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Soil solarization in relation to potato production: A review

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ABSTRACT

Soil solarization is a non-chemical and non-hazardous method known to possess numerous beneficial effects in crop production. It is mainly useful for commercial application in areas with very high air temperatures during the summer; where much of the crop area is kept fallow - due to excessive heat. A review of the available information on soil solarization reveals the numerous advantages of the technique in relation to crop production. Solarization of soil has been reported to manage weeds, control nematodes, soil borne diseases and insects. Besides these, it increases thermo-tolerant micro-fauna in the soil, most of which are beneficial – the bioagents, nutrient solubilizers and nitrifiers, and thus results in higher availability of essential plant nutrients and improvement in soil tilth. The effectiveness of soil solarization as soil-borne pests control method is well demonstrated. In potato, soil solarization is known to increase the potato yield coupled with better quality of tubers through the reduction of several soil borne diseases and weeds.

Key words: Nutrients, Potato, Soil borne pathogens, Soil solarization, Weeds

Soil solarization is an environment friendly method used to manage weeds, nematodes, diseases and insects in the soil. It is a non-chemical and non-hazardous method that can successfully be employed in organic farming (Arora and Sharma 2007). Soil solarization was initially pioneered in countries in the Middle East, where intense solar radiation and high temperatures are appropriate for solar heating. This technology originated during the 1970's and was intended for soil disinfestation by means of solar energy (Hasing 2002). Solarization is mainly dependent on high levels of solar energy, as influenced by both climate and weather. Cloud cover, cool air temperatures and precipitation events during the treatment period reduce solarization efficiency (Chellemi 1997). The potato is the most important vegetable crop in the world and is produced primarily in regions with moderate temperatures. The potato tubers is grown underground and are exposed to numerous soil-borne pathogens including fungi, bacteria, and nematodes. Since, soil borne diseases of potato may lead to heavy losses in terms of tuber quality and quantity, this crop is an excellent candidate for investigating the effects and principles of solarization on crop production. Investigations with the potato show that the practice of solarization has positive effects even under conditions of temperate climate (Davis and Sorensen 1986). The use of soil solarization with the potato introduces a wide spectrum of possibilities for future food production. Therefore, an attempt has been made to review the work done on the various aspects of soil solarization with special reference to potato.

THE TECHNIQUE

In soil solarization, the soil is covered with transparent sheets, usually transparent polythene which allows the short-wave radiation from the sunlight to pass through the plastic sheets in order to heat the soil in an open field or glass house. Once the light passes through the plastic sheet, it is reflected back from the soil, hence increasing the wavelength of light that cannot pass through the plastic. Thus, the trapped light heats the soil to a temperature that can kill most of the living microorganisms. The process is carried out in summer and works best in regions that have hot, sunny weather for 4 to 8 weeks (Krueger and McSorley 2009). The heating of the soil due to the absorption of radiation by the soil is best when the plastic sheet is laid close to the soil with a minimum of air space to reduce the insulating effect of air layer. Therefore, good land preparation is essential to provide a smooth and even surface (Yaduraju 1993). It has been seen that in comparison to the light colored soil, dark colored soil absorbs more radiation (Smith 1964). The technique of soil solarization or solar heating of the soil is just similar to the summer ploughing of the soil to expose and kill the soil pathogens, nematodes, insect-pests and vegetative propagates of weeds, especially the perennial weeds (Patel *et al.* 2005). Solarization can be

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done in any type of soil. However, for the better results it should be done in open and unshaded areas where the sun is not blocked by trees or buildings during the day. The soil solarization method is carried out using the following sequence of steps:

Step 1: The area to be solarized is cultivated and cleared of weeds and other debris that might harbor the pest. Sticks, old roots, and other debris should be removed so they do not poke holes in the plastic.

Step 2: The soil is irrigated very well to increase its heat conductivity. If the soil is very dry and dusty, the solarization will not work as well (Hanson 2013).

Step 3: Soil is covered with a clear plastic sheet or strip which is stretched out over the area to be treated. The plastic piece should be a little larger than the area treated because the edges will need to be buried in soil. Black plastics or reflective plastics should be avoided as they get hot on the surface, and will not allow the sunlight to heat the soil below.

Step 4: The plastic is stretched tightly so that it is in contact with the soil. The edges sealed completely by burying in soil. If edges are not completely sealed heat will leak out and problems may result in these cooler areas. The heating is better if the plastic is closer to the soil surface.

Step 5: The plastic should be left in place for about 4 to 6 weeks and 8 weeks for really persistent weeds (Hanson 2013, McSorley and Gill 2010). After that, the plastic can be removed. Planting can be done after removing the plastic sheets. After planting, avoid cultivating for more than the upper 2 inches of soil, since weed seeds at deeper levels may still be viable. The control of weed pests and soil borne pathogens is a serious challenge for the farmers. The use of soil fumigants is often not favourable as it causes toxicity in plants as well as soil. Thus, soil solarization has proved to be an effective method to control many damaging soil borne pathogens and pests (Pokharel 2011). In addition, it also increases the availability of essential plant nutrients and improves the soil tilth.

WHY SOIL SOLARIZATION IN POTATO

Potato is an important food source since it produces more food per unit area per unit time than the conventional cereal crops and thereby holds promise for food for the fast growing human population. It is grown commercially in almost all the agro-climates mainly under dry temperate, temperate and sub-tropical conditions. Being grown underground, the potato crop is affected by soil-borne pathogens including fungi, bacteria and nematodes causing soil borne tuber diseases of potato (Kumar and Sharma 2005). All these soil pathogens not only lower down the potato yields but also affect the tuber quality adversely and thus reduce their marketability on account of various diseases on tuber surface. With the reduction in cultivable land due to fast urbanization and cultivation of potato year after year in the same land, the soil and tuber diseases are emerging as a major problem and pose great challenge for their management. Soil solarization has previously been found effective against various potato diseases and pests (Davis and Sorensen 1986, Davis 1991, Denner 2000, Triki 2001). It has been reported to reduce the weeds, soil pathogens and improve the quality of potato tubers (Arora 2005, Sharma and Singh 2003). Increase in potato yield coupled with better quality of potato tubers through the reduction of several soil borne diseases and weeds has also been reported (Singh 2009).

EFFECT OF SOIL SOLARIZATION ON SOIL MOISTURE

Decline in the population of soil-borne pathogens during solarization depends upon soil moisture and soil temperature. Soil moisture makes organisms sensitive to heat and transfer heat to living organisms in soil. The success of soil solarization depends on moisture content for maximum heat transfer and maximization of heat in soil increases with increasing soil moisture. Small differences in soil moisture content can translate into large differences in soil heat transfer characteristics (Smith 1964). Soil moisture conducts heat, evaporates, and increases the maximum soil temperature (Mahrer and Shilo 2012). It have a great impact on cellular activities and growth of soil-borne microorganisms and weed seeds, thereby making them more vulnerable to the lethal effects of high soil temperatures associated with soil solarization. The interaction between temperature and soil moisture brings about cycling of water in soil during soil solarization (Pokharel 2011). The magnitude of rise in temperature decreases with the soil depth (Singh 2009). Solarization has potential to raise the maximum soil temperature under the trap by 8-12°C (Yaduraju 1993).

EFFECT OF SOIL SOLARIZATION ON SOIL TEMPERATURE

Soil solarization has a great impact on soil temperature. It usually depends upon the function of time and temperature relationships. Significant control of several diseases in crop plants has been reported by many authors through soil solarization due to increase in soil temperature (Chauhan 1988). During soil solarization, temperatures commonly reach up to 95°F to 140°F (35-60°C) depending on soil type, season, location, soil depth and other factors. In order to kill 90% of the population of mesophylic fungi, an exposure of 37°C temperature is required for 2 to 4 weeks, whereas, only 1-6 hr exposure at 117°F (47°C) may be required to get the same result (Pokharel 2011). The maximum temperature of soil solarized in the field is usually from 108° to 131°F (42° to 55°C) at a depth of 2 inches (5 cm) and from 90° to 99°F (32° to 37°C) at 18 inches (45 cm). Control of soil pests is usually best in the upper 4 to 12 inches (10-30 cm) (Elmore 1997). In case of potato fields, maximum soil temperature recorded under the polythene mulch were 53.3°C at the surface, 50.5°C at 5 cm, 44.0°C at 10 cm and 38.6°C at 15 cm soil depth, which were higher by 10.96°C, 9.4°C, 5.6°C and 3.9°C than unsolarized plots at respective depths (Singh 2009). The magnitude of rise in temperature decreased with soil depth (Habbeburrahman and Hosmani 1996). The double tent technique, in which the soil is mulched with two layers of polythene sheets (with a space of 3 to 7cm between the sheets), increases soil temperature by an addition of 10ºC with respect to a single-layer solarization (Ben-Yaphet 1987). The double tent technique was found to be more effective than single polythene sheet (Mc Govern et al. 2004), especially against weeds in nursery containers (Stapleton 2000a, Stapleton 2002).

EFFECT OF SOIL SOLARIZATION ON SOIL-BORNE PATHOGENS

Planting the crop again and again on the same piece of land, sooner or later results in high inoculums accumulation thus, forces the farmers to either change the crop or the land. Therefore, the effective control of soil borne pathogens increases not only the yield and quality but also the availability of lands, by prolonging its use for crop production. The effectiveness of soil solarization as an established soil-borne pests control method is well demonstrated under various agro-ecosystems (Peachey 2001). Solarization controls populations of many important soil borne fungal and bacterial plant pathogens, including *Verticillium dahliae*, which causes *Verticillium* wilt in many crops; certain *Phytophthora cinnamomi*, which causes *Phytophthora* root rot; *Agrobacterium tumefaciens*, which causes crown gall disease; *Clavibacter michiganensis*, which causes tomato canker; and *Streptomyces scabies*, which causes potato scab (Elmore 1997 and Pokharel 2011). It also reduces soil populations of different plant parasitic nematodes, especially *Meloidogyne* spp. (root-knot), *Pratylenchus thornei* (root lesion), *Pratylenchus* (root lesion) and *Xiphinema* (dagger) nematodes. Within the uppermost 15 cm of the soil, the population of *Verticillium dahliae* in potato genotypes was reduced to up to 97% by the solarization treatment. The population of *Pratylenchus* sp. was also reduced in that particular region. However, the reductions of population were not evident within 15-30 cm zone for either *Verticillium* sp. or *Pratylenchus* sp (Davis and Sorenson 1986). 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 1986). Nematode control by solarization is usually adequate to improve the growth of shallow rooted, short-season plants. It is particularly useful for organic gardeners and home gardeners (Elmore 1997). The inoculum density of *Fusarium* species at the upper and lower 15 cm layer of the soil reduced to about 96% and 76% due to solarization (Triki 2001 and Yao 2016). Soil solarization with transparent polyethylene mulching during hot summer months in Indian subtropical plains has been found to control soil borne *Rhizoctonia solani* and a significant decline in the disease (Arora 2006). Addition of organic materials such as *Cannabis sativa*, *Toona ciliata* and *Eucalyptus* sp. together with soil solarization further reduced black scurf disease incidence in potatoes (Arora and Jyotsana 2007). Soil solarization reduces the disease severity of russet scab to almost one third as compared to the unsolarized plots (Arora 2005).

EFFECT OF SOIL SOLARIZATION ON WEED DENSITY

Soil solarization helps in controlling weed density. Increasing the durations of keeping plastic cover on plots consequently reduces the weed dry weight. Temperature and the high level of humidity play a major role in weeds demolishing process, because increasing the solarization time subsequently increases the soil temperature and humidity (Golzardi 2014). Some of the weed species are very sensitive to soil solarization, while others are moderately resistant and require optimum conditions (good soil moisture, tight-fitting plastic and high radiation) for control.

Soil solarization at 37°C for 14 to 30 days almost completely prevents the emergence of many annual weeds, at the top most layer of the soil because temperature increases more slowly at deeper depths. Efficacy of soil solarization for weed control in the field is increased by providing irrigation at least 2-3 weeks prior to solarization, letting the weeds grow, and incorporating them in soil before establishing the solarization treatments (Pokharel 2011). It also has been suggested that irrigation 48 hours prior to solarization results in breaking dormancy of weed and pathogen propagules present in soil. Soil solarization significantly reduced weed population by 94.1% and fresh weight of weeds by 98.4% in the first season compared to the unsolarized soil (Singh 2012). Marenco and Lustosa (2000) reported that 3, 6 and 9 weeks of solarization respectively decreased the weed dry weight at the rate of 22, 38 and 60%. They also indicated the upper temperature and CO_2

Fig 1 Soil solarization in net houses and multiplication of *in vitro* planting materials in field condition.

level as the main reason of this reduction under the plastic situation. The effect of thickness of plastic cover on weed dry weight was significant at the level of 1%. The plastic cover with thickness of 100 micron reduced the weed dry weight to approximately 33.9% (Golzardi 2014).

Solarization generally controls the annual weeds but does not control the perennial weeds as the perennials often have deeply buried underground vegetative structures such as roots and rhizomes that may re-sprout. Seed of Bermuda grass (*Cynodon dactylon*), Johnson grass (*Sorghum halepense*), and field bindweed (*Convolvulus arvensis*) are controlled by solarization. Rhizomes of Bermuda grass and Johnson grass may be controlled by solarization, if they are not deeply buried. In potato fields, all the major weeds like, dicotyledons *Coronopus didyma*, *Gnaphallicum indicum, Spergula arvensis, Anagallis* sp., *Rumex* sp. and *Veronica* sp. and monocotyledons *Poa annua* and *Digitaria* sp are effectively controlled by soil solarization (Singh 2009) except *Cyperus rotundus* (monocotyledons) which showed resistance to control by solarization. Rubin and Benzamin (1984) and Egley (1983) reported enhanced germination of *C. rotundus* in solarized soils. Final *Cornopus* population was decreased by 70.2%, while final total weeds population was decreased by 62.1% due to solarization. Earlier studies reported the effectiveness of solarization against weeds especially annual weeds (Katan and DeVay 1991, Triki 2001).

EFFECT OF SOLARIZATION ON BENEFICIAL SOIL ORGANISMS

When the soil is heated during soil solarization, many of the soil pests are killed but certain beneficial organisms are either able to survive or recolonize the soil very quickly afterwards. Some of the important beneficial soil organisms are mycorrhizal fungi, fungi and bacteria. They parasitize the plant pathogens and helps in plant growth (Pokharel 2011). The use of Arbuscular mycorrhizal fungi (AMF) and soil solarization as disinfestation method enhances the crop productivity and reduces fertilizers and pesticide inputs. AMF are the soil fungi that colonize roots of the majority of crop plants forming a mutualistic symbiosis (Ngakou 2006). AMF have also proven to alleviate cultural and environmental stresses and enhance disease resistance and plant health (Davies 1999). *Trichoderma* (Levy *et al*. 2015)*, Talaromyces*, and *Aspergillus* spp., are some of the beneficial fungi that survive and even multiply in solarized soil. Earthworms are generally thought to burrow deeper in soil to escape the heat. *Bacillus* and *Pseudomonas* spp. are beneficial bacteria which are reduced during solarization but recolonize the soil rapidly afterward. Populations of *Rhizobium* spp., which fix nitrogen in root nodules of legumes, may be greatly reduced by solarization and should be reintroduced by inoculation of leguminous seed (Elmore 1997).

EFFECT OF SOLARIZATION ON SOIL NUTRIENTS

Solarization helps in initiating certain changes in the physical and chemical features of the soil. Thus, it results in the overall growth and development of plants. The breakdown of organic material in the soil, results in the release of soluble nutrients such as nitrogen (NO_3^-, NH_4^+), calcium (Ca^{++}), magnesium (Mg^{++}), potassium (K^+), and fulvic acid, making them more available to plants (Elmore 1997). Pokharel (2011) concluded that the increased availability of mineral nutrients following soil solarization includes those tied up in the organic soil fraction (e.g. NH_4-N, NO_3-N, P, Ca and Mg). An increase in soil nitrate nitrogen by more than 3000 kg/ha was obtained by adding chicken manure and growing mustard and incorporation in soil before soil solarization. Ultimately, these nutrients, especially the nitrogen, benefits crop growth. In a field study in southwest Florida, it was found that soil nutrients were not affected by solarization when compared to conventional treatment with methyl bromide (Ozores-Hampton 2004). The soil nutrient level was increased when the solarization was coupled with the compost. This increase in the soil nutrient level was more than the treatments with methyl bromide or solarization alone, both of which were combined with inorganic fertilizer. Seman-Varner (2008) measured nutrient concentration in the soil and plant tissues of an okra crop following different durations of solarization. While soil potassium (K) and manganese (Mn) were higher following solarization, copper (Cu) and zinc (Zn) were lower. In addition, soil pH was slightly decreased by solarization. Soil phosphorus (P), magnesium (Mg), calcium (Ca) and iron (Fe) were not affected by solarization. Nutrients supplied to the crop were exclusively provided by chopped cowpea hay. Solarization increased okra biomass; the longer the duration of solarization, the greater the increase in okra biomass (based on comparison among 2, 4 and 6-week solarization periods). The positive yield response indicated that solarization did not impair organic matter decomposition and subsequently release the plant nutrients. Thus, these studies (Ozores-Hampton 2004 and Seman-Varner 2008) suggest that solarization does not interfere much with beneficial soil organisms that decompose organic matter. Sofi in 2014 reported that the mean pH, EC (electrical conductivity), calcium, magnesium, nitrogen, phosphorous, potassium and carbon observed in solarised soil was significantly higher than non-solarized soil. In potato crop, soil nutrients (N, P and K) were influenced by soil solarization both at the time of planting as well as harvesting. Singh (2009) found that the availability of nutrients at the time of planting was 17.7% N, 63.2% P, and 27.14% K and at the time of harvesting was 16.25% N, 21.9% P, and 14.7% K due to solarization. Arora (2005) has also reported an increase in N and P due to soil solarization. The reduction in available K_2O (64.4%) and NO_3–N (29.79%) was higher in solarized soil as compared to unsolarized soil during the potato growth period. This could partially be due to increase in potash solubilizers and nitrifying microorganisms in the solarized soil, as solarization increases thermo-tolerant micro-fauna in the soil (Arora 2007), most of which are beneficial – the bioagents, nutrient solubilizers and nitrifiers (Katan

Fig 2 Soil solarization and its impact on potato production

and DeVay 1991). This would result in more numbers and bulking of potato tubers and with higher tuber yield. AMF have also been reported to improve nutrient uptake, particularly phosphorous (Abd-Alla 2000). It has also been suggested that potatoes can be grown on solarized soils inoculated with effective AMF without the need of P and N fertilizers, since the outcome of these techniques is the improvement of the soil with N and P nutrients in particular (Sieverding 1991).

EFFECT OF SOIL SOLARIZATION ON POTATO YIELD

Research has shown that soil solarization improve plant growth and health (Banu 1998). It is expected that AMF inoculation and soil solarization may reduce the cost of potato production, thus encouraging the farmers to valorize this important crop (Ngakou 2006). Sharma and Arora (2005) found that there was a significant increase in the tuber yield of most of the varieties of potatoes. Increase in yield was 8.62% in Kufri Pukhraj to 73.67% in Kufri Chandramukhi. On an average, 26.8% increase in yield was recorded due to soil solarization. Increase in tuber yield was genotype specific and ranged between 16-20% in Kufri Jyoti, Kufri Jawahar and Kufri Dewa, between 20-30% in Phulwa, Kufri Ashoka and Kufri Sherpa, between 30-40% in Kufri Giriraj, Kufri Bahar, Kufri Sutlej, Kufri Badshah and Kufri Lalima. An increase in yield between 18-40% in potato has also been reported (Arora 2006 and Arya 2002). Singh (2005) concluded that solarization increased tuber yield in the potato crop raised from micro-tubers, in all the cultivars evaluated. Mean tuber yield was the highest in Kufri Ashoka (27.78 tonnes/ha) followed by Kufri Pukhraj (23.42 tonnes/ha) and Kufri Badshah (19.63 tonnes/ha). The highest yield of Kufri Ashoka was mainly due to early and higher emergence of micro-tubers and early duration cultivars. Emergence of micro-tuber crop was 58.2% and 54.8% in solarized and unsolarized soil treatments respectively, whereas in mini-tuber crop it was 100% in both the treatments. On an average 48% of the yield of mini-tubers was recorded due to soil solarization. Significant increase in yield (64.2%) due to solarization in the crop raised from micro-tubers of Kufri Badshah has also been reported by Singh (2004). A significant increase in the yield of potato mini-tuber crop in solarized plots has been reported (Arora 2007, Rai 2003) under the conventional method of propagation. The mean rate of multiplication was significantly highest in Kufri Ashoka (11.41 times) followed closely by Kufri Pukhraj (10.45), whereas it was significantly lowest in Kufri Badshah (8.46), Kufri Chandramukhi (8.35), Kufri Surya (8.10) and Kufri Jyoti (7.70) (Singh 2012). Triki (2001) have also reported improvement in the potato yield due to soil solarization. Even under temperate climate, a positive effect of soil solarization on potato has been reported (Davis and Sorenson 1986). Davis and Sorenson (1986) concluded that the potato clones susceptible to *Verticillium* showed a very high yield increase up to 118%. Long term effects of solarization in disease control and yield increase extending for a second or even fourth crop had been observed (Stapleton and DeVay 1986, Katan 1983 and Abdel-Rahim 1988). Such long-term effects of solarization in control of *Verticillium* wilt of potato were also reported (Davis and Sorensen 1986).

The present study reveals that a lot of information is available on the beneficial effects of soil solarization on crop production in general and potato in particular. But, yield advantage in potato due to solarization has been reported to vary in different agro-ecological regions as well as among genotypes. Thus, some of the issues which need further addressing include standardization of technology in different agro-ecological regions separately for the major crops and cultivars of the area to harness the maximum benefits of the technology. An in-depth study of micro-fauna in relation to soil solarization and subsequent crops grown may also be taken up. The fertilizer doses to be applied in combination with soil solarization should be worked out for different crops and cultivars (including potato) for achieving higher productivity with better economy. There is also a need to standardize the use of bio-fertilizers after soil solarization to improve soil health, quality and productivity for sustainability of the system.

Conclusions

It can be concluded from the information reviewed that solarization of soil is a beneficial practice in crop production. It manages weeds, controls nematodes, soil borne diseases and insects. Beside this, it is more beneficial in the crop like potato where edible portion lies underground. Higher yield of potato with better quality of tubers are obtained after soil solarization. However, the beneficial effects of soil solarization are known to vary with area as well as genotype. Thus, standardization of technology for different regions, crops and cultivars is must. Also, the use of technology for organic cultivation in combination with other amendments like bio-fertilizers, as well as on minimization of inorganic inputs including fertilizers need to be standardized. It may prove the way for the future.

REFERENCES

Abd-Alla M H, Omar S A and Karanxha S. 2000. The impact of pesticides on arbuscular mycorrhizal and nitrogen fixing symbiosis in legumes. *Applied Soil Ecology* **14**: 191–200.

Abdel-Rahim M F, Satour M M, Mickail K Y, E1-Eraki S A, Grinstein A, Chen Y and Katan J. 1988. Effectiveness of soil solarization in furrow-irrigated Egyptian soils. *Plant Disease* **72**: 143–6.

Arora R K. 2005. Efficacy of soil solarization in reducing tuber russet and improving yield of different cultivars. *Potato Journal* **32**: 185–6.

Arora R K and Sharma J. 2007. Eco-friendly alternatives to pesticides in management of soil and tuber borne diseases of potato in organic farming. (*In*) *Sustainable Environmental Management*, pp 1-6. Gangawane L V and Khilare V C (Eds). Daya Publishing House, New Delhi.

Arora R K, Sharma J and Singh R K. 2006. Soil solarization in: Technologies in aid of healthy potato production. Tech Bull. No. 35, Central Potato Research Institute, Shimla, pp 1-7.

Arya A. 2002. Soil solarization for integrated disease management. *Annual Review in Plant Pathology* **1**: 213–30.

Banu S P, Shald A, Abawi G S, lausen J G, Duxbury J M and Meisner C A. 1998. Diagnosing soil constraints to rice, wheat productivity with soil solarization. (*In*) *90th Annual Meeting of American Society of Agronomiy*, Crop Science Society of Amercia at Baltimor, 18-20 October, M D USA, pp 79-97.

Ben-Yaphet Y, Stapleton J J, Wakeman R J and DeVay J A. 1987. Comparative effects of soil solarization with single and double layers of polyethylene film on survival of *Fusarium oxysporum* f.sp. *vasinfectum*. *Phytoparasitica* **15**: 181–5.

Chauhan Y S, Nene Y L, Johansen C, Haware M P, Saxena N P, Singh S, Sharma S B, Sahrawat K L, Burford J R, Rupela O P, Rao JV D KK and Sithananthan S. 1988. Effect of soil solarization on pigeonpea and chickpea. ICRISAT Research Bulletin No. 11, Andhra Pradesh, p 16.

Chellemi D O, Olson S M, Mitchell D J, Secker I and McSorley R. 1997. Adaptation of soil solarization to the integrated management of soilborne pests of tomato under humid conditions. *Phytopathology* **87**: 250–8.

Davies Jr F T, Eggilla J N, Miller J C and Saraiva Grossi J A. 1999. Influence of Mycorrhiza and isoflavonoid on plant growth gas exchange of potatoes started from minitubers. *Hort. Sci.* **34**: 498.

Davis J R and Sorensen L H. 1986. Influence of soil solarization at moderate temperatures on potato genotypes with differing resistance to *Verticillium dahliae*. *Phytopathology* **76**: 1021–6.

Davis J R. 1991. Soil solarization: yield and quality benefits for potato in a temperate climate short and long-term effects and integrated control. FAO Plant Production and Protection Paper 109, pp 28-36.

Denner F D N, Millard C P and Wehner F C. 2000.Effect of soil solarization and mould board ploughing on black dot of potato caused by *Colletotrichum* coccodes. *Potato Research* **43**: 195– 201.

Egley G H. 1983. Weed seed and seedling reduction by soil solarization with transparent polythene sheets. *Weed Science* **3**: 404–8.

Elmore Clyde L, Stapleton James J, Bell Carl E and Devay James E. 1997. Soil Solarization: A Nonpesticidal Method for Controlling Diseases, Nematodes, and Weeds. Publication 21377 Division of Agriculture and Natural Resourses, University of California Oakland, p 14.

Golzardi Farid, Yavar Vaziritabar, Yazdan Vaziritabar, Shabnam Sarvaramini and Zohreh Ebadi Seyedeh. 2014. Solarization period and thickness of polyethylene sheet effects on weed density and biomass. *Indian Journal of Fundamental and Applied Life Sciences* **4** (S3): 587–93.

Habbeburrahman P V and Hosmani M M. 1996. Effect of soil solarization on weeds and nematodes under tropical conditions. *Weed Research* **33**: 423–9.

Hanson Beth. 2013. Harness the sun's power to defeat soil borne pest and pathogens. Garden soil, Organic Gardening Magaine, p 25.

Hasing Eduardo Julio. 2002. Agroeconomic effect of soil solarization on fall-planted lettuce. Thesis, Graduate Faculty, Department of Horticulture, Louisiana State University and Agricultural and Mechanical College, p 125.

Katan J and DeVay J E. 1991. *Soil Solarization,* p 267. CRC Press Inc., Boca Raton, USA.

Katan J.1987. Soil solarization. (*In*) *Innovative Approaches to Plant Disease Control*, pp 77-105. Chet I (Ed). Wiley, New York.

Katan J, Fishier G and Grinstein A.1983. Short- and long-term effects of soil solarization and crop sequence on Fusarium wilt and yield of cotton in Israel. *Phytopathology* **73**: 1215–9.

Krueger R and McSorley R. 2009. Solarization for pest management in Florida. ENY-902, Entomology and Nematology Department, Florida Cooperative Extension Service, IFAS, University of Florida, Gainesville, FL.

Kumar Raj and Sharma Jyotsana. 2005. Effect of soil solarization on true potato (*Solanum tuberosum* L.) seed germination, seedling growth, weed population and tuber yield. *Potato Research* **48**: 15–23.

Levy N, Okon Meller, Harel, Y, Haile Z M, Elad Y, Rav-David E, Jurkevitch E and Katan J. 2015. Induced resistance to foliar diseases by soil solarization and *Trichoderma harzianum*. *Plant Pathology*. **64**: 365–74.

Mahrer Y and Shilo E. 2012. Physical principles of solar heating of soils. (*In*) *Soil Solarization: Theory and Practice*, pp 147–52. American Phytopathological Society, St. Paul.

Marenco R A and Lustosa D C. 2000. Soil solarization for weed control in carrot. *Pesquisa Agropecuária Brasileira* **35**: 2025–32.

McGovern R J, McSorley R and Wang K J. 2004. Optimizing bed orientation and number of plastic layers for solarization in Florida. *Annual Proceedings of Soil Science Society of Florida* **63**: 92–5.

McSorley Robert and Gill Harsimran K. 2010. Introduction to Soil Solarization. ENY-062. Entomology and Nematology Department, Florida Cooperative Extension Service, IFAS, University of Florida, Gainesville, FL.

Ngakou A, Megueni C, Nwaga D, Mabong M R, Djamba F E and Gandebe M. 2006. *Solanum tuberosum* (L.) responses to soil solarization and arbuscular mycorrhizal fungi inoculation under field conditions: Growth, yield, health status of plants and tubers. *Middle-East Journal of Scientific Res*earch **1(1)**: 23–30.

Ozores-Hampton M, McSorley R, Stansly P A, Roe N E and Chellemi D O. 2004. Long term large scale soil solarization as a low-input production system for Florida vegetables. *Acta Horticulturae* **638**: 177–88.

Patel R H, Shroff Jagruti, Dutta Soumyadeep and Meisheri T G. 2005. Weed dynamics as influenced by soil solarization - a review. *Agricicultural Reviews* **26**(4): 295–300.

Peachey R E, Pinkerton J N, Ivors K L, Miller M L and Moore L W. 2001. Effect of soil solarization, cover crops and methane on field emergence and survival of buried annual bluegrass (*Poa annua*). *Weed Technology* **15**: 81–8.

Pokharel Ramesh. 2011. Soil solarization: an alternative to soil fumigants. Western Colorado Research Center, Colorado State University, p 12.

Rai R P. 2003. Raising potato crop through micro-tubers: Some recommendations. Souvenir and Abstract in Conference on Processing and Export Potential within Asia, Modipuram, Meerut, India, pp 57–8.

Rubin B and Benjamin A. 1984. Solar heating of the soil: involvement of environmental factors in the weed control process. *Weed Science* **32**: 138–42.

Seman-Varner R, McSorley R and Gallaher R N. 2008. Soil nutrient and plant responses to solarization in an agroecosystem utilizing an organic nutrient source. *Renewable Agriculture and Food Systems* **23**: 149–54.

Sharma Jyotsana and Arora R K. 2005. Efficiency of soil solarization in reducing tuber russet and improving yield of different potato cultivars. *Potato Journal* **32**(3-4): 185–6.

Sharma Jyotsana and Singh R K. 2003. Effect of soil solarization on fertilization, yield and tuber health of potato. *Journal of Indian Potato Association* **30**: 105–6.

Sieverding E. 1991.Vesicular-arbuscular mycorrhiza management in tropical agrosystems. GTZ, FRG, p 281.

Singh R K, Sharma Jyotsana, Jha S K and Singh A K. 2012. Solarization technique: its use in the multiplication of *in vitro* planting materials. *Current Science* **102**(10): 1433–4.

Singh R K, Sharma Jyotsana, Singh G K and Trehan S P. 2009. Effect of soil solarization on multiplication of *in-vitro* planting materials of potato under field conditions. *Potato Journal* **36**(3-4): 143–8.

Singh R K, Jyotsana Sharma and Sarjeet Singh. 2004. Effect of soil solarization and organic mulch on quality and quantity of mini-tubers in nucleus seed potato production. *Proceedings of National Symposium on Organic farming in Horticulture for Sustainable Production*, CISH, Lucknow, India, pp 218-20.

Smith E M. 1964. Proc. National Agrlc. Plastic Conl. 5: 90–2.

Sofi T A, Tewari A K, Razdan V K and Koul V K. 2014. Long term effect of soil solarization on soil properties and cauliflower vigor. *Phytoparasitica* **42**: 1–11.

Stapleton J J and Devay J E. 1986. Soil solarization: a non-chemical approach for the management of plant pathogens and pests. *Crop Protection* **3**: 190–8.

Stapleton J J. 2000a. Developing alternative heat treatments for disinfestation of soil and planting media. International Plant Propagators' Society. Combined Proceedings of Annual Meetings **50**: 561–3.

Stapleton J J, Parther T S, Mallek S B, Ruiz T S and Elmore C L. 2002. High temperature solarization for production of weed-free container soils and potting mixes. *Hort Technology* **12**: 697–700.

Triki M A, Priou Sylvie and Mahjoub M E L. 2001. Effects of soil solarization on soil-borne populations of Pythiumaphanidermatum and Fusariumsolani and on the potato crop in Tunisia. *Potato Research* **44**: 271–9.

Yaduraju N T. 1993. The role of solarization on weed management. (*In*) *Proceedings of International Symposium,* held during 18-20 November 1993 at Hisar, Indian Society of Weed Science, New Delhi.

Yao Yanlai, Zhu Fengxiang, Pan Zaifa, Hong Chunlai, Wang Weiping, Chen Xiaoyang and Xue, Zhiyong. 2016. Efficiency of different solarization-based ecological soil treatments on the control of Fusarium wilt and their impacts on the soil microbial community. *Applied Soil Ecology* **108**: 341–51.