Soil Disinfestation: From Soil Treatment to Soil and Plant Health

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Abstract

This feature article tracks 100 years of soil disinfestation, from the goal of eradicating soilborne pathogens and pests to much milder approaches, aimed at establishing a healthier soil, by favoring or enhancing the beneficial soil microflora and introducing biological control agents. Restrictions on the use of many chemical fumigants is favoring the adoption of non-chemical strategies, from soilless cultivation to the use of physical or biological control measures, with more focus on maintaining soil microbial

diversity, thus enhancing soil and plant health. Such approaches are described and discussed, with special focus on their integrated use.

Keywords: biofumigation, biological control, disease management, epidemiology, fumigation, fungi, increased growth response, pathogen survival, plant health, soil health, soil microbiome, soil suppressiveness, solarization, system-based approach

“If we can destroy or inhibit the soil pathogens we wish to control without indiscriminately destroying large groups of soil organisms willy-nilly, so much the better. If we can accomplish our purpose in the soil with only a minimum increase of substrate and available energy, so much the better. Specificity in soil toxicants is a desirable thing. A good hunter uses a rifle instead of a shotgun.”

W. A. Kreutzer (1963)

Soilborne Pathogens: A Never-Ending Challenge for Intensive Horticultural Systems

Soilborne pests (pathogens, weeds, arthropods, and parasitic plants) can cause heavy losses to all crops, affecting both yield and quality, with severe economic, environmental, and social consequences. Soilborne pathogens have many mechanisms for survival and dissemination, including many forms of resting structures in soil. Moreover, certain *Fusarium* pathogens form aerial spores, which make their management especially challenging. Plant diseases caused by these pathogens are especially severe and devastating under monoculture. The inoculum builds up rapidly in the soil under

monoculture conditions due to its frequent enrichment with infected tissues (Katan and Gamliel 2012b). Part of soilborne pathogens' life cycles occurs in the soil (except when the inoculum comes from external sources), which make their management difficult. An effective control agent has to reach the inoculum at all desired soil depths while being exposed to the biological, chemical, and physical processes taking place in the soil, which diminish its effectiveness; this is one of many major challenges facing soil disinfestation (Katan 2000).

Soilborne pests garnered significant attention during the second half of the 19th century, with the outbreak of the soil-dwelling arthropod pest *Phylloxera*, which caused severe damage to vineyards in Europe, especially France, and demonstrated the devastating capacity of soilborne pests. This catastrophic event triggered the development of chemical soil disinfestation in 1870, in France, by introducing carbon disulfide (CS₂) (Wilhelm 1966). Soil heating by steam was also developed in Europe. Another very effective and durable solution was achieved with resistant rootstocks—one of the most remarkable examples of the benefit of using resistance to manage pests. For the first half of the 20th century, chloropicrin was the major fumigant and it was used successfully with many crops. From the 1950s on, methyl bromide (MB) became the major fumigant in the world until it was phased out in 2005 (Gullino et al. 2003; Katan 1999).

The concept underlying soil disinfestation is a significant reduction of pathogen populations to the desired soil depth before planting by introducing a control agent that penetrates the soil—usually a volatile or liquid-based agent, or heat. The main difficulty is adjusting an appropriate dosage that is effective at pathogen control but has a minimal detrimental effect on desirable biotic and abiotic components of the soil. Moreover, this adjustment must be made individually for every soil, crop, and agricultural system. The agent must have dissipated by planting time because it is usually toxic to the crop. Unfortunately, the possible effects of soil disinfestation on soil pathogen suppressiveness, although observed in practice, have never

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been studied intensively. It is not correct to use the term “soil sterilization,” because the aim is not to eradicate the soil biota. Soil disinfestation is effective only if reinfestation of the previously disinfested soil by pathogens is minimized. Therefore, effective sanitation, especially in greenhouses, should be part of the disinfestation procedure. Other important factors to consider are the mode of application, as discussed further on, and the cost of the treatment. Therefore, an effective method of soil disinfestation has many requirements; it is not surprising, then, that only a few effective methods of soil disinfestation have been developed. Kreutzer’s statement (in the box above), made in 1963, remains valid, and should be further pursued by researchers.

Chemical Soil Fumigation: CS₂, MB, and Others—Efficacy, Evolution, Advantages, and Limitations

Worldwide, soil fumigation reflects an industrialized approach for the control of soilborne diseases. Notably, it is an essential component for secure food production and supply in intensive crop-production systems. In addition, soil fumigants are frequently used for the shipment of pest-free products, and for quarantine purposes. The development of soil fumigants started more than 150 years ago, targeted to insect and nematode control. In 1927 to 1928, chloropicrin was available from government stocks (used in World War I as tear gas) for soil fumigation and was used to control nematode infection in pineapple plantations. Johnson and Godfrey (1932) reported effective control of nematodes and significant increases in fruit yield, and that the value of the increased yield was higher than the cost of the fumigation (Godfrey 1935; Johnson and Godfrey 1932). Taylor and McBeth (1941a) tested the efficacy of MB, and it appears that they established its dominance over all other soil fumigants for the following 50 years. The advantage of MB was its efficacy at controlling a wide range of soilborne organisms, including nematodes, fungal pathogens, and many weeds. However, its expense limited its use to high-value crops. Taylor and McBeth (1941a) also established the method of releasing the fumigant as a gas in tile lines buried under soil covered with glue-coated paper sheets, to minimize its escape. Later fumigants included ethylene dibromide, 1,3-dichloropropene, and metam sodium (Wilhelm 1966). Following the publication by Wilhelm and Koch (1956), application of soil fumigants became common preplanting practice for most vegetable crops in intensive horticulture. Indeed, from 1960 to 1990, the use of soil fumigants expanded dramatically as the major strategy to achieve healthy crops and improved yields. Wilhelm and Paulus (1980) indicated increased production of strawberry fruit in California following repeated use of MB.

It is clear that the introduction of nonselective agents such as soil fumigants into the soil will significantly change soil microbial communities. In fact, soil fumigants kill many microorganisms beyond the target pests. Most fumigants reduce the populations of many bacteria, including those involved in element cycles in the soil (e.g., nitrogen, sulfur, and so on). These changes affect plant growth (positively or negatively) and the pathogens’ ability to reestablish in disinfested soils.

In the last 50 years, a gradual phaseout of a number of fumigants has occurred due to negative ecological, toxicological, and environmental effects. Today, the list of fumigants that are registered and available for use in various cropping systems is very limited (e.g., 1,3-dichloropropene, metam sodium, dazomet, and chloropicrin). These fumigants control a narrower range of pests than many of the now-banned products. Moreover, new compounds for soil fumigation are not being registered, for toxicological and environmental reasons. Most of today’s commercial fumigants are characterized by inferior physical and chemical properties compared with MB (e.g., boiling point, vapor pressure, and water solubility). The limited currently available fumigants, particularly in Europe, combined with public awareness call for an intensive effort toward the careful use of fumigants in soils together with other strategies to achieve optimal results with minimal impact on soil health.

Nonchemical Strategies and Tools for Soil Disinfestation

Today, the focus is on maintaining soil microbial diversity, thus enhancing soil and plant health (Meng et al. 2019). Such approaches, which were not considered practical only 50 or 60 years ago, are now enjoying much broader acceptance. This is due to major investments in research in the last 30 years, as well as a much better understanding of the soil microflora and microbiome (Larkin 2015). In the following sections, several nonchemical strategies are considered separately but with special attention to their integrated use.

Physical methods. *Steam.* Steam was initially developed as a soil and substrate treatment for ornamentals and, later, for other crops, mostly those grown in greenhouses. This treatment (100°C for 30 min) is very effective against pests and weeds. However, it is costly and of great environmental concern, due to the labor involved and high fossil fuel consumption (Samtani et al. 2012). Due to its high microbiological impact on nontarget organisms, as well as possible physicochemical modifications of the steamed soil, an interval between treatment and planting is required to avoid phytotoxicity. To expand its usage and reduce its cost and negative impacts, new application technologies have been exploited, with significant cost reductions (Runia 2000). Attempts to reduce the maximum temperature reached or the length of the treatment, in relation to soil or substrate type (sandy versus loamy soil, for instance), were successful and are of practical interest for short-term crops (such as leafy vegetables), against pathogens colonizing the upper layer of the soil (such as *Rhizoctonia solani*). Moreover, bench treatment can be carried out for shorter times, because the treated soil will quite easily reach the needed effective temperature (Gullino et al. 1998).

Improved application methods aimed at expanding outdoor use were tested, such as subsurface steam injection, surface steam application by iron pan, and sheet steaming (Lu et al. 2010b). Steam injection and pan steaming were more effective and feasible than sheet steaming at a soil moisture of 60% field capacity (Lu et al. 2010b) (Fig. 1). Soil moisture did not influence pathogen suppression in the upper soil layer with the pan steaming treatment. However, at 80% field capacity, all tested pathogens were completely eradicated. Steam injection also strongly controlled the tested fungi at 40 and 80% field capacity. Heat can be released through injection under a metal pan at different soil depths. Injection can heat soil at a 19-cm depth, whereas the pan distribution system can reach depths of 9 to 13 cm (Lu et al. 2010b). Such results suggest the use of pan steaming for short-cycle intensive crops such as lettuce and other leafy vegetables, which are harvested before the risk of pathogen reinfestation. Deeper steam injection may be adopted for long-term crops, because it results in strong pathogen reduction in the deepest layers as well, as a function of injector length. Models using thermal death kinetics parameters for selected pathogens

Fig. 1. Soil disinfestation in open field with a mobile steam injection machine (Agrolinnova).

(e.g., *Fusarium oxysporum* f. sp. *basilici*) have been developed to predict pathogen reduction and to design the most effective treatment duration and temperature during soil steam disinfection (Gay et al. 2014). Although there is no one answer for all problems, different steam-distribution systems can be used to suppress different pathogens according to the crop system. However, adoption of the treatment by commercial growers requires well-trained extension service support to differentiate among those options.

Soil solarization. This technique was developed well before the phaseout of MB (Katan et al. 1976). Largely exploited all over the world, wherever climatic conditions allow it, soil solarization has proven effective and reliable for the control of many soil pests and weeds (Katan and DeVay 1991, Katan and Gamliel 2012a) (Figs. 2, 3, and 4). Over the years, it has been adapted for application in greenhouses in cooler areas as well (Gamliel and Katan 2012; Garibaldi and Gullino 1991). Microbial activity against soil pathogens can weaken propagules during solarization or suppress their reestablishment in the soil and plant roots after treatment. These synergistic effects have been observed for several soilborne fungi (*Verticillium* spp., *R. solani*, *Pythium* spp., *Sclerotium rolfsii*, and others), nematodes, and many weeds (Gamliel 2000; Mattner et al. 2008). Since its development, soil solarization has been applied in more than 70 countries. The advantages of soil solarization are its simplicity, ease of application, and lower cost compared with most other soil-disinfection technologies. Limitations of this method are its climate dependence and the fact that, during its application, which lasts 3 to 6 weeks, the soil is without crops. Additionally, it does not consistently control certain pathogens, such as nematodes in Florida

(Chellemi et al. 2016). To make solarization more appealing to growers and adaptable to more situations, it has been combined with other methods of control to improve its efficacy, shorten its duration, and expand its use outdoors and in cooler areas. The combination of shorter periods of soil solarization (2 weeks) with reduced application rates of fumigants such as dazomet or metam sodium has been effective, and this may increase the number of growers who will consider using soil solarization (Eshel et al. 2000). Soil solarization also works well with biological control agents when they are applied after termination of the solarization process (Gamliel 2020); however, sometimes results regarding this combination were inconsistent (Chellemi 2010). In other words, soil solarization can be combined with many other methods in an integrated pest management (IPM) approach.

Soil amendments for biofumigation and anaerobic soil disinfection. *Soil amendments.* Organic and inorganic amendments (compost, manure, crop residues, and so on) are commonly used in traditional agricultural systems to provide the crops with nutrients and improve soil fertility. They can also help manage soilborne pathogens due to several biochemical and biological changes associated with their incorporation into the soil (Noble 2011). Such features, first exploited in ornamental crops (Hoitink et al. 1991), are being increasingly investigated for many other crops as well (Bonilla et al. 2012). When added to soil, amendments such as cruciferous residues and manure are subject to microbial degradation, thus indirectly encouraging biological control.

The use of *Brassica* spp. as fresh plant material (green manure) is a type of biofumigation that involves the release of isothiocyanates, thiocyanates, nitriles, or oxazolidinethiones that control multiple soilborne pests (Larkin and Griffin 2007). It is particularly exploited in less intensive agricultural systems. Biofumigation can be achieved by incorporating green manure, seed meals (a byproduct of seeds crushed for oil), or dried plant material treated to preserve isothiocyanate activity, or by using *Brassica* spp. in intercropping. A significant reduction in the severity of *Fusarium* wilt of lettuce, caused by *F. oxysporum* f. sp. *lactucae*, was observed after the application of *Brassica carinata* pellets. In contrast, *Brassica* green manure, as well as cattle and chicken manure, provided only partial control of *Fusarium* wilt (Gilardi et al. 2016). The same study showed an increase in *Pseudomonas* spp. populations, which are beneficial for suppressing soilborne pathogens, as well as a significant reduction in the total fungal population and pathogen density in the growing medium after two consecutive lettuce crops (Gilardi et al. 2016). When compost and *Brassica* seed meal were used alone or combined with a treatment simulating solarization by increasing the temperature of soil artificially infested with *F. oxysporum* f. sp. *basilici* and *F. oxysporum* f. sp. *conglutinans*, causing wilt of basil and rocket,

Fig. 2. Farmer preparing the soil for soil solarization (AgrolInnova).

Fig. 3. Soil solarization in open field (Agricultural Research Organization, Volcani Center).

Fig. 4. Control of the parasitic plant broomrape by soil solarization in a tomato field. A nonsolarized row is visible in the center, with solarized plots to either side.

aerobic mesophilic bacteria and *Pseudomonas* spp. populations were generally enhanced compared with the untreated control (Ferrocino et al. 2014). Moreover, soil amendments for lettuce were effective against *F. oxysporum* f. sp. *radicis-cucumerinum*, the causal agent of root and stem rot of cucumber (Pavlou and Vakalounakis 2005). *Brassica* green manure and *Brassica* defatted seed meal were successfully applied in combination with grafting and soil solarization against Verticillium wilt of eggplant and Fusarium wilt of lettuce and basil (Garibaldi et al. 2011).

The use of organic soil amendments for soilborne disease suppression is not widely implemented because of concerns about potential side effects. Several disadvantages (such as dependence on environmental conditions; the nature and incidence of the pathogens; and type, consistency, and availability of the product used) make large-scale adoption of these methods difficult, especially for protected crops. In addition, high labor costs, the large amount of organic amendments required (50 to 70 ton/ha), and the possible release of phytotoxic compounds resulting in a longer waiting period between treatment and planting all limit practical application. The incorporation of grass with plastic mulching proved effective against many soilborne pests and pathogens through the creation of anaerobic conditions (Goud et al. 2004). However, some studies have indicated that the effectiveness of organic amendments, including *Brassica* residues, is variable and, in some cases, can even enhance disease severity. The negative effect of these amendments may result from the increase in pathogen inoculum potential when the substrate serves to sustain saprophytic growth of pathogens (Manici et al. 2004), or by the *Brassica* amendments themselves, which can carry soilborne pests (Lu et al. 2010a). Seed meals have been tried as organic amendments but some studies have shown a possible negative effect due to an increase in the initial *Pythium* sp. composition (Mazzola et al. 2012).

Compost. Compost is commonly used as a soil amendment to increase organic matter content and fertility by improving physical, chemical, and biological soil conditions (Hoitink and Fahy 1986). Composts have the advantage of significantly increasing soil organic matter content, a key soil-quality indicator that is declining in many regions worldwide (Bellamy et al. 2005). Additional benefits of compost addition to soil are promotion of soil biological activity, reduction of erosive losses, decrease of bulk density, improvement of structural stability and nutrient availability for plant uptake, and increased water-holding capacity (Shiralipour et al. 1992; Tejada and Gonzalez 2007) (Fig. 5).

Compost, derived from the decomposition of organic material such as recycled plant waste, biosolids, fish, or other organic material, is gaining importance not only as a soil amendment but also for its suppressive potential. Compost suppressiveness of soilborne pathogens can be exploited for both potted plants and field crops, and can be combined with other management strategies such as soil solarization and grafting. Induced resistance by compost has also been observed and, consequently, tested for the control of some pests (Bonanomi et al. 2018; Hadar 2011; Pugliese et al. 2015). Compost suppression of soilborne pathogens has been demonstrated in several studies with a number of soilborne diseases, benefiting growers (Bonanomi et al. 2018; Garibaldi 1988; Hadar 2011; Hoitink and Boehm 1999; Hoitink and Fahy 1986; Noble and Coventry 2005; Pugliese et al. 2015). In field trials, compost was shown, in most experiments, to be suppressive with an application rate of at least 15 tons/ha. Disease suppressiveness depends on soil or substrate properties, including both abiotic and biotic parameters (Janvier et al. 2007; Mazzola 2004). Quality standards for compost are required to avoid phytotoxic effects on plants and reduce variability in disease control. Consequently, it is also important to define and use agronomic tests to assess compost quality and suppressiveness to plant pathogens.

Water extracts from composts were also shown to suppress several soilborne pathogens (El-Masry et al. 2002). Compost acts as a food source and shelter for the antagonists that compete with plant pathogens or parasitize them, for the beneficial microorganisms that produce antibiotics, and for those microorganisms that induce resistance in plants. High-quality compost should contain disease-suppressive

microorganisms (Hadar 2011; Noble and Coventry 2005). Variability of disease suppression also depends on the pathosystem. A compost from wood chips and horse manure stimulated disease caused by *R. solani* on cauliflower but suppressed it on pine (Termorshuizen et al. 2006). Success or failure of compost for disease control depends on the nature of the raw materials from which the compost was prepared, on the composting process used, and on the maturity and quality of the compost (Termorshuizen et al. 2006). Composting temperatures are also important for the eradication of plant pathogens and nematodes (Noble and Roberts 2004). Fortifying composts with beneficial microorganisms can improve their success rate by increasing the efficacy and reliability of disease control (De Clercq et al. 2004). Compost can be combined with a number of other control methods. Its combination with grafting, for instance, was successfully exploited against *Phytophthora capsici* on bell pepper (Gilardi et al. 2013).

Beneficial shifts in the microbial community following the application of soil amendments and biofumigation have been reported (Bellini et al. 2020; Gamliel 2020; Meng et al. 2018). New approaches to monitoring how soil microbial community structures change as a result of organic amendment may lead to a better understanding of which changes are responsible for conferring disease-suppressive effects. Increasing the opportunities to use compost in agriculture and, in particular, horticulture as a (potting) substrate for plants will contribute to the recycling of wastes and to reducing the use of nonrenewable fertilizers.

Anaerobic soil disinfestation. Another interesting soil disinfestation method is the so-called anaerobic soil disinfestation (ASD), also referred to as “biological soil disinfestation” (Blok et al. 2000) and “reductive soil disinfestation” (Shinmura et al. 1999). The method involves the incorporation of organic amendments—possibly produced locally—that include a labile carbon source, tarping with gas-impermeable film, and saturating the soil pore space to create anaerobic conditions, which favor decomposition of the amendments

Fig. 5. Compost application in an experimental trial (Agrolnnova).

by anaerobic and facultative anaerobic bacteria (Roskopf et al. 2015). Studies carried out in different geographical areas and different soils have shown important changes in microbial communities associated with the efficacy of the method (Mazzola et al. 2018; Momma 2015; Ueki et al. 2018). The type of amendment influences efficacy of the treatment, contributing to the accumulation of nutrients as well as decreasing potential losses of nutrients to the environment (Di Gioia et al. 2017; Maeda et al. 2016). In an attempt to address the many issues that still hinder the practical application of ASD, a multidisciplinary team of researchers conducted regional ASD field trials in the United States in various locations with different crops. The results were inconsistent, depending on many factors (Roskopf et al. 2020). In Florida, ASD conducted with composted poultry litter and molasses provided tomato growers with a nonfumigant soil disinfestation method with crop yields comparable with those obtained with chemical soil fumigation. A thorough evaluation of nutrient input requirements for the use of ASD, which are crop and soil type specific, is needed to ensure that the nutritional needs of the crop are met while preventing nutrient oversupply. Information on the generation of nitrous oxide in conventional cropping systems is also needed, as is an elucidation of how the carbon content and carbon-to-nitrogen ratio of amendments influence the generation of greenhouse gases (Maeda et al. 2016).

Research is now focusing on the development of a systems approach in which the residual nitrogen from the vegetable crop can be used to produce the carbon input for the following ASD cycle. Cover crops and crop residues did not give good results for ASD on tomato in Florida (Roskopf et al. 2020) but they did work in other locations and with other pathosystems (Messiha and van Diepening 2007; Mowlick et al. 2014). In coastal California, where ASD was adopted by strawberry growers on a commercial scale using rice bran as the carbon source, the main constraint was the rising cost of the amendment. Large experiments carried out on strawberry, using triticale and mustard mixed with rice bran as carbon sources, were effective as summer cover crops against *F. oxysporum* f. sp. *fragariae* and in the fall against *Verticillium dahliae* (Muramoto et al. 2020), and this mixture reduced the cost of the ASD. In The Netherlands, “soil resetting” has been patented as a new approach in ASD, using carbohydrates and proteins as probiotics (Meints 2020). This method, called “Herbie”, stems from the observation that amendments based on proteins are more effective than those based on high-carbon content, achieving disease suppression of more than 99%. Research conducted at multiple sites on the factors governing nutrient cycling in relation to ASD treatment suggests that the risk of nutrient loss is not higher than that associated with standard chemical soil fumigation. (Di Gioia et al. 2020). Moreover, there is evidence of both short- and long-term effects on soil fertility, with positive effects on plant growth and crop yield (Di Gioia et al. 2020). Long-term experiments on organically grown strawberry in California showed that crop rotation with broccoli prior to growing the strawberry plants, and the use of ASD, controlled *V. dahliae*. Rotation with lettuce, on the other hand, increased *Verticillium* wilt (Shennan et al. 2020). When ASD was tested in controlled production systems against several pathogens, it provided variable results. For instance, it provided only partial disease control against *R. solani* on lettuce, which was not satisfactory under intensive cropping systems. However, ASD based on the use of species of Brassicaceae and compost as the carbon source, applied in a sandy loam soil, was suggested to be valuable for reducing *R. solani* incidence at temperatures lower than those required for soil solarization or biosolarization (Gilardi et al. 2020).

Taken together, many studies have demonstrated that ASD, carried out in the traditional way or with the new concept of soil resetting, requires profound adaptation to crop, soil, climate, and agricultural systems. All of these factors make the technique scientifically challenging and complicated to be implemented under practical conditions (Roskopf et al. 2020).

Interaction of soil disinfestation with host resistance and grafting. Commercial cultivars that are resistant to or tolerate one or more soilborne pathogens are available for many vegetable crops

(Cuartero et al. 1999; Lefebvre et al. 2020) (Fig. 6A and B). Development of improved strawberry cultivars with resistance to root and crown rot diseases caused by *P. cactorum*, *Macrophomina phaseolina*, and *Colletotrichum* spp., as well as increased fruit quality, helped strawberry growers who were affected by the MB phase-out (Li et al. 2020). However, resistant genotypes are not always completely protective under field conditions that are highly favorable to disease development. Under severe infection of crops, new pathogen races can appear and infect the resistant cultivar. Moreover, resistant plant cultivars commonly provide protection against a narrow spectrum of pathogen species and races but they do not protect against other pathogens. The integration of soil disinfestation with resistant plant genotypes can offer wider and improved disease suppression, resulting in enhanced crop production. Haji and Brandle (2001) achieved improved biomass yield of tobacco cultivars resistant to *Thielaviopsis basicola* when they were grown in fumigated soil compared with nonfumigated and infested soil. Soil fumigation enhanced nematode suppression in resistant tomato cultivars and increased tomato fruit yield in a nematode-resistant cultivar grown in infested soil (Regmi and Desaegeer 2020). Moreover, Thies and Fery (2002) showed that fumigation improved total and marketable yield of a resistant pepper cultivar, even though soil disinfestation did not contribute to nematode control compared with the resistant cultivar grown in nonfumigated soil. Vector-mediated pathogens demonstrate another challenging aspect in plant resistance, such as sugar beet rhizomania caused by Beet necrotic yellow vein virus. The virus is transmitted by the fungus *Polymyxa betae* (Scholten and Lange 2000). Sugar beet resistance was inadequate under conditions of severe rhizomania. Hence, the integration of soil solarization to suppress the fungus population, together with use of a virus-resistant cultivar, further suppressed disease development (Lewellen and Wrona 1997).

Fig. 6. A, Susceptibility test and **B,** close up of test against *Fusarium* wilt of lettuce (Agrolinova).

Grafting of vegetables (i.e., fusing a scion from one seedling to a rootstock of a different genotype) can provide plants with tolerance to environmental stresses, including soilborne pathogens (Louws et al. 2010). Grafting is also faster to implement than breeding for plant resistance. Lockwood et al. (1970) demonstrated this concept for effective resistance to *Verticillium* wilt of an eggplant scion grafted on a resistant tomato rootstock. Since then, grafting has progressed to a well-accepted cultural technology for controlling soilborne diseases in intensive production of vegetables (e.g., tomato, cucumber, melon, watermelon, and bell pepper) (Louws et al. 2010). For crops such as tomato and bell pepper, the combination of grafting on resistant rootstock and soil fumigation with dimethyl disulfide or metam sodium was effective (Garibaldi et al. 2008; Gilardi et al. 2013). The added value of combined solarization and grafting was demonstrated with eggplant grown in nematode-infested soil. The combination of grafted plants and solarized soils provided complete protection against disease, whereas grafted plants alone suffered some resistance breakdown of the rootstock due to the high soil temperature (Ioannou 2001). The combination of grafted plants and solarized soil also increased yield. In another study, soil fumigation significantly improved the yield and quality of grafted watermelon fruit grown in soil infested with *M. phaseolina* (Zaaroor et al. 2016). Grafting utilization in the United States in large commercial production systems is limited by the cost of grafted transplants. Economics is likely to slow its adoption in the United States and its coupling with fumigation (Djidonou et al. 2013).

Interaction of soil disinfestation and biological control agents. Extensive study of biological control of soilborne pathogens in the last few decades has led to relatively few practical applications (Bardin and Pugliese 2020; Whipps 2001). The chances of success with biological control may be greater for greenhouse crops because the environment can be controlled to a greater extent than in the field (Albajes et al. 1999). The controlled environment of greenhouses, the high value of greenhouse-grown crops, and the limited number of registered fungicides offer a unique opportunity for the biological control of plant diseases (Bardin and Pugliese 2020; Paulitz and Bélanger 2001; Spadaro and Gullino 2005) (Fig. 7).

Soil disinfestation creates microbial changes in the soil and, more specifically, in the rhizosphere and plant roots. Pathogen control engenders a biological vacuum; hence, vulnerability to reinfestation can occur under extreme disinfestation procedures. This sequence, however, can present an opportunity for successful introduction of beneficial organisms and biocontrol agents.

Solarization in combination with the biocontrol agent *Trichoderma harzianum* was effective against *R. solani* (Chet et al. 1982) and, in combination with *Gliocladium virens*, against southern blight of tomato (Ristaino et al. 1991). Sivan and Chet (1993) combined *T. harzianum* with soil solarization under field conditions to obtain significant control of *Fusarium* crown and root rot of tomato and a significant yield increase. Soil solarization and *Streptomyces griseoviridis*

were effective against *Fusarium* and *Verticillium* wilts and corky root, increasing yield and the range of pathogens controlled compared with the single treatments (Minuto et al. 2006). Combining biological control agents with solarization may also enable shortening of the solarization process and its adoption under marginal climatic conditions. Biological control agents can also be applied after steam disinfestation of soils and substrates, an approach that is broadly applicable to ornamental and vegetable crops (Garibaldi et al. 2014).

Heat-tolerant spores of *Bacillus firmus* can be incorporated before solarization into field soil to obtain improved control of root-knot nematodes (Giannakou et al. 2007). In contrast, *Pasteuria penetrans* does not survive heating above 40°C. Hence, this bacterium can be effective in controlling eggs of *Meloidogyne* in the soil only if applied at the end of the solarization process (Freitas et al. 1997). Incorporating arbuscular mycorrhizal fungi (AMF) following soil disinfestation improved chive productivity and reduced the incidence of pink root relative to untreated plots (Gamliel et al. 2004). Under field conditions, when solarization treatment did not provide maximal control of pink root, AMF application further suppressed this disease in chive. The success of combined application of AMF with solarization may extend to a second crop season, as shown by Megueni et al. (2006).

Healthy plant material and diagnostic tools. The availability of rapid and reliable detection methods is essential to identifying the causal agents of a disease. In this context, new developments are offering growers and extension services many practical and effective tools for early pathogen detection, which can be a highly effective preventative measure (Thomas et al. 2017). With the recent increase in the use of commercial seeds produced outside the area of use, there is greater potential for introducing and disseminating pathogens into areas where they were not previously reported. In the case of leafy vegetables, for example, availability of rapid detection methods to check seed health is very useful (Gullino et al. 2019).

Because traditional pathogen-detection techniques may lack the sensitivity or speed required to detect some seedborne pathogens, molecular techniques have been developed which permit quick and reliable identification. For instance, reliable diagnostic tools are available for many formae speciales and races of *F. oxysporum* from seeds, plants, and soil samples, including amplified fragment length polymorphism, random amplified polymorphic DNA, and restriction fragment length polymorphism (Lievens et al. 2012). Loop-mediated isothermal amplification, based on a sequence-characterized amplified region, was recently developed for the detection of *Fusarium* wilt on lettuce seeds, and in soil and plant material; its specificity was demonstrated with a panel of target and nontarget species (Franco Ortega et al. 2018). Molecular tools allow easier detection of pathogens such as *Phytophthora* spp. (Grote et al. 2002; Ivors et al. 2004; Tomlinson et al. 2007) and in soilless systems (Li et al. 2009; Minerdi et al. 2008).

Stock seeds should be subjected to precautionary decontamination treatments in order to further reduce the risk posed by seedborne pathogens. Chemical seed treatments have been applied successfully to vegetable seeds and are in commercial use for a wide range of crops against different seedborne pathogens (Koch and Roberts 2014; Munkvold 2009). Heat treatments with hot water, aerated steam, or dry heat can be very effective but they need to be optimized due to the different temperatures and times required for different target pathogens and crops (Koch and Roberts 2014; Nega et al. 2003). Nonchemical seed treatments, including the use of resistance inducers, antagonistic microorganisms, and fungal and plant extracts, are especially valuable for seeds produced under organic farming rules (Koch and Roberts 2014); their use is becoming more important due to restrictions in the use of fungicides.

Effects of Artificial Substrates and Soilless Cultivation on Soilborne Pathogens

The use of hydroponics, soilless cultures, and artificial substrates has gained popularity in many countries, despite the significant constraints of high initial investment costs and problems related to

Fig. 7. Evaluation of the effect of biocontrol agents applied to peat soil in an experimental greenhouse (Agrolnova).

the disinfestation, recycling, and disposal of recirculated solutions. Soilless cultivation avoids the need for soil fumigation. This method is now widely used for high-value vegetable and ornamental crops such as rose, carnation, gerbera, basil, spinach, and lettuce (Fig. 8) but it is also expanding to other crops thanks to the adoption of simpler systems and local, inexpensive substrates (Savvas and Gruda 2018; van Os 2017) (Figs. 9 and 10). In theory, soilless cultivation allows starting a production cycle completely free of pathogens. Although such systems are ultimately intended to reduce production costs and maximize profits, precise environmental and nutritional controls which push plants to new limits of growth and productivity can generate chronic stress conditions that are conducive to diseases caused by water-borne pathogens such as *Phytophthora* and *Pythium* spp. (Gullino and Garibaldi 1994; Stanghellini and Rasmussen 1994). The spread of diseases in soilless cultivation systems can be avoided by adopting proper disinfestation methods such as slow sand filtration for the recirculating solution to eradicate pathogens (van Os 2001). Moreover, cultural methods that make plants less susceptible to diseases, as well as the use of diagnostic tools, permit a fully integrated approach in such systems (Garibaldi et al. 2014).

Closed recirculating soilless systems represent an interesting environment for exploiting innovative disease-management options (Fig. 11). For instance, increasing the electrical conductivity of the nutrient solution, use of potassium silicate amendments, and their combination have proven effective against a number of foliar and soilborne diseases such as powdery mildews, downy mildews, several leaf spots, and Fusarium wilts. When associated with high electrical conductivity, potassium silicate promotes deposition of

amorphous silica in the cell wall; furthermore, a possible increase in the production of lignin due to the presence of NaCl could contribute to limiting penetration of pathogens, especially foliar pathogens, into the plant cell.

Soilless systems also allow application of microorganisms that can colonize the root system of plants grown in a strictly controlled environment. The indigenous microflora present in the recirculating solution, along with introduced microbial antagonists, proved effective at reducing disease incidence in soilless systems (Garibaldi et al. 2014; Postma 2004; Postma et al. 2003). Slow sand filtration combined with the application of different antagonistic strains of *Fusarium* and *Trichoderma* spp. proved effective against *Phytophthora cryptogea* in gerbera (Grasso et al. 2003).

Suppressiveness of substrates that are reused in soilless cultivation has many possible practical applications (Clematis et al. 2009). Antagonistic microorganisms that are isolated from and may be better adapted to the soilless systems have proved effective against Fusarium wilt of rocket and tomato (Srinivasan et al. 2009a, b), and strains of *Trichoderma* spp. isolated from soilless systems controlled *Pythium ultimum* on cucumber (Liu et al. 2009) and Fusarium crown and root rot on tomato (Liu et al. 2010). This development in biological control could be exploited to introduce biocontrol agents that are best suited to the specific conditions of soilless cultivation systems.

The Concepts of Soil and Plant Health

Several definitions of soil health have been proposed (Lehmann et al. 2020; O'Neill et al. 1986). Doran et al. (1996) defined soil

Fig. 8. Basil grown soilless in New Growing System (AgrolInnova).

Fig. 9. Tomato transplant grown soilless (Agricultural Research Organization, Volcani Center).

Fig. 10. Soilless grown tomato (AgrolInnova).

Fig. 11. Experimental greenhouse equipped with soilless system (AgrolInnova).

health as the continued capacity of a soil to function as a vital living system, within the ecosystem and land-use boundaries, to sustain biological productivity health. van Bruggen and Semenov (1999) distinguished between short-term disturbances and long-term chronic stresses in the soil. Infestation with pathogens may fall into both of these categories, depending on the nature of the pathogen and the soil, with soil suppressiveness being an important factor.

Resilience is the soil's ability to maintain disease at low levels, despite the presence of the pathogen and favorable environmental conditions (Kibblewhite et al. 2008; van Bruggen and Semenov 2000). Soil suppressiveness can be regarded as naturally occurring resilience, as with Fusarium disease of banana in Honduras (Stotzky and Martin 1963) or Fusarium disease of melon in France (Nel et al. 2006). Soil suppressiveness can also be induced by agricultural practices such as soil solarization (Greenberger et al. 1987), monoculture (Cook and Baker 1983), and compost application (Hoitink et al. 1997; Yogeve et al. 2006). We should regard soil suppressiveness as an important resource for soil health. Soil disinfestation has implications for soil health because harming the activity of soil microbes will also harm suppressiveness. The goal is to find a way to disinfect an already suppressive soil or to avoid disinfestation to retain suppressiveness. We should identify other crop production tools or agrochemicals that address the pests to which the soil is not suppressive and target them. Information on a soil's level of suppressiveness is required to apply an appropriate measure. Thus, protocols for disinfestation of suppressive soils are highly needed.

Microbial activity and diversity, and interaction with soil disinfestation. Soil disinfestation may affect microbial activity in different ways in different soil niches. Thus, soil solarization (a relatively mild treatment with regard to microbial disturbance) reduced populations of fluorescent pseudomonads in the nonrhizospheric soil but increased them in the rhizosphere and roots of the subsequent crop (Gamliel and Katan 1991). Certain species of these bacteria are known as plant-growth promoting. Below are some examples, among many, illustrating interactions among soil disinfestation, microbial activity, and soil health.

Kanaan et al. (2018) studied the effects of soil solarization with various combinations of compost on soil bacterial community structure and function, along with effects on plant productivity and biomass. Soil solarization, regardless of compost amendment, had the strongest effect on soil microbiome structure and function, along with an impact on plant development. Heating soil during solarization has a beneficial impact on thermotolerant organisms (e.g., bacilli and γ -proteobacterial), while having an adverse effect on heat-sensitive ones such as α -proteobacteria. Soil solarization reduced the diversity and species richness of the soil bacterial community. The bacterial communities in the compost-amended and solarized soils clustered together, regardless of compost type, and were separate from the cluster of communities in nonsolarized soils with all amendments.

Soil fumigants (e.g., MB, chloropicrin, 1,3-dichloropropene, iodomethane, and propargyl) were examined in the field for their impact on microbial populations and activity (Stromberger et al. 2005). These fumigants reduced the populations of soilborne fungal pathogens and other cultured fungal populations 4 to 6 weeks postfumigation, and also reduced the activities of various enzymes in the soil, including phosphatase, arylsulfatase, glycosidase, and dehydrogenase, with a significant impact on microbial respiration and nitrification. These fumigant effects may depend on soil properties, climatic conditions, soil-management practices, and fumigant mode of action. It is clear that further adoption of the principles of soil and plant health is a major tool for achieving our goal of making soil disinfestation safe for growers and environmentally and economically acceptable.

Plant health. Soil disinfestation affects the soil's chemical, physical, and biological microenvironments and these, in turn, affect the morphology and physiology of both belowground and aboveground organs of the plant, usually reflected in the plant's size and shape. Soil disinfestation has major long-term and short-term effects on the quantity and quality of soil biota, which determine the success of the disinfestation in preventing diseases. According to Berendsen et al. (2012), the diversity of microbes associated with plant roots is enormous.

Soil disinfestation and the increased growth response. Soil disinfestation increases the biomass and, frequently, the yield of plants growing in soil infested with major destructive pathogens compared with plants growing in the same soil without soil disinfestation. The impact of improved plant growth following the elimination of harmful pathogens is obvious and expected. Less expected, however, is the increase in plant development in disinfested soil that does not appear to have any major pathogens. This phenomenon is referred to as increased growth response (IGR) (Chen et al. 1991; Katan et al. 2012; Patricio et al. 2006). IGR has been recognized since the early days of soil disinfestation and has been verified in many experiments with a wide spectrum of plants and soil types. Several mechanisms have been hypothesized to explain IGR in various situations: release of mineral micro- and macroelements in the soil (Chen and Katan 1980; Grünzweig et al. 1999; Stapleton et al. 1985); elimination of minor pathogens (see below); detoxification of toxic substances; stimulation of beneficial organisms; and release of soluble organic substances, which enhance plant growth, in the solarized soil (Chen et al. 1991).

It appears that soil with no known pathogens can be regarded as healthy soil, enabling the growth of apparently healthy plants. However, in many cases, such soil can harbor deleterious fungi such as *Pythium* and *Penicillium* spp. and certain bacteria, which can retard the plant's growth without visible symptoms of disease. Their presence can be recognized through the effect of IGR following soil disinfestation. This raises the question: What term should be given to such soils? Which soils can we regard as healthy?

The phenomenon of IGR presents a fundamental question: Is it a sign of improved plant health or is it a result of the manipulation of an agricultural practice? Soil disinfestation could be regarded as a practice that improves plant health if it had no negative side effects. However, there are cases in which it results in growth inhibition (Bendavid-Val et al. 1997).

IPM—Systems Approach

Soil disinfestation has evolved during the last 60 years from using a single measure (steaming or fumigation) to integrated management. Soil disinfestation is a pillar of IPM and should be assessed for efficacy versus economic and environmental action thresholds before application. The IPM program should consider the technical challenges involved, including the incorporation of measures that are different in nature and sometimes considered in conflict (e.g., combining nonselective fumigants with sensitive biocontrol agents).

IPM has been implemented for soilborne pests in high-value crops following the withdrawal of MB from agriculture. The use of a combination of solarization with a reduced rate of fumigant is a good example of effective manipulation of IPM (Gamliel 2012). Application of solarization with fumigants resulted in improved control of sudden wilt of melon and crown rot of tomato (Cohen et al. 2000; Gamliel et al. 2000), showing that techniques for disease suppression that are only partially effective when applied alone become more effective when combined with other methods. Another example of improved overall sustainability of a system was shown with the application of mycorrhizae following solarization to improve chive growth and further suppress pink root disease in chive production (Gamliel et al. 2004). These examples illustrate the quest for achieving pathogen control without compromising soil and plant health.

The systems approach to pest management is an evolution of the IPM concept that makes a further contribution to plant health (Chellemi et al. 2016). The aim of the system approach is to break free of the loop of intensive pesticide use by taking a holistic view of the entire production system. It incorporates all of the agricultural practices that are relevant to the crop production–pest onset interaction, and embraces response measures to control the pest, together with proactive steps to improve soil and plant health. Chellemi (2010) elaborated the principles for a system-based approach to managing soilborne pathogens. These are added to the basic IPM principles (Chellemi 2010; Klein et al. 2011, 2012). Understanding the entire system is crucial for effective management of soilborne pests.

Soil disinfestation is the major pillar of any approach for managing soilborne pests and achieving soil health. Successful execution is essential for effective disease management and obtaining a productive crop.

Technology, Application, Knowledge Transfer, and Extension Service

Application of soil disinfestation is key for the successful control of soil pathogens. Successful application means effective delivery of a small quantity of the agent (which can be a fumigant or a biocontrol agent) to a vast volume of heterogeneous (in structure and porosity) soil. In other words, we need to mix a few kilograms of active agents into hundreds of tons of bulk soil. Hence, attention is given to application methods and technology to ensure optimal delivery and distribution for maximum effect on the targeted pest. Indeed, Taylor and McBeth (1941b) were the first to show improved efficacy of fumigation with MB when injecting it into buried pipes under a glue-enforced paper sheet. This procedure was later adapted to plastic sheets when they became available.

Most of the commercial fumigants that are still available today are introduced into the soil in liquid form to the desired depth with various equipment. The chemicals are distributed in the liquid phase and diffused into the soil with the aim of reaching every niche occupied by pests. Injection of fumigants with various chisel structures is common for broadcast application of soil fumigants in the open field. The liquid formulation is injected into the soil through special nozzles mounted behind the chisel. The level of pest control depends on the fumigant's primary distribution in the soil, on the fumigant (and its secondary distribution properties) and dosage, and on the depth of injection. The latter varies according to target type and location. Injection of fumigants for field-crop pests is usually confined to the upper 30 cm of the soil (Klein 1996). Application of a fumigant with water through the irrigation system ensures delivery to deeper layers and is the most common practice worldwide. It ensures uniform delivery, provided that the water distribution is uniform and that the chemical does not leach into the deeper layers. Application of soil fumigants through the drip irrigation system is practiced mainly in bed applications and greenhouse production. The main advantage of this type of application is the improved distribution of the fumigants in the soil; however, it requires a special emulsified formulation of the fumigant and a suitable irrigation system. Subsurface drip irrigation and plastic mulch are also used to improve distribution and minimize fumigant volatilization (Ajwa et al. 2003). In fact, one of the main constraints of fumigant application, especially with injection, is fumigant volatilization and escape (Fig. 12). Hence, special plastic formulations have been developed to minimize escape

Fig. 12. Injection of metam sodium into the soil with a machine equipped with a soil covering system with virtually impermeable film (Agrolnnova).

and ensure effective control. The use of a barrier film also enables reducing the fumigant rate, thus minimizing its negative attributes (Cohen et al. 2000; Gamliel 2014; Gamliel and Katan 2012).

As already noted, combining fumigants with solarization is now well accepted and commonly practiced. An improvement in this technique was reported by Eshel et al. (2000), who showed that sequential application of solarization first, then fumigant injection 2 weeks later, further enhanced pest control at a reduced fumigant rate. This approach is now widely adopted in Israel in fields with drip-irrigation system or with side-shank injection using a special machine (Gamliel 2012).

Future Prospects

The search for economically and environmentally sound methods for the management of soilborne pathogens and management of healthy soils and substrates remains a challenging task for growers, despite intensive research. Crucial assumptions and promising outcomes of any disease control strategy should be tested under commercial production conditions, including economic aspects, before recommendations are made to growers.

Research efforts associated with the phaseout of MB generated new knowledge of the biology, ecology, and management of soilborne pathogens (Gullino et al. 2007; Katan 2000), and suggested that more attention be paid to crop and soil health (Katan 2017; Katan and Vanachter 2010). Introducing a new agricultural technology to farmers requires a coordinated effort to avoid failures and economic losses resulting from premature introduction. Growers require answers to practical problems, and researchers and extension services should be aware of the fact that newly proposed strategies must be validated in different situations.

Regulatory pressure, which is especially severe in Europe, is stimulating the development of sustainable practices to effectively control soilborne pests and diseases and provide decision-making tools to professional users. Future research should address the need for specific tools to determine pathogen populations and economic thresholds. High priority should be given to the production and use of pathogen-free propagation material. More research is also needed on disease etiology, monitoring, and modeling as well as breeding for disease resistance.

Understanding changes in the biotic and abiotic components of the soil or substrate caused by any treatment such as soil treatment with compost or other amendments may enable full exploitation of its control potential and avoidance of undesirable and unexpected side effects. Monitoring how microbial community structures in the soil change as a result of compost amendment may lead to a better understanding of which changes in microbial communities are responsible for conferring the disease-suppressive effects of the compost. This may eventually lead to improved and more reliable disease control resulting from compost amendment of soil, sand, or peat for container crops in greenhouses and in the field. There is a need for more effective disease control agents (biological and chemical) and new developments in their application. More research in the field of biological control is certainly needed to expand its present application potential. A common drawback in biocontrol research is inconsistency of results, which can be partially attributed to the biology and survival of biocontrol agents, particularly those which are introduced from very different environments.

When tested against a single pathogen strain, single-strain biocontrol agents can be efficient. However, when confronted with a variable pathogen population, biocontrol may be inconsistent. The selection of potential biocontrol agents based on colonization efficiency of plant tissues should be included in future work. Considering the increasing importance of organic agriculture, an interesting field of research is the development of disease-management strategies for organic production.

The problems generated in many agricultural regions and systems by the phaseout of MB made it clear that dependence on a single method should be avoided and that traditional but still effective methods such as crop rotation, use of organic amendments, and grafting

should be reintroduced (Katan 1999, 2000). Today, there is no single answer to the many questions posed by growers, and the different options need to be applied in a system-based approach for more effective management of soilborne diseases (Panth et al. 2020) (Fig. 10). Extension services, as well as growers, have developed a positive perception of the application of combined strategies, with a shift toward the adoption of nonchemical methods. Even more important, they are now very careful to check for long-term effectiveness. Sustainable cropping systems go beyond technical changes and refer to organizational and even strategic change. Integrating economic, environmental, and social goals into the design of agricultural production systems will require broad multidisciplinary cooperation (Chellemi et al. 2016; Katan 2017).

Finally, there is a strong need for improved information flow among researchers, extension staff, and growers to maintain close links between the production and marketing sectors of the industry, and to give more attention to consumer education. Monitoring fields and greenhouses where innovative methods are being applied is important, to detect the spread of new diseases; here, the presence of experienced field technicians is crucial.

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Maria Lodovica Gullino

Maria Lodovica Gullino, professor in plant pathology, director of the Center of Competence AgrolInnova, and vice rector for the Valorization of Human and Cultural Resources at the University of Torino, has been president of the Italian Association for Crop Protection (AIPP, 2003–2006), Italian Association of the Agrarian Societies (AISSA, 2004–2006), International Society for Plant Pathology (ISPP, 2008–2013), and Italian Society for Plant Pathology (2017–2019). Her research interests cover plant disease management, food safety and security, plant and food biosecurity, and effects of climate change on plant diseases. She is coauthor of 25 books and over 900 scientific papers. She is fellow of the American Phytopathological Society (APS) and of the ISPP. She received several national and international awards for her research achievements as well as for her international activities. She has been and is responsible for, mostly as coordinator, many research projects from the European Union (FP5, FP6, FP7, Horizon 2020, Tempus, Life, and EuropaId), Ministry of University and Research, Ministry of Agriculture, Ministry of Environment, regional governments, and private industry. Some of the projects are related to agriculture in the Middle East, China, India, and North Africa. She has organized national and international meetings and workshops in the field of plant disease management and has organized courses at the national and international level for training technicians and researchers working in the extension service in the field of integrated pest management, as well as policymakers from China and central Europe. She is a founder of AgriNewTech S.r.l., an academic spin-off, and was CEO until 2011. As a professional journalist and writer of popular books aimed at attracting people at large and children to science, she is very much involved in communication and public engagement activities.

Angelo Garibaldi

Angelo Garibaldi, Emeritus Professor and president of the Centre of Competence AgrolInnova at the University of Torino, is still very much involved in research in the field of plant disease management, diseases of ornamental crops, and biology and epidemiology of emerging diseases on horticultural crops. In particular, he has been and is very much involved in studying the biology and epidemiology of diseases affecting ornamental plants, with much attention to new trends in this sector. On his eightieth birthday, a cartoon book “Angelo, the Flower’s Doctor” was dedicated to him. He has been president of the Associazione Fitopatologica Italiana (AFI, 1986–1990), dean of the Faculty of Agriculture (1990–1996), and vice-chancellor of the University of Torino (1996–2004). He has managed many national and international research projects, funded by the European Union and different ministries and agencies, and has always been strongly involved in technology transfer. He has mentored hundreds of students during his long academic career. He is author or coauthor of eight books and over 1,000 scientific articles. In 2009, he founded AgriNewTech S.r.l., an academic spin-off, where he is currently president.

Abraham Gamliel

Abraham Gamliel is a senior researcher of pest management research, Agricultural Research Organization (ARO), Volcani Institute, Rishon Le Zion, Israel, and adjunct professor of plant pathology, The Faculty of Agriculture, Food and Environment at The Hebrew University at the Rehovot campus. He received his Ph.D. in 1990 from the Hebrew University of Jerusalem, Israel. He joined the ARO in 1992. The focus of his research activities is on effective pest management while minimizing environmental and other negative attributes arising from pesticides used for pest control in agriculture. It involves fundamental studies of various aspects of crop–pest systems in order to develop optimal strategies combined with practical approaches and available technologies. His interest in pest control is oriented to the overall system approach to manage agricultural pests, especially those with unique features and those not easily controlled by a single method. He has authored several book chapters and invited reviews on soil disinfection and pest management. He chaired the soilborne pathogen group, the International Society for Horticultural Sciences (ISHS), and convened the 7th International Symposium on Soil Disinfection in 2009. He served as a member of the United Nations Environmental Protection Program (UNEP), Methyl Bromide Technical Option Committee (MBTOC). He has over 200 publications, including 140 in refereed journals, reviews, and book chapters, and has coedited four books and symposium proceedings.

Jaacov Katan

Jaacov Katan is the Buck Family Professor Emeritus of Plant Pathology, The Faculty of Agriculture, Food and Environment at The Hebrew University at the Rehovot campus. He was born in Iraq in 1936 and immigrated to Israel in 1951. He specializes in soilborne pathogens: epidemiology, genetics, management, their interactions with pesticides, soil microbiology, soil solarization, pesticide degradation, biocontrol, and cooperation with breeders. He is the former president and honorary president of The Israeli Phytopathological Society. He is fellow of the American Phytopathological Society (APS), American Association for the Advancement of Science (AAAS), and the International Society of Plant Pathology (ISPP), and is a foreign member of The Russian Academy of Agricultural Sciences. His awards include the Rothschild, the Eriksson Award (by the Swedish Academy of Sciences and ISPP), Milcan Prize (for distinction in teaching), Award of Distinction by the International Society of Crop Protection, and Israel Prize in Agriculture and Environment bestowed upon by the president of Israel. He has published over 280 publications, including 190 in refereed journals, reviews, and chapters, and has coedited three books and symposium proceedings. He has had over 70 graduate students, postdocs, and guest scientists. He has been an invited speaker at national and international conferences. He initiated and led multidisciplinary soil solarization research since 1976, which expanded to over 70 countries.

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