Physical Methods for Soil Disinfestation in Intensive Agriculture: Old Methods and New Approaches

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Abstract

Physical soil disinfestation is worldwide mainly applied in protected cropping systems or in small-scale intensive field crops. Continuous cropping of monocultures or different host plants for the same pest or pathogen often leads to heavily infested soils which forces growers to disinfest the soil thoroughly. The oldest method is steam sterilization which is applied for more than a century. In the 1970s hot water treatment of soils was developed in Japan. Hot water is applied to the soil surface to raise soil temperatures to lethal levels. Since the 1980s inundation became a new method in the Netherlands and is applied in bulb cultures. This so-called flooding of soils creates anaerobic soil conditions in which toxic compounds like greenhouse gases are produced. A new approach in soil disinfestation in the current century is hot air treatment which is developed in Israel. The method is based on blowing extremely hot air into soil particles which are thrown above soil surface into a heat chamber by a rotary spading device.

In the Netherlands renewed interest has started in radiation of soil with micro waves. Radiation of soil or other substrates has been studied for decades. The mechanism is that the heat produced by radiation is lethal to pathogens and pests. Anaerobic soil disinfestation (ASD) with incorporation of fresh organic matter in soil is a method developed in the Netherlands. A new and promising Dutch development in ASD is the application of defined products. Advantages and disadvantages of all methods are presented in this paper.

INTRODUCTION

Intensive agriculture can be characterized by growing cash crops with high yields on small areas in comparison with arable crops. Investments per m^2 are high and thus require high returns. High yields may result into high profits but depend strongly on two factors. On one hand the market price for the product is a factor which can hardly be managed by the grower but on the other hand both quality and quantity of the product are decisive for the growers' income. Continuous cropping of monocultures or different host plants for the same pest or pathogen often leads to heavily infested soils. Fungal soilborne pathogens and parasitic nematodes threaten these crops frequently which forces growers to disinfest the soil thoroughly. For this reason several methods of physical soil disinfestation are worldwide applied in protected cropping systems and in small-scale intensive field crops.

Possibilities for soil disinfestation are studied intensively and permanently. However soil disinfestation should be the ultimate measure for growers, even in monocultures. Many measures may diminish the necessity of soil disinfestation. Requirements of a healthy crop start with healthy plant material, clean irrigation water, use of resistant varieties and optimum growing conditions from the point of soil tillage, fertilization and irrigation. In monocultures catch crops can be grown when intervals between two successive crops are some months. If in spite of all these measures soil-borne pathogens or pests still cannot be managed soil disinfestation might be applied.

Nevertheless in horticultural and bulb crops with mainly monocultures soil disinfestation is commonly used to control soilborne pathogens. Initially soil disinfestation methods were developed with a general biocidal effect like methyl bromide or steam sterilization. The withdrawal of methyl bromide from the market due to ozone depleting properties of the product has forced the development of other disinfestation methods of which the physical methods are discussed in this paper. In the Netherlands methyl bromide as a soil fumigant was completely banned in 1992 (Ministry HPPE, 1992). Also other chemical compounds are prohibited since then like dichloropropene or limited in use like metam sodium. Soilborne pests and pathogens are nowadays controlled in the Netherlands by using soilless cultures, steam sterilization, inundation (flooding) or by anaerobic soil disinfestation. Hot air treatment and radiation are both still under investigation for practical application. Steam sterilization of soil and soilless cultures are common practice in protected cultivation. Bulb fields are sometimes flooded to control plant parasitic nematodes and fungi; this method is called inundation. Another option for bulb fields is the application of metam sodium once in 5 years. Anaerobic soil disinfestation is incidentally applied in high cash crops like *Asparagus*. In Japan hot water is used in intensive agriculture for soil disinfestation.

All physical soil disinfestation methods mentioned are discussed chronologically in this paper. Biofumigation and solarization may be also regarded as physical soil disinfestation methods but do not fit in the scope of this review for different reasons and therefore are not included.

CHRONOLOGY OF PHYSICAL SOIL DISINFESTATION METHODS

Twentieth Century

1. Steam Sterilization. Baker (1962) stated that ‘most plant pathogenic micro-organisms, insects, viruses and weed seeds in soil may be destroyed at 140°F (±60°C) for 30 min’. Additional and detailed information about heat tolerance of soil micro-organisms, both pathogenic and non-pathogenic, became available in the next decades. Heavily infested moist soils were treated for 30 min at a temperature range thus establishing lethal temperatures. Thanks to these studies recommendation for soil sterilization became 70°C for at least half an hour to eliminate fungal and bacterial plant pathogens, parasitic nematodes and soil insects, slugs, worms and centipedes (Bollen, 1969, 1985). In Dutch soils treated for 30 min at 70°C growth of seed weeds was never noticed.

Sheet Steaming. The oldest method is steam sterilization which is applied for more than a century. Sheet steaming is most common; steam is applied under a sheet which covers the soil and is anchored along all edges. The steam pressure build up under the sheet forces the steam to penetrate into the soil.

The efficacy of this method depends on several factors of which soil type is of crucial importance and so is soil tillage. In situ under optimal soil conditions clay soils can be disinfested very well but on sandy and loam soils lethal soil temperatures are achieved only in the upper soil layers. Sheet steaming is not very effective on peat soils because of its water retaining capacity.

Another disadvantage of sheet steaming is the length of the steaming period, which may last for about 8 h, in which much energy is lost by radiation when no precautions are taken to prevent this.

An advantage of sheet steaming is the relative simplicity of the method. Sheet steaming may be a practical solution for weed control or for shallow soil disinfestation in case of crops with a short growing season. Sheet steaming of a furrow of 30 cm or deeper can only be realized effectively on clay soils.

When soil is used as growing medium in containers, bags, etc. and collected afterwards for disinfestation sheet steaming can be applied providing that the layer of soil to be steamed is not too thick and sufficient drainage of condensation water is arranged. The acceptable soil layer depends on the type of soil (Runia, 2000).

Negative Pressure Steaming. Another more active method of steam sterilization is negative pressure steaming. With this method steam is blown under a steaming sheet and pulled into the soil by negative pressure, created by a fan, which sucks air out of the soil through buried polypropene tubes. The flexible tubes with an internal diameter of 5 cm and a porosity of 12 cm^2/m tube length are wrapped in polypropene fibre to prevent blocking of the perforations. In areas with a high water table the system is dug in at a depth of 55-60 cm, which is 20 cm above the drainage system responsible for drainage of condensation water during steaming. The polypropene tubes in the soil are connected to an above-ground main, which is connected to a fan. When the steam system should also function as drainage system the tubes are installed slopingly at a depth of 70-80 cm and with an underground main, connected to a drainage pit with plunger pump onto which also the fan is connected (Runia, 1983). Tubes are dug in over the total length of the area to be treated at an interval of approximately 2 m. Crucial for the efficacy of this system is that the fan should be functioning before steam is applied and is switched off not earlier than 2 h after steam supply has been stopped. By doing so penetration of steam into the soil is stimulated from the start and heat transfer to deeper soil layers afterwards is realized without any further energy input.

Steaming with negative pressure has proven to be more effective on clay, sand, loam and peat soil. In clay soils which can also be steamed with sheet steaming differences in temperature achievement may be small under optimal conditions but under less favorable conditions negative pressure steaming can still be effective. For disinfestation of a soil layer of at least 30 cm with negative pressure steaming the exposure time to steam is only 4 to 5 h for all soil types which reduces energy loss due to radiation considerably.

In comparison with sheet steaming negative pressure steaming is an important improvement with respect to efficacy and fuel savings (Runia, 2000). This method can also be applied when soil is collected from containers or bags and piled up for disinfestation by connecting the drainage system to a fan.

In the Netherlands both sheet steaming and negative pressure steaming are applied in protected cultivation. Fuel consumption with these methods is 7 and 4 m^3 gas/m^2 soil, respectively.

Mobile Steaming Methods. For outdoor application of heat treatment in general two types of mobile machinery are available. A Dutch steam device disinfests occasionally complete flower bulb fields against weeds and nematodes. The soil is rotovated to a depth of 25 cm which is also steaming depth. Capacity of the mobile steam device however is limited to 100 m^2/h which hampers wide application. Fuel consumption is 1 L of diesel oil per m^2 of soil (Runia and Molendijk, 2008).

Another commercial mobile steam device nowadays is developed for steaming raised beds. This method is mainly meant to control seed weeds and plant pathogens in the shallow upper soil layer of 5-10 cm. For short-term leaf salad crops grown in monoculture this method proved to be effective to a depth of 10 or 15 cm, depending on soil type (Pinel et al., 2000).

2. Pasteurization. The fact that treatment of soil for 30 min at 60°C was sufficient to eliminate most plant pathogens and pests (Baker, 1962) enhanced the development of a less detrimental method than steam sterilization. Heating naturally infested soils in pot experiments at 60°C for 10 to 30 min eliminated *Rhizoctonia solani* and pathogens causing brown root rot e.g. *Colletotrichum* spp. and survival and growth of tomato and lettuce seedlings was better than at higher temperatures. This information led to the recommendation to disinfest soils at 65-75°C (Dawson et al., 1965).

In the Netherlands in glasshouses around the 1970s a rotation of tomato or cucumber followed by lettuce was common practice with steam sterilization in summer after tomato or cucumber to control soilborne pathogens. Negative side effects like manganese toxicity however caused problems in the lettuce crop after steaming. Changing to steaming after lettuce crop was not regarded as realistic since in autumn and winter soil conditions in the Netherlands are not suitable for steam sterilization with low temperatures and high soil humidity. Therefore effects of pasteurization of soil with a steam-air mixture at 70°C on butter head lettuce was compared with steam sterilization at

100°C. No negative effects on growth were noticed when soil was pasteurized with steam-air mixtures at 70°C. Manganese levels only slightly increased and damage level was seldom reached. Only at low pH level manganese toxicity may occur but also in unsterilized soil (Sonneveld and Voogt, 1973). Technically pasteurization was feasible but disadvantages proved to be increased electricity consumption, no savings in fuel costs and increase in labour costs. For these reasons it was concluded that pasteurization was no practical alternative for steam sterilization in field situations (Nederpel, 1979).

Pasteurization however was regarded as feasible for disinfecting container medium used in avocado nurseries. An exposure time of at least 1 h at 75°C with a commercial pasteurizer was recommended at that time based on scientific data with divers media infested with *Phytophthora cinnamomi* (de Jager and Kotzé, 1994).

In 2002 efficacy of low temperatures was established in a laboratory against resting structures of potato cyst nematodes (*Globodera rostochiensis* and *G. pallida*), of fungal soilborne pathogens (*Verticillium dahliae*, *Sclerotinia sclerotiorum*, *Sclerotium cepivorum* and *Pythium ultimum*) and of weeds (*Chenopodium album* and *Agropyron repens*). Lethal temperatures of these organisms in imbibed state were never higher than 60°C after an exposure time of 3 min and another 8 min in treated soil. In dry state the maximum temperature required for efficacy was 80°C. Based on these data it was concluded that for cooler climates ‘short duration steaming at low temperatures’ could be an alternative for solarization, which is only feasible in warmer climates (van Loenen et al., 2002).

3. Hot Water Treatment. In the 1970s hot water treatment of soils was developed in Japan. In contrast with hot water treatment of plant propagation material which is applied worldwide since decades to ensure disease free propagation plants hot water treatment of soil is mainly applied in Japan. In the late 1970s two research stations in Japan developed different methods for hot water application to the soil but the idea behind both prototypes were the same. Hot water of 70 to 95°C was poured to the soil surface before planting in order to raise soil temperature to levels lethal for plant pathogens, pests and weed seeds. Nowadays two systems are available for hot water treatment in protected cultivation. The so-called dragging system comprises a boiler, winch and hot water sprayer and can treat up to 9 m wide plots with a capacity of 45 m^2/h maximum. The amount of water applied depends on machine speed and varies between 100 and 300 L of water per m^2 soil area. This method is regarded as suitable for large-scale treatments of flat fields in Japan. Another method distributes hot water by heat-resistant tubes, placed on the soil surface at 20 to 60 cm intervals under a plastic film and can be used at small-scale and sloped fields (Nishi et al., 2003). High efficacy was noticed with this method against several fungal and bacterial pathogens as well as against cyst nematodes and non cyst forming nematodes and lethal temperatures can be achieved up to a soil depth of 30 cm. Hot water treatment also remarkably decreased viruses from the tobamo group as well as pathogens causing ‘damping off’ in shallow upper layers of the soil (Nishi et al., 2003).

Hot water treatment is regarded by the authors as an environmental friendly alternative to methyl bromide since soil microflora is less disturbed by this treatment than after steam sterilization as many saprophytes survive hot water treatment. In Japan hot water treatment is adopted by pioneer growers and farmers associations for production of organic crops. High investments hamper a wide-scale use until now (Nishi et al., 2003).

Hot water treatment at 50°C completely destroyed a pathogenic fungus threatening Japanese pear trees and lasted for at least 16 months. For this reason hot water treatment can be applied in soils where fruit trees are grown providing these trees are heat tolerant to these water temperatures (Eguchi, 2008).

Tubers of yellow nutsedge *Cyperus esculentus* survived temperatures of 55°C up to 30 min without any damage in sprouting. From these data it can be concluded that for controlling this weed temperatures higher than 55°C are required. Tubers did not sprout anymore when treated for at least 20 min at 64°C (García-Jiménez et al., 2004). This temperature may be achieved at approximately at 25 cm soil depth in a permeable soil (Nishi et al., 2003).

Hot water treatment against all kinds of leafy weeds is mainly applied at hard surfaces where weeds grow in soil between pavements and not against seeds of weeds in the soil. In general hot water treatments require large amounts of water and energy and are expensive for these reasons. Moreover transportation of large amounts of hot water is inconvenient (Ascard, 2007).

4. Inundation. Inundation is flooding of fields and thus creating anaerobic conditions in the soil underneath in which apart from physical also chemical and microbial changes take place. The oxygen concentration drops within 1 or 2 days to practically zero. Chemical changes are the production of greenhouse gases like carbon dioxide, ammonia and methane. Also organic acids are produced and hydrogen sulfide (Maas, 1987). It is concluded in his paper from literature about flooding that soil disinfestation is caused more by an indirect effect due to an increase of toxic substances produced by anaerobic microbiological activity in the soil, rather then by lack of oxygen. However, low oxygen levels lead to inactivation of plant parasitic nematodes which may affect survival of these nematode populations (Maas, 1987). The same conclusion was drawn by Spaull et al. (1992). In tests with flooding whether or not together with organic amendments flooding was more effective against *Globodera pallida* than anaerobic conditions alone. Hydrogen sulfide was produced at a higher rate in amended flooded soil than in non-amended soil and led to increased efficacy.

The method was applied in the USA for nematode control and was alternated with drying of soils. In banana fields in Surinam heavily infested with the burrowing nematode *Radopholus similis* flooding was applied for 4-5 months (Maas, 1987).

In flooded rice fields the root lesion nematode *Pratylenchus zea* could be controlled but not the root-knot nematode *Meloidogyne graminicola*. The latter multiplied even more in wet rice fields than in dry rice fields although the nematode was present in both rice cropping systems (Prot and Matias, 1995).

Since the 1980s inundation became a new method in the Netherlands and is applied in ornamental bulb cultures. Until then bulb soils were mainly disinfested with fumigants.

In the Netherlands ornamental bulb crops are grown on sandy soils with high water tables and regulated water supply which enables flooding of soils. In Dutch research after 10 weeks of flooding at 17°C the stem nematode *Ditylenchus dipsaci* was completely eradicated (Muller and van Aartrijk, 1989).

Inundation proved to have a selective effect on pathogenic fungi; *Rhizoctonia solani* was not affected by flooding, *Stromatinia* partially whereas *Sclerotinia* was eliminated by this method. Efficacy against weeds was also selective. Parasitic nematode species like *Ditylenchus dipsaci* and *Pratylenchus penetrans* could be controlled by flooding but most beet cyst nematodes (*Heterodera* spp.) survived inundation. A temperature of 22°C was more effective than 17°C which leads to application in Dutch summer season (van Zaayen, 1985).

Trichodorids which are vector for tobacco rattle virus (TRV) could not be eliminated by inundation completely. Even after 16 weeks of inundation 2% Trichodorids survived treatment which makes this method unsuitable to prevent transmission of TRV by Trichodorids (Asjes et al., 1996). The efficacy against *Pythium* is discussed; in the Netherlands flooding was not effective against *Pythium* species occurring in Dutch flower bulb fields while in literature control of *Pythium* species from vegetable fields was reported by flooding which suggests species specific efficacy (van Os, 2003).

Twenty-First Century

1. Hot Air Treatment. A new development in physical soil disinfestation in the current century is the application of hot air. The method has been developed in Israel. The method is based on blowing extremely hot air into rotavating soil. Soil particles are thrown above soil surface by a rotovator and are treated in a heat chamber with hot air. Only the outside of each individual soil particle is thus shortly treated with hot air but after treatment soil is cooled down immediately.

After building and testing various prototypes the inventors reached an optimal speed of blowing air and rotavating and used the latest prototype commercially for some years empirically in fields, infested with plant parasitic nematodes or pathogenic fungi. Considerable improved growth response (IGR) was noticed in several crops like potato, cauliflower, kohlrabi and the flower *Esclepia*.

In the Netherlands naturally infested fields infested with parasitic nematodes and fungal pathogens with global importance were selected for research with this Israeli prototype. Three plant parasitic nematodes were tested: the root knot nematode *Meloidogyne fallax*, the potato cyst nematode *Globodera pallida* and the root lesion nematode *Pratylenchus penetrans*. Next to the parasitic nematodes three fungal pathogens were treated with hot air: *Synchytrium endobioticum*, causal agent of potato wart disease and the wilting diseases *Fusarium oxysporum* f.sp. *asparagi* and *Verticillium dahliae.*

Soil type of the infested fields varied from sand to clay loam and from 2 to 9% organic matter content. In the *Meloidogyne* infested field efficacy of hot air treatment was compared with standard Dutch application of the fumigant metam sodium by rotary spading injection and steam sterilization with a mobile steam device.

Nematode counts in the Netherlands showed that after hot air treatment, cold air and in untreated plots *Meloidogyne* was not eliminated by the treatments. Steam sterilization and metam sodium eradicated nearly all nematodes in the soil. In all treatments the remaining *Meloidogyne* nematodes multiplied on the roots of potato crop planted half a year after soil disinfestation. A minor potato yield increase after hot air treatment was not significant whereas increase in yield after metam sodium and steam sterilization was statistically reliable. In a bio assay in pots with treated soils however young tomato plants produced heavier fruits both in hot air treated as well as in steam sterilized soil. Nematode counts of *Pratylenchus penetrans* were not reduced by hot air treatment and nematodes multiplied on potato. Neither was any effect on potato yield noticed. Also juveniles of the potato cyst nematode *Globodera pallida* were not eradicated by hot air treatment. Fungal pathogen counts of *Fusarium oxysporum* f.sp. *asparagi*, *Verticillium dahliae* and *Synchytrium endobioticum* were not affected after hot air treatment (Runia et al., 2005).

After these disappointing results in the Netherlands under temperate climatical conditions scientific trials were performed on *Meloidogyne* spp. infested fields in Israel and Cyprus to establish the efficacy of this method on sand (IL) and sandy loam (CY) under Mediterranean climatical conditions. The efficacy of hot air was compared with the fumigants methyl bromide (500 kg/ha) and metam sodium (500 L/ha) both applied by drip irrigation. Negative references were cold air treatment by only rotovation of soil particles and an untreated control. In both Mediterranean countries squash was grown in plastic tunnels after treatment with these disinfestation methods.

In Israel, hot air treatment increased squash yield (A-quality) by 90% from 15 ton/ha to 29 ton/ha, in comparison with cold air. Second best results were achieved by methyl bromide treatment, which increased yield by 70%. Metam sodium increased marketable yield by 22%. In Cyprus, application of hot air resulted in a 150% increase in yield, compared with cold air treatment and the untreated control. This was remarkable because visually in the vegetative stage there were no differences in the development of the plants. Height of the plants and the colour was for all the treatments the same.

The increase in yield cannot be explained by eradication of the nematodes because *Meloidogyne* counts performed in Cyprus indicated that second-stage juveniles in the soil were not reduced by hot air treatment. Moreover root assessments in both countries showed that after hot air treatment root-knot nematodes infested roots of squash plants and as reaction to this infestation caused galling damage as much as in the untreated or cold air treated soil. In contrast, root galling was nearly eliminated and hardly any galls were formed on roots after both metam sodium and methyl bromide treatment.

After hot air application in combination with rotavating the soil to a depth of 30-35 cm weed germination was retarded long enough not to interfere with the development of squash seeds into mature plants. In cold air treated plots some weeds did occur but they had no influence on the development of squash. In untreated plots squash seedlings were overgrown with weeds. Weed development obviously can be restricted by soil tillage and to some extent hot air treatment may contribute to control seed germination (Runia et al., 2006).

After the successful results in the Mediterranean countries the Israeli prototype was replaced by a Dutch hot air device based on this prototype which was tested in the Netherlands in radish in a non-infested sandy soil. Radish tubers grown in hot air treated soil produced a higher tuber weight and increase in yield was higher than in steam sterilized soil by negative pressure steaming. Both soil treatments resulted in higher radish yields in comparison with untreated soil of which in hot air treated soil radish yield was significantly highest (Runia et al., 2007).

It can be concluded that the general concept of soil disinfestation is not applicable to hot air treatment. Any positive effect in yield can not be explained by reduction or elimination of pathogen or pest counts.The question rises even whether *Meloidogyne* nematodes were the main reason for poor harvests. Squash yield increase in hot air treated soils was even higher than in methyl bromide treated soil although in roots were heavily infested with *Meloidogyne* nematodes whereas roots were nearly without galls in methyl bromide treated soil. Obviously the increase in production of squash after methyl bromide is realised via another route than after hot air treatment. Another fact supporting the hypothesis that *Meloidogyne javanica* is not the main reason for poor yields is that although metam sodium eliminates the nematodes, yield was statistically not different from the control treatment with cold air.

In all trials performed counts of fungal pathogens and plant parasitic nematodes were not reduced by hot air treatment which means that soils are not disinfested. Changes in chemical, microbial and/or physical properties of the soil may explain the phenomenon of improved growth response which is a crucial factor for growers.

Until the underlying process of hot air treatment is understood after scientific research, recommendations cannot yet be made in which crops and under which climatical and soil conditions this method will be most effective. Technically this method is ready for practical application. Advantages of hot air application are a significant reduction in energy use of approximately 80 to 90% in comparison with mobile steam sterilization and a capacity sufficient for both intensive and extensive agriculture.

2. Radiation. New developments in the Netherlands are radiation of soil with micro waves. Microwaves are electromagnetic radiation with frequency ranges between 300 MHz and 300 GHz. Wavelengths vary between 1 mm and 30 cm. The mechanism of radiation is that water molecules absorb certain frequencies which cause oscillation within the molecules and thereby increase in temperature; so-called dielectric heating (Vela-Múzquiz, 1983; Ascard et al., 2007). Micro wave radiation has been studied since 1940 and the potential of micro wave radiation eliminating weeds, seeds, insects and nematodes was established in several studies. Micro wave radiation was most effective when seeds were moist but germination rate decreased in that situation (Vela-Múzquiz, 1983).

Ascard (2007) also mentioned that microwave radiation can be effective if humidity of the target seeds or pests is high and added that soil humidity should be low. Promising results are achieved in laboratory experiments and at the soil surface but Ascard states that the efficacy in killing soil-borne weeds seeds is limited under field conditions. Microwave radiation does not penetrate in the soil deeply but only treats the upper soil layer, especially in moist soils where radiation waves are absorbed rapidly. On the other hand for small amounts of soil micro wave radiation might be practical (Ascard et al., 2007).

This hypothesis was confirmed in trials with small amounts of peat substrate infested with *Fusarium oxysporum* f.sp. *melonis*. The fungus could be completely irradicated at an energy level of ≥24000 J with 2.45 GHz microwaves (Soriano-Martín et al., 2006).

Until recently micro wave radiation focused mainly on disinfestation of soil surfaces. The last few years a Dutch company has developed a mobile microwave device as alternative for sheet steaming. Equal distribution of the microwaves and hence heat distribution in the soil downwards to a depth of 50 to 70 cm is still under investigation (Runia, pers. commun.) These tests will be decisive whether this machinery will be suitable for practical use and at what costs (www.Koppertmachines.nl/agritron).

3. Anaerobic Soil Disinfestation. Anaerobic soil disinfestation (ASD) with incorporation of large amounts of fresh organic matter in soil followed by irrigation and then sealing off the soil with virtually impermeable film (VIF) is a method developed in the Netherlands. The method is based on the principle that under gastight plastic anaerobic conditions are created which converts organic material into other organic compounds. These compounds are supposed to be lethal to soilborne pathogens and pests at the concentrations realized. Moreover the lack of oxygen may support the efficacy (Blok et al., 2000). The method is applied successfully in the Netherlands mainly in asparagus production crops and in fields allocated for strawberry runner production. These crops are grown on sandy soils with low organic matter content. ASD with grass as organic source has proven to be effective against parasitic nematodes as well as against fungal soilborne pathogens like *Fusarium oxysporum* spp. and *Verticillium dahliae*. The method is applied in summer during 6 weeks to guarantee temperatures high enough and a long exposure time to anaerobic conditions for adequate digestion of the incorporated organic material. Although effective under these conditions the method is implemented on a small scale due to several factors. The most important factor however is the lack of fundamental information about the mode of action of ASD which hampers the progress into an effective reliable soil disinfestation method for arable crops and field vegetables. When data are available about which compounds at what concentrations are responsible for the efficacy and how important anaerobic conditions are, recommendations for application may be more specific. For a successful introduction of ASD in rotations of arable crops, other field vegetables and protected cultivation several questions have to be answered. Apart from knowledge about effective digestion compounds other factors like soil temperature, pH, soil fertilizer status, soil organic matter, soil humidity and type of organic matter to be incorporated have to be studied. The range of all these factors within efficacy can be guaranteed needs to be known before implementation on (inter)national scale can be expected. In 2009 a new research program was funded by the Dutch Ministry of Agriculture, Nature and Food Quality to achieve fundamental information about the mechanism behind ASD. Applied Plant Research of Wageningen University and Research has started research on advanced ASD in order to realize an effective, environmentally friendly and affordable soil disinfestation method in the near future based on this fundamental information. Within this project a new and promising Dutch development in ASD with incorporation of several defined products with varying C/N ratio in soil is compared with incorporation of fresh grass. The mechanism of ASD will be studied by measuring oxygen and other gases like methane, ammonia and nitrous oxide. Ammonia has proven to be lethal against root lesion nematodes *Pratylenchus penetrans* (Min et al., 2007). Apart from gases also fatty acids like (iso)butyric acid, maleic acid, (iso)valeric acid, acetic acid, lactic acid, citric acid, propionic acid and formic acid are analysed in treated soils. Nematicidal effects of fatty acids have been demonstrated recently by several research groups (Abdel-Rahman et al., 2008; Mahran et al., 2008; Xiao et al., 2008). In our research the correlation between gases, fatty acids and efficacy will be studied against root lesion nematodes *Pratylenchus penetrans*, potato cyst nematodes *Globodera pallida* and *Verticillium dahliae* in sandy soil as well as in organic soil. Microbial shifts have to be studied when promising products are selected for field application in order to understand the mechanism behind anaerobic soil disinfestation.

CONCLUDING REMARKS

For all soil disinfestation methods it is crucial to know under what conditions they are effective and all advantages and disadvantages of these methods must be known in order to be able to establish their value for growers. Most of this knowledge is disclosed by publications and presentations on symposia and congresses, etc. Worldwide transfer of knowledge enables researchers worldwide to develop best strategies applicable to their countries.

Reliable and sustainable soil disinfestation techniques or methods should be developed which are affordable for growers and are effective against specified soil-borne diseases growers want to control. Sustainable methods require relatively low energy input and effects on the environment are minimized. It is a challenge to develop such strategies worldwide in order to facilitate growers with a tailor-made approach to cope without methyl bromide.

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