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Review: Soil solarization and its effects on medicinal and aromatic plants

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Abstract. *Khalid KA. 2012. Review: Soil solarization and its effects on medicinal and aromatic plants. Nusantara Bioscience 4: 36-44.* Soil solarization or solar heating is a non-chemical disinfestation practice. Solarization effectively controls a wide range of soilborne pathogens, insects, and weeds. Soil solarization is based on the exploitation of solar energy for heating wet soil mulched with transparent plastic sheets to 40-55ºC in the upper soil layer. Thermal killing is the major factor involved in the pest control process, but chemical and biological mechanisms are also involved. The efficacy of the thermal killing is determined by the values of the maximum soil temperature and amount of heat accumulated (duration x temperature). The use of organic amendments (manure, crop residues) together with soil solarization (biofumigation) elevates the soil temperature by 1-3ºC, and improves pest control due to a generation and accumulation of toxic volatiles. Although cheaper than most chemicals used as soil fumigants, not all crops are worth the plastic prices, particularly in developing countries. Not all soilborne pests and weeds are sufficiently controlled. Cheaper and more environmentally accepted mulching technologies are needed before expanding the range of the controlled pests by solarization. Medicinal and aromatic plant production was affected by soil solarization.

Keywords: solarization, soilborne diseases, disinfestation, mulches, plastic.

Abstrak. *Khalid KA. 2012. Review: Solarisasi tanah dan dampaknya pada tanaman obat dan aromatik. Nusantara Bioscience 4: 36-44.* Solarisasi atau pemanasan tanah dengan matahari adalah praktek pembasmian hama dan penyakit secara non kimia. Solarisasi efektif mengendalikan berbagai patogen bawaan tanah, serangga dan gulma. Solarisasi tanah didasarkan pada pemanfaatan energi matahari untuk memanaskan tanah basah bermulsa dengan lembaran plastik transparan dengan suhu 40-55ºC pada bagian atas lapisan tanah. Pembasmian dengan panas merupakan faktor utama dalam proses pengendalian hama, tetapi mekanisme kimia dan biologi juga terlibat. Efektivitas pembasmian dengan panas tergantung oleh nilai-nilai suhu tanah maksimum dan jumlah panas yang terakumulasi (durasi x suhu). Penggunaan penutup organik (pupuk kandang, sisa tanaman) bersama dengan solarisasi tanah (biofumigation) meningkatkan suhu tanah 1-3ºC, dan meningkatkan pengendalian hama karena pembentukan dan akumulasi senyawa-senyawa volatil beracun. Meskipun lebih murah daripada kebanyakan bahan kimia yang digunakan sebagai fumigant tanah, tidak semua hasil panenan sepadan dengan biaya penyediaan plastik, terutama di negara berkembang. Tidak semua tanah yang mengandung hama dan gulma dapat dikendalikan sepenuhnya. Teknologi mulsa yang lebih murah dan lebih ramah lingkungan diperlukan sebelum memperluas jangkauan pengendalian hama dengan solarisasi. Produksi tanaman obat dan aromatik dipengaruhi solarisasi tanah.

Kata kunci: solarisasi, tanah penyakit bawaan, disinfestation, mulsa, plastik.

INTRODUCTION

Soilborne plant pathogens survive in the soil and cause extensive damage to many crops. The most common approach for their control is by elimination before or after planting, by means of destructive methods of soil disinfestation. This should be done in such a manner as to reach the pathogens in all physical and biological niches in the soil. Chemical fumigants have proved to be of great advantage to agricultural production for many years. They are strong eradicators by nature, resulting in simultaneous control of a variety of pests. However, negative effects, i.e., eradication of beneficial organisms, and a negative shift in the biological equilibrium in the soil, are also possible during their use. Unfortunately, certain fumigants were found to possess limiting negative attributes, such as acute and chronic health hazards, environmental pollution, and even potential atmospheric ozone depletion. The increased environmental concern due to these negative effects has been a major factor in triggering regulatory restriction on the use of soil fumigants. In many countries, the use of fumigants, especially nematicides including 1,2-dibromochloropropane (DBCP), ethylene dibromide (EDB) and 1,3-dichloropropene, has been discontinued or suspended, and phase-out of methyl bromide, which is the most widely used soil fumigant, is currently underway. Few soil disinfestation chemicals are still available, leaving the farmers in many cases without effective means to combat soilborne pests. None of the available methods used to control soilborne diseases is effective against all pathogens (including those caused by nematodes and bacteria, which are difficult to control), or can be used in all instances. Thus, development of nonchemical methods for effective control of soilborne diseases is needed (Gamliel and Stapleton 1997; Pokharel and Larsen 2007; Pokharel et al. 2008).

Concern over environmental hazards and increased public awareness on human health issues caused by pesticides such as methyl bromide (MB) to the stratospheric ozone have directed much attention to alternative practices for chemical pest control (Katan 2000). Soil solarization or *solar heating* is a non-chemical disinfestation practice that has potential application as a component ofa sustainable integrated pest management (IPM) approach. In addition, it also increases the availability of soil mineral nutrients, reduces crop fertilization requirements and results in improved plant growth and yield (Stapleton and DeVay 1986). Solarization was originally developed to control soilborne pathogens as first reported by Katan et al. (1976), but it was soon found to be an effective treatment against a wide range of other soilborne pests and weeds including more than 40 fungal plant pathogens, a few bacterial pathogens, 25 species of nematodes and many weeds (Stapleton 1997; Okharel and Hammon 2010). The virtues of solar energy are not new; however, the innovation in developing soil solarization is the use of a modern tool to this end, namely, plastic sheets. Thus, implementation of this technology is easy to accomplish under a wide range of crop production systems. Soil solarization is based on utilizing the solar energy for heating soil mulched with a transparent polyethylene (PE) sheet, reaching a level of 40-55ºC in the upper soil layer. There is a gradient of temperatures from the upper to lower soil layer during the appropriate season. The temperature elevation is facilitated by wetting the soil before and/or during mulching with the PE sheet. The main factor involved in the pest control process is the physical mechanism of thermal killing. In addition, chemical and biological mechanisms are involved in the pest control process.

BASICS PRINCIPLE

The basic principle of soil solarization is to elevate the temperature in moist soil to a lethal level that directly affects the viability of certain organisms. The heating process also induces other environmental and biological changes in the soil that indirectly affect soilborne pests as well as survival of beneficial organisms (Katan 1981). The values of the maximum soil temperature and amount of heat accumulated (duration x temperature) determine the potential of the thermal killing effect on soilborne pests (Katan 1987) and weed seeds (Stapleton et al. 2000a, 2000b). Currently, the most common practice of soil solarization is based on mulching moistened soil with transparent PE. The duration of soil mulching that is required for successful effect is usually four to six weeks, depending on the pest, soil characteristics, climatic conditions and the PE properties (Katan 1981, 1987; Rubin and Benjamin 1984). Pest population and environmental conditions are unmanageable variables, while soil moisture and PE properties could be modified as needed. Soil pretreatment and appropriate PE technology may overcome unfavorable environmental conditions prevailing in some regions or in certain seasons, increasing weed (or pest) sensitivity and soil, shortening soil mulched duration (Stevens et al. 1991). Soil moisture improves temperature conductivity in soil and the sensitivity of microorganisms to toxic agents. Hence, pest control is better under *wet heating* than *dry heating*. This applies also to weed control, presumably because moist seeds are in a more advanced metabolic activity (Shlevin et al. 2004). Therefore, all soil pretreatments that improve water capacity, such as soil cultivation or drip irrigation during mulching, may improve soil solarization efficacy. Drip irrigation during the solarization process is essential for maintaining a wet soil surface, enabling the heat transfer to deeper layers. Moreover, good soil preparation that leads to a smooth soil surface facilitates plastic mulching and prevents tearing (Figure 1).

Soil energy balance

Mahrer (1991) discussed the mechanisms that affect the soil energy balance on bare and mulched soils. Soil energy balance can be mathematically described as follows: Rs + Rl-S-H-E = 0. Where Rs and Rl are the net fluxes of short and longwave radiation at the soil surface (radiative fluxes), S is conduction of heat in the soil (soil heat flux), H is the net heat exchange due to convection (sensible heat flux) and E is the net heat exchange due to evaporation and condensation of water (latent heat flux). These fluxes determine the temperature regime of the soil, and can be manipulated by covering the soil with appropriate mulches. Radiative fluxes are determined by the photometric characteristics (transmission, absorption, and reflection of electromagnetic radiation) of both the soil and the mulch. Soils of darker colors tend to have higher temperatures due to increased light absorption. Mulches that are transparent to short-wave radiation and reflective to long-wave radiation increase the influx of heat into the soil by inducing a greenhouse effect.

Plastic mulches

Mulches used for solarization are films of plastic polymers, usually polyethylene (PE), polyvinyl chloride (PVC), or ethylene-vinyl acetate (EVA). PE films are the most widely used. Among the desirable characteristics that make PE films popular are tensile strength, resistance to tearing when exposed to strong winds and low cost (Brown et al. 1991; Stevens et al. 1991). The optical properties of PVC and EVA are more desirable than those of PE for soil solarization, but their manufacture is more complicated and therefore, they are more expensive (Lamberti and Basile 1991). Gutkowski and Terranova (1991) observed that temperatures in soils mulched with EVA films are higher than in soils mulched with PE films. Noto (1994) found that temperatures for PVC film were slightly higher than those for PE. Cascone and D'Emilio (2000) compared the performance of EVA and co-extruded EVA-EVA and EVA-PE films on the effectiveness of greenhouse soil solarization for controlling soilborne pathogens, but since

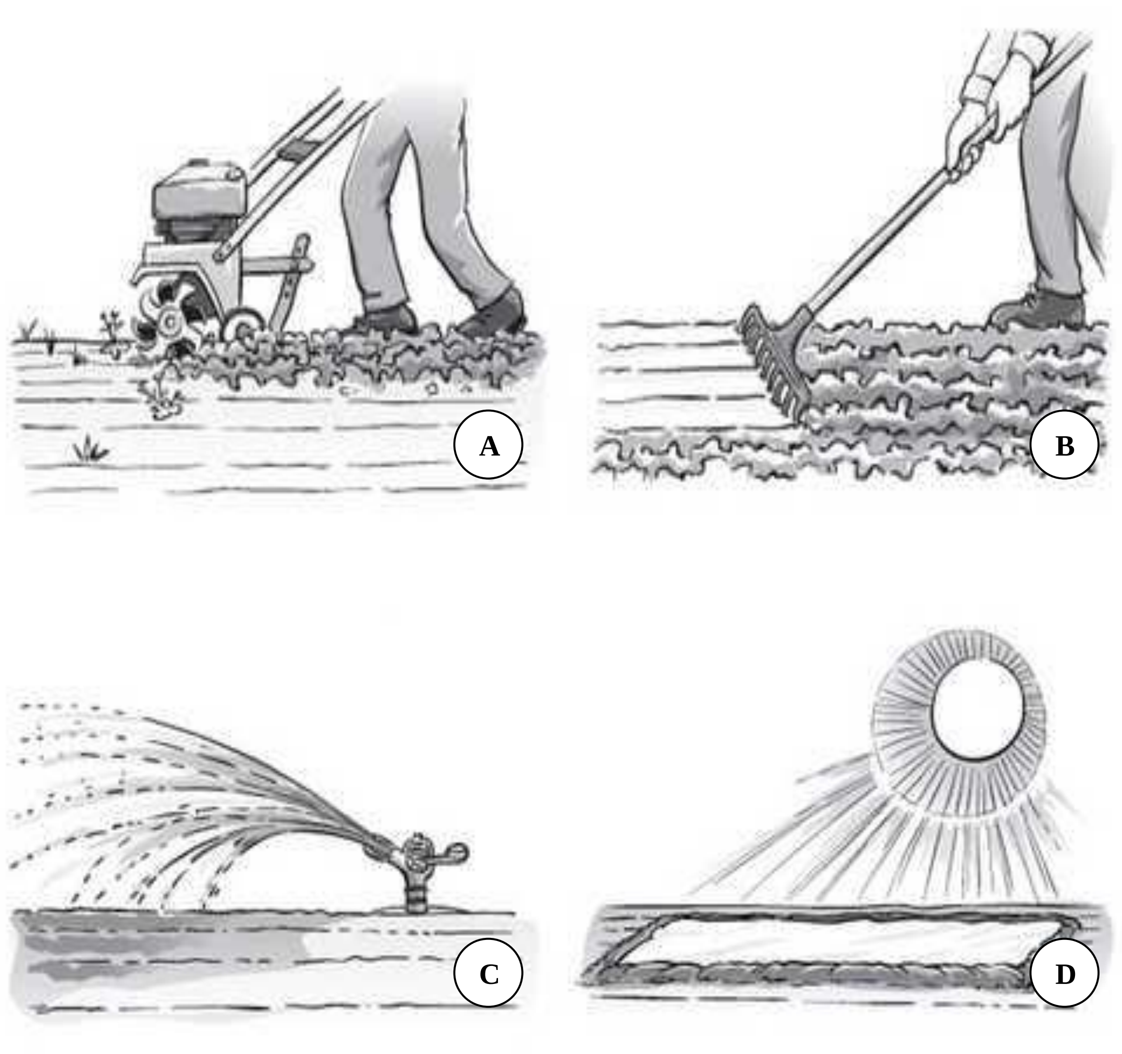

Figure 1. The four steps to solarize soil. A. cultivate and remove plant matter, B. level and smooth the soil, C. irrigate, D. and lay a clear tarp on the soil surface for 4 to 8 weeks, depending on local conditions (Stapleton 2008).

the mulches were of different color and thickness, an identification of the polymer effects could not be done. Plastic films can contain additives that improve their properties for use in solarization. Additives include pigments, heat-retaining substances, wetting agents, ultraviolet stabilizers and photodegradable or biodegradable additives (Brown et al. 1991; Stevens et al. 1991).

Pigmentation of the plastic influences the efficiency of the mulch in soil energy management. Alkayssy and Alkaraghouli (1991) tested the performance of different color plastic mulches for soil solarization and reported that soil temperatures decreased for the colors in the following order: red, transparent, green, blue, yellow and black. Traditionally, soil solarization has been implemented using either transparent or black mulches. Black PE films are usually pigmented with carbon black fillers, while transparent films have no pigment at all. Chase et al. (1999) and Campiglia et al. (2000) observed that soil temperatures under transparent film were higher than under black mulch, while Ham et al. (1993) reported the opposite. Rieger et al. (2001) found black and clear mulches were equally effective for increasing soil temperatures.

Heat-retaining substances and wetting agents also influence the photometric characteristics of mulch. Mineral additives such as aluminum silicates can be added to PE films to increase their opacity to long-wave radiation and enhance the greenhouse effect in the soil (Chase et al. 1999). Wetting agents in the film allow humidity to condense in a thin, continuous layer that also traps heat without significantly reducing the light transmittance of the plastic (Lamberti and Basile 1991).

Plastic films degrade when exposed to ultraviolet (UV) radiation, one of the components of natural light. This degradative process compromises film integrity, which is required in order to minimize heat losses from the soil. Plastic degradation due to exposure to natural radiation has been slowed down by the addition of UV stabilizers, such as benzophenones, nickel compounds and hindered amines. Carbon black, a common pigment for black films, also acts as a UV stabilizer: as a general rule, black films last longer than films of other color (Abu-Irmaileh 1991; Brown et al. 1991; Stevens et al. 1991).

The durability of plastic films can be further controlled by the addition of other substances that increase the rate of degradative processes. Photodegradable PE films contain substances that accelerate the degradation of plastic exposed to light (for example, ferric ion complexes or calcium carbonate). Biodegradable plastics include substances in the polymer matrix that can be metabolized by microorganisms in the soil, accelerating the disintegration of the film into small particles. Film degradation has been considered as an alternative to inconvenient and costly removal and disposal procedures traditionally used for plastic mulches (Brown et al. 1991; Stevens et al. 1991).

Physical and chemical changes

In addition to direct physical destruction of soilborne pest inoculums, other changes in 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, NH_4-N and NO_3-N concentration in the top 15cm 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 on the mineral soil particles undergoing solarization. Improved mineral nutrition is also often associated with chemical soil fumigation (Chen et al. 2000). According to Stapleton et al. (1985), summer solarization of six wet field soils of four different textures raised soil temperatures by l0-12°C at 15 cm depth. Soil solarization increased concentrations of NO_3-N and NH_4-N up to six times those in nontreated soils. Concentrations of P, Ca^{2+}, Mg^{2+} and electrical conductivity (EC) increased in some of the solarized soils. Solarization did not consistently affect available K^+, Fe^{3+}, Mn^{2+}, Zn^{2+}, Cu^{2+} Cl-concentrations, soil pH or total organic matter. Concentrations of mineral nutrients in wet soil covered by transparent polyethylene film, but insulated against solar heating, were the same as those in nontreated soil. Increases in NO3-N plus NH_4-N were no longer detected in fallowed soils 9 months after solarization.

Biological changes

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). Solarization has been used successfully to reduce various plant pathogenic fungi (Katan 1981). The reduction of pathogens during solarization has been ascribed not only to high temperatures but also to the production of some volatiles such as carbon dioxide, ethylene, and other substances which are toxic to fungi (Rubin and Benjamin 1984). 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 that kill 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; Gamliel and Stapleton 1993a; Stapleton and DeVay 1995).

Restrictions

The major constraints that limit the adoption of soil solarization in practice are the relatively long duration of the process and the climatic dependency. The cost of solarization is relatively low compared with other available alternatives; however, it can be a limiting factor depending on the country, the crop type, the production system (e.g. organic versus conventional farming) and the cost and availability of alternatives. Soil solarization as a non-chemical tool for weed management was proven to be more cost-effective and profitable than MB (Stapleton et al. 2005) or some other treatments (Boz 2004), especially in highly-valued crops (Abdul-Razik et al. 1988; Vizantinpoulos and Katranis 1993). Technological innovations, such as mulching the soil with sprayable polymers or using a variety of PE sheets or other mulch techniques (Gamliel and Becker 1996; Al-Kayssi and Karaghouli 2002), will facilitate the application and use of soil solarization in agriculture. These facilitations should result in reduced mulch duration, an increased geographical range of usage, a broader range of controlled weeds, improved persistence of the PE sheets, decreased PE pollution and a significant decrease in the total economic cost of mulching. However, in addition to the favorable effects of soil solarization, there are also unfavorable ones: (i) there are geographical limitations on where the method can be used in terms of solar radiation availability; (ii) the soil is occupied for at least one month with the mulch; (iii) although cheaper than most chemicals used for soil fumigation, not all crops are worth the PE prices ; (iv) it is difficult to protect the PE sheets from damage caused by wind and animals; (v) there is no fully environmentally- accepted solution for the used

PE; and (vi) not all soil-borne pests and weeds are sufficiently controlled.

Perfection

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 reliability 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 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 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 nearly undetectable levels to a soil depth of 46 cm (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 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 inundating 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 sublethal 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 is likely to remain to be a topic of interest and experimentation for many researchers.

EFFECT OF SOLARIZATION ON MEDICINAL AND AROMATIC PLANTS

Stapleton et al. (1985) indicated that fresh and dry weights of radish, pepper, and Chinese cabbage plants usually were greater when grown in solarized soils than in nontreated soils. Fertilization of solarized soils sometimes resulted in greater plant growth responses than observed in solarized than non-fertilized soils. Solarization of soil within plastic bags for 4 weeks also increased availability of nutrients such as NH_4+, N, PO_4+, and K+ for gerbera *(Gerbera jamesonii* L.) plants (Kaewruang et al. 1989). The long-term effect of solarization on the control of pink root disease and on onion yields was studied during four successive years. No disease symptoms were noted in the first year. However, total and quality yields were increased by 29% and 57%, respectively, denoting an increased growth response phenomenon. In the following years, disease incidence increased substantially in the untreated plots, but solarization had a long-term effect in reducing disease incidence. Soil solarization has great potential for increasing onion yield in the Mediterranean region (Satour et al. 1989).

Solarization of soil was found beneficial for plant growth in cowpea under field conditions. Root nodulation, infection by mycorrhizal fungi and yield were higher in plants grown in solarized soil. These increases were to the extent of 104.7, 20.0 and 23.7% respectively when compared to control treatment without solarization (Nair 1990). Solarization of soil within plastic bags for four weeks increased availability of nutrients; solarization also significantly controlled annual weed and increased strawberry yield 12% over the yield of nontreated plots (Hartz et al. 1993). Two field experiments resulted in the reduction to undetectable levels of *Sclerotium cepivorum* in the upper 20 cm layer of soil, even in heavily infested soils, after solarization for 8-11 weeks. White rot progress curves in subsequent crops of garlic indicated disease onset ~ 4 months after planting. Rates of disease progress and final incidence of dead plants were greatly reduced in solarized plots, with yield increments of 40.6-155.5% over the unsolarized control plots. However, a garlic crop in the second year after solarization had increased disease levels and yield reductions that was unacceptable to the growers; this is, apparently, attributable to the high incidence of white rot of garlic that can be induced by low inoculum densities in the soil. Disease progress curves in the unsolarized plots suggested that secondary infections occur.

The effect of soil solarization on the quality of garlic was beneficial because of the increased growth response observed. Soil solarization, during the summer, before the susceptible crop is planted, provides a reliable and practical method of control of white rot of garlic (Basallote-Ureba and Melero-Vara 1993). Soil solarization on raised Strawberry beds was complicated by weed growth on the top edges and sides of the bed. Soil solarization is a useful alternative for flatbed culture, but is practically limited on raised beds due to insufficient weed control (Himelrick 1995).

Combining organic amendments with soil solarization is a nonchemical approach to improvement of the control of soilborne plant diseases. Pathogen control in solarized-amended soil is attributed to a combination of thermal killing and enhanced generation of biotoxic volatile compounds. Apparently, pathogen sensitivity to biotoxic volatile compounds is enhanced with an increase of soil temperature and acts in combination with antagonistic microbial activity. Enhanced biocontrol may also be involved in some amendments. Toxic volatile compounds including alcohols, aldehydes, sulfides, isothiocyanates, and others were detected in soil amended with cruciferous residues during heating so field solarization of soil amended with composted chicken manure gave better control of pathogens and higher yield of lettuce and tomato than either treatment alone (Gamliel and Stapleton 1997). Marketable Tomato yields in plots using soil solarization and similar to yields obtained in plots fumigated with methyl bromide + chloropicrin (Chellemi et al. 1997).

According to Grünzweig et al. (1999), the effect of solarization on plant nutrients and their role in the IGR (increased growth response) was studied with tomato plants grown in solarized or non-solarized (control) sandy soil, under controlled conditions. Solarization considerably increased the soil concentrations of water extractable N, K, Ca, Mg and Na at most sites, whereas Cl and diethylenetriaminepentaacetic acid (DTPA) extractable Mn, Zn, Fe, and Cu were decreased by the treatment. Plant growth and specific leaf area were enhanced in solarized as well as in N-supplemented control soil. In tomato plants grown in solarized soil, concentrations of most nutrients in the xylem sap, including N, were increased compared to the control, whereas Cl and SO4 levels decreased. The most significant increase in leaf nutrient concentration caused by soil solarization was recorded for N. Furthermore, leaf N concentration was highly and positively correlated with shoot growth. The concentration of Cu increased in leaves from the solarization, whereas that of SO4 and Cl decreased, the latter presumably below the critical toxicity level. The correlation between shoot growth and leaf concentration was positive for Cu and inverse for Cl and SO4. In conclusion, we found that soil solarization significantly affects nutrient composition in tomato plants, and provided strong evidence that N, and eventually also Cl, play a major role in IGR.

Soil solarization experiments were completed in three commercial olive orchards in southern Spain; soil-solarized plots remained free of weeds, but tress in solarized plots did not show significant growth increase measured by trunk perimeter (Lopez-Escudero and Blanco-Lopez 2001). Raising the cuttings in solarized mixture fortified with *Trichoderma harzianum* and VAM is reported to produce robust disease-free rooted black pepper cuttings (Sarma 2000; Anandaraj et al. 2001). Solarization mediated favorable effects were observed in bhindi (Bawazir et al. 1995), onion (Adetunji 1994), coriander (Herrera and Ramirez 1996), lime (Stapleton and Devay 1986), chilies (Haripriya and Manivannan 2000) and black pepper (Sainamole et al. 2003).

Solarized soil with different levels of cattle manure resulted in a significant increase in growth and yield characters, i.e. plant height, branch number (plant-1), flower-head number (plant-1), fresh and dry weights of flower heads (g plant-1), fresh and dry weights of vegetative parts (g plant-1) and seed yield (g plant-1) as well as increase the chemical composition (essential oil, total flavonoids , total carotenoids, N, P, K, Fe, Zn and Mn) compared with the treatments of cattle manure only (Khalid et al. 2006).

According to Thankaman (2008) solarized potting mixture in combination with nutrients and biocontrol agents was evaluated for production of vigorous disease-free rooted cuttings of black pepper. Plants raised in solarized potting mixture had better growth than plants rose in nonsolarized potting mixture (soil, sand, and farmyard manure 2: 1: 1 proportion). Among the various treatments, plants raised in solarized potting mixture with recommended nutrients (urea, superphosphate, potash, and magnesium sulphate 4: 3: 2: 1) showed significant increase in number of leaves (5.3), length of roots (20 cm), leaf area (177 cm2), nutrient contents and biomass (3.7 g pl-1). The results indicated the superiority of solarized potting mixture for reducing the incidence of diseases besides yielding vigorous planting material. Cost of production of rooted cuttings with biocontrol agents was found to be cheaper in the case of rooted black pepper cuttings raised in solarized potting mixture. Biocontrol agents or biofertilizers can be mixed with solarized potting mixture. The tomato yield and nutrient contents (N, P, K, Ca, Mg, Mn, Zn, and Cu) were increased in leaves by soil solarization (Cimen et al. 2010).

FUTURE EXPECTATION

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 disinfectant 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 disinfestations. 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 disinfectants (Stapleton 2000a). 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 to become increasingly important (Stapleton 2000b). Known limitations of soil solarization are high implementation costs for developing countries, and the requirement of special logistics and managerial abilities. Because of these limitations, solarization is used primarily for highly-valued crops (Chen et al. 2000).

According to Barakat and Al-Masri (2012a), soil solarization tests against *Fusarium oxysporum* f. sp. *lycopersici*, the causal agent of tomato *Fusarium* wilt, were conducted for seven weeks through July and August 2008 and 2009 in the climatic conditions of Al-Aroub Agricultural Experimental Station, located in the southern mountains of the West Bank, Palestine. Double polyethylene (DPE) sheets, regular polyethylene (PE) sheets, and virtually impermeable films (VIF) were compared to examine their effects on soil temperature, disease severity, and plant growth. Results showed that in comparison to the control, PE, DPE, and VIF treatments increased the mean maximum soil temperatures by 10.2, 14.1, and 8.8ºC, respectively, in 2008 and by 10.2, 12.6, and 8.3ºC respectively, in 2009. The longest length of time recorded for temperature above 45ºC under DPE sheets were 220 hours in 2008 and 218 hours in 2009. The treatments reduced the pathogen population by 86% and the disease by 43% under the DPE treatment in 2009 and to a lesser extent by the other treatments. Increases of up to 94% in fresh plant weight and up to 60% in plant dry weight were evident under the same treatment. The treatments also increased soil organic matter, both nitrogen forms, and major cations.

According to Lombardo et al. (2012), the relative efficacy of soil solarization and fumigation with chloropicrin and 1, 3- dichloropropene (CP+1, 3-D) was evaluated in greenhouse-grown tomatoes. Experiments were conducted over two seasons in southern Italy, aimed at evaluating the effects of soil treatment on soilborne pest control, and the vegetative growth and fruit production of tomato. Solarization provided a better level of control over the major fungal pathogens (*Fusarium oxysporum* f. sp. *lycopersici* and f. sp. *radicis-lycopersici*, as well as *Pyrenochaeta lycopersici*) than CP+1, 3-D fumigation. Solarization was also more effective in reducing the population of *Meloidogyne* spp. in the soil, and was particularly valuable for the suppression of the parasitic plant branched broomrape *Phelipanche ramosa* (syn. *Orobanche ramosa*). In both seasons, solarization was more beneficial than CP+1, 3-D fumigation in terms of plant growth and crop productivity. In conclusion, solarization provided a good level of control over some important tomato pests and weeds, while at the same time improving productivity in an environmentally friendly manner. It should, therefore, represent a viable alternative to methyl bromide fumigation for the greenhouse production of tomato.

According to Barakat and Al-Masri (2012b), the use of integrated pest management is a valid alternative to conventional chemical treatments. This study was carried out to evaluate the effects of *Brassica carinata* seed meals amendment, combined with solarization, on soil activity and lettuce cultivation. *B. carinata* seed meals pellets are biofumigant plant tissues originated as byproducts of the biodiesel industry. Microbiological data combined with lettuce production results suggested that, after biofumigation, soil microbial communities changed toward a new equilibrium that creates better root plant conditions to improve high lettuce yields. Moreover, *Brassica* seed meals, combined with solarization, preserved soil microflora against detrimental effects of heating, as revealed by enzymatic and functional analysis.

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