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**Control of Soil-Borne Plant Pathogens by
Solarization of Soils by Means of
Polyethylene Mulching:
Phytopathological, Microbiological,
Agronomic, Chemical and Physical
Approaches.**

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Control of soilborne plant pathogens by solarization of soils by means of polyethylene mulching: phytopathological, microbiological, agronomic, chemical and physical approaches.

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ABSTRACT

Solar heating of soils (solarization) is a new method for controlling soilborne pests by covering (mulching, tarping) the soil with transparent polyethylene, thereby increasing temperatures and killing the pests. We examined the effectiveness of this method against a variety of diseases and the mechanisms involved were investigated.

The results of the research carried out in Israel were as follows: The effectiveness of solarization against many pathogens (e.g. Verticillium, Fusarium, Pyrenochaeta, Rhizoctonia) under a variety of conditions was shown. Pathogen populations were reduced or eliminated to the depth of at least 50 cm and the yields were increased. Long term effects, namely, an effective disease control lasting for more than one season after solarization, were observed with six diseases. Integrating solarization with other methods of control; (e.g. Trichoderma) improved and extended the effectiveness of control. The measured soil temp were close to those predicted using numerical models. Chemical changes (e.g. release of mineral and organic substances) were detected in the solarized soils. These were often accompanied by increased growth response of the plants. Microbial changes and biological control phenomena were induced in the solarized soils. Fusarium incidence in inoculated tomato plants transplanted into solarized soils was lower than in nontreated ones. This resulted in an increase in lytic bacteria and suppression of chlamydospore formation in the solarized soils.

The results of the research carried out in the USA were as follows:

Thermal sensitivity of soilborne pathogens e.g. V. dahliae, Thielaviopsis basicola, Pythium etc. were determined. Linear relationships between temperature level, exposure time and mortality (using suitable factor corrections) were established, and served for evaluating control by solarization under field conditions. Solarization was very effective in killing the pathogen and in controlling V. dahliae disease in cotton under field conditions. The effectiveness of various tarp materials was studied. Long term effects were noticed. Feasibility of solarization in controlling a variety of pathogens in six sites in California, at various periods was studied. The response of phytoparasitic and free-living nematodes to soil solarization, with or without addition of a nematicide, was studied. In many cases solarization was more effective than a nematicide.

A plant growth response following solarization, similar to results obtained in Israel, was recorded. This was accompanied by chemical changes in the soil solution, in some cases comparable to those obtained in Israel. Extensive microbial studies in the solarized soils were carried out.

BODY OF THE REPORT

Background and approaches for the research

Soilborne plant pests cause heavy losses to most agricultural crops; in severe cases they may cause a complete destruction of the plants. Since the causal pathogens survive in the soil in the absence of the host, one approach for disease control is the killing of the pathogen before planting, by means of destructive methods, e.g. by soil fumigation or heating.

In this research we deal with studies on the effectiveness of the solar heating method for controlling soilborne diseases. This is accomplished by mulching (tarping) the soil with transparent polyethylene during the hot season, thereby increasing soil temperatures such that pests, including pathogens as well as weeds, are killed. This research deals with the further development and improvement of the solarization method for the control of soilborne pests--the emphasis has been given to soilborne pathogens of crops of economic importance to both Israel and the USA. A second part of the research deals with the mechanisms involved in disease control and in yield increase. A part of this project was carried out jointly with another project supported by US-Israel BSF. The approach followed during this research was as follows:

Experiments were carried out in soils known to be naturally infested with various pathogens or which were artificially infested. Disease incidence, plant growth, pathogen populations and crop yields were recorded throughout the indicated periods, before and/or after planting.

Chemical, physical and microbiological changes in the soil were followed both for field experiments and on soil maintained in the laboratory under simulated conditions. Data in temperature changes were recorded and were

compared to the numerical ones obtained, using computerized model systems.

I - Research carried out in Israel

1. Effect of solarization on disease control and pathogen populations

Many field experiments were carried out during the three years of the project, most of them financed by the Ministry of Agriculture. We used these experiments in order to follow, under field conditions, pathogen populations in the soils, disease control and yield increase. The general conclusion is that solar heating of the soil is very effective in reducing populations of many pathogens, in disease control and in increasing the yield under a variety of soils and agricultural regimes, though some exceptions exist. The emphasis in our research was placed on wilt disease which usually attack the plants during the whole season and are therefore difficult to control. The following are examples of diseases which were effectively controlled by solarization in our experiments. Some of these experiments were repeated several times in various regions and at various years, with similar results:

1. Fusarium wilt of cotton, melon, and tomato
2. Fusarium rot of onions
3. Verticillium of eggplant, potato, tomato and peanut
4. Sclerotium rolfsii of peanut
5. Corky root rot of tomato
6. Pink rot of onion
7. Pythium root rot of tomato
8. Rhizoctonia diseases of onion, iris and potato
9. Broomrape of potato, eggplant and carrot
10. Pod rots of peanuts

11. Pratylenchus thornei in potato

12. Ditylenchus in garlic

The yield was increased between 35 to several hundreds percent. In extreme cases, the yield in the untreated controls was entirely destroyed while it was normal in the solarized plots. Few diseases are not controlled by solarization, e.g. Fusarium wilt of carnations and collapse of pepper and melon and results with root knot nematode were variable.

In certain experiments pathogen populations was followed. In all cases, pathogen populations were eradicated or reduced at the tested depths up to 50 cm tested in Israel (but also at deeper layers tested in the USA, see section II). For example, in one experiment percentages of killing of V.dahliae after 14 days were 100, 100, 10 and 0 for 10, 30, 40 and 50 cm depth, respectively. After additional 3 weeks a complete killing was obtained at all depths. Populations of Fusarium oxysporum f. sp. melonis were entirely eradicated to the depth of 30 cm within 20 days. A typical example is given for D. dipsaci (Fig. 1).

Three examples of diseases or pest control are given below in more detail:

Control of Ditylenchus dipsaci in garlic

In a soil heavily infested with this pathogen, nematode populations in the untreated plots were initially low but rapidly increased 100 days after planting, resulting in total loss of plants by the end of the season. An excellent control was obtained by treating the soil with methyl bromide (MB) or solar heating with transparent polyethylene sheets prior to planting. However, MB treatment caused a severe stunting of the plants. Treatment with ethylene dibromide (EDB) initially controlled the pathogen but later in the season its population level increased (Fig. 1). The yield (kg/m^2) was: untreated - 0;

solar heating - 2.325; EDB - 0.813 and MB - 1.152. Thus, solar heating resulted in an excellent control of the pathogen and reduced population throughout the season without negative side-effects.

The control of *Fusarium* in melons

The effectiveness of solar heating was tested in a field highly infested with this pathogen. This soil treatment was very effective in controlling the disease and killing the pathogen (95-100% reduction). In the first season after solarization, mulching for 3, 5 or 8 weeks were equally effective. The yield was increased by 180-200% over the untreated control (Figs. 2 & 3).

The control of bulb mite by solar heating (in cooperation with U. Gerson and S. Yathom).

The bulb mite *Rhizoglyphus robini* is a soil pest of onion and garlic in Israel. Laboratory-infested peanut seeds were buried to various depths either in non-mulched or in mulched soil. At depths of 10 and 20 cm all mites died within 10 days; at 30 cm most mites died after 20 days and complete mortality occurred after 30 days. This is the first time that we have demonstrated the effectiveness of solar heating against an anthropod pest.

2. Long term effects of solar heating of soil

Long term field experiments were done to test whether disease control by this method lasts for more than one season, thereby reducing costs and increasing control efficiency. Solar heated and nonheated plots were sown repeatedly with test crops. Disease incidence, plant growth and yield were estimated for each crop and season. In several fields, naturally and heavily infested with *Fusarium oxysporum* f. sp. *vasinfectum*, solar heating was very effective in killing off the pathogen in the soil, decreasing wilt incidence in

cotton plants and improving plant growth, weed control and yield. Disease incidence in the untreated plots was significantly and negatively correlated with the yield. Solar heating had a long term effect on disease control and yield increase lasting for as long as 3 years after treatment. The susceptible Pima cultivar (Gossypium barbadense) and the resistant Acala (G. hirsutum) were grown in infested plots, all of which were planted with the Pima cultivar in the following year. Disease incidence was lower and the yield higher in plots where Acala was the preceeding crop, in both untreated and solarized plots. The long term effect of solarization was improved by this crop sequence (Fig. 3A).

Solar heating had a long term effect with other five diseases. It reduced the frequency-index of delimited shellspots in peanuts by 51% and 33% in the first and second year after treatment, respectively, and in both years yield was increased by 17%. Similarly, incidence of Verticillium wilt of peanuts, initially low, was reduced further by the treatment. The disease index of onion pink-root in the second year after treatment was more than twice as high in the untreated as in the solar-heated treatment. A root rot of tomato caused by Pythium sp. was also controlled in the first and second years after treatment. Control of Fusarium in melons was evident also in the second year after treatment.

In conclusion, solar heating of the soil had a lasting effect for at least two or three seasons, as tested with six different diseases. This points to a more general phenomenon, which may involve one or both of the following: a drastic reduction of pathogenic inocula; and a shift in the biological equilibrium in favor of antagonists, which retard a rapid build-up of pathogen populations (see biological control section).

3. Integrating solarization with other methods of control

Various experiments showed that combining solarization with chemical, biological or cultural methods for pest control may improve disease control, extend its duration and provide a wider spectrum of pest control. In addition, this may enable the use of solarization at marginal climatic regions. This approach has been clearly shown with cotton. As described in the previous section, combining solarization and crop rotation resulted in improved *Fusarium* control and a better long term effect by solarization. Combining *Trichoderma* application with solarization improved control of *Rhizoctonia* in potatoes and iris. Synergistic effects resulting from these combinations has been also shown. For example, combining ethylene dibromide and solarization at sublethal dosages resulted in a complete control of *Fusarium*. Activity of Benomyl, when heated in the soil, was much increased.

4. Physical, chemical and microbial changes in the solarized soils

A. Physical aspects of heating

Numerical models for predicting the extent of solar heating of soils under polyethylene mulch were developed in the past by I. Mahrer. These served for further examining of the relationships between climatic condition, soil types, polyethylene type and agrotechniques, e.g. irrigation. A very good correlation between predicted and observed soil temperatures were obtained during 3 successive years of the research (see below). The following two aspects were studied in a more detail:

a. Interactions between soil moisture and solar heating

Different soil moisture regimes were created in a sandy soil by mulching plots 1, 5, 10 and 20 days after irrigation. Soil moisture much affected soil

temperatures. Maximal temperatures at 10 cm depth in the wet (mulched 1 day after irrigation) and in the dry soil (20 days) were 39 and 48°C, respectively. The driest treatment was only 1°C warmer than nonmulched soil. A positive correlation was found between soil moisture and the killing of Verticillium dahliae. Using drip irrigation, for supplying additional water under the polyethylene sheets during mulching, decreases maximal soil temperatures up to 3°C, but improved heating at a later stage.

b. We continuously tested novel plastic materials which have better heating efficiency which may enable us to heat the soil in cooler seasons or regions. Except for one case, the many plastic types which were tested did not show a better efficiency in soil heating. One plastic material was more effective in heating the soil; the soil temperatures were 1-2°C higher than those under usual polyethylene (Fig. 4). It appears that we are still far from achieving the goal of replacing the ordinary polyethylene.

B. Microbial changes in the solar heated soil and biological control

Both decline of pathogen populations in the solarized soils and disease control are frequently better than expected. These phenomena may be attributed to the microbial activity following soil solarization. Our experiments showed that the pathogens were killed even in those depths that temperatures did not exceed 35°C, thus possibly indicating that solar heating may enhance biological control in the soil which may further contribute to the decline of pathogen. For example, weakening the pathogen by sublethal heating may render it more sensitive to the action of microorganisms existing in the soil which otherwise can't attack the resting structures. This was shown with Fusarium oxysporum f. sp. lycopersici and Sclerotium rolfsii. Decline of Verticillium population in

previously heated soil was faster than in nontreated soil. In greenhouse tests, tomato seedlings were inoculated with F. oxysporum f. sp. lycopersici and planted in previously disinfested soils. In several cases, incidence of disease in seedlings planted in solar heated soils was lower than that in seedlings planted in the respective nontreated soils. The opposite was true with seedlings in methyl bromide-treated soils (Fig. 5). Moreover, incidence of Fusarium disease in tomato seedlings planted in soils which were artificially heated similar to solar heating, was lower than in a nontreated soil, thus confirming the results with solar heating. Chlamydospore formation and mycelial growth of Fusarium were enhanced in methyl bromide-treated soil. In solar heated soils, the mycelium was lyzed and chlamydospore formation was suppressed. In non-heated soils the mycelium was lyzed and chlamydospore formation was only partially suppressed. The survival of Fusarium in solar heated soils was similar to that in nontreated soils. The survival in artificially heated soils, however, depends on the extent of heating. In soil heated at 95°C the survival was much improved and Fusarium population was increased five-fold as compared to a nontreated soil. In soils heated at lower temperatures the Fusarium survival was lower.

It is concluded that the establishment of Fusarium in solar heated soils is frequently more difficult than in nontreated soils. It appears that in most cases, a "biological vacuum" is not created in solar heated soils as may happen in artificially heated or methyl bromide soils. We suggest that a suppressiveness was developed in solar heated soils. Thus, biological control occurs in the solar heated soils both during the solarization process (resulting in reduction of pathogen populations) and also after removal of the polyethylene,

thus reducing the chances of reinfestation of the soil. These phenomena are possibly related to the long-term effect in disease control described in the previous section.

Studies carried out under controlled conditions in the last period of the research clearly showed that volatiles, produced and accumulated in the heated soil, enhance the killing of the pathogens and the attack of its cells by invading microorganisms. For example, sclerotia of S. rolfsii exposed to these volatiles loosed their viability and pathogenicity and became heavily colonized by soil microorganisms. The identity of these volatiles is as yet unknown. We believe that a more detailed study on the nature and formation of these volatiles in soil may provide an additional tool for improving the solar heating method.

In parallel to the above studies, we established heat mortality curves of several plant pathogens. The relationships between temperature level and exposure time for obtaining various degrees of killing were studied. These studies serve for predicting the potential use of solarization for disease control. With two Fusarium pathogens the relationships between temperature level and exposure time at various ED values were established using different methods. For example, plotting temperature against logarithm of exposure time required for obtaining ED₅₀ or RF₉₀ resulted in a linear relationship at the ranges of 38° to 46°C. Similarly, a linear relationship between temperature and logarithm of survival was obtained.

C. Chemical changes and increased growth response

Our results indicated that the growth of plants grown on previously solar heated soils was frequently enhanced, even in the absence of known pathogens.

Thus, explanations other than usual pathogen control, are sought. We found that saturated extracts of the upper soil layers of different solar heated soils showed increased concentrations of soluble organic matter and minerals, e.g. NO_3^- , NH_4^+ , K^+ , $\text{Ca}^{2+} + \text{Mg}^{2+}$, Fe^{++} , Zn^{++} . Changes in soil pH, total organic matter, NaHCO_3 -extractable P, were small or inconsistent. Tomato seedlings grown on extracts of heated soils showed enhanced growth in comparison with seedlings grown on extracts of unheated soils. Changes in physical properties of solar heated soils were inconsistent, using one method. The increase in $\text{Ca}^{2+} + \text{Mg}^{2+}$ concentrations may have an additional beneficial effect, as bivalent cations play a role in the resistance of plants to certain soilborne pathogens.

The presence in solar heated soil solutions of larger amounts of soluble organic compounds that are known to react as chelates and carriers for heavy metals suggests that higher levels of available microelements may be present in these solutions.

The variety of soils on which solar heating treatment was imposed exhibited similar chemical change patterns. This suggests that these phenomena are general and fundamental ones. In addition, a detailed characterization of these changes may provide us with a chemical tool for testing the effectiveness of the solar heating of any particular soil, which is a simple and quick test in comparison with the biological tests which are employed. An infrared spectrum of an extract from solarized and nonsolarized soil is shown (Fig. 6).

II - Research carried out in the USA

Research objectives and major results

The research objectives of the project conducted at the University of California, Davis, were complementary to the objectives of the project work in Israel. The objectives at Davis were as follows:

- a) To find out what changes were caused in populations of soil microflora by soil solarization.
- b) To determine the limitations of soil solarization in regard to climatic conditions (especially cloud cover and air temperatures), soil moisture, and soil type.
- c) To determine time/temperature dosages for ED₉₀ of selected pathogens in moist soil.
- d) To determine the biological and chemical changes in soil that causes the increased plant growth responses associated with soil solarization.
- e) To determine for how many growing seasons the benefits of soil solarization are cost effective in crop production.
- f) To determine whether or not solarized soils would be quickly recolonized or invaded by fungal pathogens.
- g) To determine the effect of soil solarization on populations of thermo-tolerant fungi in soil.

The following studies addressed the above objectives but considerable work is still required to complete the research on mechanisms of soil solarization and its cost effectiveness in different cropping systems:

- 1) Thermal sensitivity and death of plant pathogens during soil solarization.

Temperatures of 37-50 C for different time periods were lethal to mycelia, spores, and resting structures of Verticillium dahliae, Pythium ultimum, and Thielaviopsis basicola on an agar medium. At 37 C, exposure times for an LD₉₀ were 28.8, 25.8, 17.9, and 33.5 days, respectively, for V. dahliae (strains T9 and SS4), P. ultimum, and T. basicola. At 50 C, LD₉₀ values were 23, 27, 33, and 68 min, respectively, for the same fungi. Field-produced propagules of V. dahliae in moist field soil also were killed when incubated at temperatures of 37-50 C for specific time periods. Temperatures of 39 and 50 C killed cultures of Rhizoctonia solani on agar medium in 14 days and 10 min, respectively. A linear relationship existed between logarithms of times required to kill 90% of the propagules when plotted against temperatures. This linear relationship was observed for populations of fungi in both agar and soil tests. These fungi were killed in field soils solarized for the necessary time periods. The exposure times and temperatures necessary to kill these fungi are useful for evaluating the progress of soil solarization under field conditions.

- 2) Influence of soil solarization on Verticillium wilt in cotton and soil-borne populations of Verticillium dahliae and mycorrhizae.

In field tests during the summers of 1977-1979, solarization of soil by covering it with transparent polyethylene tarps was examined for effectiveness in controlling soilborne pathogens. Propagules of Verticillium dahliae, Pythium spp., Thielaviopsis basicola, and Rhizoctonia solani were greatly reduced or completely eliminated 0-46 cm in soil tarped for 14-66 days. Higher soil temperatures and a more rapid decline in pathogen populations occurred in soils irrigated after placement of tarps than in those preirrigated and then tarped. Tarps 25 μ m (1-mil) thick were more effective in heating soils and in killing soilborne fungi than were 100- μ m (4-mil) tarps. The mycorrhizal fungus Glomus fasciculatus survived tarping treatments as measured by colonization of cotton (Gossypium hirsutum) roots. Incidence of Verticillium wilt was reduced and cotton yields were increased in plants of cultivars Acala SJ-2 and SJ-5 planted in tarped compared with nontarped soil.

3) Influence of soil solarization on soil-borne fungal and bacterial populations and growth response of fruit trees.

Two fallowed fields sites of differing soil type in the San Joaquin and Sacramento valleys in California, were treated by soil solarization for 4.5 wk in the summer. Soil samples from solarized and nonsolarized plots were periodically collected and assayed with selective media for population densities of certain microorganisms. Plots were planted with English walnut and cultivar Nemaguard peach seeds after solarization. Population densities of Agrobacterium spp., fluorescent pseudomonads, Gram-positive bacteria, and fungi recoverable on PDA were greatly reduced immediately following solarization. Actinomycetes and thermophilic/thermotolerant fungi were affected to a lesser extent. Agrobacterium spp. and populations of Gram-positive bacteria remained significantly depressed in solarized soil after 6-12 mo. Fluorescent pseudomonads and "total" fungi quickly recolonized the treated soil, while actinomycetes and thermophilic/thermotolerant fungi attained higher population densities following soil solarization. After one growing season, there were no detectable differences in stand counts of peach or walnut seedlings. However, peach seedlings grown in solarized soil showed increases in plant height of 25% and fresh weight of 42%, and walnut seedlings showed increases in height and fresh weight of 26 and 58%, respectively, compared with those grown in nonsolarized soil.

4) Changes in microbial populations in solarized soils as related to increased plant growth response.

Solarization of moist soils usually results in increased plant growth response (IGR), even when no pathogens are detected. Qualitative and quantitative changes in soil microflora have been observed following solarization. Isolation from roots of greenhouse-grown plants, however, revealed no significant quantitative differences of bacteria and fungi between solarized and nontarped treatments when plated on selective media. Qualitative differences of bacteria and fungi, based on colony morphology, were observed. Sugarbeet seed coated with plant growth promoting rhizobacteria (PGPR) showed no additional growth response when planted into a solarized soil in the greenhouse. However, population densities of the PGPR on roots in solarized soil were 469% higher than on roots in the nontarped soil ($P=0.05$). Covering tarped moist soil with sheetrock to prevent solar heating resulted in reduced population densities of some microorganisms ($P=0.01$), but no IGR occurred.

- 5) Increased soluble mineral nutrients in soils as related to increased plant growth response following solarization.

Four field soils of different textures were solarized for 6 wk. Maximum soil temperatures during treatment were 44-46 C at 15 cm depth. Following solarization, increased levels ($P \leq 0.05$) of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ by KCl extraction were found in the 0-15 cm depth range of all soils tested. Increased P ($P \leq 0.05$) by 0.5M NaHCO_3 extraction was found in three of the experimental soils, and increased EC, Mg, and Ca ($P \leq 0.05$) by H_2O extraction were detected in two of the four soils. Increases in $\text{NO}_3\text{-N}$ plus $\text{NH}_4\text{-N}$ were equivalent to 26 kg/ha (+608%) in loamy sand, 60 kg/ha (+137%) in fine sandy loam, 43 kg/ha (+221%) in loam, and 177 kg/ha (+602%) in silty clay soil, as compared to nontreated control soil (0-15 cm depth) of each texture. Increases in plant growth of 32-491% fresh or dry wts. ($P \leq 0.05$) were obtained with field or greenhouse-grown pepper and radish plants in each of the solarized soils, as compared to nonsolarized soils.

- 6) Response of phytoparasitic and free-living nematodes to soil solarization and 1,3-dichloropropene.

Ten field sites in the California counties of Merced, Napa, Sonoma, and Yolo were pre-plant or post-plant treated for 4-6 wk with soil solarization and/or 56-150 l/ha Telone II (50-100% label dosage of 92% 1,3-dichloropropene [=1,3-D]). Results of soil assays immediately following treatment by solarization and solarization plus 1,3-D included significant population density reductions of 42-100% of Meloidogyne, Heterodera, Pratylenchus, Paratrichodorus, Criconeimmella, Xiphinema, and Paratylenchus spp., total phytoparasitic nematodes, and total nematodes, as compared to nontreated control soil. Nematode population density reductions following treatment by 1,3-D alone were usually significantly less. At two of the sites, moist soil covered by polyethylene film was shaded from solar heating by sheets of gypsum sheetrock (building construction wallboard). Subsequent soil assays from the shaded treatments showed significant population density reductions that were approximately half of those attained following solarization, indicating partial control directly or indirectly due to the polyethylene film cover and/or maintaining high soil moisture during the treatment. When soil nematodes were assayed several months after solarization, population density reductions were usually greater than those found immediately following treatment, even when susceptible crops were planted in the soil during the interim period. At one site, significant population density reductions of Helicotylenchus digonicus were found in solarized plots three months after, but not immediately after treatment. Soil was assayed to a maximum depth of 91 cm. Field and greenhouse-grown plants usually showed significant increased growth responses in solarized (32-87%) or solarized plus 1,3-D-treated (43-152%) soil, as compared to nontreated control soil. No plant growth responses were observed following soil treatment by 1,3-D alone, or from orchard trees at post-plant-treated sites.

7) Feasibility of soil solarization for pathogen and pest control.

Soil solarization tests were made at six CA field sites ranging from hot inland valleys to cool coastal areas during the summer of 1981. Plots were covered with 25 m clear polyethylene tarps, irrigated under the tarps, and solarized for 4-wk periods from May-September or left fallow. Maximum soil temperatures of 42-51 C and 32-40 C occurred at depths of 15 and 46 cm, respectively, in plots solarized during June or July at all but the coolest site. Maximum air temps ranged from 26-45 C. Buried populations of plant pathogens (Verticillium dahliae, Fusarium oxysporum f. sp. lycopersici), weed seeds (Convolvulus arvensis, Digitaria sanguinalis, Poa annua, Portulaca oleracea), and nematodes Meloidogyne spp.) were greatly reduced in most plots solarized in June or July; populations also decreased, although less, in May, August and September. Cotton, sorghum and tomato seeds planted in a greenhouse in solarized soils (0-20 cm) germinated more rapidly and showed an increased growth response which was correlated to soil temperatures.

Fig. 1. Comparative effect of solar heating of the soil, or fumigation with methyl bromide (MB) or ethylene dibromide (EDB), on populations of *Ditylenchus dipsaci* in soil (A) and in bulbs of garlic plants (B) in a heavily infested soil.

Fig. 2. Effect of solarization (L = 8 weeks, S = 5 weeks) on the control of Fusarium in melons. CK = control.

Fig. 3. Effect of solarization (8 or 5 weeks) on the yield of melons in Fusarium-infested field. CK = control.

Fig. 3A. Incidence of Fusarium oxysporum f. sp. vasinfectum disease in cotton plants (Pima) planted in either untreated or solar heated soil (single irrigation) as a second crop (second year) after soil treatment. The preceeding crop was either Pima (P-P) or Acala cotton (A-P).

Figure 4. The heating of soil by improved plastic as compared to polyethylene (PE). CK = Non mulched soil

Fig. 5. *Fusarium* disease incidence in tomato seedlings inoculated with the pathogen and transplanted to solar heated, methyl bromide-treated (MB) or nontreated (CK) soils.

Figure 6. Infrared spectrum of soil extracts of solarized soils (SH) and non solarized one (C) at two locations.

EVALUATION OF THE RESEARCH ACHIEVEMENT WITH RESPECT TO THE ORIGINAL RESEARCH

PROPOSAL

The two major goals of this research i.e. exploring the potential and the reliability of solarization in disease and pest control, under a variety of conditions and, gaining a better understanding of the physical, chemical and microbial changes occurring in the solarized soils, have been achieved. We started our research in November 1979, three years after our first publication. At the time, most of work was carried out with Verticillium with four crops. Upon termination of our project the effectiveness of solarization against many pathogens, with a variety of crops, soils and environmental conditions, was examined. The mechanisms involved in solarization were investigated. The models for predicting soil heating were found to be reliable. The chemical changes occurring in the solarized soils were followed as specified in the research plan. Many studies regarding microbial changes and biological control were carried out. To our best knowledge, the long term experiments which were carried out in the solarized soils in the framework of this research, are the most extensive done, so far, with any soil disinfestation method.

DESCRIPTION AND RESULTS OF COOPERATION

The research was carried out in cooperation and close contact between the Israeli and the American investigators. Parallel studies conducted at both laboratories, as regarding the control of Verticillium wilt yielded similar results, i.e., a highly effective control was obtained. Similarly designed field experiments were carried out in both Israel and California. During the mutual visits the results were thoroughly discussed and evaluated and accordingly additional experiments have been planned. The meteorological and

soil temperature data from experiments conducted in Israel and California were exchanged, analysed, and compared.

Dr. Jerry Pullman, a former student of Dr. DeVay, was engaged in postdoctoral work with J. Katan in Israel, studying the interactions between sublethal heating and stress factors. His work contributes to improved communication between both parties. We are certain that the contacts between Katan and DeVay will continue in the future. The cooperation extended beyond Katan and DeVay. As a result of our work, other scientists (e.g. weed scientists) started their own research on solarization, in many cases with a close contact with us. This opened new dimensions to our work. Though it is not a direct purpose of the Israel - US cooperation, it is interesting to mention that research on solarization is or was carried out in at least eleven countries in addition to Israel and the USA (Greece, Italy, Jordan, Pakistan, Iraq, Morocco, England, Portugal, S. Africa, Australia, Egypt). The results of their work were of a great benefit to us.

BENEFITS TO AGRICULTURE

The ultimate goal in developing any nonchemical pest management method for pest control is to replace existing chemical ones. This may reduce hazards to the farmers, consumers and the environment, expand the options for control, reduce costs of pest control and increase farmer's income. Developing the method to a final commercial stage usually takes several years. We, therefore, did not anticipate that after three years of solarization research, it will be possible to replace other methods in a large scale. Nevertheless, as a consequence of the work of our team and others, commercial use of solarization already started in Israel, the USA and other countries and we believe that this trend will

continue. In Israel, the pink root disease of onions caused in the past heavy losses to thousands of acres of onion at the "Southern Arava" region. Now, this disease is practically eradicated by solarization, where other methods failed. In strawberry fields (where solarization is very successful) some farmers already use solarization instead of methyl bromide. They are other examples of commercial use of solarization in Israel. In the USA, thousands of acres of pistachio were successfully solarized (by private companies) for the control of Verticillium which became a major threat to these plantations. Our solarization research was the basis for their work. In Italy, combining solarization with methyl bromide enabled the reduction of its dosage and consequently phytotoxicity was reduced (personal communication).

It should be emphasized, however, that solarization should not be regarded as a universal method for control but rather as an additional one option which, if used correctly, can reduce pest damage, safely and effectively.

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