



Soil solarization in various agricultural production systems

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Abstract

Soil solarization is a natural, hydrothermal process of disinfesting soil of plant pests that is accomplished through passive solar heating. Solarization occurs through a combination of physical, chemical, and biological mechanisms, and is compatible with many other disinfestation methods to provide integrated pest management. Commercially, it is used on a relatively small scale worldwide as a substitute for synthetic chemical toxicants, but its use is increasing as methyl bromide, the major chemical fumigant, is phased out due to its ozone-depleting properties. Solarization currently is an important and widespread practice for home gardeners. In production agriculture, the principal use of solarization (on a treated area basis), is probably in conjunction with greenhouse grown crops. Another application for which solarization has come into common use is for disinfestation of seedbeds, containerized planting media, and cold-frames. Around the world, solarization for disinfesting soil in open fields is being implemented at a relatively slow but increasing rate. It has been mainly used for commercial production in areas where air temperatures are very high during the summer and much of the cropland is rotated out of production due to excessive heat. As global concerns regarding environmental quality grow along with the human population in the 21st century, concepts such as solarization and other uses of solar energy in agriculture will likely become increasingly important. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Principles and mechanisms

Soil disinfestation treatments, primarily utilizing bio-cidal chemicals or various forms of heat, are used by agricultural producers to reduce soilborne inoculum of crop pests including fungal, bacterial, and nematode pathogens, weeds, and certain insects. These effects afford protection and stimulation of root growth and crop yield, and are often interrelated through complex mechanisms involving drastic qualitative and quantitative changes in the soil environment (Chen et al., 1991). Soil solarization is an approach to soil disinfestation which uses passive solar heating of moist soil mulched with plastic sheeting (usually transparent polyethylene). Although the execution of solarization is simple, the overall mode of action can be complex, involving a combination of several inter-related processes which occur in treated soil and result in increased health, growth, yield, and quality of crop plants (Katan, 1987; Stapleton and DeVay, 1995; Stapleton, 1997).

1.1. Physical mechanisms

Direct thermal inactivation of soilborne pathogens and pests is the most obvious and important mechanism of the solarization process. Under suitable conditions, soil undergoing solarization is heated to temperatures which are lethal to many plant pathogens and pests. Thermal inactivation requirements have been experimentally calculated for a number of important plant pathogens and pests (Katan, 1987; Stapleton and DeVay, 1995). Although most mesophilic organisms in soil have thermal damage thresholds beginning around 39–40°C, some thermophilic and thermotolerant organisms can survive temperatures achieved in most types of solarization treatment (Stapleton and DeVay, 1995).

Because solarization is a passive solar process, soil is heated to maximal levels during the daytime, then cooled at night. The highest temperatures during solarization are achieved at or near the soil surface, and soil temperature decreases with increasing depth. Typical, diurnal maximum/minimum soil temperatures during summer solarization of open field soils in the inland valleys of California might be 50/37°C at 10 cm, and 43/38°C at 20 cm with 35/20°C air temperature flux (Fig. 1a)

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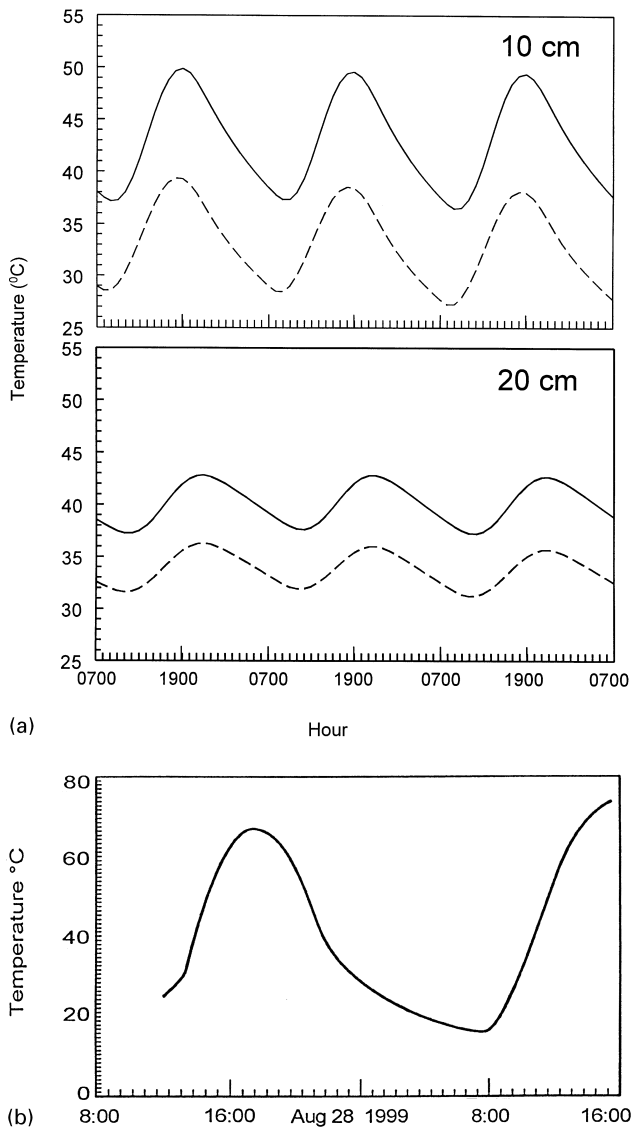


Fig. 1. (a) Effect of open field solarization (solid lines) on soil temperature at two depths (10 and 20 cm — August 1991). Dashed lines indicate temperatures in bore soil (adapted from Gamliel and Stapleton, 1993a); and (b) effect of solarization on temperature of soil in plastic nursery containers (3.8 l soil volume — August 1999) (adapted from Stapleton et al., 2000), Parlier, California, USA.

(Gamliel and Stapleton, 1993a). Solarizing soil in closed greenhouses or in containers with a limited volume of soil may produce considerably higher soil temperatures. For example, solarizing soil in 3.8 l plastic containers resting on steel pallets under low plastic tunnels constructed using two layers of transparent film separated by ca. 23 cm air space (“double tent”) gave maximum/minimum soil temperatures of 75/16 °C with corresponding air temperatures of 38/17 °C (Fig. 1b) (Stapleton et al., 2000). During solarization of open fields or greenhouse floors, destruction of soilborne pest inoculum usually is greatest near the surface and efficacy decreases with increasing depth (Stapleton, 1997). There are a number of physical

factors which influence the extent of soil heating during solarization. First, solarization is dependent on high levels of solar energy, as influenced by both climate and weather. Cloud cover, cool air temperatures, and precipitation events during the treatment period will reduce solarization efficiency (Chellemi et al., 1997). Solarization is commercially practiced mainly in areas with Mediterranean, desert, and tropical climates which are characterized by high summer air temperatures. In order to maximize solar heating of soil, transparent plastic film is most commonly used for solarization. Transparent film allows passage of solar energy into the soil, where it is converted into longer wavelength infrared energy. This long wave energy is trapped beneath the film, creating a “greenhouse” effect. Opaque black plastic, on the other hand, does not permit passage of most solar radiation. Rather, it acts as a “black body” which absorbs incoming solar energy. A small portion of the energy is conducted into soil, but most of the solar energy is lost by re-radiation into the atmosphere. Nevertheless, solarization with black, or other colors of plastic mulch is sometimes practiced under special conditions (Abu-Gharbieh et al., 1991; Stapleton, 1997).

Apart from solar irradiation intensity, air temperature, and plastic film color, other factors play roles in determining the extent of soil heating via solarization. These include soil moisture and humidity at the soil/tarp interface, properties of the plastic, soil properties, color and tilth, and wind conditions. The procedure of covering of very moist soil with plastic film to produce microaerobic or anaerobic soil conditions, but without lethal solar heating, can by itself produce varying degrees of soil disinfection (Katan, 1987; Stapleton and DeVay, 1995).

1.2. Chemical mechanisms

In addition to direct physical destruction of soilborne pest inoculum, other changes to the physical soil environment occur during solarization. Among the most striking of these is the increase in concentration of soluble mineral nutrients commonly observed following treatment. For example, the concentrations of ammonium- and nitrate-nitrogen are consistently increased across a range of soil types after solarization. Results of a study in California showed that in soil types ranging from loamy sand to silty clay, $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentration in the top 15 cm soil depth increased 26–177 kg/ha (Katan, 1987; Stapleton and DeVay, 1995). Concentrations of other soluble mineral nutrients, including calcium, magnesium, phosphorus, potassium, and others also sometimes increased, but less consistently. Increases in available mineral nutrients in soil can play a major role in the effect of solarization, leading to increased plant health and growth, and reduced fertilization requirements. Increases in some of the mineral nutrient concentrations can be attributed to decomposition of organic components of

soil during treatment, while other minerals, such as potassium, may be virtually cooked off the mineral soil particles undergoing solarization. Improved mineral nutrition is also often associated with chemical soil fumigation (Chen et al., 1991).

1.3. Biological mechanisms

In addition to direct physical and chemical effects, solarization causes important biological changes in treated soils. The destruction of many mesophilic microorganisms during solarization creates a partial “biological vacuum” in which substrate and nutrients in soil are made available for recolonization following treatment (Katan, 1987; Stapleton and DeVay, 1995). Many soilborne plant parasites and pathogens are not able to compete as successfully for those resources as other microorganisms which are adapted to surviving in the soil environment. This latter group, which includes many antagonists of plant pests, is more likely to survive solarization, or to rapidly colonize the soil substrate made available following treatment. Bacteria including *Bacillus* and *Pseudomonas* spp., fungi such as *Trichoderma*, and some free-living nematodes have been shown to be present in higher numbers than pathogens following solarization. Their enhanced presence may provide a short- or long-term shift in the biological equilibrium in solarized soils which prevents recolonization by pests, and provides a healthier environment for root and overall plant productivity (Katan, 1987; Stapleton and DeVay, 1995; Gamliel and Stapleton, 1993a).

2. Improving solarization efficacy

Under conducive conditions and proper use, solarization can provide excellent control of soilborne pathogens in the field, greenhouse, nursery, and home garden. However, under marginal environmental conditions, with thermotolerant pest organisms or those distributed deeply in soil, or to minimize treatment duration, it is often desirable to combine solarization with other appropriate pest management techniques in an integrated pest management approach to improve the overall efficacy of treatment (Stapleton, 1997). Solarization is compatible with numerous other methods of physical, chemical, and biological pest management. This is not to say that solarization is always improved by combining with other methods. Many field trials have shown that, under the prevailing conditions, pesticidal efficacy of solarization or another management strategy alone could not be improved upon by combining the treatments (Stapleton and DeVay, 1995). However, even in such cases, combination of solarization with a low dose of an appropriate pesticide may provide the benefit of a more predictable treatment which is sought by commercial users. For

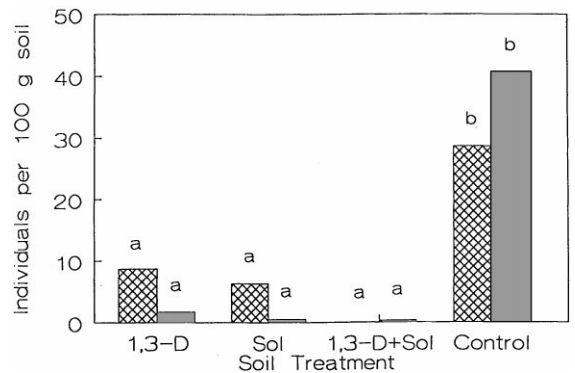


Fig. 2. Effect of 1,3-dichloropropene (1,3-D) broadcast applied at 1221/ha and/or solarization on numbers of *Meloidogyne hapla* in soil (0–46 cm depth) 1 day (cross-hatched bars) or 8 mo (stippled bars) after treatment. Davis, California, USA (adapted from Stapleton and DeVay, *Phytopathology* 73,1429-1436, 1983).

example, although combining solarization with a partial dose of 1,3-dichloropropene did not statistically improve control of northern root knot nematode (*Meloidogyne hapla*) over either treatment alone, it did reduce recoverable numbers of the pest to near undetectable levels to a soil depth of 46 cm (Fig. 2) (Stapleton and DeVay, 1983).

Solarization can also be combined with a wide range of organic amendments, such as composts, crop residues, green manures, and animal manures to sometimes increase the pesticidal effect of the combined treatments (Ramirez-Villapudua and Munnecke, 1987; Gamliel and Stapleton, 1993a, b; Chellemi et al., 1997). Incorporation of these organic materials by themselves may act to reduce numbers of soilborne pests in soil by altering the composition of the resident microbiota, or of the soil physical environment (“biofumigation”). Combining these materials with solarization can sometimes greatly increase the biocidal activity of the amendments. However, this appears to be an inconsistent phenomenon, and such effects should not be generalized without first conducting confirmatory research. The concentrations of many volatile compounds emanating from decomposing organic materials into the soil atmosphere have been shown to be significantly higher when solarized (Gamliel and Stapleton, 1993b).

The successful addition of biological control agents to soil before, during, or after the solarization process in order to obtain increased and persistent pesticidal efficacy has long been sought after by researchers. There have been great hopes of adding specific antagonistic and/or plant growth promoting microorganisms to solarized soil, either by inundative release or with transplants or other propagative material, to establish a long-term disease-suppressive effect to subsequently planted crops (Katan, 1987; Stapleton and DeVay, 1995). Although no consistent advantage has been shown by

this method to date, there have been a few instances of demonstrated benefit. For example, Tjamos and Fravel (1995) showed that the fungus *Talaromyces flavus*, when added to solarized soil which was heated only to sub-lethal levels, was detrimental to the survival of *Verticillium dahliae* microsclerotia. In most studies, however, it appears that re-colonization of solarized soil by the native biota is just as beneficial to subsequent crops as the addition of specific microorganisms (Stapleton and DeVay, 1995). This area will likely remain a topic of interest and experimentation for many researchers.

3. Current usage

Generally speaking, although soil solarization is used on a relatively small scale worldwide as a substitute for synthetic chemical toxicants, its use is expected to increase as methyl bromide is phased out due to its ozone-depleting properties. However, there are pockets of more intensive adoption for specific uses in some locations. Solarization, as any other soil disinfestation method, has both benefits and drawbacks. While it is simple, safe, and effective within its use limitations, and can be readily combined with biological and chemical control measures, solarization is dependent upon high air temperatures, is most effective near the soil surface, does not consistently control certain heat-tolerant pests (e.g. *Macrophomina phaseolina*), should be done during the hottest part of the year (possibly interfering with planting schedules), and requires disposal of plastic film (Katan, 1987; Stapleton and DeVay, 1995; Stapleton, 1997). The practical value of soil solarization, as of any pest management strategy, is judged by end users according to several criteria, including pesticidal efficacy, effect on crop growth and yield, economic cost/benefit, and acceptance by peers. The major use of solarization appears to be in greenhouse culture. The ability of greenhouse operators to close up greenhouses during the hot summer months allows higher solarization temperatures than achievable in treatment of open fields. For example, more than 5000 ha of greenhouses in Japan were reported to undergo regular solarization treatment in 1988 (Horiuchi, 1991). Solarization in greenhouses is also commonly practiced in other Mediterranean and Near-Eastern locations (Cartia, 1998).

Another application for which solarization may come into common use, particularly in developing countries, is for disinfestation of seedbeds, containerized planting media, and cold-frames. As with use in greenhouses, these are ideal niches for solarization, since individual areas to be treated are small, soil temperature can be greatly increased, the cost of application is low, the value of the plants produced is high, and the production of disease-free planting stock is critical for producing healthy crops (Stapleton, 1997; Stapleton et al., 1999).

In the USA, solarization for disinfesting soil in open fields is being implemented at a relatively slow but increasing rate. It has been mainly used on a commercial basis in areas where air temperatures are very high during the summer and much of the cropland is rotated out of production due to excessive heat, such as the central and southern desert valleys of California. Most growers in California who are now using solarization in production fields are those that have some aversion to the use of methyl bromide or other chemical soil disinfestants, either because of their close proximity to urban or residential areas, personal preference, or because they are growing for organic markets (Stapleton, 1997). Implementation of production field solarization in other areas with suitable, but more tropical climates, such as Florida, USA, appears to be progressing at a similar rate (Chellemi et al., 1997).

Other special solarization techniques which have been tested or used include disinfesting wooden tomato stakes of *Didymella lycopersici* (Besri, 1983), using black polyethylene film in open fields or in existing orchards or vineyards (Abu-Gharbieh et al., 1991; Stapleton and DeVay, 1995), and closing greenhouses in summer to provide “space solarization” of aerial structures and equipment (E. Shlevin and J. Katan, personal communication).

In addition to commercial use, the importance of solarization in home gardening and subsistence production is widely recognized. Although most of these users do not use chemical soil disinfestants under any circumstances, solarization has been widely embraced and mainstreamed by gardeners, and contributes to improved plant health and production in these settings (Stapleton, 1997).

4. Outlook

Having user-friendly mathematical models for predicting treatment duration and efficacy (i.e. when a solarization treatment is “done”) available to end-users would greatly aid the adoption of solarization, but these generally have not been successfully implemented as agricultural production tools because of the passive and complex mode of action of the process over a broad range of target organisms. Nevertheless, because of the potential utility of such predictive models, they continue to be a focus of development (Katan, 1987; Stapleton, 1997). Also, though solarization can be an effective soil disinfestant in numerous geographic areas for certain agricultural and horticultural applications, there are inherent limitations, and situations are presented where it may be desirable to increase the efficacy and/or predictability of solarization through combination with other methods of soil disinfestation.

Since solarization is a passive process with biocidal activity dependent to a great extent upon local climate

and weather, there are occasions when even during optimal periods of the year, cool air temperatures, extensive cloud cover, frequent or persistent precipitation events, or other factors may not permit effective soil treatment. In these cases, integration of solarization with other disinfestation methods may be essential in order to increase treatment efficacy and predictability. As methyl bromide is phased out, many current users will turn to other pesticides for soil disinfestation. Combining these pesticides (perhaps at lower dosages) with solarization (perhaps for a shorter treatment period) may prove to be the most popular option for users who wish to continue using chemical soil disinfestants.

In any case, as global environmental quality considerations grow in importance along with the increasing human population in the 21st century and beyond, evolving concepts such as solarization and other uses of solar energy in agriculture will likely become increasingly important.

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