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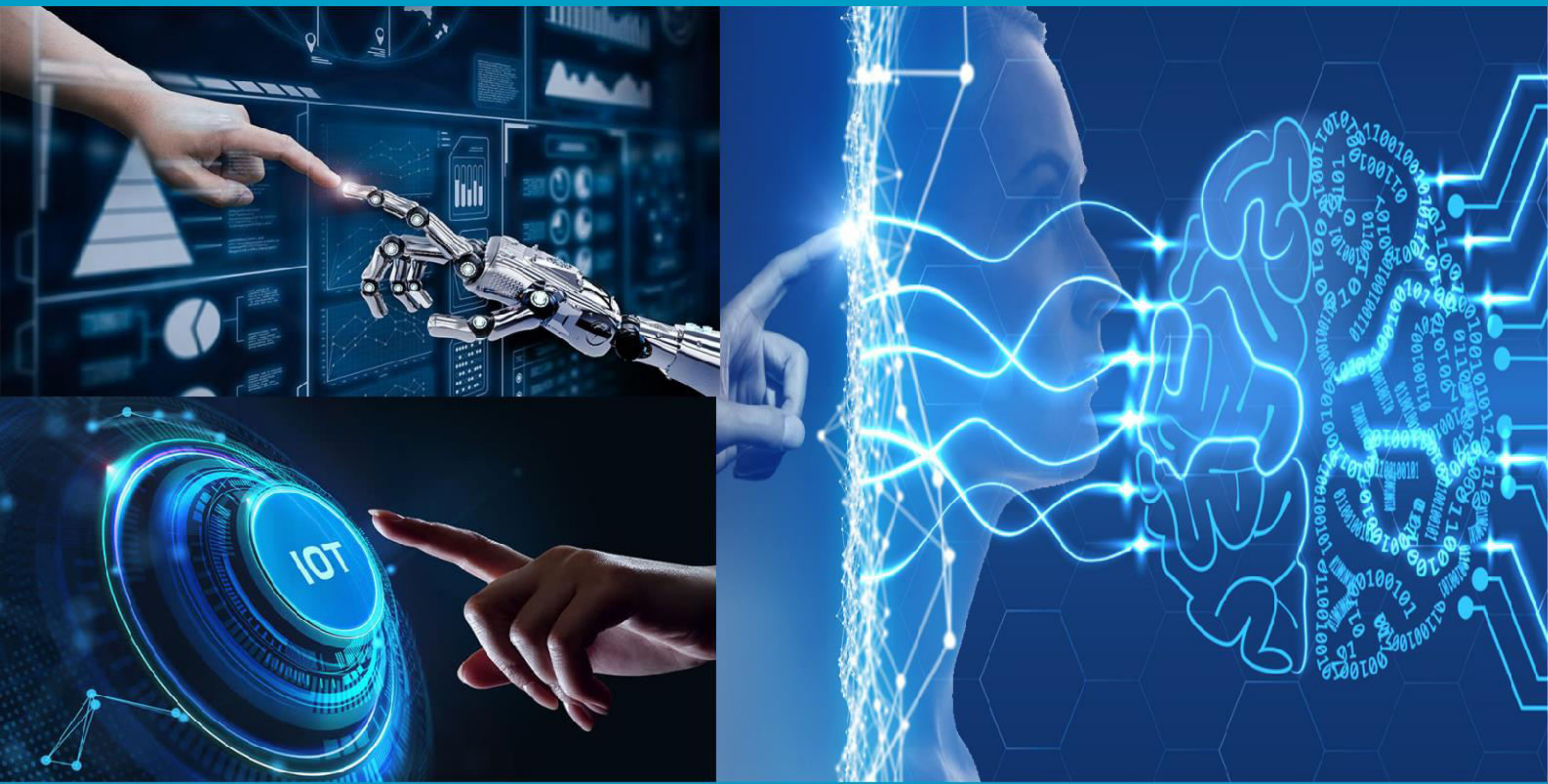

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Soil Solarization - Nonchemical Weed Control : A Review

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ABSTRACT: Soil solarization is a method of soil-disinfestations based on its solar heating by mulching a soil with a transparent polyethylene during the hot season, thereby controlling soil borne pests and weeds as well. Weed control is attributed to microbial, chemical, and physical processes in addition to the thermal killing. These occur in the soil during the solarization treatment and even after its termination. Frequently, a beneficial microbial shift is created in the solarized soil, resulting in soil suppressiveness. Soil solarization can be combined with other control measures for an integrated approach, thus improving its performance. The uses of soil solarization have expanded beyond soil disinfestation including structure disinfestation, sanitation, controlling human pathogens, and more. Soil solarization was originally developed to control soil borne pathogens [35]. It was then quickly discovered that it was effective against a wide range of soil borne pests and weeds. Solarization works by heating the soil to sufficient temperatures (at least 40–55°C) for sufficient duration (several weeks), that it kills weed seeds in the soil, and some perennial weeds close to the surface. This is achieved by ensuring the soil is maintained at field capacity, then covering with transparent polythene sheet. The soil needs to be kept moist as this improves heat conduction into the soil and also some pests and weed seeds are more susceptible to thermal treatment when moist. Transparent polythene acts in a similar fashion to a glasshouse, in that it allows the visible light from the sun to warm the soil, but then traps the infrared heat released by the soil. Black polythene does not work as well, as although the polythene itself heats up, most of that heat is lost to the atmosphere and not transferred to the soil. The duration required is dependent on both air temperature and the amount of solar radiation, so the technique works best in hotter climates and at lower latitudes, e.g., below approximately 50°C,latitude. In many climates it will only work in summer, even mid-summer, and with treatment durations of 3–6 weeks, it ties up productive land in the middle of the cropping season. Solarization is therefore not used as a routine measure, but is mostly reserved to address weed problems that are intractable by other means.

KEYWORDS: soil solarization, non-chemical, weed control, environment friendly

I. INTRODUCTION

Soil solarization is a non-chemical method in which the soil is heated to lethal temperature by using solar radiation for weed control. It can be an alternative to agricultural chemicals that have significant environmental risk and pose negative impact on the beneficial soil micro-organisms. In the present study, efficacy of soil solarization process was dependent on length of solarization period and temperature. First reports of soil solarization practice date back to late '800 in German Empire and United States, where it started being used commercially. Solarization is a chemical-free way of controlling pests such as pathogenic microorganisms (mainly fungi, bacteria, and nematodes), insects, and wild plants in the soil before crops planting [34,42,26]. First reports of soil solarization practice date back to late '800 in German Empire and United States, where it started being used commercially. Solarization is a chemical-free way of controlling pests such as pathogenic microorganisms (mainly fungi, bacteria, and nematodes), insects, and wild plants in the soil before crops planting [34]. Soil solarization proves efficient to kill microbes

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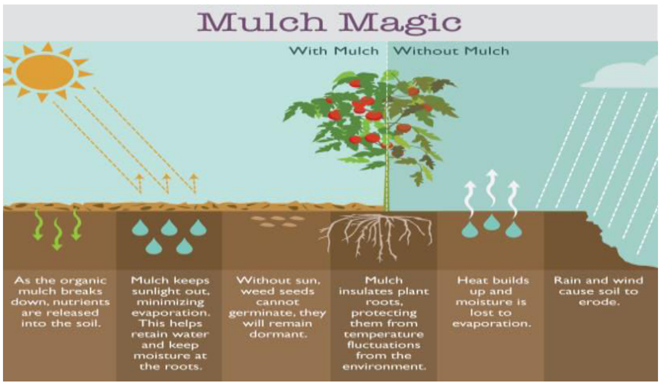
and control diseases, pests, and weeds. Yet, its benefits are more extensive – it boosts soil health. The soil solarization technique employs the energy of water and the sun to reach its goals and dismisses chemicals, which makes it environmentally-friendly. For this reason, soil solarization best practices have been adopted around the world, and in the U.S. in particular. Offering advantages, the method also demands certain efforts and knowledge for proper preparation of soil before solarization and regular control. The technique implementation and management are far easier with remote sensing and AI-powered analytics. The process suggests covering weed-clean earth with a transparent air-proof substance (typically plastic) to accumulate solar energy, which raises soil temperature. The major purpose of soil solarization is to kill weeds and all sorts of pests with the obtained heat. Depending on location, the temperature in the 5-cm (2-inch) topsoil under solarization may range from 108-140°F (42-60°C).Additionally, soil solarization improves soil chemistry (enhancing fertility) and provides quite a decent protection from soil erosion also. Land covered with plastic is not subjected to destruction by water and winds. When expecting to enjoy the soil solarization advantages in full, farmers should arrange the process thoroughly and keep up with all the requirements, from earth preparation to plastic after treatment. It is important to bear in mind all the factors with a possible impact on the soil solarization process. The required knowledge will empower agronomists to avoid what hinders and enhance what helps.[2,3].

II. METHODOLOGY

The specific factors to consider include:

- Soil type and color;
- Presence of weeds and their removal;
- Possible shade-casting objects (e.g., agroforestry);
- Season of the year;
- Soil solarization duration and timelines;
- Moisture content and irrigation plan if natural soil moisture is not enough;
- Plastic type and color;
- Bed orientation (north to south for raised beds is preferable);
- Plastic further use and recycling, etc.



Preparation: Proper preparation of soil before solarization is the initial step to success. At this stage, it is important to complete the following steps:

- Choose the plastic to use;
- Perform soil testing to know the soil type;
- Get the field ready.

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Plastic Types : The choice of plastic type, color, and thickness plays an essential role. Plastic typically stands for plastic polymers including:

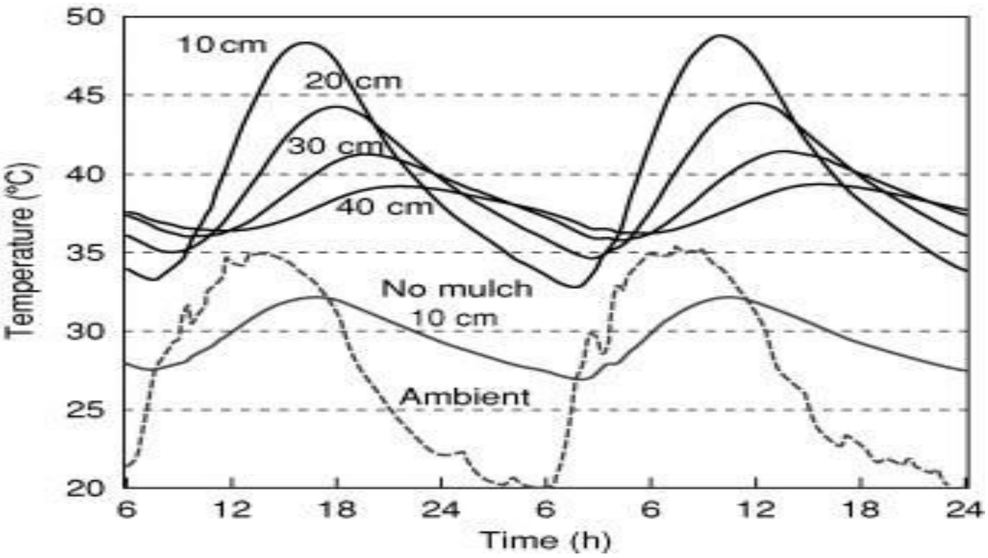
- polyethylene (PE),
- polyvinyl chloride (PVC),
- Ethylene-vinyl acetate (EVA).
- PVC and EVA have better optical properties but are more expensive. For this reason, polyethylene (PE) is the most common option.[5,8].

Plastic Color: The colorless (clear) plastic is the best for the sun rays to penetrate and supply heat to the earth (compared to black or white). However, in cooler regions, black polyethylene is justified since even though it absorbs heat, it also controls weeds that may develop under transparent plastic when the heat is insufficient.

	
White Plastic	Black Plastic

Plastic Thickness : The thinnest polyethylene (1 mil) is the best to get maximum heating, but it is damaged easily, too. In windy areas,1.5-2 mils polyethylene is typically used. Smaller territories are sometimes covered with thicker plastic (4 mils). The studies indicated that, solarization treatment receiving mulching with thin polythene sheet (0.03 mm) recorded significantly higher soil temperature at all stages. Soil temperature recorded in treatments with thin (0.03 mm),medium (0.06 mm) and thick polythene sheet (0.12 mm) was 56.0, 54.4 and 53.7^0 C, respectively.

Preliminary Soil Testing: Soil testing matters because the soil solarization method is not equally efficient for all types. It works better in soils with good water retention properties (containing clay or loam).



Heating by polythethylene at various soil depths, as compared to nonsolorized soil [25]

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Preparatory Agricultural Activities : The field preparation includes :

- Cleaning from weeds and debris not to spoil the plastic and because vegetation cover hinders heat penetration;
- Making central elevations for covered strips for rainwater to run off the plastic and not to cool it down;
- Arranging beds (flat or raised);
- Tilling to break big earth pieces that may damage or raise the cover;
- Facultative soil aeration to decrease compaction since bulk earth density adversely affects water-holding capacity;[10,11]
- Placing drip irrigation lines if necessary;
- Assessing moisture content and moisturizing the beds when needed.

Either excessive or insufficient soil moisture won't allow achieving the desired results. For soil solarization success, it is necessary to wet the beds at least 12 inches deep.There are two options to place the plastic: it may either cover the field completely or in strips, as wide as the sheet size allows. Strip coverage is more cost-effective, yet pests and weeds may re-infest the covered areas by penetrating from the uncovered ones. It is important to bury the plastic film edges thoroughly; otherwise, heat will escape outside. For this reason, the sheet should be wider than the strip. If the film is damaged, it can be patched with clear tape.It is important to fit the plastic as tight to the ground as possible as air space reduces heating and will cause plastic "waves" on windy days, which will dissipate heat. It would be wrong to consider that soil solarization increases soil temperature by merely trapping and harnessing the sun. The method combines solar and aquatic properties that jointly produce steam (vapor), and it is the steam to credit for the killing power. This is why, even though plastic-covered earths are more disinfected than bare ones, soil solarization without moisture is not quite effective. Vapor becomes visible when it condenses on the plastic in the form of water beads. If there are no beads, it is high time for water supply[12,58].

Solarization of the soil kills microbes when the earth is not only hot but wet because moisture conducts heat more efficiently. Irrigation may take place both before or after laying the plastic, depending on the soil moisture content. Water can be supplied via pipes or furrows, with undercover drip irrigation being a perfect choice. Additional irrigation cools down the earth, yet it is still necessary to produce evaporation, which brings a better outcome in the end.Typically, the process lasts from four to eight weeks. It should be enough time to conduct soil solarization before planting fall crops. Provided all the requirements are met, the earth treatment spares agronomists the trouble of pests for three to four months.For soil solarization success, it is logical to take advantage of the hottest season, which is usually the summer months of June, July, and August. If the weather permits, late May and early September will do, too.[18,19].

Removing Plastic : When solarization of soil is over, the plastic can be either removed or painted:

- Black to suppress weed growth;
- White to cool down the earth;
- Silver to repel flying pests.

However, if the plastic is not removed, it wears out and gets dirty quickly, which makes it impossible to reuse the same material in the next season. The film can be also used unpainted for crop transplantation.

III. RESULTS

The literature points to the success of solarization in managing weeds even up to 98% in corn, while on the other hand 90% crop damage due to weeds alone is also reported in unsolarized control plots. Worldwide, solarization has managed to control annual weeds such as annual bluegrass, *Ageratum* spp., *Amaranthus* spp., barnyard grass, cogongrass, commonpurslane, *Digitaria* spp., *Portulaca* spp., redroot pigweed, *Setaria* spp., and many others. The weeds elimination also prevents the growth and widespread of pathogenic microorganisms or insects which may spend their lifecycle on wild plants. Generally, winter wild plants are easier to eliminate, whereas summer wild plants such

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as *Cyperus* spp. or *Convolvulus arvensis* showed a good resistance against the disinfection treatment. In areas with extended periods of hot weather, use of plastic tarps to heat moist soil prior to planting (soil solarization) has proven useful as a means of killing weed seeds and reducing weed seedling densities in subsequent crops [36] provided data indicating the positive effects of soil solarization on both weed suppression and crop yields, although the effect on crop yield might be attributed to reductions in pathogen populations as well as reduction in weed pressure. Solarization is used as a pest control measure, but its impact on different pathogens and pests varies. Earth's temperatures as high as 86-91°F (30-33°C) kill most earth pests. The treatment duration is different, depending on species. While some will die just in several days, only 4-6-week sun exposure will be lethal to others.[20,21,22]. The method is effective with many fungi and bacteria species that cause plant diseases, though certain pathogens are resistant to it and require additional treatment. In particular, solarization destroys *Verticillium dahliae, Phytophthora cinnamomi, Clavibacter michiganensis, Streptomyces scabies, Rhizoctonia, Fusarium, Sclerotinia, Agrobacterium tumefaciens*, which explains the role of soil solarization in disease control. However, the practice is not strong enough for *Macrophomina, Pythium, Pseudomonas solanacearum* responsible for stem and root rots.[21,9].

Soil solarization is a novel technique of controlling soil-borne pests including weeds. It involves covering the wet soil with a thin transparent polyethylene sheet during the summer months. The process would raise the surface soil temperature by 8 to 12°C as compared to non-solarized soils. Transparent polyethylene found highly effective for heating the soil than black polyethylene. Thinner (19 to 25 µm) transparent polyethylene sheets are more effective for solar heating than thicker (50–100 µm) one. A duration of 4 to 6 weeks is sufficient to give satisfactory control of most of weeds. Many annuals, some perennials and parasitic weeds are highly sensitive to solar heating of the soil. *However, weeds such as Cyperos rotundus (tubers),Melilotus spp.(hard seed coat) and Cynodon dactylon* (rhizomes) are not controlled easily by solarization. Solarization, thus proved to be not only as an efficient method of weed control but was also safe to the crop as well as invariably it produced healthy and vigorous seedlings and eventually resulted higher yield in all crops as compared non solarized plots even treated with herbicides. Application of solarization technique in general and its scope in India is reviewed here.

A field experiment was conducted in Karnataka, India, during the summer and kharif seasons of 1995, to determine the effect of soil solarization on weeds. Polyethylene mulch was applied on 10 April 1995 at 3 thickness levels (0.5, 0.1 and 0.125 mm) for 30 and 60 days solarization period on wet and dry soil. Groundnut JL-24 was sown on 15 June 1995. Soil temperature was recorded on alternate days from 13.30 h to 14.30 h.that the stale seedbed recorded significantly the lowest dry weight of weeds, followed by soil solarisation and deep ploughing having WI of 19.47, 21.57 and 21.44%, and WCE of 53.91, 50.44 and 47.63%, respectively. Similarly, the weed-free registered significantly the lowest dry weight of weeds, followed by HW and straw mulch with WI of 0.00, 6.75 and 22.67% and WCE of 97.39, 72.32 and 32.93%, respectively. Effective control of weeds starting from sowing of the crop under the above mentioned treatments might have resulted in less dry weight of weeds and eventually exhibited excellent weed indices. Effective control of weeds in *kharif* groundnut along with higher yield under organic farming could be achieved by stale seedbed and either hand weeding at 15, 30 & 45 DAS or wheat straw mulch @ 5 t/ha.

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Table : Intensity of the weeds present in unsolarized and solarized soil.

Weed	Degree of occurrence of weeds			
	Control (Unsolarized soil)	(4 weeks)	(6 weeks)	(8 weeks)
Avena fatua.	+++	++	-	-
Amaranthus spinosus	+++	-	-	-
Chenopodium album	+++	-	-	-
Convolvulus arvensis	+++	-	-	-
Cynodondactylon	+++	++	+	-
Cyperus rotundus	+++	++	-	-
Digera arvensis	+++	-	-	-
Echinochloa colona	+++	-	-	-
Parthenium hysterophorus	+++	++	+	-
Sorghum halepense	+++	-	-	-

Signs such as - = No weed, + = Low weed occurrence, ++ = Medium weed occurrence, +++ = High weed occurrence by [33]

Soil solarization before sowing soyabean, using either transparent or black poly-ethylene film for 15 or 30 days, greatly reduced weed growth. Transparent polyethylene for 30 days had the best effect, and increased soyabean yield by 90 %. The major weeds observed in the experimental field were *Trianthema portulacastrum*, *Cyperus rotundus*, *Digera arvensis*, *Dactyloctenium aegypticum*, *Echinochloa colona*and, *Acrachne racemosa*. *T. portulacastrum*, the predominant weed in summer in this regionof India, had the maximum density (51.5%), followed by *C. rotundus* (13.0%). The solarization treatments significantly reduced the population and dry weight (Table 3). Mulchingfor 30 days reduced the emergence of *T. portulacastrum* by 91.2 and 87.6% with transparent and black film respectively. In general, solarization for 30 days was significantly better than15 days. The findings confirm that solarization controls weeds as reported by [52] and [36].The population of *C. rotundus* was unaffected by solarization, perhaps because it did not increase the soil temperature sufficiently at the lower depths to kill its tubers. [52] and [36]considered that the poor control of *C. Rotundus*. By solarization was due to high heat tolerance of its tubers. Solarization before sowing significantly increased the growth of soybean at 60 DAS (Table 4), especially for 30 days with transparent polyethylene. All the treatments significantly increased the yield, with a 90 % increase after 30 days with the transparent film. The improvement in growth and yield is probably due to decreased weed competition after solarization. Increased nutrition availability, stimulation of beneficial micro-flora and reduced incidence of soil-borne diseases through solarization might also have contributed. *Rhizobium* population in different pulses decreased with solarization, but re-established quickly aftersowing, whereas nodulation was unaffected, increasing the yield.[46].Soil solarization is a novel technique of management of soil-borne pests and weeds through heating of surface soil by using plastic sheets placed on moist soil to trap the solar radiation. [61] reported reduction in population of grassy and broad-leaf weeds due to soil solarization. By this method the soil temperature in creased by 8–10^{o} C over the corresponding non-mulch soil and thereby most of the annual and perennial weeds belonging to genera *Amaranthus, Anagallis, Avena, Chenopodium, Convolvulus, Digitaria, Eleusine, Fumaria, Lactuca, Phalaris, Portulaca, Solanum and Xanthium* were effectively controlled. However, weeds such as *Cyperus rotundus* (tubers), *Melilotus spp.* (hard seed-coat) and *Cynodon dactylon* (rhizomes) are not controlled by solarization [25]. The solarization effect diminishes with soil depth and the weeds which are capable of putting up growth from deeper layers, survive the treatment. This technique is however applicable to nurseries and high-value crops like vegetables, and cannot be followed for large-scale cultivation of field crops because of cost considerations [61]

Solarization can be an effective method of controlling many weeds such as bermudagrass, bindweed and other annual weeds. Keep in mind that some of these weeds have extensive root systems and many re-sprout, even after being subjected to super high temperatures. It may take several solarization attempts to completely eliminate them from the area. In the end, it may take a few more months before you are ready to plant, but you have not used chemicals to control these problem weeds. Soil solarization before sowing soybean, using either transparent or black polyethylene

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film for 15 or 30 days, greatly reduced weed growth. Transparent polyethylene for 30 days had the best effect, and increased soybean yield by 90% [51]. Field experiments were conducted to find out the effect of soil solarization on weed control in irrigated groundnut during 2000 and 2001 at farmer's field, Chidambaram, Tamil Nadu. Soil solarization with the use of 0.05mm transparent polyethylene sheets for 40 days was effective in controlling weeds than the use of 0.1 mm thickness polyethylene sheet and the lesser duration of soil solarization. Soil solarization with 0.05 mm thickness for 40 days recorded significantly higher pod yield and least weed seed reserves in the top 5cm soil. The inhibitory effect of different duration of soil solarization on weed plants was in the order: 8 weeks > 6 weeks > 4 weeks > control. Maximum number of leaves/plant, pod number, pod length and weight, seed number and weight of seeds/pod of *Abelmoschus esculentus* L. Moench were observed in the pots which were filled with soil that was solarized upto 8 weeks. Hence, the high productivity of *Abelmoschus esculentus c*an be obtained by the utilization of soil solarization process in agricultural fields [33]. Among crop husbandry practices, wheat straw incorporation brought about a significant reduction in *Cyperus rotundus* population and soil solarization in *Cynodon dactylon* population at 20 DAS in soybean. The total monocot weed population due to these two treatments was thus significantly lower. Summer cowpea for fodder, on the contrary, recorded the highest population of Cynodon and total monocot weeds, but the population of *Commelina benghalensis* was zero/nil and *Parthenium hysterophorus* was greatly reduced. Wheat straw incorporation had significantly higher *Trianthema portulacastrum* population, which resulted in very high dicot and total weed population. At 40 DAS of soybean, total monocot weed distribution was almost similar to what observed at 20 DAS. However, total weed population was the lowest in soil solarization and differed significantly with others. The monocot, dicot and total weed dry weight followed similar trend as their respective population and soil solarization proved most superior. At harvest of wheat, wheat straw incorporation; however, recorded the lowest total weed dry weight comparable with soil solarization and summer cowpea for fodder. Soil solarization and wheat straw incorporation were at par with each other on soybean grain yield, but solarization recorded significantly higher grain yield than others. Repeated tillage with irrigation and summer cowpea for fodder also recorded soybean grain yield significantly higher than in control/farmers' practice. Wheat straw incorporation and repeated tillage with irrigation being at par with soil solarization recorded significantly greater number of ear-bearing tillers and grain yield of wheat. However, soil solarization recorded the highest system productivity in the soybean-wheat cropping system closely followed by wheat straw incorporation and repeated tillage with irrigation, [16]. A combination of solarization and hand weeding was effective for decreasing weeds and increasing groundnut pod yield compared to other treatments which includes solarization along, hand weeding and Alachlor chemical [56]. The maximum weed reduction was obtained by transparent plastic film of 0.05 mm thickness for 60 days in wet soils, and maximum yield (28.75 q/ha) was also recorded in groundnut [6]. Plasticulture with polyethylene film significantly increased NO_3^- and NH_4^+ nutrients in comparison with untreated soils. Thirty days of soil solarization strongly control seeds of many wild plants such as *Phalaris minor* and *Avena fatua*, whereas the treatment was poorly effective against *Asphodelus tenuifolius* and *T. monogyna*. Such different effect on weeds can be esteemed calculating the ratio of seed germination in solarized condition on seed germination in untreated soil. The index, named solarization reduction index, esteemed as easier to control plants with low value [2].The decrease in weed counts due to integration of glyricide and soil solarization was 77% at 3 months after sowing and 74% at harvest in groundnut, whereas weed reduction was 55% at 55 days after sowing in French bean. Similarly, integrated treatment of soil solarization and crop residues increased the yield and other yield components [43].Rajasthan With biggest desert of India located in this state, it has a typical arid climate with average day high of 41°C. Uncovered soil temperature frequently reaches deadly ranges (up to 60°C) [28]during summer months. Lot of studies on soil solarization have been conducted in this region, in Jodhpur. Polyethylene mulching of irrigated and amended loamy sand soil raised the temperature to 57 and 50°C at 0–15 and 16–30 cm soil depths, respectively [39]. In a separate trial the soil temperature of unshaded amended pits achieved 41–45°C, however, under shade temperature remained 6.5–11°C lower than corresponding unshaded pits. Maximal air temperatures ranged from 34.5 to 47.2°C during the corresponding period [40]. Same research team documented that temperature of amended soil increased by 2.5°C in non-amended soil (42–51°C) at various soil depths. Integration of soil solarization and amendments also increased the soil temperatures compared to plasticulture (1–5°C) or untreated soils (3–13°C) [30]. [29] also observed that in mustard-amended polyethylene mulched plots temperatures may exceed 50°C.So even with the bare soil temperatures reaching at lethal ranges of 50–60°C during summer months, Could soil solarization represent one of the tools that can contribute to fill the yield gap in India? The environmental conditions of many Indian States indicate that plasticulture is an efficient techniques to protect plants and support production. This evaluation is also supported by experimental trials carried out in various States, suggesting how soil solarization could be applied beyond actual contests. Higher levels of soluble minerals nutrients and nitrate-nitrogen were found in solarized soil. Parasitic weed, broomrape (*Orobanche* spp.), and rainy and winter season annuals are adequately controlled by solarization. In Jabalpur (Madhya Pradesh), the yield increase of about 100–125% in onion, 50–55% in groundnut, 70–75% in *Sesamum*, and 77–78% in soybean have been observed using soil solarization (Success Story, Yadav, ICAR, New Delhi, India). These increments could drastically change food availability in India and whole South Asia in the next years if solarization will be widespread.However, successful of soil solarization trials in arid zone of India such as Rajasthan [28,30] indicate as low precipitation did not compromise results, while increase of temperatures could support solarization in moist sub-humid zones such as Himachal Pradesh. Furthermore, the Indian perspective in bioplastic production could support application and development of biodegradable films for solarization. Biodegradable films showed a good potential of using in place of plastic films, but further development is needed to obtain performances comparable to conventional techniques [7] and plastic waste management of Indian rural area may have benefits from bio-industry development. India perfectly fits into requirement for soil solarization application and potential bioorganic plastic production, due to large areas in which wheat or maize are cultivated. In a 2050 scenario, the bioplastic will be mainly produced in Asiatic continent, and India is showing the higher rate of increase per year (more than 5 %) in the bioplastic sector [37]. Thus, a local production and local consumption model should be achievable for biodegradable films, supporting development of national economy.

Table : Soil solarization temperatures achieved in different climate zones of India.

State	Soil*	PE (µm)	Solarized soil		Control soils		Reference
			Max	Min	Max	Min	
Moist sub-humid							
Himachal Pradesh	CL	25	49	25	37	21	[27]
Himachal Pradesh	LS	25	47	18	37	15	[54]
Uttarakhand	–	25	55	–	44	–	[55]
Kerala	–	50	42	–	36	–	[44]
West Bengal	CL	25	48	39	39	30	[13]
Dry sub-humid							
Madhya Pradesh	LS	110	52	–	46	–	[59]
Semi-arid							
Delhi	LS	100	48	34	40	32	[36]
Uttar	–	47	54	–	45	–	[17]

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State	Soil*	PE (µm)	Solarized soil		Control soils		Reference
			Max	Min	Max	Min	
Pradesh							
Telangana	V	100	48	38	39	33	[14]
Tamil Nadu	CL	200	46	–	28	–	[32]
Arid							
Rajasthan	LS	50	54	49	49	44	[39]

Steps to Solarization

- It is best to use this method during the longest, hottest days of summer. The goal is to get soil temperatures under the plastic above 140 degrees. It is easier to reach these temperatures in June through August.
- This is a process that will last for a couple months. Plan ahead in your planting schedule so solarization has enough time to work. Some of the more aggressive weeds will not be eliminated in just a few weeks.
- It is best to remove existing growth and lightly till the entire area.
- Remove stalks and debris that will puncture the plastic.
- Rake the area smooth. It is critical that the area is completely flat so plastic lays right on the soil with no air pockets.
- Irrigate the entire area so it conducts heat better. The soil should be moist to 12 inches deep, but not muddy. This is a real trick in clay soils. This is a critical step in the process, because it is not recommended to re-irrigate after the solarization process has started.
- Dig a 8-12 inch trench around the solarization area.
- Lay one entire piece of plastic over the area and tuck the edges into the trench you just dug.
- Cover the edges of plastic in the trench with soil, pulling plastic tight as you move across the whole area. This makes a good seal around the entire site.

Solarization incorporates the same principles of a hot compost pile to kill weed seeds and break down organic matter. We have used this technique in smaller areas here at the Arboretum from time to time with mixed results. Some have been very successful, but others have not completely eliminated some of the target weeds. Smaller areas have had better results than larger areas especially when dealing with aggressive weeds like Bermudagrass [53]. The down-side of soil solarization is that the same effect it has against soil pests also works against beneficial microbes. It also significantly reduces organic matter content in the soil. For this reason, soil solarization should be used in the context of a larger soil management program that includes cover cropping, crop rotation and composting, all of which will help mitigate the negative effects. Nonchemical weed control is an essential part of modern farming systems when attempting to reduce the dependence on chemical pest control and increase the use of alternative pest control approaches. Nonchemical weed control is a very important tool for conventional vegetable growers. Soil solarization is based on exploiting solar energy (irradiation) to elevate the temperature of the upper soil layer to 55 degrees C by mulching it with transparent polyethylene (PE) film for several weeks. It can be done on the entire field surface or on raised beds. Under the mulch, the temperature gradually decreases with soil depth. The efficacy of weed control is significantly improved when the soil is kept wet (around field capacity) during the mulching period. The factors involved in the killing process during and following soil solarization were recently reviewed and are described here only briefly. Thermal killing is the main physical mechanism involved in weed control; however, chemical and biological mechanisms also play an important role in the lethal process. Phase out of most chemicals available for weed

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management renewed the interest in soil solarization as a technically effective and environmentally safe practice for lettuce weed control in hot summer areas. Properties of solarizing films and lettuce crop system may considerably affect weed control and yield response of soil solarization. Different solarizing films, including low-density polyethylene, ethylene-vinyl acetate copolymer, low-density polyethylene–ethylene-vinyl acetate coextruded and a biodegradable corn starch-based film, were evaluated in 2003 and 2004 for weed control and lettuce yield response under field and greenhouse conditions in Southern Italy. Soil solarization strongly reduced weed density and biomass in both greenhouse and in the field, with no significant differences among the tested plastic films. Most annual weeds were completely controlled by soil solarization, except amaranth, *Amaranthus* spp., in soil solarized with biodegradable film in the field. Emergence of mediterranean sweetclover, *Melilotus sulcatus*, was stimulated by soil solarization in greenhouse. In the field, Cyprus vetch, *Lathyrus ochrus*, was found in solarized plots though absent in untreated soil. Perennial weeds were not affected by soil solarization, except a strong control of canadian thistle, *Cirsium arvense*, in the field. Lettuce yield resulted significantly higher in solarized soil than in control plots, with no significant differences among the solarizing materials. All tested materials proved to be technically effective for soil solarization in lettuce, though low resistance and short durability of biodegradable film may suggest its application mainly to soil solarization in greenhouse or in organic systems.[62]. Soil solarization proved most superior in terms of system productivity in the soybean-wheat cropping system. Crop husbandry practices like wheat straw incorporation and repeated tillage with irrigation were also as effective as soil solarization towards prevention/ management of composite weeds and production of crops' yield. They, therefore, can be adopted in soybean-wheat cropping system to exhaust weed seed bank in soil for better weed management [27].

IV. DISCUSSION

The method proves efficient both in the short and long run for weed management. If weeds develop under plastic, it means the process is carried out incorrectly. The soil solarization technique for weed management is efficient when the temperature is hot enough to kill certain species. In this regard, it will bring more results in controlling winter weeds rather than summer ones due to higher heat tolerance in summer plants. Soil solarization for weed control of perennials is less effective compared to annuals due to the deep earth penetration of perennial seeds and roots.The method combats such annual species as *Ageratum, Amaranthus, Digitaria, Portulaca, Setaria,* and others. Weeds reproducing with multiple tiny seeds are easier to control than those spreading with stolons.[24;41]. Soil solarization accords with the principles of permaculture, regenerative agriculture, and organic farming since it prefers traditional knowledge to intensive farming methods. This explains the benefit of soil solarization technique for weed management in permaculture and other chemical-free practices. However, permaculturalists' opinions differ. Some of them think that plastic does not fit into natural landscapes. Another point is that permaculture promotes perennial plants, and solarization works better with annuals. High temperatures are not favorable for earthworms, preferring damp but cool areas. The solarization impact on them is understudied. Yet, it is believed that they just escape the heat by digging deeper. Soil solarization for nematode control is most beneficial for shallow-rooted, fast-growing crops. It does kill many nematode species (pin, sting, cyst, spiral, root-knot, etc.). In particular, studies report a positive impact of soil solarization on root-knot nematodes in transplanted tomatoes. Root-knot nematodes and their eggs are killed when exposed to 125°F for 30 minutes or 130°F for 5 minutes. Nonetheless, nematodes are worms, so they are relatively mobile. Therefore, they can escape high temperatures and return when circumstances are favorable – unlike their eggs. Besides, temperature decreases under the plastic down the earth profile, which reduces the effect on nematodes dwelling deep in the subsoil. For this reason, nematodes may be incompletely controlled with soil solarization only. In this case, the combination of chicken manure and solarization provides better control. Solarization kills many bacteria and may threaten beneficial biota, too. This is why it is important to restore the balance by adding organic matter after completion[53,55]. The good news is that beneficial microorganisms can either resist the soil solarization process or re-establish their populations faster soon after the crucial impact. In particular, this refers to:

- Microorganisms parasitizing bacteria and fungi that are pathogens to plants;

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- Symbiotic mycorrhizal fungi that colonize plant roots and trade moisture and nutrients (particularly phosphorus) for photosynthetic products.

The method may also destroy nitrogen-fixing *Rhizobium*. In this case, nitrogen fixation can be encouraged by planting N-fixing leguminous crops to be inhabited by the symbiotic *Rhizobium.*

A rise in soil temperature also means a rise in the split of organic matter that contributes to soil fertility. In particular, solarization helps increase the content of N (NO_3, NH_4), K, Mg, Mn, Ca, Fe, Cl, and Cu. Thus, the technique is effective in pest control but still beneficial to soil health. With the increased availability of nutrients, plants become stronger, which makes them more resistant to pathogens and boosts yields. However, each crop type requires a specific balance of nutrients for healthy development. Despite the current soil solarization adoption worldwide is still relatively small, it is expected to gain more popularity as a chemical-free measure because of the methyl bromide bans due to ozone depletion. Under proper conductivity and heat exposure time, solarization kills many microbes that are thermosensitive enough or cannot dig deep into the earth. However, in cooler regions or when the obtained temperatures are not lethal but sublethal, soil solarization efficacy can be enhanced with biological, physical, or chemical methods of control and organic amendments. Biological control efficacy presents a certain interest for researchers since its possibilities are understudied. Yet, it is already known that the fungal genera of *Talaromyces yavus, Trichoderma harzianum, Glomus fasciculatum* are effective biological agents of plant disease control [60]. Organic amendments also increase solarization efficacy. For example, chicken manure slightly raises the earth's temperature during solarization. When combined, chicken manure and solarization kill *Orobanche crenata* seeds at all depths compared to unamended solarization efficacy only at the surface. Warmer temperatures in solarized earths typically increase the effect of chemical amendments but may also speed up their volatility or degradation. On the other hand, chemicals eliminate the soil solarization benefits in pest and disease control, which may negatively affect the crops in the long run.

V. CONCLUSION

Soil solarization was found to be an effective tool for sustainable weed management in different lettuce systems. Different solarizing materials were found similarly effective for weed control and yield response. Biodegradable plastics sheets reduce the environmental impact of soil solarization. Replacement of conventional solarizing materials with biodegradable plastic film can be suitable to soil solarization in greenhouse systems[6]. Soil solarization proved most superior in terms of system productivity in the soybean-wheat cropping system. Crop husbandry practices like wheat straw incorporation and repeated tillage with irrigation were also as effective as soil solarization towards prevention/ management of composite weeds and production of crops' yield. They, therefore, can be adopted in soybean wheat cropping system to exhaust weed seed bank in soil for better weed management. Soil solarization as a method of pest control is unique. It is (i) non-hazardous, (ii) user-friendly, (iii) environmentally benign, (iv) not dependent on fossil fuel, (v) effective on a wide variety of weeds, (vi) often effective for more than one season or a year, and (vii) stimulatory to crop. The solarization technique is simple and easy to use by farmers. However, its immediate application appears to be more promising in nursery areas and in high value crops such as vegetable growing, floriculture etc. In addition, TPE sheet of pre-plant solarization mi C\Y be left in place after plant emergence, as a post-plant mulch. As far as its application in India is concerned, almost every area is climatically suitable for soil solarization. Vast majority of the areas experiences mean daily maximum temperature in excess of 40°C in the months of April to June. It is also the time when the land is fallow enabling farmers to practice this technique without sacrificing land/crop. The use of crop protection techniques should be evaluated with regard to novel approach of sustainability in agricultures; among them, agroecology carefully specify the part of technology in food production. As defined by [1].Soil solarization may represent crop protection techniques that substantially relay on locally available resources—that can be considered as local as solar radiation—and it does not generate dependence of farmers to agrochemical producers. Furthermore, the contribution of soil solarization to fill the yield gap may play a significant role in achieving Indian food sovereignty. To conclude, the literature reviewed in this paper indicates more than

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encouraging effects on production and protection of Indian crops, which can be feasible according to climate change in India and that can be integrated or can support development of national bio-industry.

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