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Soil solarization: a non-chemical approach for management of plant pathogens and pests

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ABSTRACT. Soil solarization is a special mulching process which causes hydrothermal disinfestation and other physical and biological changes in soil which are beneficial to plant health and growth. Plastic film laid over moist soil during periods of high air temperature, usually for 1–2 months, can greatly reduce or eradicate a number of pathogens and pests including fungi, bacteria, nematodes, arthropods and weeds. Following soil solarization, growth of microflora beneficial to plant growth or antagonistic to pathogens and pests may slow the reinfestation of soil by these organisms for more than one growing season. Increased plant growth and yield of annual and perennial field, row, and nursery crops usually occur following soil solarization. In addition, the availability of increased mineral nutrients following solarization may reduce crop fertilization requirements. Soil solarization has been effective as a pre-plant and as a post-plant treatment, and has been compatible with chemical soil treatments and also biological soil amendments after solarization. Soil solarization is a significant advance in the non-chemical control of many pathogens and pests.

Introduction

Mulching—the covering of the soil surface with organic or inorganic materials to increase crop production—has been used for at least several hundred years. Mulches increase plant growth through increased soil moisture accumulation, infiltration and retention, weed control, soil temperature management, protection against soil erosion, improvement of soil tilth, increases in available soil nutrients and pest and disease control. Traditional mulches include intact or decomposed plant residues, sawdust, animal wastes, stones or other materials. More recently, mulching technology has included application of thin sheets of paper or plastic materials to the soil surface, resulting in similar or increased benefits to crops (Jacks, Brind and Smith, 1955; Rowe-Dutton, 1957; Courter and Oebker, 1964; Lippert, Takatori and Whiting, 1964; Lal, 1974; Balderdi, 1976; Unger, 1978). Mulches have historically been used as post-planting treatments: hence, much of the work on plastic mulches has been done under post-planting conditions. Pre-plant application of film mulches was mainly to warm soil to provide an early start for crop plants (Hopen, 1965; Voth, Bringhurst and Bowen, 1967; Waggoner, Miller and De Roo, 1960).

Yield and growth increases of many vegetable, fruit, field and landscape crops have been reported in conjunction with plastic mulching. The modes of action are similar to those obtained with other mulching materials. Weed control is one of the primary benefits of mulching with black plastic, but other forms of pest and disease control have been reported. Several of the following reports cite increased plant growth even when diseases are not controlled. Greater activity of *Rhizoctonia solani* was found in soil planted to strawberry mulched with translucent, black or aluminium polyethylene films than in untreated control soil in a relatively cool climate; however, plant growth and yield were increased in the mulched treatments (Waggoner *et al.*, 1960). Control of southern blight on tomatoes and dwarf bean caused by *Sclerotium rolfsii*, as well as control of tomato fruit rot, was reported using black polyethylene film mulches (Geraldson, Overman and Jones, 1965; Reynolds, 1970). Significantly less infection of lettuce plants by *Sclerotinia minor* was found using black film mulching (Hawthorne, 1975). In addition, reductions in soil populations of the phytoparasitic nematodes *Criconemoides ornatus* and *Pratylenchus penetrans* were found by using black polyethylene mulching (Miller, 1977; Johnson, Sumner and Jaworski, 1979).

Increased numbers of second stage larvae of

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Meloidogyne incognita in soil and increased root galling found in cucumber were associated with black film mulching, although yields with the mulch treatment were significantly increased over untreated control soil; however, fewer *Pratylenchus penetrans* larvae were found in tomato roots under black film mulching (Miller, 1977; Johnson *et al.*, 1979). Reflective plastic and aluminium film mulches have been successfully used to repel vectors and reduce the severity and spread of several virus diseases (Price and Poe, 1976; Chalfant *et al.*, 1977; Toscano *et al.*, 1979). Chalfant (1969) reported reduced damage to turnips by root aphids with the use of aluminium film mulch. In several of the above studies, as well as in those of Hankin, Hill and Stephens (1982) and Sumner *et al.* (1978), soils mulched with polyethylene film were assayed for effects on fungal and bacterial populations; in all studies, insignificant or inconclusive differences were found between mulched and unmulched control soils.

A major improvement in agricultural mulching was reported from Israel where moist soil mulched for 4–5 weeks before planting with transparent polyethylene film during the hot summer months, was effectively disinfested of certain phytopathogenic fungi and weed seeds (Katan *et al.*, 1976). In addition, yields of test crops were markedly increased. A considerable amount of research on this method of soil disinfestation has since been done. The treatment has been referred to in various publications as solar pasteurization, solar heating of soil, polyethylene mulching, soil tarping and soil solarization. The term soil solarization is now widely used (Katan, 1981; Pullman *et al.*, 1984).

Solarization technology

The term solarization, if used in the strict sense, refers to a chemical change in glass, caused by sunlight or other ultraviolet radiation, which causes a photochemical reaction resulting in a decrease in ultraviolet transmission in addition to a noticeable colour change (Koller, 1965). Our use of the term extends the meaning of solarization to include the thermal, chemical and biological changes in soil caused by solar radiation when covered by clear plastic film, especially when the soil has a high moisture content. Many of the physical bases of soil solarization have been reviewed by Katan (1981). The following factors are involved:

1. Soil preparation. Absorption of radiation by the soil and therefore heating of soil is best when the plastic film is laid close to the soil with a minimum of airspace to reduce the insulating effect of an air layer. Good land preparation is essential to provide a smooth, even surface.
2. Soil characteristics. Dark soils absorb more radiation than light-coloured soils; this may partly account for the higher maximum temperatures achieved in some soils. Small differences in soil characteristics or moisture content can translate into large differences in soil heat transfer characteristics (Smith, 1964).
3. Soil moisture. Moist soil, either irrigated before mulching or irrigated under the plastic film, increases the thermal sensitivity of soil-borne microflora and fauna, as well as heat transfer or conduction in the soil. Saturated soils are optimal (Mahrer *et al.*, 1984).
4. Film type and characteristics. The plastic film reduces heat losses from soil that would be caused by evaporation and heat convection. Clear transparent polyethylene is usually employed, mainly because of its low cost and high strength, and allows maximum transmittancy of radiation from $0{\cdot}4\,\mu m$ to $36\,\mu m$ (Waggoner *et al.*, 1960). However, other plastics are superior to polyethylene in radiation transmission characteristics (Trickett and Goulden, 1958). Polyvinylchloride films have been used for solarization in greenhouses in Italy and Japan (Garibaldi and Tamietti, 1983; Horiuchi, 1984). Coloured transparent films may reduce the deposition of water droplets on the underside of the plastic, thereby increasing radiation transmission and soil temperature (Trickett and Goulden, 1958; Inada, 1973). Thinner films, 19–25 μm (¾–1 mil*) are more effective for soil heating than thicker films (50–100 μm) and are proportionally less expensive. The increased heating of moist soil during solarization and the associated effects on the physical, chemical and biological environments in solarized soil are the principal effects of solarization.

In level fields, without deep furrows, irrigation water can be run under the film in the shallow furrows made by tractor wheels during application of the plastic. If such irrigation is not feasible, soils can be preirrigated and the plastic film laid on the soil as soon as possible thereafter (Pullman *et al.*, 1979). For certain cash crops and in fields where weed control in the seed-bed is a major objective, the fields may be bedded-up before film application; the plastic strips which tightly cover the raised beds are anchored in soil at each side of the beds. These fields can then be furrow-irrigated and the water sub-soiled into the raised beds. The plastic film should not be placed across deep furrows, because air insulation in the furrow will greatly reduce the effectiveness of the solarization treatment and stimulate weed growth. The solarization treatment is most effective when applied during the warmest summer months and the plastic sheeting left in place for as long as practical (at least 4 weeks).

Maximum temperatures in upper soil layers under ideal conditions are achieved within 3–4 days after solarization begins (Mahrer, 1979). The upper 6–12 inches (≈15–30 cm) of soil show diurnal temperature changes influenced by day and night air temperatures.

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* 1 mil = 0·001 inch = 0·0254 mm.

Usually, however, the time/temperature dosage during high-temperature periods of 4–6 weeks of treatment is enough to kill most plant-pathogenic fungi and bacteria, weeds and weed seeds, certain mites, and to reduce nematode populations.

Soil solarization: modes of action

Hydrothermal effect

The hydrothermal effect of the solarization process is probably the most critical for effective soil disinfestation. Although the solarization process in very moist soils without the heating component may mimic the effects of soil flooding to reduce populations of soil microflora and nematodes, and result in increased plant growth response (IGR) (Stapleton and DeVay, 1983, 1984), the treatment becomes more effective as heating of moist soil is increased.

Thermal death studies of various micro-organisms *in vitro* have shown that at or above 50°C (a temperature often exceeded in the upper soil layers during solarization), survival is limited to a maximum of a few hours. At temperatures of 37–50°C eradication or marked reductions in populations occur within 2–5 weeks (Pullman, DeVay and Garber, 1981a; Pullman *et al.*, 1981b; Porter and Merriman, 1983). The greatest reductions in soil biota during solarization and the longest duration of reductions after treatment occur near the soil surface. In this area soil temperatures are highest, but also are most subject to diurnal temperature fluctuations (pulse effect). Deeper in the soil, temperatures are lower but are more constant. Effects of pulse heating vs. constant temperature on pathogen survival during solarization have not been clarified.

In addition to direct thermal death, the effects of sub-lethal heating result in delayed propagule germination, reduced growth rates, greater sensitivity to soil fumigants, and possible induced biological control of several phytopathogenic fungi (Pullman *et al.*, 1981a; Lifshitz *et al.*, 1983; Greenberger, Yogev and Katan, 1984). Studies on the effects of solarization on phytoparasitic nematodes have shown near-eradication of *Meloidogyne hapla* and other nematodes below the depth where direct thermal killing would be expected. Possible explanations include sub-lethal heating causing inhibition of subsequent reproduction of nematodes or egg hatching, resulting in delayed control greater than that of the initial kill (Stapleton and DeVay, 1983).

Effect on soil properties and mineral nutrients

Plastic-mulched and steamed soils usually contain higher levels of soluble mineral nutrients than untreated soils (Baker and Cook, 1974; Jones, Jones and Ezell, 1977). This phenomenon was also found in soils treated by solarization in Israel (Chen and Katan, 1980) and in California (Stapleton, Quick and DeVay, 1985). The kinds of nutrients increased by solarization in soils in both Israel and California were similar. Significant increases in ammonium-nitrogen, nitrate-nitrogen, Ca^{2+}, Mg^{2+} and electrical conductivity were consistently found. Phosphorus, K^+ and Cl^- increased in some soils. Other micronutrients (Fe^{3+}, Mn^{2+}, Zn^{2+} and Cu^{2+}) were not increased. Wet soil which was covered with polyethylene film but protected from solar heating did not differ in chemical properties from untreated control soil (Stapleton *et al.*, 1985), indicating that heating released soluble mineral nutrients from organic material and heat-killed soil biota.

Increases in nitrate-nitrogen following solarization of four field soils in the California study were equivalent to 12–50 kg/ha, ammonium-nitrogen to 0–127 kg/ha, and nitrate plus ammonium-nitrogen to 26–177 kg/ha. Soils high in organic matter released the most nitrogen. Soil P, Ca^{2+} and Mg^{2+} were increased by 2–12, 1–2 and 2–7 kg/ha, respectively. These increases in soluble mineral nutrients following soil solarization, although temporary, give an additional economic benefit to the use of the treatment. Soil which is solarized in the summer may not maintain the increased level of soluble nutrients over the winter fallow (Stapleton *et al.*, 1985).

Effects on potential biological control agents

In comparison with most other methods of soil disinfestation (Kreutzer, 1965; Baker and Cook, 1974), the effects of solarization are more selective on soil micro-organisms. Thermotolerant fungi and actinomycetes were affected to a lesser degree than phytopathogenic and total fungi, and they recolonized solarized soil with higher populations than in untreated soil. Fluorescent pseudomonads were greatly reduced by solarization, but quickly recolonized treated soil. Populations of most Gram-positive bacteria remained reduced up to a year after solarization; however, *Bacillus* spp., with spore bacteriostasis often broken by high temperatures, flourished in solarized soils (Stapleton and DeVay, 1982, 1984). Most of these groups of micro-organisms have been implicated as biological control or plant-growth stimulating agents (Baker and Cook, 1974). Sclerotia of *S. rolfsii* which were apparently damaged by moist heating of soil were subsequently colonized by bacteria and actinomycetes (Lifshitz *et al.*, 1983). Radish and sugar-beet seeds, coated with strains of fluorescent pseudomonads selected for their effects on plant growth and yields, produced plants with up to a six-fold increase in colonization of roots compared with roots of plants from untreated soil (Stapleton and DeVay, 1984). In other studies, the antagonistic fungus *Trichoderma harzianum* aggressively colonized solarized soil in Israel (Katan, 1981). These observations suggest that solarization causes changes in soil biota and substrate that provide a favourable environment for colonization by micro-organisms with greater competitive ability. These organisms are usually saprophytes, rather than phytopathogens which tend to have more specialized growth requirements. Many of these saprophytes may subsequently inactivate surviving phytopathogenic fungi, bacteria, nematodes and weed seeds that were damaged or weakened by solarization. Although the effects of this population shift in favour of beneficial organisms are temporary, they may persist for several seasons.

The effect of solarization on mycorrhizal fungi has not been thoroughly explored: however, roots of annual and perennial crops growing in recently solarized soil were well colonized by vesicular-arbuscular mycorrhizae (Pullman *et al.*, 1981b; Stapleton and DeVay, 1984).

Pathogen control and limitations

Reductions in population densities of some pathogens have been found to soil depths of approximately 1 m; these reductions have often persisted for more than one growing season and in some cases restrict the re-establishment of pathogenic fungi (Katan, Fishler and Grinstein, 1983).

Effect of soil solarization on soilborne fungi

Verticillium and Fusarium wilts of several crops have been successfully controlled by solarization, as well as diseases caused by *Bipolaris sorokiniana, Didymella lycopersicii, Phytophthora cinnamomi, Plasmodiophora brassicae, Pyrenochaeta lycopersici, Pyrenochaeta terrestris, Pythium myrothecium, Pythium ultimum, Rhizoctonia solani, Sclerotium oryzae, Sclerotium rolfsii,* and *Thielaviopsis basicola.* Pathogenic fungi including *Pythium irregulare, Sclerotium cepivorum,* and *Sclerotinia minor* were reduced in artificially inoculated soils (Table 1). However, in some studies the success of soil solarization has been poor for control of some pathogens, including *P. brassicae, S. rolfsii, Macrophomina phaseolina, Pythium aphanidermatum,* and *F. oxysporum* f. sp. *pini.* Fungi such as *M. phaseolina* and *P. aphanidermatum* are more heat tolerant than most pathogens and thus are more resistant to the effects of solarization. In other cases where soil solarization has been unsuccessful for control of pathogens and weeds, adverse environmental conditions or differing techniques of treatment may have contributed. Post-plant soil solarization for control of Verticillium wilt of both pistachio and olive has been achieved in established orchards (Ashworth and Gaona, 1982; Katan, 1984). In addition, root infections of young almond trees by *Pythium* spp. were sometimes significantly reduced by post-plant soil solarization (Stapleton and DeVay, 1984). No heat injury was evident to the fruit trees from post-plant soil solarization treatments.

Effect of soil solarization on soil-borne bacteria

Some species of soil-borne bacteria are sensitive to soil solarization; their thermal sensitivity depends upon the nature of the individual taxa. *Agrobacterium* spp., fluorescent pseudomonads, pectolytic pseudomonads and some Gram-positive bacteria have all been reduced in population density in solarized soils by 69–98% immediately following treatment. Fluorescent pseudomonads rapidly recolonized treated soil and no significant difference between treatments was apparent 3–6 months later. However, *Agrobacterium* spp. and some Gram-positive bacteria did not fully recolonize solarized soil 6–12 months after treatment (Stapleton and DeVay, 1982, 1984). Moreover, crown gall of walnut seedlings caused by *Agrobacterium radiobacter* biovar *tumefaciens* was undetectable following soil solarization, and complete control of crown gall in Nemaguard peach seedlings (rootstock) was attained (Stapleton, 1981).

Actinomycetes and *Bacillus* spp., many of which are thermotolerant, were sometimes reduced to a much lesser extent (45–58%) or were even increased (26–158%) following solarization (Stapleton and DeVay, 1982). Increases in these thermotolerant bacteria may also increase disease resistance and increased crop growth response (Stapleton and DeVay, 1984). Populations of *Rhizobium* spp., sufficient to cause heavy nodulation of bean roots, survived solarization in Israel (Katan, 1981).

Increased colonization (183–631%) of plant roots by plant-growth-promoting fluorescent pseudomonads from inoculated seed also occurred following soil solarization (Stapleton and DeVay, 1984).

Effect of soil solarization on soil-borne nematodes and mites

Population reductions, varying from 42% to 100%, were achieved by soil solarization for species of plant-parasitic nematodes in at least 10 genera including *Meloidogyne, Heterodera, Globodera, Pratylenchus, Ditylenchus, Paratrichodorus, Criconemella, Xiphinema, Helicotylenchus* and *Paratylenchus* in Israel (Hadar *et al.*, 1983; Katan, 1984), in California (Stapleton and DeVay, 1983) and in New York (LaMondia and Brodie, 1984). Population-density reductions as great as 99% were observed at soil depths of up to 91 cm in solarized soils. Artificial infestations of *Macroposthonia xenoplax* (= *Criconemella xenoplax*), *Meloidogyne javanica, Pratylenchus penetrans* and *Tylenchulus semipenetrans* were controlled by solarization in Australia (Porter and Merriman, 1983). However, soil solarization has not been consistent in controlling root galling caused by *Meloidogyne incognita* (Overman, 1981).

The combined application of 1,3-dichloropropene (1,3-D) soil fumigant with soil solarization was tested in several experiments. Reductions in nematode populations and subsequent increased plant growth were often greater following solarization plus fumigant than with solarization alone. Additional experimentation on specific crop–nematode interactions, particularly those where nematodes are likely to be the

TABLE 1. Response of representative plant pathogens and pests to soil solarization

A. Pathogens and pests controlled	References
FUNGI	
Phytophthora cinnamomi	Pinkas *et al.* (1984).
Plasmodiophora brassicae	Horiuchi and Hori (1983).
Pythium ultimum, Pythium spp.	Pullman *et al.* (1981a,b); Stapleton and DeVay (1984).
Pyrenochaeta lycopersici, P. terrestris	Garibaldi and Tamietti (1983); Katan *et al.* (1981); Tjamos (1983).
Didymella lycopersici	Besri (1983).
Verticillium dahliae	Ashworth and Gaona (1982); Conway and Martin (1983); Katan *et al.* (1976); Kodama and Fukui (1979); Pullman *et al.* (1981a,b); Stapleton and DeVay (1984).
Verticillium albo-atrum	Overman (1981).
Fusarium oxysporum f. sp. *vasinfectum*	Katan *et al.* (1983).
F. oxysporum f. sp. *fragariae*	Kodama and Fukui (1982).
F. oxysporum f. sp. *lycopersici; Fusarium* spp.	Katan *et al.* (1980).
Thielaviopsis basicola	Pullman *et al.* (1981a,b).
Sclerotium oryzae	Usmani and Ghaffar (1982).
S. rolfsii	Katan (1981).
S. cepivorum	Porter and Merriman (1983).
Rhizoctonia solani	Katan *et al.* (1980); Osman and Saheb (1983); Pullman *et al.* (1981a,b).
Sclerotinia minor	Porter and Merriman (1983).
Bipolaris sorokiniana	Smith *et al.* (1984).
BACTERIA	
Agrobacterium tumefaciens	Stapleton (1981).
NEMATODES	
Criconemella xenoplax	Stapleton and DeVay (1983); Porter and and Merriman (1983).
Globodera rostochiensis	LaMonda and Brodie (1984).
Helicotylenchus digonicus	Stapleton and DeVay (1983).
Heterodera schachtii	Stapleton and DeVay (1983).
Meloidogyne hapla	Stapleton and DeVay (1983).
M. javanica	Porter and Merriman (1983).
M. incognita	Katan *et al.* (1983).
Paratrichodorus porosus	Stapleton and DeVay (1983).
Paratylenchus hamatus	
Paratylenchus penetrans	Porter and Merriman (1983).
P. thornei	Katan (1984).
P. vulnus	Stapleton and DeVay (1983).
Tylenchulus semipenetrans	Porter and Merriman (1983).
Xiphinema spp.	Stapleton and DeVay (1983).
WEEDS	
Annual bluegrass (*Poa annua*)	Pullman *et al.* (1984).
Barnyard grass (*Echinochloa crus-galli*)	Elmore (1983); Porter and Merriman (1983).
Bermuda buttercup (*Oxalis pes-caprae*)	Pullman (1984).
Bermuda grass (*Cynodon dactylon*)	Rubin and Benjamin (1984).
Black nightshade (*Solanum nigrum*)	Elmore (1983); Porter and Merriman (1983).
Broomrape (*Orobanche* spp.)	Horowitz *et al.* (1983); Katan (1981).
Cheeseweed (*Malva parviflora*)	Elmore (1983).
Common chickweed (*Stellaria media*)	Pullman *et al.* (1984).
Common cocklebur (*Xanthium pensylvanicum*)	Egley (1983).
Common groundsel (*Senecio vulgaris*)	Pullman *et al.* (1984).
Common purslane (*Portulaca oleracea*)	Horowitz *et al.* (1983).
Fiddleneck (*Amsinckia douglasiana*)	Pullman *et al.* (1984).
Hairy nightshade (*Solanum sarachoides*)	Pullman *et al.* (1984).
Henbit (*Lamium amplexicaule*)	Horowitz *et al.* (1983).
Horse purslane (*Trianthema portulacastrum*)	Egley (1983).
Jimsonweed (*Datura stramonium*)	Pullman *et al.* (1984).
Johnson grass (*Sorghum holapense*)	Pullman *et al.* (1984); Rubin and Benjamin (1984).

TABLE 1 (*continued*)

A. Pathogens and pests controlled	References
Lambsquarters (*Chenopodium album*)	Elmore (1983); Porter and Merriman (1983).
Large crabgrass (*Digitaria sanguinalis*)	Elmore (1983); Porter and Merriman (1983).
Miner's lettuce (*Montia perfoliata*)	Pullman *et al.* (1984).
Morning glory (*Ipomoea* spp.)	Egley (1983).
Nettleleaf goosefoot (*Chenopodium murale*)	Pullman *et al.* (1984).
Pigweed (*Amaranthus* spp.)	Elmore (1983); Horowitz *et al.* (1983).
Prickly lettuce (*Lactuca serriola*)	Pullman *et al.* (1984).
Prickly sida (*Sida spinosa*)	Egley (1983).
Redmaids (*Calandrina ciliata*)	Pullman *et al.* (1984).
Redroot pigweed (*Amaranthus retroflexus*)	Pullman *et al.* (1984).
Scarlet pimpernel (*Anagallis* sp.)	Pullman *et al.* (1984).
Spurred anoda (*Anoda cristata*)	Egley (1983).
Velvet leaf (*Arbutilon theophrasti*)	Egley (1983).
Wild oat (*Avena fatua*)	Pullman *et al.* (1984).
Woodsorrel (*Oxalis stricta*)	Pullman *et al.* (1984).

B. Pathogens and pests partly or not controlled	References
FUNGI	
Fusarium oxysporum f. sp. *pini*	Old (1981).
Macrophomina phaseolina	McCain *et al.* (1982); Mihail and Alcorn (1984); Old (1981).
Plasmodiophora brassicae	Myers *et al.* (1983); White and Buczacki (1979).
NEMATODES	
Meloidogyne incognita	Overman (1981).
Paratylenchus neoamblycephalus	Stapleton and DeVay (1983).
WEEDS	
Bull mallow (*Malva niceaensis*)	Horowitz *et al.* (1983).
Field bindweed, established (*Convolulus arvensis*)	Pullman *et al.* (1984).
Horseweed (*Conyza canadensis*)	Horowitz *et al.* (1983).
Lovegrass (*Eragrostis* sp.)	Pullman *et al.* (1984).
Purple nutsedge (*Cyperus rotundus*)	Egley (1983).
White sweet clover (*Melilotus alba*)	Pullman *et al.* (1984).
Yellow nutsedge (*Cyperus esculentum*)	Elmore (1983).

limiting plant-growth factor, are needed to assess the potential of soil solarization for nematode control.

With regard to soil-borne mites, solarization has been used to control the plant-parasitic mite, *Rhizoglyplus robini*, in Israel (Katan, 1984).

Effect of soil solarization on weeds

One of the more visible results of solarization is the control of a wide spectrum of weeds (Table 1). Reports from Israel and the USA show that winter weeds are generally very susceptible to control by solarization, whereas summer weeds, especially *Cyperus* spp. and *Convolulus arvensis*, are generally more resistant. In Israel, excellent control of the parasitic phanerogam Egyptian broomrape (*Orobanche aegyptiaca*) was obtained on several crops with solarization (Katan, 1981). Susceptibility is further influenced by soil type, temperature and moisture content, and size and depth of seeds or vegetative propagules in soil during treatment (Katan *et al.*, 1976; Egley, 1983; Elmore, 1983; Horowitz, Regev and Herzlinger, 1983; Pullman *et al.*, 1984; Rubin and Benjamin, 1984). These susceptibility factors are generally similar or identical to those of fungi, bacteria, nematodes, and insects. Where weed control is not a primary objective of the solarization treatment, its use, nevertheless, may offset the cost of herbicide application. The elimination of weeds may also help prevent the build-up of pathogens or pests on susceptible weed species between crops.

Increased plant growth response

Increased plant growth response (IGR) is frequently observed following soil solarization with yields of field, row, and nursery crops—both annuals and perennials. In many instances, crop yields have been increased even when no major soil pathogens or pests have been detected (Chen and Katan, 1980; Stapleton and DeVay, 1982, 1983, 1985; Stapleton *et al.*, 1985).

The process of soil solarization, as previously discussed, comprises several modes of action. Some or all of these may be involved in increasing yields in any particular crop ecosystem. The overriding components of IGR are probably thermal inactivation of plant pathogens (both major and minor pathogens) and pests (nematodes and soil-borne insects), alteration of the soil microbiota to favour antagonists of plant pathogens and pests, release of soluble mineral nutrients from soil, and thermal inactivation of weed seeds. These mechanisms of action, and probably several others such as qualitative and quantitative changes in soil gas composition and volatile substances, weakened propagules and impaired reproductive ability of pathogens and pests, improved soil structure, and deeper penetration of soil moisture, combine in an integrated process to alter plant root environment and result in IGR. With the combination of such a broad scope of favourable components, it is likely that most crops would benefit from soil solarization. Only when environmental conditions or other limiting circumstances reduce the effectiveness of soil solarization would IGR not occur or be expected. IGR and related benefits of solarization such as faster seed germination, better stand establishment, and earlier maturity, are as valuable in some cases as disease and pest control (e.g. nursery plants, landscaping ornamentals, and high-value cash crops). Late-season solarization for perennials may require caution, as subsequent vigorous growth may delay dormancy and result in cold injury in some species (J. J. Stapleton and J. E. DeVay, unpublished work).

Applicability of soil solarization

Cost effectiveness and long-term benefits

In 1983 the cost of pre-plant row-coverage solarization in California was estimated at US$200–250/acre (≈4050 m²), and solid coverage at US$350/acre (Pullman *et al.*, 1984). Thus, solarization falls into the medium price range of soil disinfestation treatments. As solarization technology advances, e.g. development of thinner but stronger films, use of photodegradable or biodegradable films (Everett and McLaughlin, 1975; Gilead, 1979) or more efficient film-laying machinery (Hetzroni *et al.*, 1983), the overall cost of application should decrease. Moreover, the use of solarization may lower the requirement and expense of fertilizers (Stapleton *et al.*, 1985).

Although IGR of up to fourfold increases in crop yields are encountered in solarized fields, the cost of the treatment may be prohibitively expensive with crops not of a high cash value. In addition, solarized fields must be taken out of rotation for 1–2 months during the summer. On the other hand, benefit of disease/pest control and IGR lasting for two or more growing seasons following solarization would compensate.

Use in large-scale agriculture

The technology for applying plastic films to large acreages already exists (Pullman *et al.*, 1984) and is similar to that used in soil fumigation. However, soil-fumigation treatments (e.g. methyl bromide treatments sealed with film) are designed to be in place for only a few days, and without the necessity of high soil-moisture content during treatment. These latter considerations are the only ones needing modification to apply the soil solarization treatment.

Use in nurseries and greenhouses

The cost-intensity of nursery and greenhouse production may be ideally suited for the incorporation of solarization into routine management practice. In addition to the control of a wide range of diseases and pests without the use of toxic substances, the benefit of early stand establishment and IGR to the short-term growth culture of nursery plants may be of considerable economic advantage (Stapleton and DeVay, 1982). In addition, pre-plant solarization film may be left in place, after plant emergence, as a post-plant mulch. Plant growth has been stimulated by solarization-type mulching, even during summer months (Hartz, Bogle and Villalon, 1984; Stapleton and DeVay, 1985).

In Japan, solarization of soil, further insulated in closed plastic greenhouses (increasing the greenhouse effect), effectively controlled *Fusarium oxysporum* f. sp. *fragariae, Sclerotium rolfsii, Rhizoctonia solani,* and *Verticillium albo-atrum* (Kodama and Fukui, 1979, 1982).

Use in home gardens and landscaping

Climatic conditions permitting, the home garden may benefit greatly from soil solarization. Most home gardens are planted in the same site year after year without periodic soil disinfestation treatments. Solarization could be done between crops, and in addition to providing control of garden diseases and pests, could result in earlier stand establishment, improved crop quality, and greater yields.

These same benefits would apply to landscaping applications. The growth promotion of young woody perennials by solarization (Stapleton and DeVay, 1982, 1985) and the control of soil-borne diseases in established plantings have been reported (Ashworth and Gaona, 1982).

Future outlook for the use of soil solarization

Solarization is an integrated method of increasing plant health, growth, and yield. It appears to be adaptable to a wide range of agricultural applications, alone and in conjunction with agricultural chemicals and biological control agents. The possible uses of soil solarization, both pre-plant and post-plant, are being explored in field, orchard, nursery, greenhouse and garden situations, and in environmental and landscape improvement. Under the limitations of its applicability, soil solarization is a safe and effective method for disease and pest control that may reduce the necessity for chemical applications to soil: it represents a significant advance in soil disinfestation/mulching technology.

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