europe were conducted. This project was part of a larger one implemented by UNEP Division of Technology, Industrey and Economics (DTIE), entitled "Initiating the Early Phase Out of Methyl Bromide in Countries with Economies in Transition through Awareness-Raising, Policy Development and Training Activities", funded by the Global Environment Facility (GEF) and Environment Canada. In this project, both chemical and non-chemical alternatives were validated in field-grown vegetables (cabbage, celeriac and tomato), strawberries, greenhouse peppers and tomatoes (Slusarski and Pietr, 2001; 2002a; 2002b, 2003). The ongoing three-year GEF/UNDP/UNEP Project "Total Sector Methyl Bromide Phase Out in Countries with

Economies in Transition" was initiated in 2005 to assist Bulgaria, Hungary and Poland with the rapid implementation of available alternatives, both in pre- and post-harvest sectors, through training activities, technology transfer and delivery of modern equipment. FAO was also actively involved in training activities related to the issue of MB phase-out.

II. Past and current uses of methyl bromide for soil fumigation in Poland

In 1964 in Poland, MB was first registered in 1964 as a fumigant for controlling stored product pests in structures and durable commodities. From 1970 to 1990, the average annual consumption of MB for this purpose ranged only between 150 and 250 tonnes. In contrast to most European countries, in Poland, MB (formulation containing 98 percent MB and 2 percent chloropicrin) for soil fumigation was registered as late as 1988 and introduced into practice in 1990. However, extensive research work initiated in 1977 aimed at obtaining the efficacy and residue data necessary for the registration process of MB as a soil fumigant.

This study was completed before registration. This research was carried out by the Research Institute of Vegetable Crops in Skierniewice in cooperation with the State Enterprise for Stored Product Pest Control, which at that time was the only institution with access to and authorization to use MB. It must be recalled that, at that time, a stormy worldwide discussion was taking place on the problem of inorganic bromide residues in vegetables following soil fumigation with MB. As a result, hundreds of analyses were conducted to determine the residue levels in fruits of tomato, cucumber, pepper and eggplant, and causes related to the factors influencing the accumulation of bromide ion in plants, such as rate of application, exposure time, leaching in soil, the growing method, fertilization and cultivar (Czapski *et al.*, 1982).

On the MB label, containing both soil and general fumigation uses, the following crops were listed: tomato, cucumber, eggplant, gerbera and carnations, as well as transplants of cabbage, cauliflower, strawberry and tomato. MB in glasshouses and plastic tunnels was applied by the commonly known “hot gas method”. The application rates varied from 70 to 100 g/m^2, depending on the target organism to be controlled, the crop and local soil or substrate characteristic.

In Poland’s relatively short history of the use of MB for soil fumigation, three periods can be distinguished, each characterized by a different pattern of the fumigant consumption by crop. In the first period (1990–92), more than 60 ha of greenhouses were fumigated yearly. Soil fumigation was carried out mainly on large, still state-owned, glasshouse farms prior to tomato (75–80 percent) and cucumber (20–25 percent) growing, and the annual use of MB for soil fumigation in protected cultivation amounted to 48–52 tonnes (Figure 8).

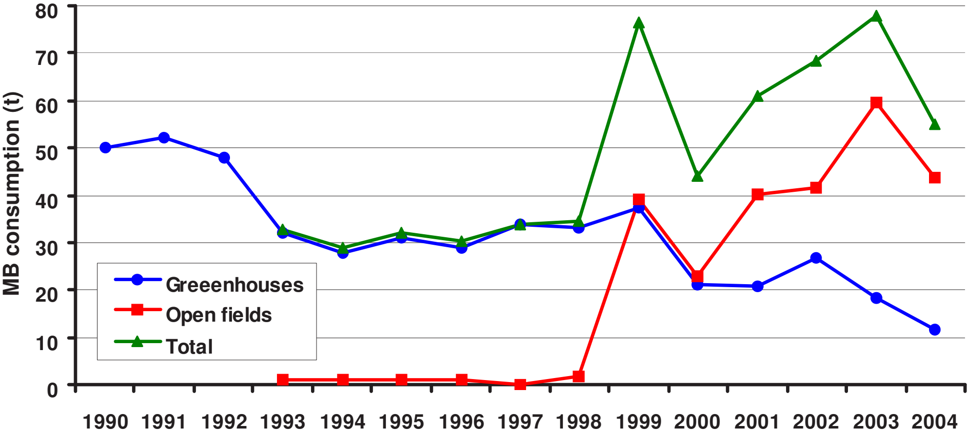
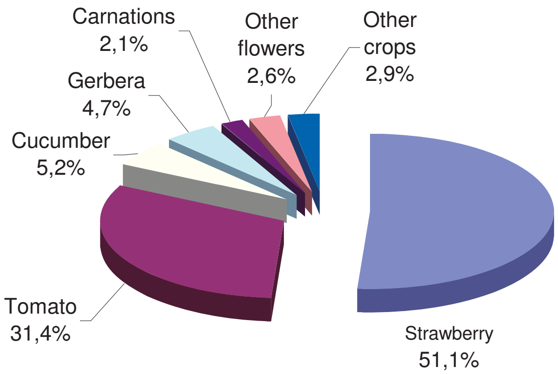


Figure 8: Consumption of MB for soil fumigation in Poland, 1990–2004

Since 1993, a substantial and constant decrease in the consumption of MB for greenhouse uses has been observed. This trend reflects the beginning of a rapid shift from traditional tomato and cucumber growing in the soil to a rockwool cultivation system on numerous large glasshouse farms, which were previously the largest end users of MB. From the mid-1990s until 2004, MB was mainly used on small and medium-sized greenhouse farms, predominantly prior to planting ornamental plants (e.g. gerbera, chrysanthemum, carnations, roses, lilies and other bulbous ornamentals), grown in the soil or organic substrates. At that time, a decreasing use in tomato and cucumber crops was still evident. Occasionally, MB was also used in the forest and fruit tree nurseries on a very limited scale, but generally, it was not used in a commercial production of field vegetables for economic reasons.

Since 1999, when some Western European companies began to move part of their strawberry runner production from southern Europe to Poland, farms involved in export production of runners became the biggest MB consumers. As a consequence, a substantial increase in the consumption of MB for soil uses took place (Figure 8). The highest (and very similar) level of MB use in the soil sector was 76.4 and 77.8 tonnes in 1999 and 2003, respectively. Figure 9 illustrates the changes in the proportions of MB used per crop in 1999 and 2003. In these two years, the highest percentage of MB usage was in the production of strawberry runners and accounted for 51.1 percent in 1999 and 76.3 percent in 2003. In 1999, the use in greenhouse tomatoes was still relatively high (31.4 percent), but four years later, the amount of MB consumed by this crop decreased to about 5 percent.



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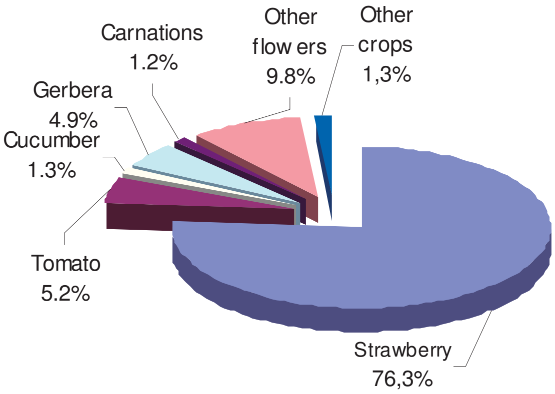

2003

Figure 9: Usage of MB by crop in Poland, 1999 and 2003

Table 8 shows the historical consumption of MB for soil fumigation in strawberry runner production. Although the area of strawberry nurseries treated with MB in 2003 and 2004 was almost the same (99 vs 100 ha), it is worth noting that the amount of MB used for this purpose in 2004 was lower than in the previous year by nearly 27 percent. This substantial reduction in MB use was directly related to Poland's accession to the EU. Since the use of almost impermeable films (VIF) is compulsory under EC Regulation, it was necessary to replace the previously used plastic films (Eurofilm) for soil covering with VIF, and to reduce the application rate of MB from 600 to 400 kg/ha.

Table 8: The historical pattern of the use of MB in strawberry nurseries in Poland, 1999–2007

Year	1999	2000	2001	2002	2003	2004	2005
Area treated (ha)	65	38	67	69.5	99	100	88.3
Amount of MB active ingredient used (kg)	38 220	22 344	39 396	40 886	58 212	42 762	33 908
Application rate of 98:2 formulation (kg/ha)	600	600	600	600	600	436*	400

Note: * Mean application rate, since MB was used in part at 400 kg/ha and in part at 450 kg/ha.

In 2004, Poland submitted for the first time an application for critical use exemption in the production of strawberry runner plants. Since 2005, the "third period" of our MB history, MB has been used for soil fumigation in this crop only. The quantities of MB licensed for critical use in strawberry runners were as follows: 34.6 tonnes in 2005, 28 tonnes in 2006 and 24.5 tonnes in 2007 (Maczey, Vos and Ritchie, 2006). For 2008, the Methyl Bromide Technical Options Committee (MBTOC) recommended 12 tonnes of MB as the critical use in this crop.

In 2006 in Poland, a prior approval system for fumigation was introduced to control the critical use of MB and to avoid illegal treatments. It consisted of application of fumigators with detailed information on proposed use, including the site, the area, the name of user, the dose of MB per hectare and confirmation that VIF is used during soil fumigation.

Such information is to be reviewed by the Ministry of the Environment for its further approval. Moreover, the fumigators should report in detail the amounts of MB used.

III. Major soil-borne pests of horticultural crops

Crops grown in the open field

In Poland, approximately 36 vegetable species are cultivated commercially in an area of approximately 225 000 ha. However, only seven of them play a leading role in the structure of outdoor vegetable production: cabbage, carrot, onion, red beet, tomato, cucumber and cauliflower. In addition, strawberry is another important horticultural crop in the country.

There are several polyphagous soil-borne fungi that affect different crops at various times and locations throughout the country. *Rhizoctonia solani, Thielaviopsis basicola, Pythium* spp., *Phytophthora* spp. and *Fusarium* spp. are the most common components of the complex of pathogens responsible for damping-off and root-rot of various crops, especially under cool and wet soil conditions. *Sclerotinia sclerotiorum* is a cool temperature pathogen, primarily infecting at temperatures of 13–17 ^{o}C. *Sclerotinia sclerotiorum* is a fungus with a very wide host range, particularly harmful to bean, cabbage, carrot, celeriac, cucumber, lettuce, onion, parsley, pea and squash. *Verticillium dahliae* is widely distributed throughout the country, but the destructiveness of this fungus is observed predominantly in light soils. Among field crops, the most frequently affected are pepper, eggplant, horse radish, tomato and strawberry.

There are a few soil-borne bacterial pathogens regarded as typical soil inhabitants, including *Erwinia carotovora* subsp. *carotovora*, the causal agent of bacterial soft rot of several crops such as carrot, celeriac, onion, leafy vegetables, cucurbit, pepper and others. It has probably become the major pathogen in onions and Chinese cabbage due to losses caused to crop yields and during the post-harvest process. The most severe outbreaks of bacterial soft rot disease have been observed in years when the summer is hot and humid. Another soil-borne bacterium, *Streptomyces scabies*, can produce scab symptoms on carrot, parsley, radish and red beet, but occurs relatively rarely on horticultural crops in the country. A more severe incidence can be expected on freshly limed soils or rich in calcium, notably after warm and dry weather.

Soil-borne fungal diseases

Onion, leek, garlic

White rot, which is caused by *Sclerotium cepivorum*, occurs only in some regions of the country, predominantly in the fields where onion is grown in monoculture or following other host plants (leek, garlic). The fungus *Sclerotium cepivorum* can also cause damping-off and reduce plant stands early in the season.

In Poland, pink root, caused by *Pyrenochaeta terrestris*, is a very common disease in onion, but it rarely causes severe yield losses, since the pathogen often attacks nearly mature plants. The disease mainly occurs in poorly drained soils of low organic matter content.

Onion smut, caused by *Urocystis cepulae* (synonym *Urocystis magica*), occurs only locally and almost solely in the fields where a proper crop rotation is not implemented. Under Polish climatic conditions, too early sowing and cool weather in the springtime seem to be factors that favour the disease.

Winter onion is especially susceptible to infection with *Urocystis cepulae*.

Fusarium basal rot of onion is caused by *Fusarium oxysporum* f. sp. *cepae* and other species of the genus *Fusarium,* including *Fusarium avenaceum*, frequently isolated from diseased garlic bulbs.

Fusarium basal rot usually appears in fields with a previous history of this problem or planted with contaminated sets. Wet soils, moderate to high soil temperatures, especially late in the season, and early infections of the roots with *Pyrenochaeta terrestris* enhance the incidence and severity of this disease.

Carrot and parsley

Various species of fungus-like *Pythium* (*Pythium debaryanum, Pythium irregulare, Pythium sylvaticum, Pythium violae* and others) cause several characteristic diseases on carrot roots, such as cavity spot, root dieback, Pythium brown rot and root forking. Cavity spot and root dieback are common diseases of carrots, especially on muck soils. Infections from *Pythium* usually occur early in the season and are generally favoured by moist soil conditions.

Rhizoctonia fungi are related to three important carrot root diseases: crown rot induced by *Rhizoctonia solani* and other species; crater rot incited by *R. carotae*; and violet root-rot caused by *Rhizoctonia crocorum* (synonym *Rhizoctonia violacea*). The incidence of crown rot and violet root-rot has mainly been observed on mineral soils. Crater rot can cause serious losses in a cold storage.

Black rot of carrot, caused by the soil fungus *Alternaria radicina*, is a common disease in areas of carrot growing throughout the country, in some years causing substantial yield losses. Parsley is affected much less. This pathogen very often occurs in association with *Alternaria dauci,* the causal agent of Alternaria leaf blight.

Black root-rot or black mould is caused by a common plurivorous soil-borne pathogenic fungus *Thielaviopsis basicola* (synonym *Chalara elegans*). Actually, it is a common post-harvest disease, since the symptoms of infection are not seen in the field. This disease can be a problem, especially on carrots grown on muck or high organic soils.

Sclerotinia rot or white mould (*Sclerotinia sclerotiorum*) is a very common fungal disease of carrot. Field symptoms appear usually late in the season. The highest losses due to *Sclerotinia* infection are during the storage period.

Cruciferous vegetable crops (cabbage, cauliflower)

Damping-off and wire stem of brassica crops can be a problem locally in the production of transplants both in outdoor and indoor seedbeds, especially if the soil has not been properly disinfected or the rotation periods are too short. Various soil-borne fungi are known to be responsible for this disease, notably *Pythium* spp., *Olpidium brassicae, Rhizoctonia solani, Fusarium* spp., *Phoma lingam* and *Alternaria* spp.

In Poland, for decades clubroot, incited by *Plasmodiophora brassicae,* has been a constant major cause of serious yield losses in cabbage, cauliflower and other cole crops. It is assumed that about 30 percent of the country's area planted with vegetable brassicas is threatened with the incidence of this economically important disease. Clubroot is a principal problem in acidic (pH 5.7 or lower) and wet soils. Cultivation of leek, bean, tomato, cucumber or cereals in infected fields for 2–3 years provides a significant disease decrease. The first cultivars of cabbage (Tekila, Kilafur, Kilaxy) and cauliflower (Clapton) resistant to *Plasmodiophora brassicae* have already been grown on a commercial scale.

Phytophthora root-rot of cabbage is caused by *Phytophthora megasperma.* The disease can be an acute problem on heavy and poorly drained soils. The pathogen is greatly favoured by longer periods of extremely high soil moisture, caused by heavy rains or overwatering, periodically standing water and soil compaction.

Tomato

Fusarium wilt of tomato, caused by *Fusarium oxysporum* f. sp. *lycopersici*, occurs extremely seldom under field conditions (even if non-resistant tomato cultivars are grown), because soil temperatures rarely reach the level optimal for the development of this disease. More frequent, although also of a limited economic importance, is Fusarium basal rot disease incited by *Fusarium solani* and Fusarium crown and root-rot caused by *Fusarium oxysporum* f. sp. *radicis-lycopersici.*

Tomato plants are often affected by *Rhizoctonia solani.* Only very early infections can cause plant death shortly after planting (crown rot). In most cases, however, the plants are not killed and the disease symptoms are manifested by a relatively severe root-rotting, which leads to the weakening of the plants and yield reduction. In some areas of tomato cultivation, the tomato root-rot syndrome is often caused by a complex of soil-borne pathogens composed of *Pyrenochaeta lycopersici*, *Rhizoctonia solani* and *Colletotrichum coccodes.* A combined infection with these three pathogens is more destructive than the infection with each fungus separately. Didymella stem canker, caused by *Didymella lycopersici*, is the disease that, in the past, posed a serious threat to field-grown tomatoes locally, especially in light and acidic soils; in recent years, it has been very uncommon, both in fields and greenhouses.

Strawberry

Verticillim wilt (*Verticillium dahliae, Verticillium albo-atrum*) is a very common strawberry disease in Poland. It is especially important in the production of strawberries for the fresh market, because cultivars suitable for this purpose (e.g. Elsanta, Candonga) are more susceptible to *Verticillum* spp. and other soil-borne pathogens than cultivars for processed fruit (e.g. Senga-Sengana). Other common destructive soil-borne strawberry diseases include leather fruit rot and crown rot (*Phytophthora cactorum*, *Phytophthora citricola*) and black root-rot disease complex caused by several pathogens, among others, *Cylindrocarpon destructans, Rhizoctonia solani, Leptoshaeria coniothyrium, Coniothyrium fuckelii, Pythium* spp. and *Fusarium* spp.

Nematodes

It is well known that plant parasitic nematodes are extremely harmful in warm climate areas, where they can develop almost throughout the year. However, the nematode problem is not restricted to the tropical or subtropical countries. Also, in regions with severe winters, nematodes can cause severe damage to a range of crops. Several examples from Poland are given.

Stem and bulb nematode (*Ditylenchus dipsaci*) is widely distributed and attacks a vast number of cultivated plants. Among horticultural crops severely damaged are onion, leek, garlic, parsley, celeriac and strawberry, as well as bulbous ornamentals (tulips, narcissus). *Ditylenchus dipsaci* can be extremely devastating in onion and garlic. Heavy infestation may cause yield losses of up to 60 percent.

Pin nematode (*Paratylenchus bukowinensis*) is common in Poland in areas where its main host plants (parsley, celeriac and carrot) are grown. The levels of yield losses of parsley are higher than those of carrot and celeriac, since parsley is extremely susceptible to this ectoparasitic nematode.

Root lesion nematode (*Pratylenchus penetrans*), with an extremely wide host range, is the most common and the most economically important of the seven species of the genus *Pratylenchus* identified in the country. This migratory endoparasite is especially harmful to fruit tree nurseries, roses, Easter lilies, gladioli, tulips, strawberries, carrots, celeriac, tomatoes and many other crops. However, there is no precise data on the magnitude of the crop losses caused by *Pratylenchus penetrans.*

The Northern root-knot nematode (*Meloidogyne hapla*) is economically important to many field crops, since *Meloidogyne hapla*, unlike other *Meloidogyne* species associated with cultivated plants, is able to overwinter in the field in the Polish climate. *M. hapla* can be severe on carrot, parsley, lettuce, parsnip, celeriac, spinach, tomato and rose. Presumably, even 60 percent of carrot fields could, to some extent, become infested with this nematode, but yield reductions are rarely up to 50–60 percent.

In addition to sugar beet as its principal host, sugar beet cyst nematode (*Heterodera schachtii)* has a relatively narrow host range (cabbage, cauliflower, Brussels sprout, radish, spinach and red beet). Of vegetable crops, the most susceptible to *Heterodera schachtii* is the Brussels sprout, followed by red beet and late cultivars of white cabbage and cauliflower.

Foliar nematodes, such as the spring crimp nematode (*Aphelenchoides fragariae*) and the bud and leaf nematode of chrysanthemum (*Aphelenchoides ritzemabosi*), can be locally a serious phytosanitary problem in strawberries, in addition to needle and dagger nematodes (*Longidorus* spp. and *Xiphinema* spp.).

In some strawberry fields, the plants can also be severely damaged by soil insects, such as strawberry root weevil (*Othiorhynchus ovatus*), European cockchafer (*Melolontha melolontha*) and larvae of click beetles (particularly *Agriotes linealus*).

Soil-borne pests and diseases in protected cultivation

Tomatoes

Almost all cultivars of tomatoes, currently grown in greenhouse, are resistant to *Verticillium albo-atrum* and/or *Verticillium dahliae,* as well as to races 1 and 2 of *Fusarium oxysporum* f. sp. *lycopersici.* Races 1 and 2 of *Fusarium oxysporum* f. sp. *lycopersici* commonly occur in Poland, but, fortunately, the occurrence of a third race has not been officially confirmed. It is for this reason that the diseases caused by these pathogens are of no concern in protected cultivation. *Fusarium* crown and root-rot of tomato, caused by *Fusarium oxysporum* f. sp. *radicis-lycopersici*, can be very harmful if non-resistant cultivars are grown. Serious disease incidences on rockwool-grown tomatoes have frequently been reported by growers. One can assume that in some cases of the disease occurrence in hydroponics, wind-dispersed microconidia of the fungus could be the primary source of infection. The disease is much worse in cooler soils (less than 18 °C).

Pyrenochaeta lycopersici, the causal agent of corky root-rot disease, is a very common and highly destructive soil-borne fungus in greenhouses where tomatoes are grown in the soil. The *Pyrenochaeta lycopersici* pathogen does not kill the plants, but is the principal agent responsible for a progressive yield decline in successive years of tomato growing in the same location, since the inoculum density in the soil increases from year to year. If appropriate management measures are not implemented at the right time, yield losses of 50 percent or more are common. The incidence and severity of corky root-rot are strongly favoured by low soil temperatures and, as a consequence, the disease is very common in unheated plastic greenhouses.

Another common soil-borne fungus, *Colletotrichum coccodes*, responsible for black dot root-rot disease, very often occurs on tomato roots – usually in association with *Pyrenochaeta lycopersici* and *Rhizoctonia solani*. However, there is a general belief that *Colletotrichum coccodes* has a little or no effect on tomato yield.

Phytophthora nicotianae var. *parasitica* (=*Phytophthora parasitica*) is the principal casual agent of Phytophthora stem and root-rot of tomato in

Poland. Cucumbers and peppers are much less affected by *Phytophthora parasitica* than tomatoes. Since *Phytophthora parasitica* is a thermophilic organism, with a thermal optimum of 28–30°C, the most severe disease outbreaks are observed on transplanted autumn tomatoes and in greenhouses in June–July. In cooler soils (20°C or less), the plants are rarely killed and the symptoms are restricted to root-rotting.

Cucumbers

The fungi of the genus *Fusarium* are the most common causal agents of soil-borne diseases of greenhouse cucumbers, especially in the traditional cultivation directly in the soil or on straw bales. *Fusarium oxysporum* f. sp. *cucumerinum*, responsible for vascular wilt of cucumber, has been found to be the most frequent species. Unless cucumber plants are grafted on a resistant rootstock, this pathogen can reduce the yield dramatically. *Fusarium solani* f. sp. *cucurbitae* ranks as the second most frequent *Fusarium* species that causes crown and foot rot disease of greenhouse cucumbers. This serious disease also occurs on cucumbers grown on rockwool. Infections of cucumber plants by either of the pathogens, as mentioned above, are usually accompanied by infections with other *Fusarium* species (e.g. *Fusarium culmorum, Fusarium avenaceum*, *Fusarium eqiuseti*).

Although the pathogenic *Fusarium* fungi are broadly distributed countrywide, the black root-rot of cucurbits, caused by the fungus *Phomopsis sclerotioides*, has long been considered the most harmful and common soil-borne disease of cucumbers grown in greenhouses. The disease is favoured by low soil temperatures, increased soil salinity and poorly drained soils.

The disease symptoms are generally more severe in unheated plastic tunnels than in glasshouses. In greenhouse soils naturally infected with *Phomopsis sclerotioides,* the yields can often be reduced by 60–70 percent. Management of the disease is very difficult. The acceptable level of the control can be obtained by soil steaming before each cucumber crop. Soil fumigation with broad-spectrum chemicals (MB, dazomet) revealed to be ineffective in most cases. Also, grafting onto *Cucurbita ficifolia* usually provides only a very limited protection of cucumber plants against infections with *Phomopsis sclerotioides.*

Several species of fungal-like organisms within the genus *Pythium*, notably *Pythium ultimum*, *Pythium irregulare* and *Pythium aphanidermatum*, are important pathogens of cucumbers grown in greenhouse. It is recognized that different *Pythium* species are very harmful, mainly at the earliest stages of plant growth, causing damping-off and root-rot. However, these pathogens can also easily infect fully mature cucumber plants at harvest time. Infections of well- established cucumber plants are especially common in rockwool and other hydroponic cultivation systems. Late infections can cause the "sudden wilt" of cucumber.

Peppers

In the regions where pepper cultivation is concentrated in unheated plastic greenhouses (west of Radom and east of Krakow), Verticillium wilt disease (*Verticillium dahliae*) has recently been gaining economic importance. This is due to the fact that in these regions, pepper is, as a rule, monocropped. The incidence and severity of this disease vary greatly from one farm to another. On some farms, more than 50 percent of the plants can be infected in single greenhouses.

A root-rot disease complex caused by several soil-borne pathogens strongly reduces yields of pepper grown in greenhouses. The most frequent isolated fungi from infected pepper roots, in descending order, are: *Colletotrichum coccodes, Fusarium oxysporum*, *Fusarium solani*, *Fusarium culmorum* and *Rhizoctonia solani*. *Pyrenochaeta lycopersici* has been found sporadically, and typical symptoms of thickenings with corky layers are absent on the roots. *Pyrenochaeta lycopersici* is much less harmful to pepper than to tomato.

Ornamental plants

In recent years, different species of the genus *Phytophthora* have been considered the most common and highly aggressive pathogens in greenhouse production of various ornamental plants. Diseases caused by *Phytophthora* spp. are also of crucial economic importance in container nurseries of ornamental trees and shrubs. During the 1993–2005 period, eight *Phytophthora* species were detected in Polish container nurseries (Orlikowski, 2006).

In glasshouses and heated plastic tunnels operated throughout the year, three species of the root-knot nematodes unable to survive in field conditions during winter time, such as *Meloidogyne arenaria, Meloidogyne incognita* and *Meloidogyne javanica*, commonly occur in addition to the prevailing *Meloidogyne hapla.*

These three stenothermic *Meloidogyne* species are especially aggressive with cucumbers, lettuce and several ornamental plants, but pose almost no threat to tomatoes because resistant cultivars are commonly grown.

IV. Available alternatives for the replacement of methyl bromide

Chemical alternatives

Methylisothiocyanateous fumigants (MITC)

At present, among the broad-spectrum chemical alternatives to MB, only dazomet and MS are available in Poland. These two compounds are the most widely used; once applied, they release volatile MITC, responsible for the biocidal effect over various soil-borne pests.

Dazomet (tetrahydro-3,5-dimethyl-3,5-thiadiazine-2-thione) is the active ingredient of the finely granulated product, which was registered in Poland as a soil fumigant in 1974. Since then, dazomet has been widely used for soil fumigation in protected cultivation of tomato, cucumber, lettuce, pepper, radish, chrysanthemum, carnation and other ornamental greenhouse plants. In recent years, dazomet has also been manufactured in Poland as a granular and a microcrystalline formulation.

The popularity and widespread use of chemicals containing dazomet are incontestably related to their relatively simple and safe method of application. The release of the MITC gases from dazomet is markedly slower than from MS. This characteristic enables personnel responsible for the application to apply the fumigant within enough time and to leave the greenhouse before irritating gases are released. Thus, this soil treatment can be conducted in a safe and convenient way, even at higher air temperatures. The standard application rate of dazomet (97 percent a.i. formulations) in greenhouses is 50 g/m^2, and soil-incorporated into the soil to a depth of 20 cm. In the open field, it is usually applied at a rate of 400 kg/ha (40 g/m^2).

Under greenhouse conditions, dazomet proved to be effective in reducing the incidence of several diseases caused by, among others, *Colletotrichum coccodes, Fusarium oxysporum* f. sp. *radicis-lycopersici, Fusarium solani, Phytophthora parasitica, Pyrenochaeta lycopersici, Pythium* spp., *Rhizoctonia solani, Sclerotinia sclerotiorum* and *Verticillium dahliae*. In commercial greenhouses, the effectiveness on *Meloidogyne* spp. ranged from 82 to 98 percent. Covering the soil with a plastic film significantly improves the biocidal activity of MITC fumigants, especially when applied in the summer or if the temperature of the treated soil exceeds 15 °C. It has been shown that covering soil with a plastic sheet enables to reduce the standard application rate of dazomet by 40 percent, without any reduction of the effectiveness of the treatment (Slusarski and Skierkowski, 1984).

The cost of soil treatment with dazomet at a rate of 50 g/m^2 (without plastic sheets) is €0.33 per m^2, or €3 300/ha.

Metam sodium (sodium-N-methyldithiocarbamate), or MS, is a liquid soil fumigant soluble in water, which can be applied by a direct injection into the soil or spraying on the soil surface immediately in front of the rotary tiller, or through sprinkler or drip irrigation systems.

MS was registered for the first time in Poland in the mid-1960s, but it was used reluctantly in greenhouses due to difficulties with the application technique (drenching method) and the pungent smell during the treatment. For the second time, MS was registered in 2000 for the control of a complex of soil-borne pests in the open field and greenhouses. According to the current label registration, the maximum application rate of this product is 700 litres/ha (70 ml/m^2). At present, MS is generally used solely for soil fumigation in the open field, and the main crop is strawberry. About 80–90 percent of MS used in the country is for soil treatment of areas for producing strawberry runners for export, and the remaining amount is used for the production of fresh market strawberry.

An evident increased use of MS and dazomet has been recorded in areas of strawberry nurseries. In 2005, about 26 ha of strawberry nurseries were treated with MS. In 2006, alternatives were applied in a strawberry runner production on an area of 77 ha (66 ha MS and 11 ha dazomet), using the application equipment delivered under the GEF Project. In 2007, about 100 ha of strawberry fields were treated with alternative fumigants, using the rotary spading injection method.

The MS applicator currently used on large fields consists of a front injection unit, equipped with four 70 cm-wide goose-foot blades to apply the fumigant, and a spading machine of 3 m working width integrated with a rotary harrow and a power-driven smooth roller. The fumigant is injected at a depth of 10–15 cm (at the midpoint of the working depth) and is mixed with the soil by the rotating spading blades. Then, the soil surface is levelled and compacted by a rotating harrow and sealed by the roller.

The recent results of field trials conducted in several European countries have shown that this method of MS application (“mixing-injection”) ensures higher efficacy of MS than other application techniques (Rabasse, 2004; Runia and Molendijk, 2006). It should be noted that the application of MS and dazomet using the rotary spading equipment is a new technology in Poland, in contrast to other countries. The increasing use of MS in strawberry nurseries is directly related to a substantial decrease every year in quantities of MB granted for the critical use exemption in this crop, and to the users’ awareness that the total MB phase-out from critical uses will soon be effective. Since all farms producing strawberry runner plants for export apply for a phytosanitary certificate, soil disinfestation is necessary to ensure a very high plant health status of runners to be exported. However, the efficacy of MS in controlling Verticillium wilt of strawberry was found to be inconsistent and, in some cases, too low to be commercially acceptable. The total costs of soil fumigation with MS conducted by a contractor vary from €1 650 to 1 900/ ha.

Metam potassium (potassium N-methyldithiocarbamate) is yet another liquid water-soluble fumigant generating MITC. The biocidal activity of this compound and its behaviour in the soil are very similar to these of MS. Metam potassium was once extensively tested in Poland, and in 1980, it was registered under the trade name Bunema as a general purpose soil fumigant. In fact, this product was used on a very limited scale and was soon removed from the registration list. Currently, metam potassium is registered as a soil fumigant in the United State of America and Spain.

Metam ammonium (ammonium methyldithiocarbamate) is also a precursor of MITC. This compound, as a commercial liquid product, was used in Poland on an experimental scale only, in the trials with soil disinfestation in plastic tunnels and outdoor seedbeds, but results were erratic. A liquid formulation of metam ammonium is registered in Hungary.

Disregarding the lower intrinsic biocidal activity of MITC than that of MB against several specific soil-borne plant pathogens, especially those causing vascular diseases, there are some serious constraints in certain situations that limit the use of compounds that generate MITC. The most important disadvantage of those chemicals is the slow dissipation rate of MITC from the soil and, as a consequence, a long waiting time between fumigant application and crop planting, from two to eight weeks, predominantly depending on soil temperature.

Among MITC fumigants evaluated in commercial glasshouses, dazomet revealed the shortest post - fumigation waiting period (Table 9).

Table 9: Mean duration of the phytotoxic after-effects (in days) of dazomet, metam potassium and MITC + DD, as determined by a cress-test, in different soils in six commercial glasshouses (1.5 ha each) (Slusarski, 1981)

Fumigants, dosages per m^2 and application method	Location and soil texture group					
	1 Silty clay loam	2 Silty clay loam	3 Medium clay	4 Sandy clay loam	5 Loamy sand	6 Loamy sand
	Mean daily soil temperature (°C)					
	19.9	21.3	20.0	22.9	23.0	15.5
Metam potassium 40 ml incorporation	–	16	18	13	13	17
Metam potassium 60 ml incorporation	–	16	19	15	14	20
Metam potassium 40 ml injection	–	19	23	20	16	21
Dazomet 50 g incorporation	13	12	16	13	12	17
MITC + DD 50 ml* injection	22	21	29	22	21	25

Note: *The fumigant is no longer used; it contained 20 percent MITC + 80 percent mixture of 1,3-dichloropropene and 1.2-dichloropropane (DD).

With respect to the production timing of most greenhouse and field-grown horticultural crops, in the climatic conditions of Poland, autumn is generally the only period available for soil fumigation with dazomet or MS. It is known from local experience that MITC fumigants should preferably be applied in the field and unheated plastic greenhouses by mid-October. In the case of late autumn fumigation, optimum conditions of soil moisture and temperatures rarely take place in the field, so MITC fumigants may provide inadequate control of soil-borne pests. In addition, phytotoxic post-effects in the spring are possible, especially if winter is severe and/or begins early.

Liquid MITC fumigants are regarded as products of only limited usefulness in greenhouses owing to their very rapid and strong release of toxic gases. The final biocidal efficacy and the influence of these fumigants on yields are strongly affected by the application method, soil temperature, texture, organic matter content, soil moisture, pH and uniformity of distribution in the soil.

Since MITC does not sufficiently penetrate undecomposed plant debris in the soil, a two-week interval should be observed between removing the old plants and fumigant application in order to allow at least a partial decomposition of the plant residues.

Dazomet and MS are generally unsuitable for treating highly organic substrates (sphagnum peat, composted bark) due to greatly reduced efficacy and long-lasting phytotoxic persistence in such media.

1,3-dichloropropene and chloropicrin mixture

The 1,3-D/Pic mixture is often considered a viable alternative to MB for controlling soil-borne fungi and nematodes. This fumigant, applied by direct injection into the soil, is registered and used in Canada, Japan, Australia and the United States. It also has a provisional registration in three countries in the EU. In trials conducted in Poland, 1,3-D/Pic mixture revealed to be the most promising chemical alternative for strawberry runners and some field vegetable crops. Nevertheless, according to the recent legal regulations, the future use of this fumigant cannot be considered, since 1,3-dichloropropene is on the list of active substances forbidden in Poland for use in pesticides. Also, chloropicrin is not registered in Poland, either as a single fumigant or as a component of mixtures (except for MB/Pic 98:2 formulation).

Non-fumigant chemicals

Contact or systemic fungicides and insecticides can hardly be considered true alternatives to MB for controlling soil-borne pests. Nevertheless, if the target organism to be controlled is well defined, such chemicals can be a useful or complementary tool in the management of a pest or disease. The pesticides registered in Poland for soil treatments are listed in Table 10. It can be seen that the choice of non-fumigant pesticides for soil uses is very limited.

Table 10: Non-fumigant pesticides currently registered in Poland for soil-borne pest control in horticultural crops

Active ingredient	Trade name	Registered use sites
Nematicides and insecticides		
Carbofuran	Furadan 5 GR	Rose nurseries, chrysanthemum, gladioli, container nurseries
Diazinon	Diazinon 10 GR	Strawberry, onion, field-grown ornamental plants
Oxamyl	Vydate 240 SL	Celeriac, onion
Fungicides and disinfectants		
Azoxystrobin	Amistar 250 EC	Drenches of ornamental plants
Dimethomorph + mancozeb	Acrobat 69 WP	Greenhouse tomatoes, flowers
Fluazinam	Altima 500 SC	White cabbage, Chinese cabbage (against clubroot)
Fosetyl aluminium	Aliette 80 WP	Disinfection of potting composts and greenhouse soils in heaps, drenches of ornamental plants
Peracetic acid	Agrosteril 110 SL	Pre-planting soil and substrate disinfection
Propamocarb HCl	Previcur 607 SL	Greenhouse cucumbers, tomatoes and flowers, disinfection of potting composts and soil in heaps
Propamocarb + fosetyl	Previcur Energy 840 SL	Greenhouse cucumbers, tomatoes and flowers, disinfection of potting composts and soil in heaps
Thiram	Sadoplon 75 WP	Seedbeds of brassica crops, soil in heaps for transplant production (except tomato)
Tiophanate-methyl	Topsin M 500 SC	Soil treatments in transplant production of brassica vegetables

Non-chemical alternatives

Past and current alternative methods in protected cultivation in Poland

As a consequence of the relatively late registration of MB for soil uses, Polish growers were forced for many years to apply methods of protection against soil-borne pathogens other than MB fumigation. This resulted in introduction and commercial use of several soilless cultural methods in protected cultivation. The most common of these growing methods are briefly described below.

Cultural methods

Several growing techniques of greenhouse crops enable to eliminate or reduce the need for soil disinfection; the best known include ring, trough, bag, straw-bale and hydroponics culture. These types of culture are characterized by utilizing growing media other than soil and confining the root system to a relatively small volume of the substrate.

Ring culture. This method was promoted mostly for tomatoes and gerbera. The tomato plant is set into a bottomless round ring – about 22 cm diameter, 20 cm tall – or sleeve of opaque plastic film. The rings are spread out in a bed containing a layer of about 10 cm of a substrate (sphagnum peat or mixtures of peat and pine bark or peat and vermiculite). The same materials are used to fill the rings. Sometimes, the ring containers are placed directly on the soil surface. Ring culture was very popular in tomato growing until the early 1990s, when the rockwool substrate started to be introduced. However, this method is still successfully used on some small farms. One of the major benefits of ring culture is the chance to minimize the hazards arising from soil infestation with different root invading pathogens, especially in the case of *Pyrenochaeta lycopersici* and *Didymella lycopersici,* but there was no protection effect against *Phytophthora parasitica, Pyrenochaeta* *cryptogea, Rhizoctonia solani* and *Fusarium oxysporum* f. sp. *radicis-lycopersici*.

Trough culture. In this system, tomato plants are grown in long, narrow beds containing a growing medium such as peat, sand, perlite, composted bark, sawdust, or many combinations of them. Troughs should be 12–15 cm deep and at least 60 cm wide to accommodate two rows of tomatoes. The troughs must be lined with PE or PVC film in order to be impermeable to roots. This system of cultivation can be considered a true soilless culture, due to the complete separation of roots from the original soil. In comparison with the ring culture, this method requires higher investment costs. Long-term use of the substrate is possible provided that it is disinfected (preferably steaming) before each new planting. Currently, this method is not used in vegetable growing, because it was replaced with the rockwool system.

Straw-bale culture. In this system, greenhouse tomatoes or cucumbers are grown on top of decomposing bales of wheat, barley or rye straw. The bales are sometimes placed on a sheet of plastic film to isolate the straw from the soil. Sphagnum peat is usually used as capping soil. This method is still very popular in Poland, especially in cucumber growing in plastic tunnels. On some farms facing severe soil infestation, soil fumigation with MB was used before setting the straw bales into the greenhouses.

The performance of plants grown on straw bales is, as a rule, very good due to increased temperature in the root zone and carbon dioxide released during decomposition of the straw. This growing system constitutes both a biological heating medium and thermal insulation from original soil, and also provides limited protection against infection of the roots by soil-borne pathogens. However, some pathogens, such as Phomopsis sclerotioides and Fusarium solani f.sp. cucurbitae, cause more severe infection in cucumber plants grown on straw bales than those plants grown directly in the soil (Leski, 1984; Nowicki, 1984).

The cultivation of cucumber and tomato on straw bales is often integrated with grafting onto resistant rootstocks. This system creates favourable conditions for introduction of biological control agents, particularly those based on Trichoderma spp., as it was found in earlier studies.

In recent years, a modified system of straw-bale culture has been developed at the Research Institute of Vegetable Crops in Skierniewice, which is considered a possible alternative to the rockwool (Babik, 2006). In this system, finely chopped wheat straw is formed under high pressure (3 MPa) into block-shaped slabs (100 x 20 x 10 cm) and enclosed in opaque white plastic sleeves, similarly to commercial rockwool slabs. In the greenhouse trials, the yields from cucumber plants grown on slabs of compressed non-fermented straw consistently tended to be higher than those of plants grown on traditional straw bales or in rockwool substrate. However, due to high microbial activity in the straw substrate at the beginning of the growing season, the nutrient composition of the solution recommended for rockwool cultivation should be modified for fertigation. Generally, the content of nitrogen (N-NO3) should be increased by 20–25 percent and the content of potassium decreased by 20 percent in comparison with the nutrient solution used in cucumber growing on rockwool.

Hydro-peat and multi-containers cultures. These two hydroponics growing methods developed in Poland in the mid-1970s can be regarded as precursors of the rockwool hydroponics system in the country. In the hydro-peat method, the rings 40 cm high, filled with sphagnum peat, were placed in troughs in layers 5 cm deep of a stagnant nutrient solution. The nutrient solution was replenished periodically (Janowski and Skapski, 1984). In the multi-container system, trays shaped like inverted cones with a perforated bottom, holding 10 litres of substrate (sphagnum peat – bark mixture, 2:1) were placed in the second container with a nutrient solution and were dipped in within a 4–6 cm limit (Bartkowski, 1984). Both systems provided doubtful protection from soil-borne diseases. In the hydro-peat method, severe outbreaks of Fusarium crown and root-rot of tomato, Phytophthora root and crown rot were observed under commercial conditions. Recently, these methods stopped being longer used.

Rockwool growing system. In Poland, the introduction of the rockwool hydroponics system on a commercial scale began in the early 1990s (Oswiecimski, 1996). This growing system was first introduced on large greenhouse farms, which previously used MB for soil and substrate fumigation. Growing on rockwool has been replacing other soilless cultures in which traditional organic substrates were used, and the total area of greenhouses growing on rockwool has increased to nearly 1 000 ha. The rockwool culture system has been successfully used for growing greenhouse tomato, cucumber, eggplant, pepper, rose and other crops. Other artificial substrates (glass wool, polyurethane foam) are also used on a limited scale.

Tomatoes and cucumbers are mainly grown in these substrates. At present, in Poland, an open rockwool system has been used, which allows the excess nutrient solution to discharge into the environment as run-off. However, one should be aware that in the future, implementation of recirculation systems may be obligatory, as it is at present in the Netherlands and in other EU countries to avoid problems with pollution of ground and surface water. Since there are serious problems with disposal of reused rockwool slabs, some decomposable materials serving as an anchoring medium (e.g. slabs made of coconut fibre) are being introduced on a commercial scale.

There is no doubt that the health status of plants grown in rockwool and other inert substrates is much better than that of plants cultivated traditionally in the soil. This technology had generally eliminated the occurrence of diseases such as corky root-rot of tomato, black root-rot of cucurbits and *Rhizoctonia* disease. On the other hand, zoosporic plant pathogens (*Phytophthora* spp., *Pythium* spp., *Olpidium* spp.) may constitute a very serious phytosanitary problem, and appropriate preventive or control measures are necessary to avoid heavy yield losses. Hydroponics creates almost ideal conditions for the introduction of different biological control agents. The convenience of using biocontrol agents in such systems was confirmed in several experiments (Slusarski, 2003).

In soilless cultivation in Poland, different organic, mineral and synthetic substrates have been widely used in the production of greenhouse flowers and vegetables (Table 11). Sphagnum peat, pine bark, straw, and more recently, also coconut fibre, are the most commonly used organic substrates. Among inert substrates, rockwool is the most utilized. Synthetic foams are used on a very limited scale.

Table 11: Substrates used in soilless cultivation in Poland

Organic substrates	Mineral substrates	Synthetic substrates
Sphagnum peat	Rockwool	Polyurethane foam
Pine bark	Glasswool	Polyphenolic foam
Wheat straw	Perlite	Polyamine foam
Sawdust	Expanded clay granules	
Coconut fibre (coir)	Gravel	
Coconut chips	Sand	
Brown coal	Vermiculite	

Use of grafted plants and resistant cultivars

Great progress has been made in resistance breeding in tomato. Many modern tomato hybrids, which are often grown in greenhouses, combine effective resistance genes against 5–7 pathogens. There are soil-borne pathogens of genetically controlled tomato, such as *Verticillium dahliae, Fusarium oxysporum* f.sp. *lycopersici* (races 1 and 2), *Fusarium oxysporum.* f.sp. *radicis-lycopersici, Pyrenochaeta lycopersici* and *Meloidogyne* spp. Various tomato-resistant rootstocks are commercially available in Poland (Table 12). Unfortunately, cultivars of cucumber and pepper resistant to the most important soil-borne pathogens are not yet available commercially.

Table 12: Tomato rootstocks available and used in Poland

Rootstock (breeder)	Resistance
He-man (Syngenta Seeds)	$ToMV_{0\text{-}2}$, V_a, V_d, $Fol_{1\text{-}2}$, For, (Pl, M_a, M_i, M_j)
Beaufort F_1 (De Ruiter Seeds)	Tm, V, $F_{1,2}$, For, Pl, M_a, M_i, M_j
Maxifort F_1 (De Ruiter Seeds)	Tm, V, $F_{1,2}$, For, Pl, M_a, M_i, M_j
PD-94 F_1 (PHO Krzeszowice)	Tm, V, $Fol_{1,2}$, Pl, $Cf_{a\text{-}e,}$ M_i
Titron F_1 (Western Seeds)	ToMV, V_a, $F_{1\text{-}2}$, For, Pl, $Cf_{a\text{-}e}$
Big Force F_1 (Rijk Zwaan)	ToMV, V_a, $Fol_{0\text{-}1}$, For, $Cf_{a\text{-}e}$, Mi
Big Power	
Spirit F_1 (Nunhems)	ToMV, V_a, V_d, $Fol_{0\text{-}1}$, (Pl, M_a, M_i, M_j)
Body F_1 (Seminis Vegetable Seeds)	$ToMV_{0\text{-}2}$, V_a, V_d, $Fol_{1\text{-}2}$, For, Pl, $Cf_{a\text{-}e}$, Ss, M_a, M_i, M_j

Resistant rootstocks provide excellent control of many vegetable diseases caused by some soil-borne fungi and root-knot nematodes. However, none of the currently available tomato rootstocks are resistant to *Meloidogyne hapla,* the most common root-knot nematode species in Poland. It should also be noted that, up to the present, there are no tomato and cucumber cultivars or rootstocks resistant to *Pythium* spp. *Phytophthora* spp and *Olpidium* spp., which are particularly important in hydroponics. This situation requires using different measures for controlling diseases caused by these pathogens. Grafted plants of cucumber on *Cucurbita ficifolia* resistant to *Fusarium oxysporum* f.sp. *cucumerinum* have been used for many years in Poland. It seems that this technique will be used more widely in the near future. Growing grafted pepper plants is a relatively new technology. To date, among the Central and East European countries, grafted peppers are only grown on a commercial scale in Hungary. The demonstration trials with bell pepper grafted on Snooker rootstock, conducted under commercial conditions in Poland, revealed unsatisfactory performance. Lack of success seems attributable to the fact that this rootstock has no resistance to Verticillium wilt, which in Polish conditions is the main factor limiting the productivity of this crop. In the past, when multiple-resistant tomato cultivars were scarce, tomato grafting on specific rootstocks became popular to combat *Pyrenochaeta lycopersici*. Recently, in hydroponically grown tomatoes, there is an increasing trend of grafting even resistant tomato cultivars on special rootstocks (e.g. Maxiford, Beaufort, He-Man). Tomato plants are grafted using the “Japanese method”, which results in a much stronger root system and higher yields (by 10–15 percent) in the absence of root pathogens. In Poland, there are several modern nursery greenhouse farms producing transplants of different crops, including grafted cucumbers and tomatoes. Moreover, the growers can order and buy grafted eggplants and pepper.

Biological control

In Poland, the number of available biocontrol agents is limited (Table 13). Biocontrol agents, when used alone, are effective only in certain cases. In general, biological control agents can provide satisfactory protection of roots against pathogens only in the case of integration with other disease control measures (fumigation, steaming, solarization, organic amendments, and others). It seems that for most of the combined applications, biocontrol agents based on *Trichoderma* spp. are most universal and relatively stable in performance.

In contrast, there is an erratic performance of biocontrol agents when applied alone in traditional soil cultivation, depending on crop and location. Crops grown in greenhouse, especially those in small volume of substrates, offer an almost ideal opportunity for the use of biocontrol products.

In the case of field crops, the antagonistic organisms should be introduced at the earliest stages of plant growth. This can be achieved using biocontrol agents for seed dressing or during production of transplants. With such treatments, improved plant growth of cabbage, celeriac, leek and tomato is observed under field conditions.

To date, Polyversum has been the most often used biocontrol agent in Poland, especially in hydroponics greenhouse vegetables and in the production of ornamental plants in organic substrates. In 2007, the first year of commercial introduction of Vital Plus (*Trichoderma viridae* B35), it was applied in the field production of Brussels sprouts, cabbage, celeriac, leek, tomato and pepper in a total area of 93 ha. In addition, the agent was used in rockwool-grown greenhouse cucumbers and tomatoes on a total area of 15 ha.

Table 13: Biological control agents for controlling soil-borne pests that are commercially available in Poland

Trade name	**Microorganism**	**Activity against**
Registered as plant protection products		
Polyversum	Pythium oligandrum	**Fungi**
Polagrocyna PC	Agrobacterium radibacter K84	**A. tumefaciens**
Contans WG	Conithyrium minitants	***Sclerotinia* spp.**
PG-IBL	Phlebiopsis gigantea	**Heterobasidion annosum in forest stands**
Larvalen	Heterorhadbitis megidis (insect parasitic nematode)	**Larvae of soil insects (Melolontha, Otiorhynchus)**
Certified as plant strengtheners and/or soil conditioners		
Aqua Bac Plus	*Bacillus subtilis, B. lentus, B. amyloliquefaciens,*	**Fungi**
EM1 (Effective Micro-organisms)	Different bacteria, fungi, yeast, actinomycetes	**Fungi**
Fytobak	Different strains of *Bacillus* spp. and *Pseudomonas* spp.	**Mainly *Phytophthora* spp.**
Vital Plus	*Trichoderma viride* B35	**Fungi**

Organic amendments and natural products

Improving soil with composts, animal manure, green manure, composted bark, residues of some brassicas and various by-products from agriculture and food industry is used in many countries to suppress certain soil-borne pathogens. This phytosanitary measure is especially important for field crops. Also, the use of cover plants (e.g. *Vicia villosa, Secale cereale,* *Trifolium incarnatum*) can be very important in developing environmentally friendly sustainable systems for vegetable production in regions of temperate climates.

Sinapsis juncea and other brassicas, mainly canola, have been used on a commercial scale in field rotation as preceding crops. The green biomass of these plants is soil-incorporated. The most effective cultivars are those rich in glucosinolates such as cv.Malopolska of *Sinapsis juncea*. The IPM strawberry fruit production system in Poland adopts mustard as the preceding crop (Szczygiel, 2002). However, in trials on field vegetables and greenhouse grown peppers soil-incorporated Indian mustard did not provide satisfactory results (Slusarski *et al.*, 2002; Slusarski and Pietr, 2002a and 2003).

In Poland, there is also commercially available a range of natural products displaying antifungal activity (Table 7). These products have mainly been used in organic and ecological farming. Some of these products are recommended for controlling soil-borne fungi. A commercial product containing chitosan, a natural polysaccharide derived from the shells of sea crustacean, provides protection of different crops against *Pythium ultimum, Pythium. splendens, Pythium* spp., *Phytophthora* spp., *Fusarium oxysporum, Fusarium avenaceum, Fusarium culmorum* and *Fusarium* spp. (Skrzypczak and Orlikowski, 1998). The extract of vermicompost, has been recommended for soil treatment against *Pythium* spp., *Phytophthora* spp. and *Rhizoctonia solani* in the production of ornamental plants and vegetables (Wolski, Orlikowski and Wojdyla, 1996). Similarly to biocontrol agents, the efficacy of the above-mentioned products applied in traditional soil and substrate cultivation systems is variable and, in most cases, only partial protection can be achieved.

Table 14: Natural plant protection products commercially available in Poland

Trade name	Active ingredient	Activity against
Antifung 20 SL	Biohumus 20%	Fungi
Biochikol 020 PC	Chitosan 2%	Fungi, bacteria, viruses
Bioczos BR	Garlic pulp	Fungi, bacteria, insects
Biosept 33 SL	Grapefruit extract 33%	Fungi, bacteria
Grevit 200 SL	Grapefruit extract 20%	Fungi, bacteria
Sincocin AL	Extract of plant tissues 0.56% (cytokinines)	Fungi, nematodes In forest nurseries
Zaprawa ziołowa PNOS-1LS (seed dressing)	Grapefruit extract + garlic extract	Fungi

Heat treatment

Soil steaming is a real alternative to MB for soil-borne pest control in protected production systems. For more than 30 years, steaming has been commonly used in Poland, and up to 300 ha could be steamed annually. At the initial stage of its use, numerous large state-owned greenhouse farms and some horticultural cooperatives were equipped with low pressure, fuelled by heating oil, mobile steam boilers of a capacity from 900 to 2 000 kg of superheated steam (up to 220 ^{o}C) per hour. In the case of a surface sheet steaming, at least 30 kg of superheated steam should be delivered per 1 m^2 to disinfect the soil layer to a depth of 20 cm. Although the effectiveness of soil steaming is unquestionable, due to its high cost this method is currently seldom applied in Poland. Nevertheless, the method seems to be acceptable for greenhouse production of ornamental plants, grown directly in the soil or substrates.

At present, only a small number of greenhouse farms are equipped with stationary steam boilers that generate saturated steam. The low pressure steam boilers fuelled by coal-dust are the cheapest source of steam. On such farms, soil steaming is often conducted on a regular basis, usually using the old Hoddesdon pipe method. This method enables much deeper soil disinfestation than sheet steaming, but the Hoddesdon method is very laborious and requires up to 120 person-hours per 1 000 m^2. Until now, the negative pressure soil steaming system, developed in the Netherlands, has not been adopted in Poland. For steaming of different organic substrates and potting composts, bunker steaming is being used. The costs of soil steaming in a greenhouse can vary from about €1.6 to 3 per 1 m^2, depending on the method used and the type of steam source. In some regions where numerous small farms growing ornamental plants are located, there are also few contractors who provide soil steaming services to the growers in the vicinity. It is well known that soil steaming creates an empty microbial niche, which provides an opportunity for rapid colonization of the soil or substrate by introduced different biological control agents.

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