CHAPTER 15

Soil Solarization: A Natural Mechanism of Integrated Pest Management

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CONTENTS

I. INTRODUCTION

Among major constraints to agricultural food, fiber, and ornamental production worldwide are the soilborne pests, including disease-causing organisms, phytoparasitic nematodes, and weed species. Historically, man has devoted a great deal of resources to combat soilborne pests, employing a wide variety of physical, chemical, and biological methods. During the past half century, agriculturists came to rely almost exclusively on chemical fumigants and disinfestants for controlling soilborne pests in many horticultural crops. Recently, however, environmental and health concerns have turned the tide, and effective nonchemical and integrated management strategies are being sought to replace heavy chemical treatments.

Production agriculture in California, as in other areas of the world, is now challenged by intense public concern regarding food safety and euvironmental pollution. Fumigants and other chemical pesticides used for soil disinfestation

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are under close scrutiny. Within the last 15 years, application of dibromochloropropane (DBCP) and ethylene dibromide (EDB) was prohibited, and use of 1,3-dichloropropene (1,3-D) was suspended. Currently, methyl bromide is under review and phase-out is expected by the end of the decade. Regulatory evaluation of metam sodium is expected to follow. These legal actions and fears thereof have put the agricultural sector under extreme pressure to develop and implement viable alternatives for nonchemical management of soilborne disease, nematode, and weed pests of agricultural crops.

One of the most effective options available for immediate adoption in certain growing areas is soil solarization. Solar energy has been used for soil disinfestation for many years in California, through repeated turning over of topsoil during summer months to control nematodes in the Coachella Valley.[1] Modern employment of solar energy for soil disinfestation, however, began with the use of polyethylene film by Katan and colleagues to cover, and heat, moist soil in Israel.[2]

Soil solarization is a hydrothermal process which utilizes solar radiation captured, with present technology, under plastic film mulching materials to heat soils and disinfest them of plant pests and pathogens which lower yield and quality of agricultural crops.[3] It is a nonchemical technique which conforms to principles of integrated pest management, since it has a complex mode of pesticidal activity, can control a broad spectrum of soilborne pathogens, weeds, and insect pests, and can be combined for greater efficacy with other methods of pest control, such as biological and chemical agents, if necessary.

Following publication of the initial Israeli results, intensive research was initiated in California in 1976 by DeVay and associates. They were optimistic about the possibilities of this method of soil disinfestation, dne to the Mediterranean and desert climates of California which include hot, arid conditions during summer months in the interior valleys; and to the established use of polyethylene film products in agriculture. The first results obtained on control of fungal pathogens of cotton in the San Joaquin Valley[4] were excellent, and the term "soil solarization" was coined shortly thereafter by extension workers in the Valley to describe the method. Since then, effective pest management and increased crop growth and yield were demonstrated for a wide range of soils and crops, and many of the mechanisms of action were elucidated.

Comprehensive review articles detailing general principles and early results of solarization research are available,[3,5,6] and two reference texts have been published. In this chapter, therefore, we wish to provide only a brief background of solarization technology and give key references to facilitate further investigation. Our principal objectives are to discuss the role of solarization in integrated pest management (IPM) strategies for soilborne pests, and how solarization may be improved and implemented, with emphasis on California conditions.

II. INTEGRATED MECHANISMS OF ACTIVITY

Thorough reviews of modes of action of solarization and its overall effect on soilborne pests are available,[5-10] as are specific discussions of solarization relating to fungi and bacteria,[11] nematodes,[12,13] and weeds.[14,15] Briefly, mechanisms of action of solarization were found to include direct thermal inactivation of pest organisms, induced biological control through quantitative and qualitative shifts in soil microbiota, and beneficial changes in chemical and physical soil properties. Pullman et al.[16] found that the direct thermal effect of solarization produced a logarithmic dosage/response effect in field and laboratory experiments on four fungal pathogens of cotton (*Verticillium dahliae, Thielaviopsis basicola, Rhizoctonia solani,* and *Pythium ultimum*). Stapleton and DeVay[17] found that, although populations of phytopathogenic fungi and bacteria decreased dramatically after solarization, numbers of saprophytic microorganisms often increased, as they exploited the partial biological vacuum produced by the treatment. This element of biological control could partially explain the increased plant growth response (IGR) frequently observed after solarization.[8] They postulated that the more competitive saprophytes accomplished this either by better adaptation for surviving solarization (e.g., *Bacillus* spp. and many actinomycetes), or by rapid, primary colonization of the substrate made available by treatment (e.g., fluorescent pseudomonads and various fungi).[17,18] These findings have been confirmed by studies in Israel,[19] Australia,[20] the southeastern region of the U.S.,[21,22] and other locations. Stapleton et al.[23] confirmed Israeli results[24] showing increased levels of soluble ammonium- and nitrate-nitrogen in a variety of solarized soils in California. In addition, increased concentrations of other mineral nutrients, including phosphorus, magnesium, and calcium sometimes were found. They showed that nutrient release was primarily a function of soil heating, since moist soil covered by film but protected from heating did not significantly differ in available mineral concentrations from nontreated soil. Increased nutrient availability was often equivalent to a preplant fertilizer application. Greenhouse work showed that IGR, which frequently occurred after solarization of soils not harboring populations of major pathogens, disappeared with depletion of soil mineral nutrients, thus pointing to the nutrient effect as a major mechanism of action. Although long-term control of plant pathogens by solarization has been shown in some locations,[25,26] other recent field studies have indicated no increase in yields when crops were planted after a winter fallow following treatment.[20,21]

In regard to pathogen susceptibility to soil solarization (Table 1), Pullman et al.[4,16] demonstrated excellent control of *V. dahliae, R. solani, P. ultimum,* and *T. basicola* in cotton, and found a logarithmic relationship between time and temperature for these pathogens in field and laboratory studies. Stapleton and DeVay[3,17] found that crown gall of stone fruit trees, caused by *Agrobacterium*

Table 1 Response of Representative Plant Pathogens to Soil Solarization

Species of Pathogens Controlled	
Fungi	**Bacteria**
Phytophthora cinnamomi	*Agrobacterium tumefaciens*
Plasmodiophora brassicae	*Streptomyces scabies*
Pythium ultimum	
Pyrenochaeta lycopersici	
P. terrestris	**Nematodes**
Didymella lycopersici	*Criconemella xenoplax*
Verticillium dahliae	*Ditylenchus dipsaci*
V. albo-altrum	*Globodera rostochiensis*
Fusarium oxysporum	*Helicotylenchus digonicus*
f. sp. *vasinfectum*	*Heterodera schachtii*
f. sp. *fragariae*	*Meloidogyne hapla*
f. sp. *lycopersici*	*M. javanica*
f. sp. *conglutinans*	*Paratrichodorus porosus*
Thielaviopsis basicola	*Paratylenchus hamatus*
Sclerotium oryzae	*P. penetrans*
S. rolfsii	*P. thornei*
S. cepivorum	*P. vulnus*
Rhizoctonia solani	*Tylenchulus semipenetrans*
Sclerotina minor	*Xiphinema* spp.
Bipolaris sorokiniana	
Species of Pathogens Partly or Not Controlled	
Fusarium oxysporum	*Meloidogyne incognita*
f. sp. *opini*	*Paratylenchus neoamblycephalus*
Macrophomina phaseolina	
Pythium aphanidermatum	

Adapted from Stapleton, J. J. and DeVay, J. E., *Crop Prot.*, 3, 190, 1986.

tumefaciens, could be controlled by solarization, and that growth of peach (*Prunus persica*) and walnut (*Juglans regia*) tree seedlings was stimulated by treatment. They also found that populations of many phytoparasitic nematodes associated with a number of crops were reduced by solarization, applied both pre- and postplant.[27] Ashworth and Gaona[28] did pioneering work on postplant solarization, and found that verticillium wilt could be controlled for up to 3 years in existing pistachio groves. Stapleton et al.[29] demonstrated excellent control of verticillium wilt of young almond and apricot orchards using season-long solarization with black polyethylene film. Other soilborne diseases and pests of existing trees also have been controlled, to various degrees, by solarization.[30,31] Morgan et al.[32] recently expanded the postplant solarization concept to annual cropping of tomato, with the idea of avoiding an out-of-production treatment period during the growing season. Elmore and other weed scientists found excellent control of many weed pests, and they defined guidelines for treating weed species which were both susceptible and tolerant to solarization (Tables 2 and 3).[14,15,22,33] Stapleton et al.[34] showed that combining solarization with certain nitrogenous fertilizers could increase control of soilborne fungal and nematode pests and increase crop

Table 2 Susceptibility of Annual Weeds to Soil Solarization

Winter Weed Species Controlled

Anagalis coerulea
Arum italicum
Avena fatua
Brassica niger
Capsella bursa-pastoris
C. rubella
Centaurea iberica
Chrysanthemum coronarium
Daucas aureus
Emex spinosa
Erodium spp.
Heliotropium suaveolus
Hordeum leporinum
Lactuca scariola
Lamium amplexicaule
Medicago polymorpha
Mercurialis annua
Montia perfoliata
Notobasis syrica
Papaver dubium
Phalaris brachystachys
P. paradoxa
Poa annua
Polygonum equisetiforme
Raphanus raphanistrum
Senicio vernalis
S. vulgaris
Sinapis arvensis
Sisymbrium spp.
Sonchus oleraceus
Stellaria media
Urtica urens

Summer Weed Species Controlled

Abutilon theophrasti
Alhagi maurorum
Amaranthus blitoides
A. retroflexus
Anoda cristata
Carthamus syriacum
Chenopodium album
C. murale
C. pumila
Commelina communis
Conyza bonarinsis
Coronilla scorpiodes
Cyperus spp.
Datura stromonium
Digitaria sanguinalis
Echinchloa crus-galli
Eleucine indica
Ergrostis magastachys
Hyperium crispus
Ipomoea lacunosa
Lavatera cretica
Malva parviflora
M. sylvestris
Orobanche aegyptica
O. crenata
O. ramosa
Polygonum persicaria
P. polyspermum
Proscopis furcata
Setaria glauca
Sida spinos
Solanum nigrum
Striga hermonthica
Trianthema portulacastrum
Tribulus terrestris
Xanthium pensylvanicum
X. spinosum

Summer Weed Species Partly or Not Controlled

Anchusa aggregata
Astragalus boeticus
Conyza canadensis
Crozophora tinctoria
Malva niceaensis
Melilotus sulcatus
Portulaca oleracea
Scorpiurus muricatus
Solanum luteum
Xanthium strumarium

Adapted from Elmore, C. L., in *Soil Solarization*, Katan, J. and DeVay, J., Eds., CRC Press, Boca Raton, FL, 1990, chap. 5.

yield; and Ramirez-Villapudua and Munnecke[35] demonstrated excellent control of fusarium wilt of cucumber by integrating solarization with cruciferous crop residues, when neither method alone was effective. Gamliel and Stapleton[36] found both qualitative and quantitative differences in volatile,

Table 3 Susceptibility of Perennial Weed Species to Soil Solarization

Weed Species Controlled	
Chloris gayana	*Equisetum arvense*
Convolvulus althaeoides	*E. ramosissimum*
C. arvensis (seed)	*Oxalis corniculata*
C. arvensis (plant)	*Plantago* spp.
Cynodon dactylon (seed)	*Sorghum halepense* (seed)
Weed Species Partly or Not Controlled	
Cynodon dactylon (plant)	*Cyperus rotundus*
Cyperus esculentus	*Sorghum halepense* (plant)

Adapted from Elmore, C. L., in *Soil Solarization*, Katan, J. and DeVay, J., Eds., CRC Press, Boca Raton, FL, 1990, chap. 5.

antifungal compounds released by organic residues during solarization. Volatile compounds in soil greatly increased in concentration as heating increased. Another advantage of combining organic amendments with solarization is that heat of decomposition may further increase soil temperature and add to the efficacy of soil disinfestation (Figure 1).

III. IMPLEMENTATION AND IMPEDIMENTS

Since its inception and early development during the mid-1970s, soil solarization has been tested and modified under local conditions in more than 38 countries.[37] The idea of harnessing passive solar energy to replace the need for highly toxic soil fumigants is intriguing, and has captured the imagination and interest of agricultural scientists and producers around the world. Because of its current cost (ca. U.S. $300 to 600 dollars/acre — one third to half the cost of chemical fumigation with tarp) — it is a method primarily compatible for use with high-value, low-acreage horticultural crops.[38,39] In addition, a number of reports have indicated its value as a research tool with various applications for low-value field crops.[4,16,40]

To date, soil solarization has primarily remained an experimental technique under continuing evaluation, although it has found successful niches as a commercial crop production practice, especially in greenhouse culture.[41–44] In other areas, it has been recommended by agricultural agencies and tested, but not widely adopted, by growers.[20,41,42,45] As previously discussed, besides disinfesting soil while eliminating the need for chemical fumigants, solarization offers other attractive benefits to users, including increased levels of available mineral nutrients, changes in soil microflora favoring biological pest control, and, usually, increased yield and quality of crops following treatment. Additional benefits may include water conservation and soil temperature modification when the solarization mulch is maintained as a row cover during the following crop.[46–48]

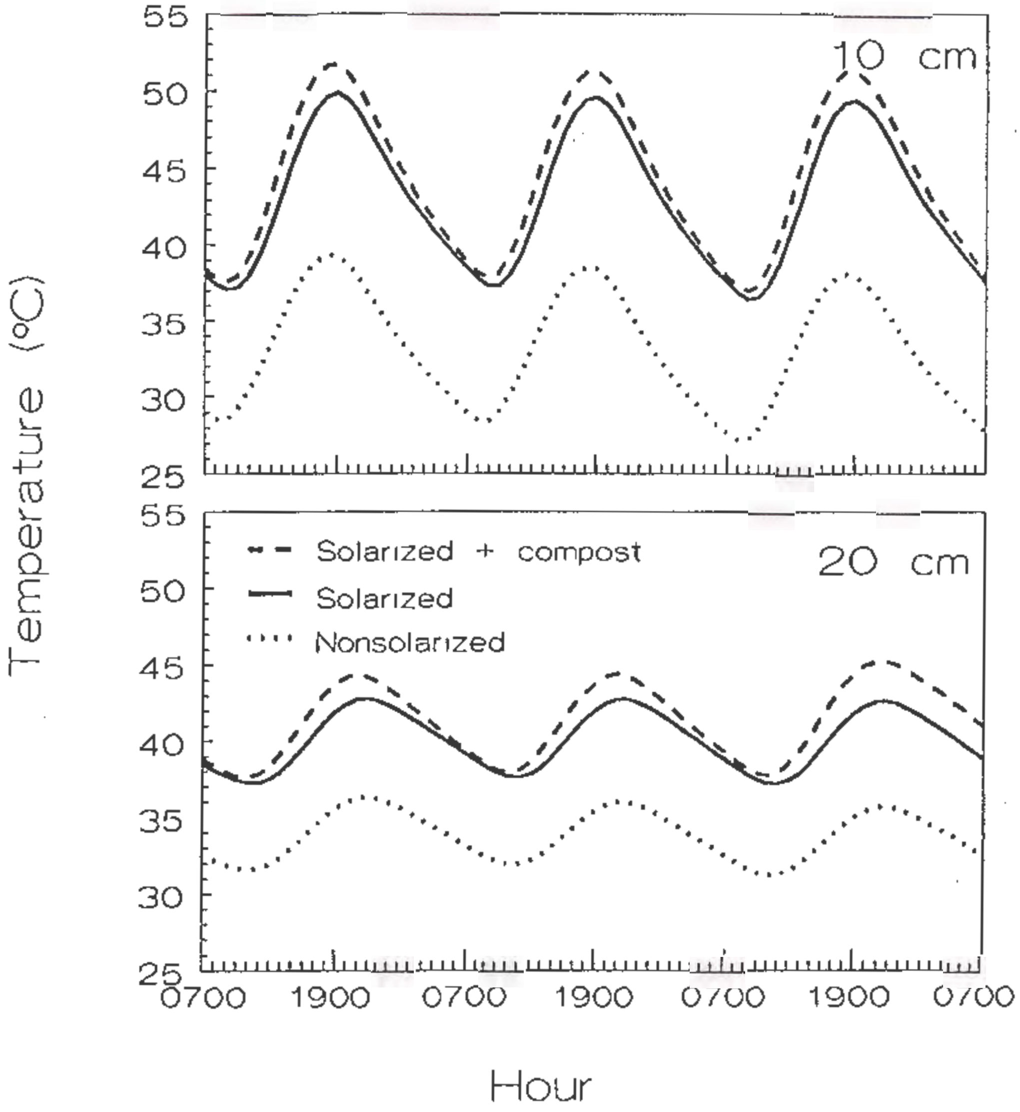

Figure 1 Effect of compost amendment on soil temperature during soil solarization at depths of 10 and 20 cm. (From Gamiel, A. and Stapleton, J. J., *Plant Dis.*, 77, 886, 1993. With permission.)

Soil solarization may be a classic example of an idea which has developed ahead of optimal technological feasibility. Although the principles of solarization initially may appear to offer a panacea, there are also a number of disadvantages to current use of the process which have minimized its implementation in large-scale agriculture.

For the past several years, research on basic and applied aspects of soil solarization has steadily progressed, but widespread implementation of the practice has been mainly confined to pockets of small-scale growers, greenhouse operators, and backyard gardeners. Acceptance for field use by commercial producers has been much slower than anticipated. There are several probable explanations for this:

1. Potential users have been satisfied with the results they received from available chemical fumigants, and they feared a loss of predictability of control with solarization, as compared to the fumigants. This is especially true with nursery production of high-value crops where regulatory agencies mandate a zero-tolerance for diseases and nematodes, necessitating pest eradication down to a soil depth of nearly a meter. As with other methods of soilborne pest control, instances of ineffective pest management by solarization have been documented, and as previously discussed, certain pest organisms are relatively insensitive to the treatment.
2. The fear of treatment unpredictability was compounded by economic considerations. Commercial application of solarization costs approximately half that of fumigating tarped soil with methyl bromide, and about two thirds that of methyl bromide without tarp. Solarization can cost as much or more as fumigation with chemicals such as 1,3-dichloropropene or metham sodium. The fumigation industry, although assisting in solarization research, did not actively promote or market this new technology, and, in many cases, discouraged its use. There are a number of reasons for this, including potential loss of profit from fumigant sales, and possible litigation arising from losses due to ineffective solarization applications. Long-term soil mulching with plastic films poses a risk in the form of tarp damage due to high winds, animal tracks, etc. that could result in loss of investment if mulch integrity is destroyed prior to efficacious treatment. Using current technology, solarization is a material- and labor-intensive practice; disposal of large amounts of polyethylene film can be problematic and expensive, since recycling facilities may be unavailable and legislation restricting pollution by plastic residues is in place in many locations.
3. Solarization requires that land be rotated out of production for 1 to 2 months during the hottest part of the year. For summer crops, especially in cooler, coastal growing regions, this requirement may be prohibitive. Because of this, implementation efforts in many areas have been focused on use of solarization prior to establishment of cool-season crops.[3,42,45,47] In some growing areas, especially those with desert climates, summers are too hot for cultivation of most crops, and solarization during the fallow period is an ideal pest management practice.
4. As with most IPM practices, solarization requires more biological knowledge by users than with pesticide application for successful treatment. Many potential users do not wish to make the commitment in time and effort to obtain such knowledge. Hence, specialized, commercial contractors are required to apply the treatment.

Despite these perceived, negative aspects, commercial producers are now demonstrating increased interest in solarization, primarily due to public and regulatory pressure to reduce the use of pesticides in agriculture. In California, several grower organizations have tested solarization on pest problems of commodities including strawberry, celery, and sweet potato, with the intent of implementing the practice only if available fumigants are lost. Recently, the suspension of 1,3-dichloropropene use and pending legislation restricting or prohibiting a number of other pesticides, as well as "low pesticide" marketing strategies, have caused the industry to begin using alternative growing practices such as solarization. A number of agricultural consultants and advisors are now recommending a period of solarization after tarped, fumigant application to increase efficacy or to reduce the amount of pesticide applied. This may signify the advent of a transitional period between the methods, or give evidence of increasing industry adoption of integrated pest management strategies. In California, soil solarization is approved for use in organic production by the major certifying organization, and many producers interested in converting part or all of their output to tap into the expanding organic market are now using or testing the method.

The primary limitation to solarization is the current necessity of large amounts of plastic film for soil mulching. These materials tend to be bulky and difficult to apply, and more importantly, they require removal and disposal after use. Disposal is a major problem currently affecting the plastics industry as a whole. In areas where agricultural plasticulture is widespread, recycling facilities usually are present and the disposal problem is minimal. Used mulch is mechanically collected and compacted by tractor-mounted implements, then hauled to regionally located recycling centers. However, this option is not always available. Environmental laws in the U.S. usually prohibit burning plastic waste, and landfills often refuse to accept plastics due to their slow decomposition.

Another current limitation is that of climate and meteorological unpredictability.[48] The efficacy of solarization is described by a dynamic dosage relationship of (incubation time) × (soil temperature). Since the passive solarization process is primarily driven by local weather conditions, the predictability of its action on soilborne pests is not as certain as when chemical fumigants are used. In the hottest climatic areas, such as California's Imperial Valley,[45] the efficacy of solarization during summer months is virtually assured. In cooler areas, however, meteorological factors such as temperature fluctuations, cloud cover, wind speed and direction, and passage of storm fronts can affect the solarization period or time necessary to satisfactorily disinfest soil of unwanted pests. If widespread implementation of solarization is desired, user-accessible, predictive models for specific soilborne pests and pathogens must be available.[49] Normally, plastic mulch film for solarization is left in place for 4 to 6 weeks incubation. However, optimal use may require a longer time, which may impede scheduling of other production practices.

Yet another potential limitation of solarization is the need for taking land out of production for several weeks during summer months. In very hot desert regions, such as the Imperial and Jordan Valleys, this is not a problem since horticultural cropland lies fallow under the excessive summer heat. In these areas, solarization can ideally occur prior to planting of cool-season crops. In more temperate areas, however, solarization may interfere with summer crops, unless a flexible cropping schedule is designed.

Because of these limitations, solarization has found its greatest usage to date in small, intensively cultivated settings such as greenhouse production, organic or ecological farms, and backyard gardens.

IV. THE FUTURE OF SOLARIZATION: DIRECTIONS AND IMPROVEMENTS

It is important that soil solarization be considered as a developing, rather than a static, technology. Improvements to the solarization process, which will facilitate application and disposal, increase durability of materials in the field, and aid treatment predictability through increased soil heating or integration with other methods of pest control, are necessary to make the appeal of solarization more attractive to a wide spectrum of users.

Adoption of solarization technology is slowly increasing, primarily for greenhouses and for high-value crops in hot, inland valley growing areas. Increasing acceptance of solarization is primarily due to recent restrictions on pesticide usage. Present limitations to more widespread adoption include climatic restrictions, treatment cost, and disruption of conventional cropping practices. Advances in polymer technology and integration of disease and pest management practices should increase the commercial attractiveness of solarization as a safe, effective method of soil disinfestation.

New-generation mulching materials, such as photodegradable and biodegradable film emphasizing enhanced degradability, are now being produced. Several recent studies have shown the feasibility of solarizing soil with water-soluble, sprayable polymer mulches, rather than with plastic sheeting.[50–52] These materials are easily applied by existing groundspray methods, eliminate the need for handling of bulky rolls of film, are less subject to destruction in the field by wind or mechanical damage, and can be removed by incorporation into the soil. Although these materials have not been perfected, their development is seen as a major breakthrough, since producers are amenable to pest control methods that can be applied by their spray rigs, and since they can avoid the necessity and expense of disposing of large quantities of plastic film residue.[53]

Combining solarization with other control methods, such as organic soil amendments, biological control organisms, or reduced doses of chemical pesticides, may increase the predictability and effectiveness of the process, and allow more widespread use of this alternative method of soil disinfestation.

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