

CHAPTER 1

INTRODUCTION

Soil borne pathogens and weeds cause severe damage to most agricultural crops and reduce both yield and quality. High losses often force a change to less profitable crops or abandonment of the affected area. This happens especially in regions where a few crops are planted frequently in the same soil. Thus, development of effective and economic methods to control diseases and weeds is necessary to assure consistently high and profitable yields.

Biological, chemical and physical methods have been used before planting to reduce inoculum density or inoculum potential of pathogens in the soil. Currently, soil disinfection is mainly accomplished through such drastic means as chemical fumigation. Fumigation with methyl bromide though effective and commonly used in most parts of the world in some crops, depletes the ozone layer, is toxic, expensive and hence restricted to certain crops and seasons (Katan, Greenberger, Alon and Grinstein, 1976). Alternative methods such as the soil solarization technology have developed fairly rapidly during the past two decades, and the results achieved so far appear promising, and the technology has moved from the experimental stage to commercial application (Stapleton, 1991).

Soil solarization is a term used to describe hydrothermal soil heating which occurs in moist soil covered with clear polyethylene sheeting during the summer months. With solarization, soil temperatures are achieved which are lethal to many plant pathogens and pests (Stapleton and DeVay, 1984). The process also results in a complex of changes, which alter the biological, physical and chemical properties of the soil that improve the growth and development of plants (DeVay, 1991a). Mashingaidze and Chivinge, 1998 described solarization as the enhancement or catchment of solar or sun's radiant energy to heat up the soil to kill the weed seeds and or seedlings, plant pests and disease propagules. It is achieved by covering soil under clear or black plastic film during the hot dry season, which raises soil temperatures to levels, which are lethal or injurious to many plant pathogens, pests and weeds.

The plastic mulch restricts the escape of gases and water vapour from the soil and these changes in the gas environment weaken the pathogens and only thermotolerant soil borne pathogens may survive the altered conditions (Ben-Yephet, Stapleton, Wakeman and DeVay, 1987). Changes in the gaseous environment have an effect on the composition of soilborne pathogen populations, which may exert a form of biological control when undesirable soilborne pathogens are out competed by desirable soilborne pathogens (Brock, 1978). The effectiveness of soil solarization in disinfecting soil is directly related to moisture, wavelength transmittance and thickness of plastic covering sheets, intensity of irradiance, day length, air temperature and soil preparation prior to the covering with the plastic sheets (DeVay, 1995). During solarization, temperature maxima of soil increase with increasing moisture content.

For best results, the soil should be about 70% of field capacity in the upper zones and moist to a depth of at least 60 cm (DeVay, 1995).

Soil solarization was studied in this research project, for controlling soilborne pathogens due to the many advantages that have been associated with this method. It is a non-chemical method, thus environmentally friendly and does not result in chemical pollution of water and other resources. Plastic mulching is relatively cheap, safe, and does not result in phytotoxicity or leave pesticide residues on the plant or soil, neither does it require sophisticated machines for its application. It can be carried out either mechanically on a large scale, or by hand in small plots. It is selective in its effects on populations of soil microorganisms because the high temperatures generated kill the mesophiles, which are mainly pathogenic, while leaving the beneficial microorganisms, which are thermostable. The process also improves the tilth and nutrient status of soil (Stapleton and DeVay, 1986).

The method has also been shown to improve soil fertility and remove accumulated salts owing to decomposition of organic amendments and temporary submerging of the soil respectively. The availability of many mineral nutrients is increased following the solarization process, particularly those tied up in organic fraction such as $\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$, Ca and Mg. The nutrients may provide the equivalent of a pre-plant fertilizer dosage (Katan, 1980). The liberation of NH_3 , CO_2 and other volatiles may play a role in the soil disinfection process. Solarization controls soilborne pests including fungi and bacteria, annual and perennial weeds and nematodes (Egley, 1983; Rubin and

Benjamin, 1984; Ham, Kluteinberg and Lamont, 1983; Katan, 1980). It thus provides a valuable alternative to chemical fumigation of the soil.

However, soil solarization has its own limitations, for example, its effectiveness is weather dependent. The process is influenced by weather parameters such as prevailing temperature, intensity and length of exposure to sunlight, as well as aspects of the field (DeVay, 1991; Katan, 1987). Soil solarization can only be effectively employed in areas with warm temperatures, that allows a build up of heating levels under the plastic that are lethal to microorganisms and weed seeds is achieved. In Zimbabwe, it means solarization is best done during the hot dry months of (August to November) to take advantage of the hottest part of the season. The technology is less effective in a field with poor water retention since the process requires high soil moisture content (DeVay *et al.*, 1990). The process takes 4 to 8 weeks whereas most growers prefer short-term methods for disinfecting the soil such as soil fumigation. This negative aspect may affect its adoption by farmers when they compare it to quick acting chemical fumigants.

1.1 Justification

Methyl bromide is the chemical, which has been widely used for soil fumigation in intensive agriculture and for stored grain commodities and post-harvest quarantine treatments. However, the Montreal Protocol (1992) has listed it as a controlled ozone-depleting substance and hence a phase-out process has been initiated. As a result, several technologies to substitute methyl bromide in the soil disinfections are being

tested in field trials to assess their suitability for commercial application. Such technologies under investigation include solarization, disease suppressive compost, steam and hot water disinfection, hydroponics and soil-less substrates (DeVay, 1995). Of these, soil solarization has emerged as a promising and effective substitute to the prevailing extensive use of soil fumigants (Lamberti and Greco, 1991). As the international phase-out date for methyl bromide of 2015 approaches, efforts to find an effective and environmentally friendly alternative to methyl bromide has intensified.

Given the imminent ban on use of methyl bromide and the non-availability of suitable substitutes, solarization is now the subject of greater research scrutiny in Zimbabwe (Mashingaidze and Chivinge, 1998). As a signatory of the Montreal Protocol, signed in Canada in 1987, Zimbabwe is obliged to stop the use of general purpose fumigants like ethyl dibromide (EDB) and methyl bromide which have been identified as ozone-depleting substances by the year 2015, except for critical uses (Methyl Bromide Fact Sheet, 1999)

The aim of this study was to assess the effectiveness of clear and black plastic mulch in controlling of soil borne pathogens and weeds in comparison with soil fumigation using methyl bromide.

1.2 Objectives

The objectives of this study were:

- To assess the effects of clear and black plastic in controlling soil borne pathogens and weeds.
- To determine the residual effect of solarization using plastic mulches on growth and yield of field beans (*Phaseolus vulgaris*).

1.3 Hypotheses

- Clear plastic mulch is more effective than black plastic mulch in controlling soil borne pathogens and weeds.
- Solarization increases bean growth and yield while at the same time reducing weed density and biomass on beans.

CHAPTER 2

LITERATURE REVIEW

2.1 Historical review

Mulching of soil for improved plant growth has been done since ancient time and various materials have been used (Stapleton and DeVay, 1986). It was from the 1970s, that research on the use of solar heating of moist soil under plastic films for controlling plant pathogenic organisms was intensified. Greenhouse applications were pioneered by the Kodama and Horiuchi in Japan (Horiuchi, 1991) while Katan and DeVay and their coworkers (1976) in Israel and California developed field applications.

Soil solarization is a mulching process that has its origin in early agriculture, where covering soil and plants with organic and inorganic materials formed a protective barrier against frost or warmed soil to increase plant growth. Mulching was also used to limit soil water evaporation, control weeds, improve soil tilth and manage soil erosion. Geraldson *et al.*, (1965) observed that black polyethylene (PE) film reduced southern blight of tomato and dwarf bean caused by *Sclerotium rolfsii*. Hilborn *et al.*, (1957) also reported reduction in lettuce head drop caused by *Rhizoctonia solani* and bacteria in solarized soils. Soil solarization was first used to disinfect soils against pathogens and weeds before planting time.

It was only recently discovered that mulching, which is widely used for warming soils during the cold months for early planting could be used to disinfect soils. Stapleton and DeVay, (1986) reported that covering moist soil with a plastic film during the warm summer months for an extended period, such as one month, was lethal to most plant pathogens and pests, and resulted in changes in the physical, biological and chemical composition of the soil. The changes included improved tilth, reduced salinity, and increased availability of mineral nutrients and increased populations of beneficial microorganisms. These changes contributed to the increased growth and yield responses of crop plants associated with soil solarization.

2.2 Principle of solarization

The mechanism of soil solarization in reducing soil borne pathogens and pests is attributed to the greenhouse effect, elimination of evaporation from the soil and other mechanisms (Katan, 1980). DeVay (1995) highlighted that the duration of soil solarization is important since the effectiveness of the technology is time and temperature dependent. Stapleton (1991) reported that many soil-borne pathogens and weeds were adequately controlled by 4 – 8 weeks of solarization at temperatures above 40°C.

The greenhouse effect is produced by the difference in permeability of two categories of radiation: solar and terrestrial radiation. To produce maximum greenhouse effect and to act effectively as a suntrap, the ideal material should be transparent to solar radiation (280 to 2500nm) but completely opaque to terrestrial radiation (5 000 to 35

000nm). Polyethylene mulch reduces heat convection and water evaporation from the soil to the atmosphere as a result of the formation of water droplets on the inner surface which reduces its transmissivity to long wave radiation, resulting in better heating of the soil (Brown, Katan and Egley, 1991).

The success of soil solarization is based on the fact that most plant pathogens and pests are mesophylic, that is, they are most active at temperatures less than 31⁰C and are unable to grow at temperatures above 31⁰C to 32⁰C (Massoori and Juliani 1996). They are killed directly or indirectly by the temperatures achieved during the solar heating of moist soil under plastic films, which greatly restricts the escape of gases and water vapour from the soil (DeVay, 1995). Thermotolerant and thermophylic soilborne microorganisms usually survive the soil solarization process (DeVay, 1991a). However, all soil borne organisms, not directly inactivated by heat, may be weakened and become vulnerable to changes in the gaseous environment in solarized soil or to changes in the populations of other organisms, which may to an extent be a form of biological control (DeVay *et al.*, 1990).

2.3 Elements Influencing Effectiveness of Soil Solarization

The thermal decline of soil borne organisms during solarization is affected by the soil temperature reached and exposure time to the process. The effectiveness of soil disinfection as a result of solarization depends on soil colour and structure, air temperature, soil moisture, length of day, intensity of sunlight and the thickness and

light transmittance of the plastic film (DeVay *et al.*, 1990; Gutkowski and Terranova, 1991).

2.4 Plastic type

Various types of plastic films have been used with success for soil solarization including polyethylene (PE), polyvinyl chloride (PVC) and ethylene vinyl acetate. Translucent PE is a petrochemical substance and is suitable for soil solarization because it is transparent to most solar radiation of 280 to 2500nm (DeVay, 1995). Additionally, PE films are flexible and have high tensile strength and resist puncturing and tearing.

Elmore (1991) reported that opaque black polyethylene, about 0.04 to 0.06 mm in thickness, prevents sunlight from reaching the weeds, so it is effective in weed control. Black plastic mulches have also been reported to cause an increase in soil temperature by 2⁰C to 3⁰C near the soil surface, when compared to the bare soil because it absorbs the heat. Clear polyethylene on the other hand causes increases of as much as 8⁰C. According to Mashingaidze and Chivinge (1998) clear or translucent plastic was generally the best for solarization.

Mashingaidze *et al.*, (1996) observed that clear plastic treatment had higher soil temperatures than the black plastic treatment. The clear plastic allows light transmission to the soil surface and causes germination of most weed species when moisture is available. Clear plastics build up higher temperatures during the day

because they permit transmission of short wave incoming radiation to the soil surface where it is absorbed and converted to heat. However, they are as effective as coloured plastic mulches, in trapping outgoing long wave radiation at night. They reduce heat convection and water evaporation from the soil to the atmosphere. The formation of water droplets by condensation on the inner surface of the plastic film and the reduction of thermal radiation result in an increase in air and soil temperatures. The top layer of the soil dries out to a very shallow depth and most important the capillary rise of water is accelerated (Katan, 1980; Chen and Katan, 1980; Mashingaidze and Chivinge, 1998; Brown *et al.*, 1991).

Black plastic on the other hand does not transmit incoming short wave radiation through the soil surface, but absorbs it and converts it to sensible heat, causing the plastic surface to heat up (Mashingaidze *et al.*, 1996; Mashingaidze and Chivinge, 1998). Any seedling, which emerges under the black plastic will etiolate because of lack of light and eventually die. Black plastic mulch can control young annual weeds or even many perennial weeds if the mulch remains for a long enough period (Elmore, 1991; Mashingaidze *et al.*, 1996). Stapleton (1991) reported that a 4 – 8 week solarization period is adequate for annual and perennial weed control. DeVay *et al.* (1990) noted that, black PE containing carbon black, absorbs solar radiation and thus reduces the heating of soil by several degrees.

2.5 Soil moisture

Soil moisture is a critical factor in soil solarization because the transfer of heat to weeds and soil borne plant pathogens in the soil is greatly increased by moisture (DeVay, 1991a). Since soil solarization is a hydrothermal process, its success depends on moisture for maximum heat transfer. Moreover, the temperature maxima of soils increase with increasing soil moisture (Mahrer, Naot, Rawitz and Katan, 1984). Cellular activities of seeds and the growth of soil borne microorganisms are favoured by soil moisture, making them more vulnerable to the lethal effects of high soil temperature associated with soil solarization.

2.6 Soil Temperature

Soil temperature is the most important variable in the process of soil solarization. For mesophylic organisms a temperature threshold of about 37⁰C is critical. The accumulation of heat effects at this or higher temperatures over time is lethal. With increasing temperature, less time is required to reach a lethal combination of time and temperature. During solarization, soil temperatures are achieved which are lethal to many plant pathogens and pests and also cause complex changes in the biological, physical and chemical properties of the soil that improve the growth and development of plants (DeVay *et al.*, 1990).

The sensitivity of organisms to high temperature is related to small differences in macromolecules, which lead to increase in intramolecular bonding involving slight changes in hydrogen bonds, ionic bonds, and disulphide bonds. Organisms sensitive to

high soil temperatures, which occur during solarization, have a greater amount of unsaturated cellular lipids than thermotolerant or thermophylic organisms. Thus, mesophilic organisms, which do not survive the high temperatures in solarized soil, have lower melting fatty acid in their membrane lipids and lower phase transition temperatures for the lipids (DeVay *et al.*, 1990).

The majority of target pathogens and pests, which have been studied in solarized soil, have been most adequately controlled in the upper 10 – 30 cm of soil. This is due to the fact that temperature of solarized soil is highest near the soil surface and becomes cooler with increasing depth.

Conway and Pickett (1999) reported temperatures ranging from 37⁰C to 53⁰C under plastic mulch at depths of 2.5 cm, in research plots. Depending on soil depth, maximum temperatures of solarized soil in the field are commonly between 42⁰C to 55⁰C at the 2.5 cm depth and range from 32⁰C to 36⁰C at greater depths (DeVay, 1991b). Mashingaidze *et al.*, (1996) using loosely stretched plastic mulch found consistently higher soil temperatures at 2 cm depth under the clear plastic than the black plastic, at 0800 and 1400 hours in the cold dry season (June to August), but the temperatures generated were not high enough to affect viability of weed seeds resident in the soil layers near the surface. Results obtained in this research suggested that solarization could be an effective method of sanitizing the soil of weed seeds, disease and pest propagules, if the plastic mulches are laid on the soil surface for the duration of the hot dry part of the season, from September to early November.

Studies carried out by Jacobson *et al.*, (1980) showed that in all cases soil temperatures in plastic mulched plots were higher than in the non-mulched ones. On extremely hot days, soil temperatures in the top layer of the clear plastic mulched plots reached 56⁰C. Masoori and Jaliani (1996) reported maximum average soil temperatures of 31⁰C and 44⁰C on non-solarized and solarized soil respectively. Temperatures commonly reached under normal conditions of soil solarization during the hot months of the year are 35⁰C and 60⁰C depending on soil depth, but soil temperatures decrease with increasing soil depth (DeVay, 1995).

Generally, soil temperatures under transparent plastic films rise by several degrees during the day. This temperature rise can vary from 2⁰C to 10⁰C depending on the season, soil type, the level of sunshine and moisture. At night, the difference in temperature between plastic covered and bare soil is less (between 2⁰C and 4⁰C). Under black film, the soil temperature at night may be 10⁰C to 15⁰C higher than the bare soil, while in some instances it can be slightly lower than bare soil.

2.7 Effect of Temperature on Soil Moisture

Soil solarization is a dynamic process, which involves a diurnal heating and cooling of soil layers. During daylight, the upper layer of solarized soil increases in temperature while at night, this soil layer tends to cool. A gradual movement of soil moisture occurs with the changes in soil temperature. At night, moisture moves upward as the soil cools while during the sunlight hours the temperatures of the upper soil layer

increases and the moisture moves deeper into the soil (DeVay, 1995). As heat penetrates to greater depths in the soil, the movement of moisture becomes more pronounced, changing the distribution of salts and improving the tilth of the soil (DeVay *et al.*, 1990).

2.8 Weed Control

Abu-Irmaileh (1991) reported that not all weeds were controlled with solarization. Some weed species were completely controlled and some weed species seemed to be enhanced by the solarization process. The heating effect of solarization diminishes with soil depth. Solar heating mostly affects the top layer, where heat sensitive imbibed weed seeds would be affected.

Elmore (1991) described soil solarization for weed control as being both visually dramatic and highly effective when properly conducted. Egley (1983) and Abu-Irmaileh (1991) reported that weed control responses varied. Annual weeds have been effectively controlled by soil solarization with clear polyethylene (CPE) or black polyethylene (BPE) mulches. Abu-Irmaileh (1991) obtained a 90% reduction in total weed emergence while Egley (1983) noted a 77% reduction in total weed emergence. Elmore (1991) reported that *Cyperus esculentus* (yellow nutsedge) was reduced by approximately 40%. Soil solarization by CPE mulch up to 6 weeks reduced weed emergence. Weed seeds were killed faster in plots solarized with CPE than those solarized with BPE mulches. Dormant weed seeds and seeds buried at deeper layers escaped the solarization effect. The number of weed seeds killed and the depth to

which they were killed varied with the species and the solarization period. The solarization process effectively controlled various annual weeds. However, perennial weeds and several annuals were only partially controlled (Rubin and Benjamin, 1984). Research by Chauhan *et al.*, (1988) showed that most annual and perennial weeds were effectively controlled, including species of the following genera: *Amaranthus*, *Eleusine* and *Portulaca*. DeVay *et al.* (1990) reported the difficulty of controlling *Portulaca* and *Cyperus esculentus* using soil solarization.

2.9 Control of Soil Borne Pathogens

Thermotolerant and thermophilic soil borne microorganisms usually survive the soil solarization process. Lethal effects of solarization are most pronounced on mesophiles, which are not good soil competitors. Many plant pathogens fall into this group, since they tend to have specialized physiological requirements, which are more adapted to coexistence with the host plant (Stapleton, 1991). However, all soil borne pathogens, if not directly inactivated by heat may be weakened and become vulnerable to changes in the gas environment in solarizing soil or to changes in the populations of other organisms, which may exert a form of biological control. The changes in the populations of soil borne micro-organisms constitutes the basis for biological control of plant pathogens and in some cases the development of disease suppressive soils (DeVay, 1991b).

The technique of soil solarization can be combined with other methods of biological control. According to Davis (1991) the use of *Trichoderma harzianum* with

solarization in fields infested with *Rhizoctonia solani* improves disease control while delaying the build up of the inoculum. He also reported that solarized soils are frequently more suppressive and less conducive to certain soil borne pathogens than non-solarized soils. Work done by Stapleton and DeVay (1991) also showed an increase in populations of green fluorescent *Pseudomonads*, along with an increase of *Penicillium* and *Aspergillus* species following solarization. Sclerotia of *Sclerotinia minor* were found to be more heavily colonized by bacteria and fungi in solarized soils than in the non-solarized soils. With solarization, the prevalence of *Fusarium* and *Trichoderma* species was also found to increase. There has been a shift in populations with solarization from a pathogenic *Fusarium* (*Fusarium oxysporum* f.sp. *niveum*) to higher populations of saprophytic *Fusarium* spp, suggesting the possibility for increased pathogen-saprophyte competition with solarization (Davis, 1991). The suppressiveness in solarized soil may result from a shift in microbial populations in favour of heat-resistant antagonists (Davis, 1991). DeVay (1991b) noted that some strains of *Bacillus* species are rhizosphere competent and either through aggressive growth or the production of antibiotics, they appear to be major contributors to the disease suppressiveness of soils after solarization.

According to Stapleton (1991) many plant pathogens are adequately controlled by 4 to 8 weeks of solarization. Solarization may also control pathogens which may be deleterious to plant health and growth. At 5cm depth, population reduction of the pathogens was 94 to 100% (DeVay, 1991b). Davis (1991) achieved reductions of *V.*

dahliae populations from 9.7 to 0.3 colony forming units (cfu) g⁻¹ of soil, at the 15 cm soil depth, while *Pratylenchus* sp was reduced from 29 to 9 nematodes/250cm³.

Stapleton (1991) reported that sub-lethal doses of heat may also adversely affect populations of soil borne pathogens and pests. Weakening of propagules may result in effects such as reduced or delayed germination or egg hatching, reduction of growth, vigour or infectibility, increased susceptibility to attack by hyperparasites or predators (biological control). Pathogenic fungi including *Macrophomina phaseolina*, and some *Pythium* and *Fusarium* spp, as well as certain nematode and weed taxa are reported to be resistant to the sub lethal heat treatment. Soil borne propagules of fungi that are subjected to sub lethal heat effects during solarization appear to have an increased sensitivity to antagonistic fungi and to bacteria which are less affected by soil solarization (DeVay, 1991b; Katan *et al.*, 1983). Sub lethal temperatures may also cause delays in germination of propagules and reduced virulence in the host plants, that vary with temperature and the duration of exposure to soil solarization (DeVay, 1991b).

During soil solarization, propagules of *Pseudomonads* and the gram positive bacteria, including *Bacillus* species are among the micro-organisms which survive the solarization process and contribute to the disease suppressiveness of soil, whereas *Trichoderma* species and *Talaromyces flavus* are representative of the main fungal antagonists which inhibit the development of pathogenic fungi and they are reduced by solarization (DeVay, 1991b).

CHAPTER 3

MATERIALS AND METHODS

3.0 Field experiment

The field experiment was carried out at the University of Zimbabwe (UZ) campus in Harare, from October 2003 to April 2004. The land was ploughed to a depth of about 30 cm using a tractor drawn disc plough, followed by disc harrowing to bring the soil to a fine tilth as well as to destroy emerged weeds.

The experiment was laid out as a Randomized Complete Block Design (RCBD) with four treatments replicated four times. The treatments were as follows: -

1. Clear plastic
2. Black plastic
3. Methyl bromide fumigation
4. No treatment

The gross plots measured 1.8 m x 11 m and the net plots were 0.6 m x 9 m. The trial plots were marked and the treatments were randomly assigned to the plots in each replication. Twenty centimetre deep trenches were dug around the plots to be fumigated and those to be covered by plastic mulch treatment.

Three soil samples were collected from each plot from the surface to a depth of 5 cm. A 30 cm x 30 cm quadrant was randomly thrown in each block three times and the soil samples were collected from the quadrant using a gardening trowel. A total of about

1 500 g of soil was collected from each block, thoroughly mixed, and one gram from the composite sample was reserved for bacterial and fungal analysis, 500 g was used for nutrient analysis and the rest of the sample was placed in 50 cm x 38 cm x 8 cm (length, width, height) asbestos trays. The asbestos trays were placed in the greenhouse for assessment of weed emergence from untreated soil at the beginning of the experiment.

The experimental area was irrigated for eight hours; applying 4 mm of water per hour to bring the first 60 cm of the soil to field capacity and the plots with plastic mulching treatments were covered immediately. The plastic sheets were tightly stretched over the plots and the edges were securely buried in the trenches dug around each of the mulched plots. Soil samples were collected at the end of each second week during the 8-week solarization period. The edges of the turned plastic were exhumed and the plastic covers rolled back and soil samples collected from three randomly thrown quadrants as previously described. Immediately after that, the plastic covers were restored as previously described. The soil samples collected fortnightly were used for assessment of weed emergence, bacterial and fungal analysis. Weed seedlings germinating under the various treatments were also identified and recorded.

The plots to be fumigated with methyl bromide were covered as described above and methyl bromide was applied under the plastics using applicators forty-eight hours after covering the soil with plastic mulches. The methyl bromide was applied at the rate of

30 g m⁻². The fumigated plots were uncovered three days after application of the chemical.

3.1 Measurements

3.1.1 Temperature

Daily minimum and maximum soil temperatures were measured at 0800 and 1400 hours respectively using a thermocouple probe Model T500K, K type (Chromel-Alumel). The tip of the thermocouple probe was inserted through tiny holes in the plastic mulch to a depth of 5 cm and the temperature was read after a three minutes period that allowed the temperature reading to stabilize.

3.1.2 Weed emergence from incubated soils

Soil samples collected fortnightly and deposited into asbestos trays were arranged on greenhouse benches in a randomized complete block design, similar to the field layout. Each tray represented a plot in the layout. The greenhouse temperature was maintained at 20/32⁰C day/night temperatures. The trays were kept moist and weeds that emerged from the trays were counted, by species at 3 weeks after the beginning of soil incubation in the greenhouse. Weed counts per species were expressed per m² and the counts were square root transformed before analyses of variance were carried out.

3.1.3 Weed emergence under the plastics

The plastic mulches were uncovered every fortnight and systematic sampling of weeds using a 30 x 30 cm quadrant was done in all plots. The quadrant was randomly thrown at three positions in each plot and the weeds were counted. Weed counts data was square root transformed before analyses of variance.

3.1.4 Weed emergence in the field 5 weeks after crop emergence (5 WACE)

Weeds were counted by species in three randomly thrown 30 cm x 30 cm quadrants per plot at 5 WACE before hoe weeding was done. The weeds were cut at ground level and oven dried at 80°C for 48 hours and then weighed.

3.1.5 Fortnightly bacterial counts from solarized soils

Identification of the dominant soil-borne bacteria was done at pretreatment, as well as at 2, 4, 6 and 8 weeks after solarization. Bacterial analysis was done by suspending 1g of soil in 10 ml of sterile distilled water and then making 10-fold dilutions using sterile pipettes. The Nutrient Agar (NA) was prepared by dissolving 28 g of NA in 1 litre of distilled water and autoclaved at 15 psi for 20 minutes in a Hirayama autoclave. The total population of bacteria in the soil was determined by spreading 1 ml of the desired serial dilutions on a plate of NA, using sterile pipettes in a lamina airflow cabinet and then incubated at 25°C for 48 hours. The bacteria colonies were counted and grouped according to colour, shape and appearance and the colony forming units (cfu) per ml were calculated.

Bacterial cell concentration was determined using a Neubauer counting chamber. A loopful of the bacterial colony was added to 10 ml of sterile distilled water, thoroughly mixed and diluted from 10^{-1} to 10^{-5} . Drops of the diluent were placed on the grid on the Neubauer chamber using dropper pipettes. The counting chamber was placed in a moist chamber to allow the bacteria to settle and prevent them from desiccation. The counting chamber was examined under the microscope after 20 minutes and the number of bacterial cells counted.

The following formula was used for calculating the bacterial cell counts:

$$\text{Cell count} = \frac{N \times DF \times 10^6}{A \times D} \text{ per litre}$$

Where: N is the number of cells

DF the dilution factor

A is the area of the chamber counted

10^6 converts to cells per litre

D is the depth of chamber (e.g. 0.1 mm)

Biochemical tests for bacterial identification were carried out on pure bacterial colonies and these included, Gram staining, KOH test, levan test, Oxidase, spore counts, oxidative/fermentation test and starch hydrolysis test (Seattler 1995; Schaad, 1988; CMI Descriptions 1987). The bacterial colonies were also grown on Casein agar

plus glucose (CAG), Yeast extract-dextrose CaCO₃ (YDC) and King's Broth, which are semi selective media.

3.1.6 Fortnightly fungal counts from solarized soils

The fungi were isolated from the soil sample collected at pretreatment, 2, 4, 6 and 8 weeks after solarization as described for bacteria and cultured on Water Agar (WA) and Potato Dextrose Agar (PDA). The plates were incubated at 25⁰C for 4 days. The fungi were identified according to colour, shape and form of the fruiting bodies and spores. The isolated fungi were also grown on Czapek medium, which is semi selective. Fungal cells were counted using the Neubauer counting chamber as described for bacteria and cell concentration was determined using the same formula as that for bacteria.

3.1.7 Pathogenicity test

The isolated bacteria and fungi were tested for pathogenicity by inoculating plants with 5 x 10⁶ cfu ml⁻¹ of either fungi or bacteria on 10-day-old seedlings of the following crop grown in sterilized soil in pots in the glasshouse:

Garden pea	-	<i>Pisum sativum</i>
Cabbage	-	<i>Brassica oleracea</i> var <i>capitata</i>
Soyabean	-	<i>Glycine max</i>
Cowpea	-	<i>Vigna unguiculata</i>
Bean	-	<i>Phaseolus vulgaris</i>
Cotton	-	<i>Gossypium hirsutum</i>

The bacterial inoculum was injected into the petioles and the leaf veins of the test plants while the fungi isolated were inoculated in sterile soil at the time of transplanting. The inoculated plants were covered with plastic bags in order to produce humid conditions required for symptom development. The control plants were inoculated with the buffer used for diluting the microorganisms. The plants were observed for disease symptoms starting from 7 days after, inoculation and continued weekly for 3 weeks. Thin stem and leaf sections of the inoculated plants were cultured on NA, PDA and WA to determine the bacteria and fungi that grew from the plant sections. The tissue sections were examined under a JENA compound microscope at a magnification of 400X for the presence of the inoculated microbes.

3.1.8 Effect of solarization on plant growth

Beans were planted during the third week of November 2003 on the plots previously covered by the plastic sheets. The plastic mulches and all the weeds were removed. Planting furrows were marked out using a hoe, and they were 0.45 m apart. The bean crop was planted at a spacing of 0.45 x 0.1 m. Compound D (8%N, 14% P₂O₅, 7% K₂O) was applied at planting at a rate of 300 kg ha⁻¹. Ammonium nitrate (34.5% N) was applied 5 WACE at the rate of 250 kg ha⁻¹. All plots were hoe-weeded at 5 weeks after crop emergence (WACE).

3.1.9 Disease assessment

Disease assessment was carried out two weeks after crop emergency and thereafter, every fortnight for 8 weeks. Symptom descriptions were used for identifying the

diseases and the diseased plants were taken to the laboratory for diagnosis. The collected samples were incubated in a moisture chamber for 48 hours and examined under a Wild Heerburg stereomicroscope for pathogen identification. Disease severity for *Fusarium* was recorded using the rating scale below;

- 1 - no evidence of infection
- 2 - slight infection, small lesions covering 5% of stem
- 3 - medium infection, several lesions covering 15% of stem
- 4 - severe infection, covering about 25%
- 5 - very severe infection, more than 30%

The plant with virus symptoms was tested in the laboratory using the Enzyme Linked Immunosorbent Assay (ELISA) technique.

3.1.10 Yield assessment

The bean crop was hand harvested at 13 WACE when both the pods and stems were dry (had turned yellow) from a net plot of 14.9 m². The pods were left to dry and the bean grain moisture determined using a moisture meter. The grain yield was adjusted to 11% moisture content. The grain yield was determined in tonnes ha⁻¹ after shelling of the beans.

3.1.11 Yield components

A random sample of five plants per plot was used to determine the leaf area, fresh weight, dry weight, number of flowers plant⁻¹, number of pods plant⁻¹ and seed number pod⁻¹.

3.2 Data analysis

All weed density and disease severity data were square root transformed before analysis and then analysis of variance (ANOVA) performed for weed density and disease severity scores using a Minitab Version 12 (2001) of Statistical Package. Least significant differences (LSDs) were calculated for all F values that indicated significance at ($P < 0.05$). Means were separated using calculated LSDs of the difference. Standard errors of the difference are shown as error bars on all figures. The disease progress curves were constructed from severity scores and area under the disease progress curve (AUDPC) was calculated for each treatment using trapezoidal integration (Sigma Plot, 2000).

The trapezoidal integration formula used is:

$$\text{Trapezoidal integration} = y_i[(x_{i+1}) - x_i] + (1/2)[(y_{i+1}) - y_i][(x_{i+1}) - x_i]$$

Where x_i = time of scoring

Y_i = severity score

CHAPTER 4

RESULTS

4.1 Soil Temperature

4.1.1 Maximum soil temperature

Maximum soil temperature, measured at 5cm depth, at 1600hrs daily and averaged per week, for the plastic mulch treatments is shown in figure 1. Maximum temperature was consistently higher ($P<0.05$) in the clear plastic covered soil than the black plastic covered soil, the uncovered and fumigated controls, weekly for the 8 week duration of solarization (Figure 1). The only exception was at the first week, when there was no difference in mean weekly maximum soil temperature between the clear plastic covered treatment and the fumigated control. The mean weekly maximum temperature under the black plastic mulch did not significantly differ with the soil temperature attained in the uncovered and fumigated control (Figure 1). Maximum soil temperature ranged from 39°C to 55°C in the first and fourth week respectively under the clear plastic and from 30°C to 43°C in the first and fourth week, respectively under the black plastic mulch. The mean weekly soil temperature ranged from 30°C to 40°C in the first and fourth week respectively in the untreated control treatment and in the fumigated control, soil temperature ranged from 37°C in the fifth week to 41°C in first, fourth, seventh and eighth weeks.

4.1.2 Minimum soil temperature

Minimum soil temperature, measured at 5cm depth, at 0800hrs daily and averaged per week, for the plastic mulch treatments is shown in Figure 2. Minimum temperature was consistently higher ($P<0.05$) in the clear plastic covered soil than the black plastic covered soil, the uncovered soil and the fumigated controls, for the 8 week duration of solarization (Figure 2). The only exception was the first and second weeks when there was no difference ($P<0.05$) in mean weekly minimum soil temperature between the clear plastic covered treatment and the fumigated soil. The mean weekly minimum temperature soil temperature under the black plastic mulch was significantly higher than the soil temperature recorded in the untreated control and the fumigated control (Figure 2). Minimum soil temperature ranged from 26⁰C to 39⁰C in the first and fifth week respectively under the clear plastic and from 24⁰C to 37⁰C in the first and seventh week respectively under the black plastic. The mean weekly soil temperature ranged from 26⁰C to 31⁰C in the first and second week respectively in the fumigated soil control and from 22⁰C to 29⁰C in the first and fifth week respectively in the uncovered control treatment (Figure 2).

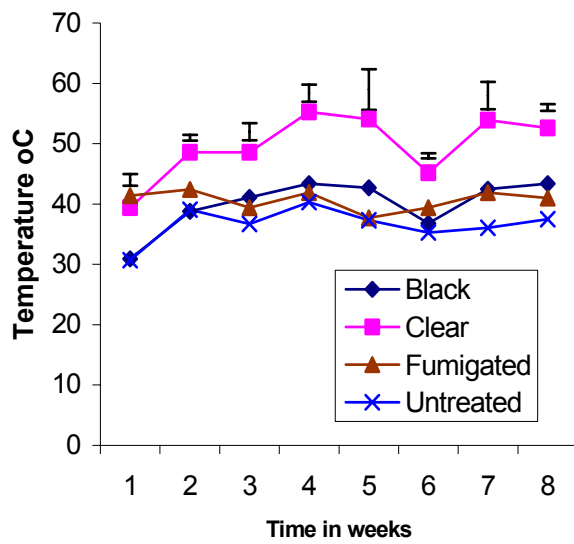


Figure 1: Effect of plastic mulching on maximum soil temperatures

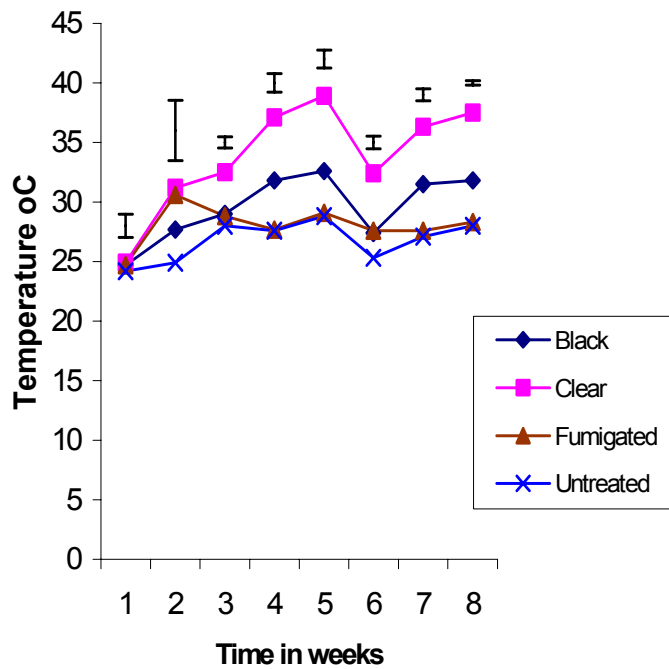


Figure 2: Effect of plastic mulching on minimum soil temperatures

4.2 Weed emergence from soil under the mulching treatments collected.

4.2.1 *Bidens pilosa*

Bidens pilosa density was consistently ($P < 0.05$) higher in the untreated control than in the fumigated control at 2, 4, 6 and 8 weeks after the beginning of solarization. Weed emergence from mulched soil, in the black and clear plastic mulched treatments was half of that achieved in the uncovered control at 2 and 4 weeks after the beginning of solarization (Figure 3).

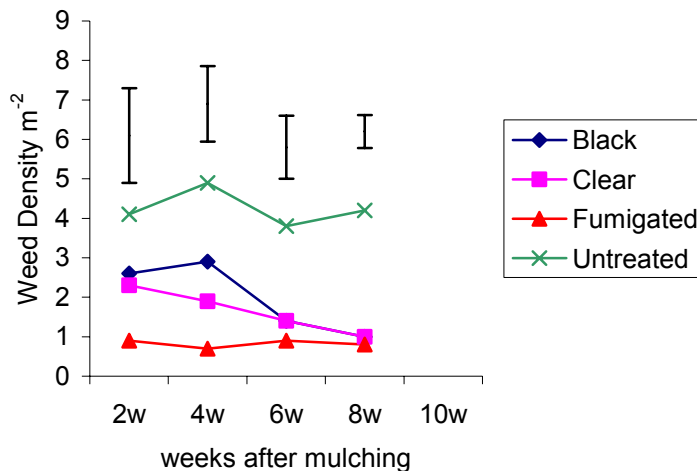


Figure 3: Effect of plastic mulches on emergence (square root transformed data) of *Bidens pilosa* from incubated soil in the greenhouse.

As the period of solarization increased to 6 and 8 weeks, the clear and black plastic mulched treatments reduced *B. pilosa* emergence from incubated soil as much as the fumigated control (Figure 3).

4.2.2 *Galinsoga parviflora*

The most effective treatment to kill *G. parviflora* seed propagules in the soil was the soil fumigation treatment (Figure 4).

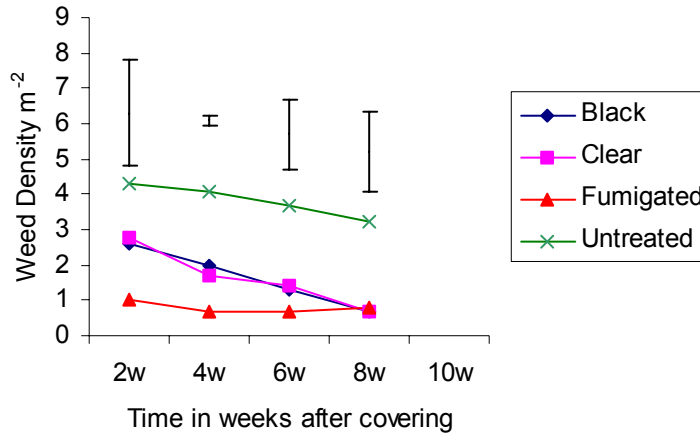


Figure 4: Effect of plastic mulches on emergence (square root transformed data) of *Galinsoga parviflora* from incubated soil in the greenhouse.

However, it is apparent that there was no difference in *G. parviflora* emergence from incubated soil collected from under the plastic treatments and that collected from the fumigated treatment (Figure 4). There was a distinct decrease in viable *G. parviflora* seeds in the soil as the period of solarization increased (Figure 4) and by the eighth week of solarization the plastic mulched soil had similar *G. parviflora* emergence with fumigated soil (Figure 4). The uncovered soil recorded high weed counts throughout the 8 week period.

4.2.3 *Eleusine indica*

Emergence of *Eleusine indica* was consistently ($P < 0.05$) higher in the untreated control than in the fumigated control throughout the 8 week period of solarization.

E. indica emergence was higher ($P=0.00$) in the soils mulched with clear and black plastic mulched than in the fumigated soil (Figure 5).

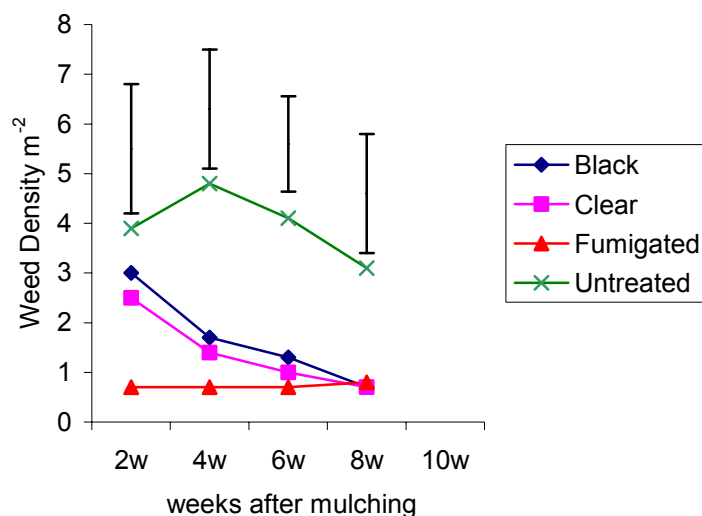


Figure 5: Effect of plastic mulches on emergence (square root transformed data) of *Eleusine indica* from incubated soil in the greenhouse.

There is a distinct decrease in viable *Eleusine indica* seed in the soil covered with black and clear plastic mulches as the solarization period increased (Figure 5). The weed counts in the plastic mulched soil were the same as those recorded in the fumigated soil by the eighth week (Figure 5).

4.2.4 *Oxalis latifolia*

The plastic mulches and fumigation had no effect on the emergence of *Oxalis latifolia* (Figure 6).

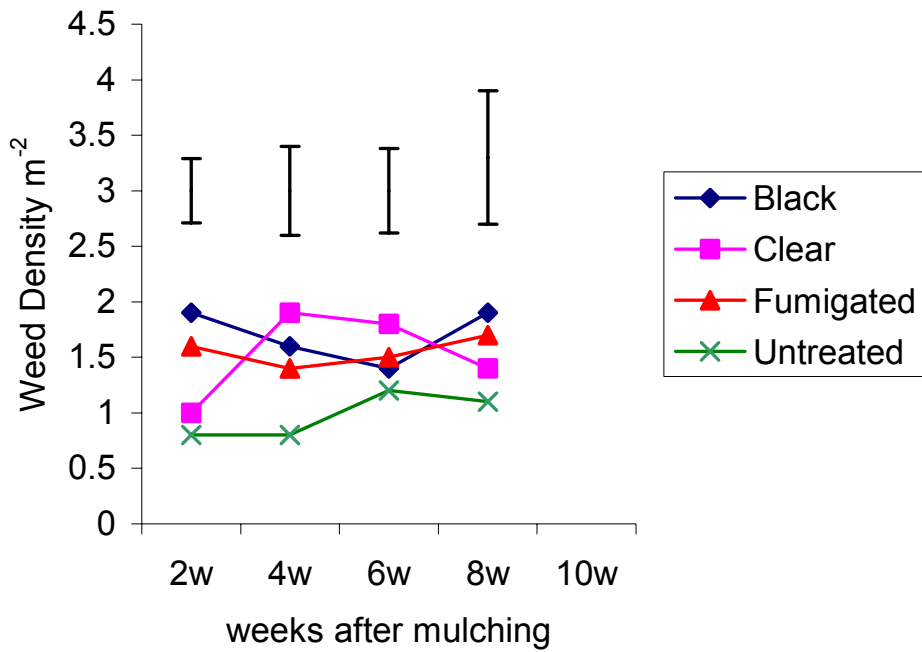


Figure 6: Effect of plastic mulches on emergence (square root transformed data) of *Oxalis latifolia* from incubated soil in the greenhouse.

4.2.5 *Cyperus*

Emergence of *Cyperus* was significantly ($P < 0.05$) lower in the untreated control than in the fumigated control and in the soil mulched with plastics at 2, 4 and 8 weeks (Figure 7). *Cyperus* emergence increased in the fumigated control to double that attained in the untreated control and the in soil covered with plastic mulches (Figure 7).

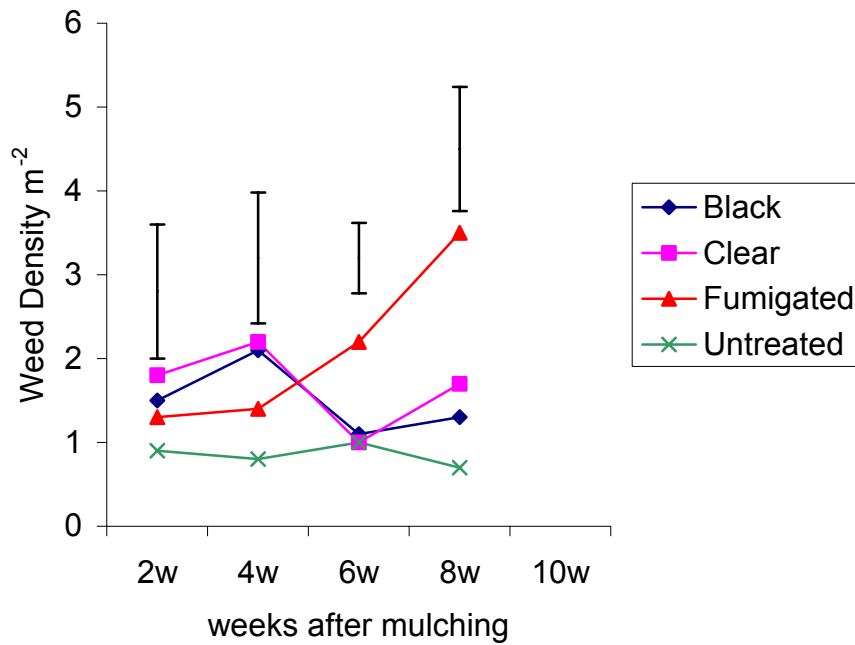


Figure 7: Effect of plastic mulches on emergence (square root transformed data) of *Cyperus* from incubated soil in the greenhouse

There was a distinct increase in viable *Cyperus* seed in the fumigated control in the sixth and eighth weeks of solarization (Figure 7).

4.2.6 The other weed species

Emergence of the other weed species was consistently higher ($P < 0.05$) in the untreated control than in the fumigated control and in the soil covered with plastic mulches at 2, 4, 6 and 8 weeks of solarization (Figure 8). Fumigation and the plastic mulches significantly reduced the weed emergence at 8 weeks when compared to the uncovered control (Figure 8).

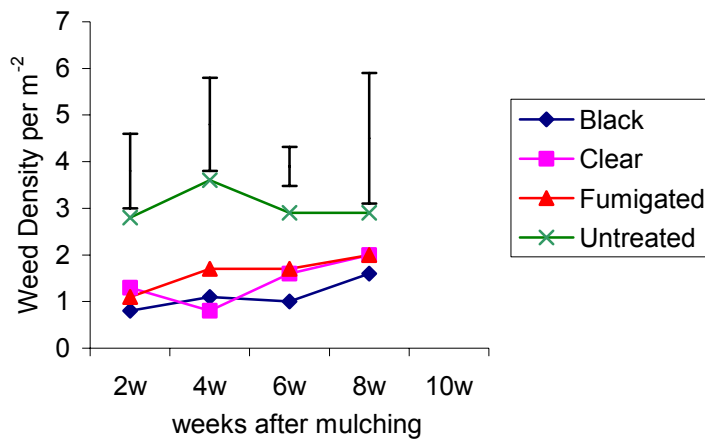


Figure 8: Effect of plastic mulches on emergence (square root transformed data) of other weed species from incubated soil in the greenhouse

4.2.7 All weed species counts

Emergence of total weeds was consistently higher ($P < 0.05$) in the untreated control than in the fumigated control and in the soil covered with black and clear plastic mulches at 2, 4, 6 and 8 weeks of solarization. Fumigation was the most effective control that killed most of the weeds at 2 and 4 weeks (Figure 9). The weed counts in the soil covered with black and clear plastic mulches decreased steadily at 2 and 4 weeks, reaching the same level as the fumigated control at 6 weeks.

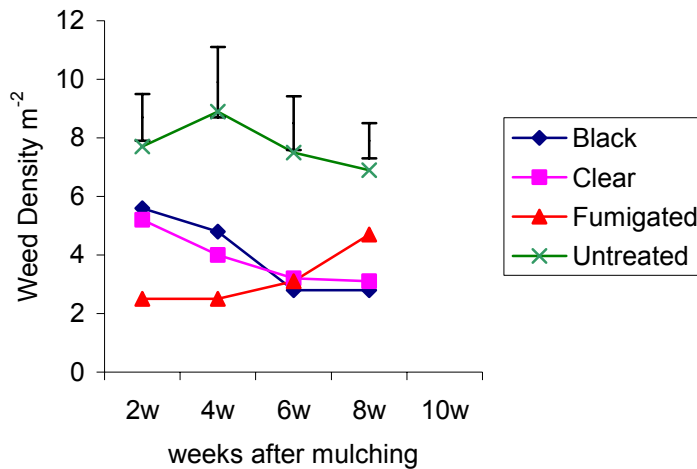


Figure 9: Effect of plastic mulches on emergence (square root transformed data) of all weed species from incubated soil in the greenhouse

Weed emergence of all weed species increased in the fumigation control at 8 weeks after solarization (Figure 9).

4.3 Weed emergence under the plastic mulches

4.3.1 *Bidens pilosa*

Mulching had significantly lower ($P < 0.05$) weed density compared to uncovered plots. The weeds did not survive the minimum solarization period of two weeks. No *Bidens* seedlings were observed in the fumigated control and under both clear and black plastic mulches (Table 1).

Table 1: Mean density per m² of *Bidens pilosa* survival (square root transformed) under the plastic mulches at the various treatment times.

Treatment	Treatments Periods			
	2wks	4wks	6wks	8wks
Black	0.7(0) ¹	0.7(0)	0.7(0)	0.7(0)
Clear	0.7(0)	0.7(0)	0.7(0)	0.7(0)
Fumigated	0.7(0)	0.7(0)	0.7(0)	0.7(0)
Untreated	4.9(24)	4.4(19)	4.6(21)	1.9(3)
P value	0.00	0.00	0.00	0.00
SED	0.58	0.19	0.19	0.45
LSD _{0.05}	1.31	0.43	0.43	1.02

¹ Figures in brackets are untransformed weed density data (number m⁻²)

4.3.2 *Galinsoga parviflora*

Fumigation and plastic mulches had virtually no weed and the differences with the uncovered treatment were significant (P<0.05) in controlling *G. parviflora* (Table 2).

Table 2: Mean weed density per m² of *Galinsoga parviflora* survival (square root transformed) under the plastic mulches at the various treatment times.

Treatments	Treatment Periods			
	2wks	4wks	6wks	8wks
Black	0.7(0) ¹	0.7(0)	0.7(0)	0.7(0)
Clear	0.7(0)	0.7(0)	0.7(0)	0.7(0)
Fumigated	0.7(0)	0.7(0)	0.7(0)	0.7(0)
Untreated	5.5(30)	4.9(24)	5.4(29)	6.6(43)
P value	0.00	0.00	0.00	0.00
SED	0.32	0.04	0.08	0.12
LSD _{0.05}	0.72	0.09	0.17	0.30

¹ Figures in brackets are untransformed weed density data (number m⁻²).

4.3.3 *Eleusine indica*

Fumigation and plastic mulches had virtually no weeds and the differences with the uncovered treatment were significant ($P < 0.05$) in controlling *E. indica* (Table 3).

Table 3: Mean density per m² of *Elusine indica* survival (square root transformed) under the plastic mulches at the various treatment times.

Treatments	Treatment Periods			
	2wks	4wks	6wks	8wks
Black	0.7(0) ¹	0.7(0)	0.7(0)	0.7(0)
Clear	0.7(0)	0.7(0)	0.7(0)	0.7(0)
Fumigated	0.7(0)	0.7(0)	0.7(0)	0.7(0)
Untreated	5.5(30)	5.4(29)	5.8(33)	5.9(34)
P value	0.00	0.00	0.00	0.00
SED	0.30	0.24	0.53	0.15
LSD _{0.05}	0.69	0.54	1.20	0.33

¹ Figures in brackets are untransformed weed density data (number m⁻²)

4.3.4 *Oxalis latifolia*

Oxalis latifolia was not controlled by the plastic mulches (Figure 10). Weed emergence significantly increased ($P < 0.05$) in the fumigated soil at 8 weeks after solarization.

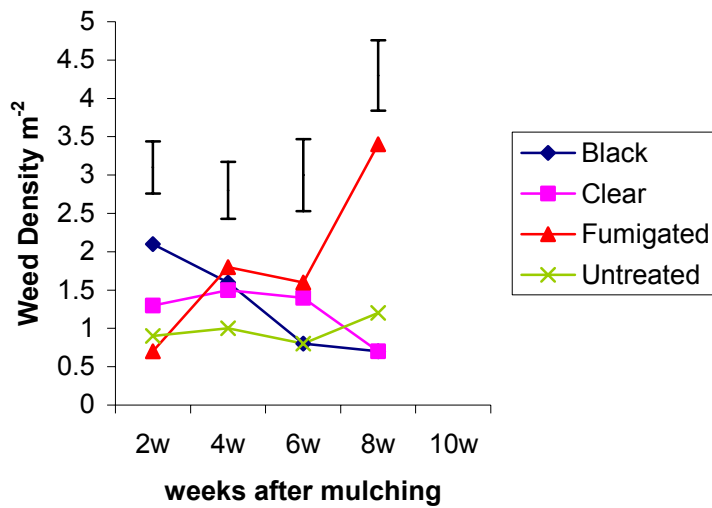


Figure 10: Mean density per m² of *Oxalis latifolia* survival (square root transformed data) under the plastic mulches.

4.3.5 *Cyperus*

Emergence of *Cyperus* was significantly ($P < 0.05$) higher in the fumigated soil compared to the untreated control and the soil mulched with plastics at weeks (Figure 11). Fumigation and plastic mulches had no effect on *Cyperus* emergence at 4 weeks (Appendix 2.12) and at 6 weeks (Appendix 2.19). *Cyperus* emergence increased significantly ($P < 0.05$) in the fumigated control to almost double that attained in the untreated control and in the soil covered with plastic mulches (Figure 11).

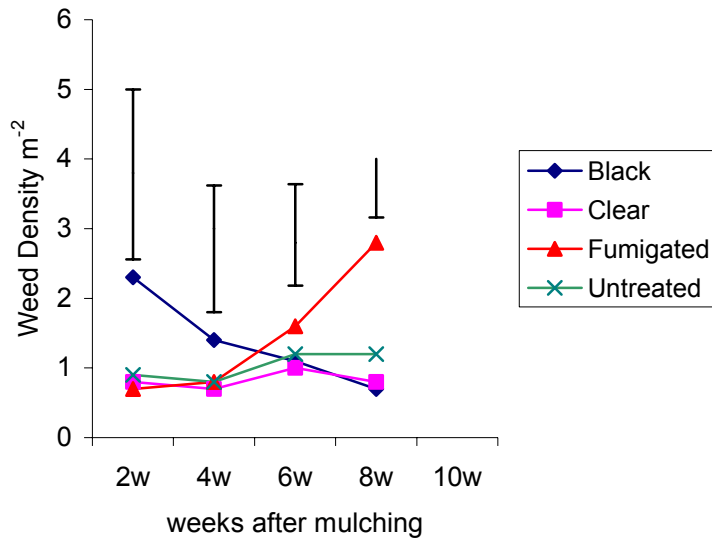


Figure 11: Mean density per m² of *Cyperus* survival (square root transformed data) under the plastic mulches.

There was a distinct increase in viable *Cyperus* seed in the fumigated control in the sixth and eighth weeks (Figure 11).

4.3.6 Other weed species

Emergence of the other weed species was significantly higher ($P < 0.05$) in the untreated control compared to the fumigated control and the plastic mulches at 2, 4, 6 and 8 weeks of solarization (Figure 12). Fumigation and the plastic mulches reduced the weed seed emergence during the 8 week period. However, there was a slight increase in weed emergence in the fumigated control and the plastic mulches, but differences were not significant (Figure 12).

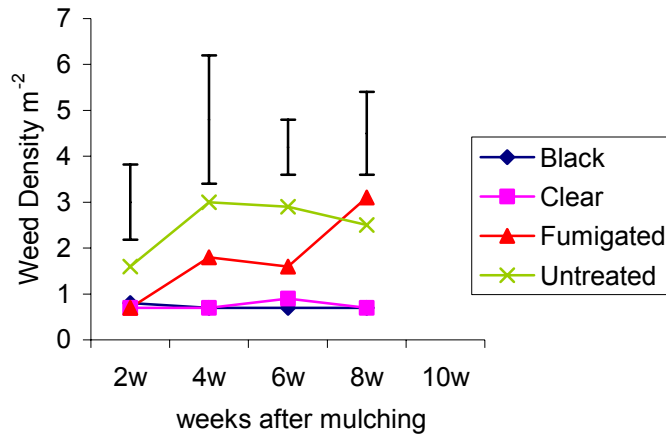


Figure 12: Mean density per m² of the survival of other weed species (square root transformed data) under the plastic mulches.

4.3.7 All weed species counts

Emergence of total weeds was significantly higher ($P < 0.05$) in the untreated control than in the fumigated control and the plastic mulches at 2, 4, 6 and 8 weeks of solarization. Fumigation was the most effect control that killed most of the weeds at 2 and 4 weeks (Figure 13). The weed counts in the soil covered with plastic mulches decreased steadily at 2, 4 and 6 weeks. The weed counts in the fumigated soil significantly increased after 6 weeks (Figure 13).

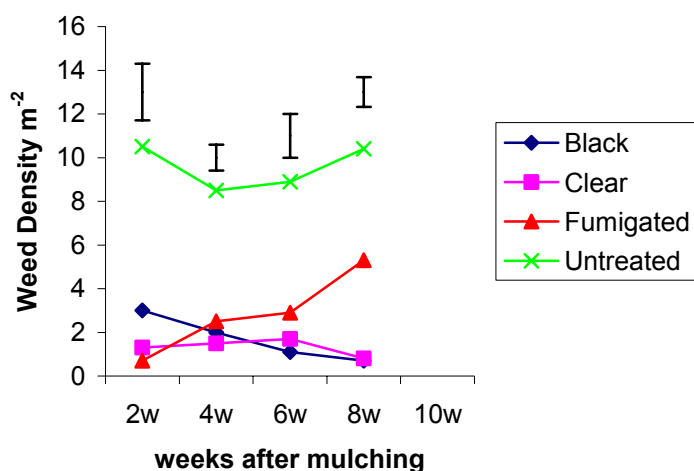


Figure 13: Mean density per m² on all weed species counts (square root transformed data) under the plastic mulches.

4.4 Assessment of bacterial types in the soil

Bacillus and *Actinomyces* were the main bacterial genera isolated from the soil. The *Bacillus* was characterized by the colonies being round with entire margins, shiny opaque, convex, pale yellow at first, becoming deeper with age on Nutrient Agar. Culturing on YDC and King's Broth (KB) did not show formation of any yellow colonies. The *Bacillus* grew on Casein agar plus glucose (CAG) medium, which is a semi selective media. The *Actinomyces* formed a ramifying network of filaments on NA. It is a fungi-like bacterium that form long, thread like branched filaments, which appear cream on nutrient agar and the colonies, grew in chains.

Actinomycetes were viewed under a JENA compound microscope as blue rod shaped bacterial cell after the gram staining. Both organisms stained blue with the crystal violet indicating a gram-positive result. These results were also supported by the KOH test in which the bacteria did not produce a mucoid gummy mixture with 3 % potassium hydroxide. *Bacillus* cells were also stained with 5% malachite green and counter stained with 0.5% safranin. The bacterial bodies stained red and the spores green. *Bacillus* hydrolyzed starch; clear zones were observed around the colonies, which were inoculated in medium containing starch after addition of Lugol's iodine. This proved that *Bacillus* is able to hydrolyze starch. The test was negative for *Actinomycetes*. The levan test was negative for both *Bacillus* and *Actinomycetes* as no convex, white mucoid colonies were observed after culturing on the appropriate media. Both genera were oxidase negative as no purple colour developed on the filter papers 60 seconds after inoculation.

The pathogenicity tests of *Bacillus* and *Actinomycetes* were negative, the organisms did not produce disease symptoms on the inoculated plants after 21 days showing that they were not pathogenic. Tissue sections from the leaves and stems of inoculated plants were plated on NA and no colonies were recovered from them.

4.5 Determination of bacterial populations in the soil

At 2 weeks after solarization, the untreated plots had the most number of *Bacillus*, *Actinomycetes* and total bacteria counts than the other treatments (Figures 14 and 15). The mulching significantly ($P=0.01$) affected the total number of bacteria as well as the individual species at the different solarization periods. Fumigated soil recorded the lowest

number of *Actinomycetes* and other bacteria types at 2 weeks after fumigation (Figures 15 and 16). Fumigation and the plastic mulches significantly ($P=0.02$) reduced the population of *Bacillus* at 2 weeks of solarization. The lowest counts were recorded in these treatments.

Fumigation and the plastic mulches did not reduce the levels of *Bacillus* in the soil at 4 weeks (Appendix 6.5), 6 weeks (Appendix 6.9) and at 8 weeks (Appendix 6.13). There was no significant difference between the control and the treated soils (Figure 14). Survival of *Bacillus* was not affected ($P>0.05$) affected by the plastic mulches.

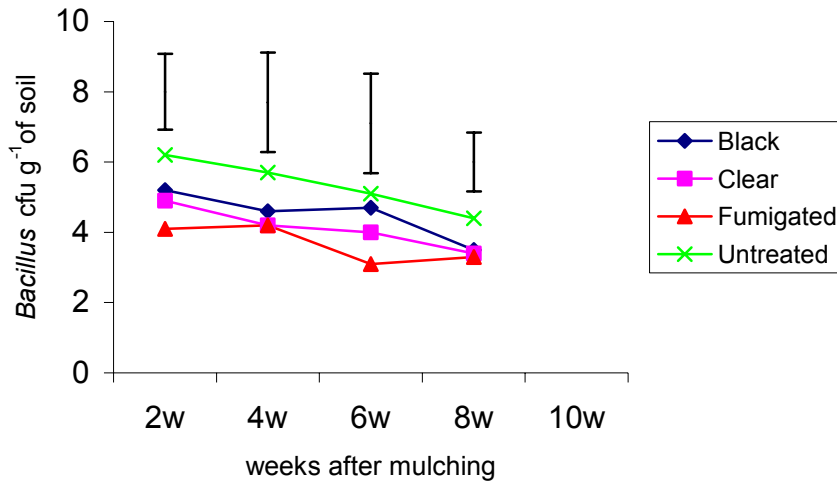


Figure 14: Mean number of *Bacillus* (cfu g⁻¹) population (log₁₀ transformed) in soil samples collected over time.

Fumigation and the plastic mulches significantly ($P=0.00$) reduced the populations of *Actinomycetes* at 2, 4 and 6 weeks compared to the untreated control. The lowest bacterial counts were recorded in fumigated soil followed by that in soils mulched with plastics (Figure 15).

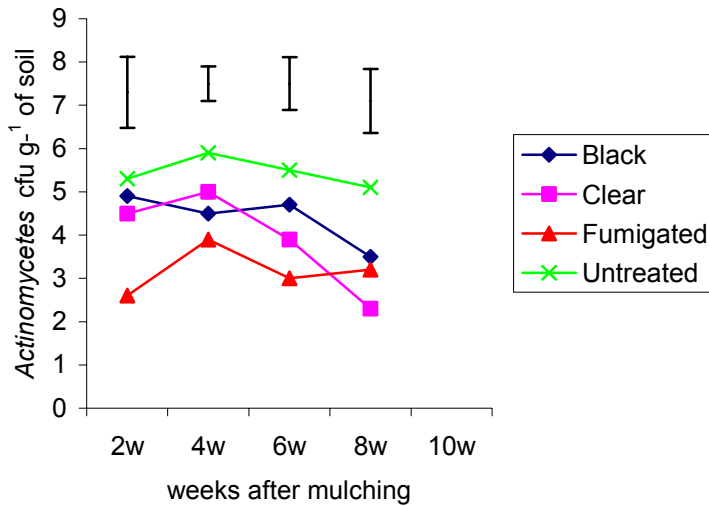


Figure 15: Mean number of *Actinomycetes* (cfu g⁻¹) population ($\log_{10}$ transformed) in soil samples collected over time.

The populations of *Actinomycetes* decreased significantly ($P=0.03$) at 8 weeks of solarization in all the treatments. The lowest counts were recorded under clear plastic and in fumigated soil followed by the black plastic mulch, while the highest population was

isolated from untreated soil (Figure 15)

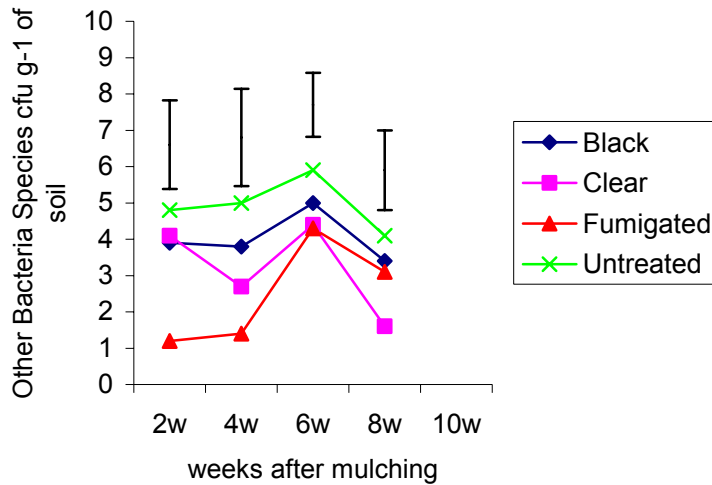


Figure 16: Mean number of the other types of bacteria (cfu g⁻¹) population (log₁₀ transformed) in soil samples collected over time.

The other types of bacteria were significantly reduced ($p < 0.05$) by fumigation at 2 weeks after treatment. There was no significant difference between soils mulched with plastics and the untreated control (Figure 16). At 4 weeks there was a significant decrease ($P < 0.05$) in the population of the other types of bacteria under the plastic mulches, but the populations remained higher than those in the fumigated soils. There was a significant increase ($P < 0.05$) in the bacterial populations at 6 weeks and then a significant decrease at 8 weeks across all the treatments (Figure 16).

The plastic mulches and fumigation significantly reduced ($P < 0.05$) all the bacterial populations throughout the 8 week period (Figure 17). The highest bacterial counts were recorded in the untreated soils for the entire period.

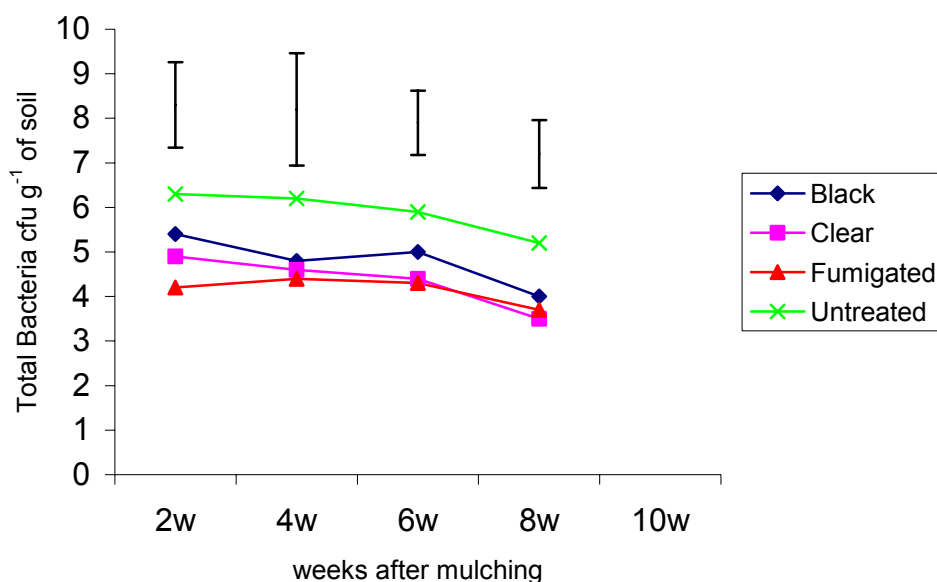


Figure 17: Mean number of all bacteria species (cfu g⁻¹) population (log₁₀ transformed) in soil samples collected over time.

4.6 Assessment of fungal soil types in the soil

Fusarium, *Aspergillus* and *Penicillium* were the main fungi isolated from the soil. *Penicillium* colonies on Czapek medium were restricted, dull green to grey-green with clear to pale yellow soluble pigment. *Fusarium* mycelia were delicate, white and peach with a purple tinge *Aspergillus* was characterized by loose white mycelium rapidly becoming black with development of conidia.

The pathogenicity test was positive for *Fusarium* only, inoculated seedlings developed some root and stem lesions. *Fusarium* was recovered from the infected plants when thin tissue sections from infected plants were cultured on PDA. Seedlings inoculated with

Aspergillus and *Penicillium* did not develop any disease symptoms after 21 days of inoculation. No colonies were recovered from thin tissue sections of inoculated plants.

4.7 Determination of fungal populations in the soil

At 2 weeks of solarization the populations of *Fusarium*, *Penicillium*, *Aspergillus*, other species and total fungi were significantly ($P=0.00$) reduced by fumigation. The fumigation treatment recorded the lowest fungal counts for the three genera at 2 weeks of solarization (Figures 18 - 20) compared to the plastic mulches and the untreated soil. The *Fusarium* was significantly ($P=0.00$) reduced by fumigation because no colonies were isolated from the fumigated soil at 4 weeks of the experiment. At 6 weeks *Fusarium* was significantly ($P=0.00$) reduced by the plastic mulches and fumigation compared to the untreated control (Figure 18). The highest fungal populations were recorded in the untreated soil. Plastic mulches significantly reduced ($P<0.05$) *Fusarium* when compared with the untreated soil. There was an increase in the *Fusarium* population in fumigated soil at 8 weeks of solarization (Figure 18).

Fumigation significantly reduced ($P<0.05$) *Aspergillus* populations when compared to the untreated and plastic mulches. The lowest number of colonies was also observed in the fumigated soil, while the highest number was in the untreated at 2 and 4 weeks of solarization (Figure 19).

The population of *Aspergillus* was significantly lower ($P=0.00$) compared to untreated from 6 to 8 weeks of the experiment and no colonies were isolated from the fumigated

soil at 8 weeks. The fungal populations increased significantly ($P=0.00$) under the clear plastics compared to the untreated control. The highest fungal counts were recorded under clear plastic at 6 and 8 weeks of solarization.

Penicillium was reduced significantly ($P=0.00$) by the fumigation at 2 and 4 weeks of the experiment compared to the untreated and the plastic mulches and no colonies were detected from the fumigated soil 4 weeks after application (Figure 20). This was followed by an increase in the population of *Penicillium* at 6 weeks and a decrease at 8 weeks. Fumigation and the plastic mulches did not reduce *Penicillium* at 6 weeks (Appendix 5.13). Fumigation significantly ($P=0.00$) reduced *Penicillium* at 8 weeks of solarization compared to the plastic mulches and the untreated control.

The other types of fungi were significantly ($P=0.00$) affected by fumigation. Fumigated soil recorded the lowest populations at 2 weeks after fumigation. At 4 weeks fumigation and the plastic mulches significantly ($P=0.00$) reduced the fungal populations compared to the untreated control. Fumigation and the plastic mulches recorded the lowest fungal counts. At 6 weeks the plastic mulches and fumigation significantly ($P=0.00$) reduced the fungal population, the untreated soil recorded the highest counts. Clear plastic effectively reduced ($p=0.00$) the other types of fungi, as no colonies were isolated from soil mulched with clear plastics after 8 weeks of solarization (Figure 21). This treatment was more effective than the black plastic and the fumigation.

Fumigation significantly ($p=0.00$) reduced total fungal counts throughout the 8 week period of solarization. Fumigated soil consistently recorded the lowest fungal populations (Figure 22).

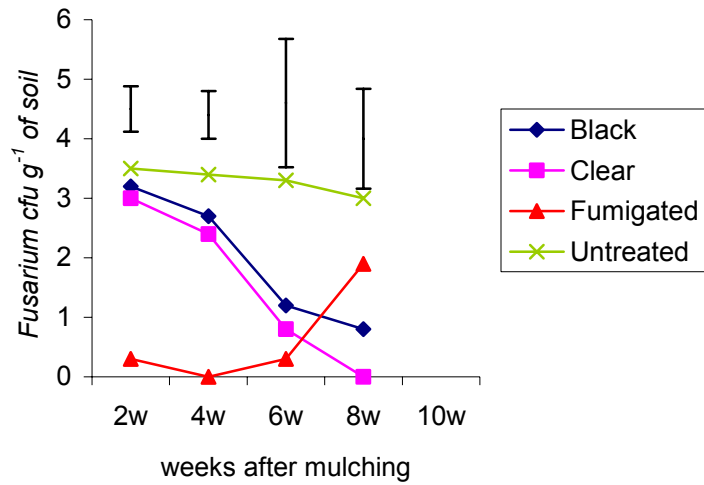


Figure 18: Mean number of *Fusarium* (cfu g⁻¹) population (log₁₀ transformed) in soil samples collected over time.

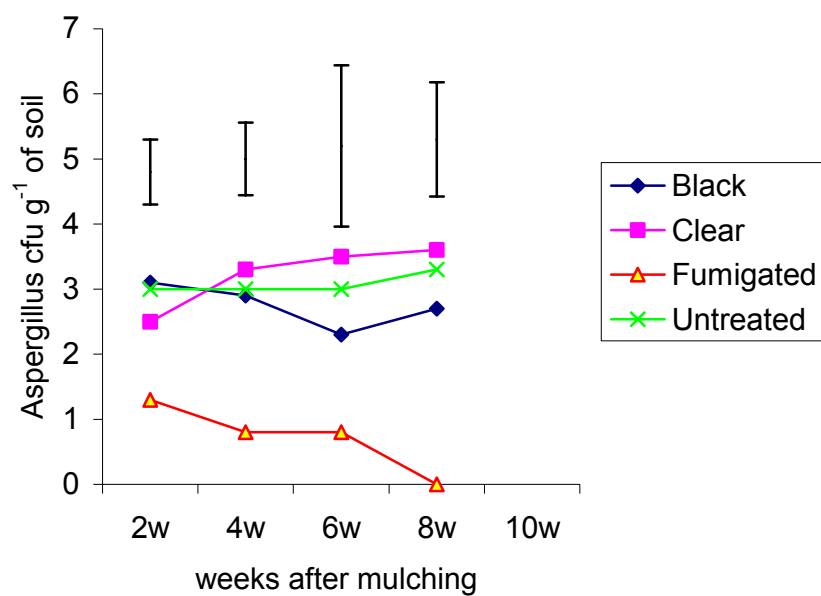


Figure 19: Mean number of *Aspergillus* (cfu g⁻¹) population (log₁₀ transformed) in soil samples collected over time.

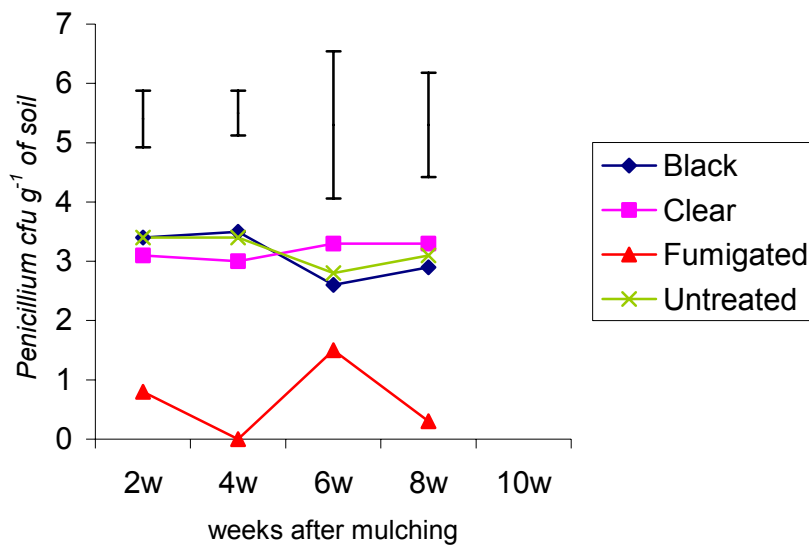


Figure 20: Mean number of *Penicillium* (cfu g⁻¹) population (log₁₀ transformed) in soil samples collected over time

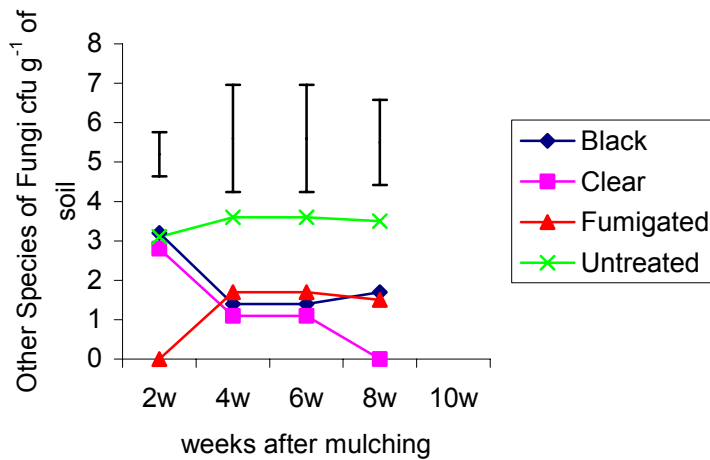


Figure 21: Mean number of other species of fungi (cfu g⁻¹) population (log₁₀ transformed) in soil samples collected over time.

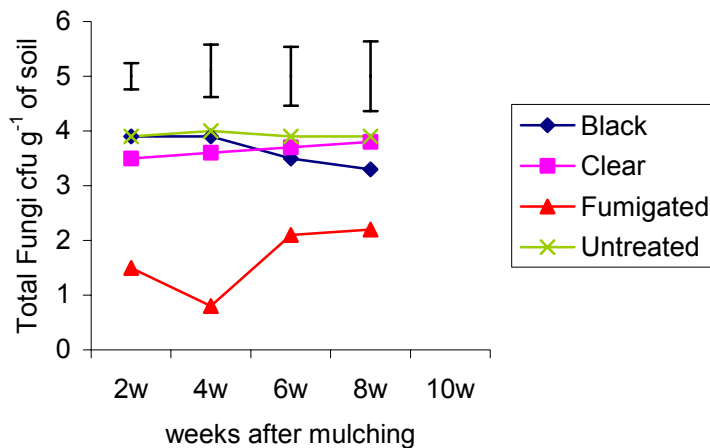


Figure 22: Mean number of total fungi (cfu g⁻¹) population (log₁₀ transformed) in soil samples collected over time.

4.8 Effect of mulching with plastic on weed density in the bean (*Phaseolus vulgaris*) field 5WACE

Total weed density was significantly ($P < 0.01$) affected by mulch type at 5 WACE in the bean crop. The soil mulched with plastics had the lowest weed counts followed by the fumigated. Mulching significantly ($P < 0.01$) reduced weed counts of *Bidens pilosa*, *Galinsoga parviflora* and *Elucine indica* when compared to fumigation and the untreated. Both clear and black plastics had the lowest counts (Figure23). The plastic mulches did not control *Oxalis latifolia*. Black plastic treatment recorded the highest *O. latifolia* counts followed by fumigation, while the untreated soil recorded the least.

Cyperus counts were significantly ($P < 0.01$) reduced by mulch type. Black plastic mulch reduced *Cyperus* more than the clear plastic. Fumigated soil had the highest

counts followed by clear plastic and the untreated soil recorded the lowest count. Fumigated soil had significantly ($P<0.05$) more counts than the untreated and the plastic mulches (Figure 23).

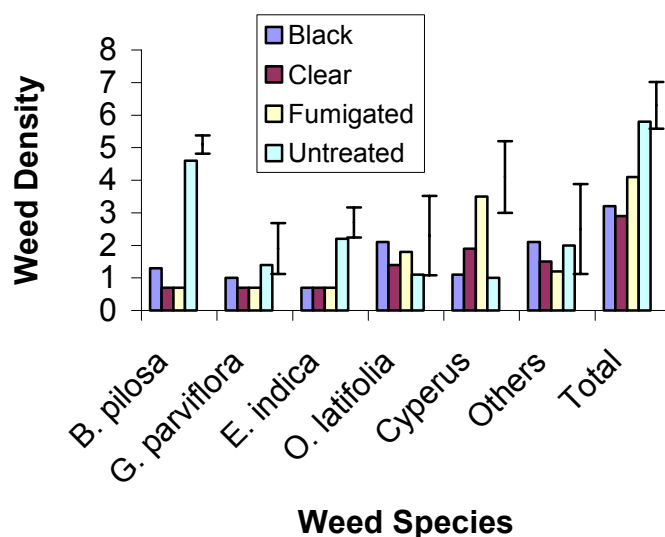


Figure 23: Mean weed density per m² 5WACE in bean (*Phaseolus vulgaris*) crop

4.9 Effect of mulching with plastic on *Fusarium* incidence and severity in the bean crop

Fusarium incidence was significantly ($P<0.05$) affected by mulching, with clear plastic recording the lowest disease incidence followed by black plastic mulching. The highest *Fusarium* disease incidence was observed in the untreated soil followed by the fumigated soil. Enzyme Linked Immunosorbent Assay (ELISA) was used for detecting viruses in plants, which were showing virus symptoms. Viral disease

incidence was not significantly ($P>0.05$) affected by mulching (Appendix 9.2). The disease was more or less evenly distributed across all the treatments.

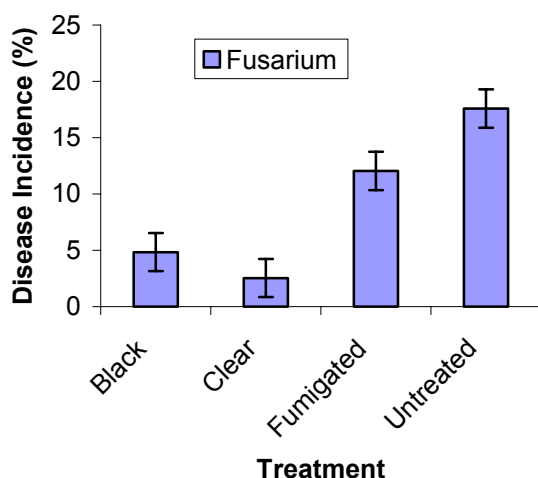


Figure 24: Percent disease incidence of *Fusarium* wilt on bean (*Phaseolus vulgaris*) at 10 WACE .

Mulching significantly ($P<0.01$) affected the *Fusarium* wilt disease severity in the field; the highest severity was recorded in the unmulched blocks (Figure 25). The plants from the mulched soils were less affected by the *Fusarium* wilt. The lowest severity was recorded from the soil covered with clear plastic followed by that treated with black plastic. The highest disease incidence was recorded in the untreated soil followed by the fumigated soil (Figure 24)

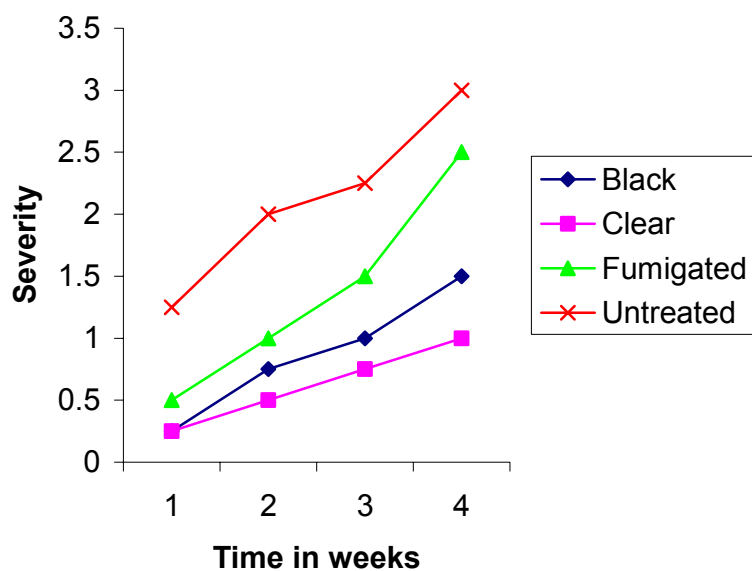


Figure 25: Area Under Disease Progress Curves of *Fusarium* severity in bean (*Phaseolus vulgaris*).

4.10 Effect of mulching with plastics on leaf area, yield components and yield.

The effect of soil solarization on leaf area, number of flowers, number of pods and number of seeds per pod is shown in Table 4. Soil solarization improved plant growth. Leaf area was significantly ($P<0.01$) affected by mulch type. Plants, which grew in blocks solarized with clear plastic, had larger leaf areas, more flowers and more pods than those from other treatments. Black plastic mulching also improved plant leaf area, number of flowers and pod numbers were also greater than those from untreated and fumigated soils. Plant growth was pronounced at 5 WACE. Plant dry weights indicated that plant growth in solarized soil had significantly ($P<0.01$) greater growth than those in the fumigated and unmulched soil. The plastic mulches also significantly ($P<0.01$) increased the bean yield. The bean yield was higher in the soils mulched with plastic, followed by fumigated soils and untreated soils (Table 5). The

plastic mulches had no effect ($P>0.05$) on the number of seeds per pod (Appendix 8.3). The plastic mulches significantly ($P<0.05$) reduced both the fresh weight and dry weight of the total weed at 5 WACE (Table 4) compared to the untreated control and the fumigated soil. The highest fresh and dry weights were recorded in the untreated soil followed by the fumigated soil, while the plastic mulches recorded the least. The plastic mulches significantly increased the fresh weight and dry weight of the bean plants. The plastic mulches recorded higher ($P=0.00$) fresh and dry weights of the bean plants at 5 WACE compared to the untreated and the fumigated soils (Table 5).

Table 4: Effect of plastic mulches on total weed fresh weight and dry weight at 5 WACE.

Treatment	Fresh weight	Dry weight
Black	3.14a	0.95a
Clear	1.01b	0.56a
Fumigated	5.70c	3.48b
Untreated	21.43d	15.13c
Probability	0.00	0.00
SED	1.65	1.86
LSD _{0.05}	3.74	4.21

NB Means followed by different letters in a column are significantly different at $P<0.05$

Table 5: Effect of plastic mulches on bean (*Phaseolus vulgaris*) fresh weight and dry weight at 5 WACE

Treatment	Fresh weight	Dry weight
Black	189.36 a	126.34a
Clear	169.12 b	121.7a
Fumigated	142.65 c	94.66b
Untreated	127.91 d	80.52b
Probability	0.00	0.00
SED	4.7	7.3
LSD _{0.05}	10.5	16.6

NB Means followed by different letters in a column are significantly different at P<0.05

Table 6: Effect of plastic mulching on yield and yield components of bean (*Phaseolus vulgaris*).

Treatment	leaf area mm²	Number of flowers plant⁻¹	Number of pods plant⁻¹	Number of seeds pods⁻¹	Yield tha⁻¹
Black	1913a	34.8a	23.8a	5.8	2.7a
Clear	1803a	38.7a	26.3a	5.8	3.0a
Fumigated	1340b	25.8b	20.3b	5.8	1.8b
Untreated	1060c	26.8b	17.3b	5.5	1.6b
Probability	0.00	0.00	0.00	0.873	0.00
SED	109	3.12	2.03	0.37	0.26
LSD _{0.05}	247.4	7.05	4.6	NS	0.60

NB Means followed by different letters in a column are significantly different at P<0.05

CHAPTER 5

DISCUSSION

The clear plastic mulches recorded consistently higher minimum and maximum temperatures than the black plastic mulch treatment. This concurs with the results of Mashingaidze *et al.*, (1996) in their paper on the effect of clear and black plastic mulch on soil temperature. The clear plastic mulch has been reported to build up higher temperatures in the air and soil under it during the day but traps outgoing radiation as effectively as black plastic mulch. Deposits of water droplets, which were formed by condensation on the underside of the plastic covers at night, have been demonstrated to trap outgoing radiation (Stapleton and DeVay, 1986). Clear plastic mulch permits the transmission to the soil of any incoming short-wave radiation which is absorbed and converted to sensible heat at the soil surface unlike black plastic mulch which does not permit transmission of the short-wave radiation, but rather converts it to sensible radiation, causing the surface of the plastic mulch to gain heat, and the heat is absorbed by the soil body (Mashingaidze *et al.*, 1996). The increased temperature of the black plastic surface increases thermal radiation exchange by conduction and convection to the surrounding air.

Morning soil temperatures were higher in the mulched treatments than in the uncovered treatments because the air gap between the soil and mulch was shown to reduce convective heat transfer to the surrounding air (Stapleton and DeVay, 1986). The plastic

has been reported to trap a portion of the outgoing long wave radiation emitted from the soil and thus prevented evaporative cooling on the mulched surfaces. Tigere, 2000 and Nhendo, 2001 reported similar findings in their researches. The temperatures decreased across the treatments during the first and 4th weeks of the experiment because of cloud cover experienced during the time of the experiment and also due to rains received during these two weeks. This shows that light intensity and length of exposure are important factors in heating the soil during solarization. DeVay, (1991a) and Katan, (1987) reported that meteorological restrictions affect the effectiveness of solarization.

Fumigation and the plastic mulches considerably reduced weed densities in the asbestos trays. Plastic mulches offered the best weed control for all weed species followed by the fumigation. Mashingaidze and Chivinge, (1998) and Elmore, (1991) reported similar results. They reported that clear plastics generated high temperatures above 50⁰C, which scorched the emerging weed seedlings as well as destroyed the seeds and propagules in the soil. The black plastic promoted weed germination but stopped light from reaching the ground, thereby prevented photosynthesis resulting in the death of emerging seedlings (Mashingaidze and Chivinge, 1998; Brown *et al.*, 1991; Elmore, 1991; Preece and Read, 1983).

Plastic mulches significantly controlled all the weed species and the scenario was different in fumigated blocks where the *Cyperus* and *O. latifolia* started to germinate after 6 weeks of treatment, showing that fumigation cannot control all weed types but can suppress their germination for a limited period in this case 6 weeks. The reduced weed

emergencies in the untreated soil, in asbestos tray at 6 and 8 weeks could probably be due to most of the weed seeds in the seed bank germinating in the field or thermo dormancy of some weed seeds. *Cyperus* was not identified to species level in this experiment because identification can only be done at flowering and the plants were removed before flowering.

In the field the plastic mulches controlled *Bidens pilosa*, *Elusine indica* and *Galinsoga parviflora* at 2 weeks of solarization. Elmore, (1991) reported successes in the control of winter annual weeds that germinate during the short days and cool temperatures. He pointed out that seeds from various weed species vary in their sensitivity to temperature (thermal death point). The plastic mulches enhanced emergences of *Cyperus* and *Oxalis latifolia* and seedlings were scorched under the clear plastic and etiolated under the black plastic. Abu-Irmaileh, (1991) observed that annual weeds were effectively controlled by soil solarization with clear polyethylene or black polyethylene. He reported a 90% reduction in total weeds emergencies and further elaborated that emergence of *Cyperus* was enhanced but the high temperatures generated in the plastics killed the seedlings.

The soil borne bacterial identification results were conclusive for the *Bacillus* species and the *Actinomycetes*. The cells of both isolates appeared blue under the microscope, showing that they were gram positive. The blue colouration was due to the retained colour of the primary dye, a complex of crystal violet and iodine (Duvellier *et al.*, 1997; Schaad, 1988). The oxidase test was negative for both *Bacillus* and *Actinomycetes* showing that in both organisms cytochrome c did not oxidize tetramethyl p-

phenylenediamine an artificial electron acceptor (Brock, Madigan, Martinko and Parker, 1994). *Bacillus* hydrolysed starch, confirming the findings of Schaad, (1988) and Brock *et al.*, (1994) who reported that some species of *Bacillus* are able to hydrolyze starch. Both *Actinomycetes* and *Bacillus* did not form levans, which are fructose polymers. The result is similar to the findings of Brock *et al.*, 1994 reported that both organisms do not form levan. The pathogenicity results were negative showing that both *Bacillus* and *Actinomycetes* are not pathogenic.

Plastic mulches and fumigation had no effect on *Bacillus*, but significantly reduced *Actinomycetes* and the other types of bacteria. This could be due to the fact that *Bacillus* is thermotolerant and is able to withstand the high temperatures created under the plastic mulches. Stapleton *et al.*, 1986 and Pullman *et al.*, 1981 observed that soil solarization targets mesophylic organisms, which include most plant pathogens and pests without destroying the beneficial growth promoting *Bacillus* species.

Studies in Western Australia showed that solarization increased the total number of bacteria and *Actinomycetes* in the soil (Kaewruang, Sivasithamparam and Hardy, 1989). The decrease in the other types of bacteria could be attributed to the high temperatures generated within the plastic as well as the antagonistic effects of *Bacillus* and *Actinomycetes*. Stapleton and DeVay, 1984 also reported similar results in a California study where they observed an increase in the proportion of antagonistic gram-positive bacteria in solarized soils (Kaewruang *et al.*, 1989). Another study done in the Western Australia showed that the proportion of bacteria (*Actinomycetes*) antagonistic to

Fusarium oxysporum, *F. solani* and *Rhizoctonia solani* was increased compared to the non-solarized. The population of the other types of bacteria increased at 6 weeks of solarization, it should be noted that some rains were also received during the same period. The increase in bacterial population could be due to the fact that solarization is not effective in controlling bacteria when temperatures are low and that the cool humid conditions favour the multiplication of bacteria.

Fusarium population densities were considerably reduced under the plastic mulches. Nelson and Wilhelm, 1958 reported that temperatures achieved at the upper layers by soil mulching are in the range of those lethal to plant pathogens. Plant pathogenic fungi were observed to be among the most sensitive soil borne organisms to soil solarization, especially, species that are unable to grow at temperatures higher than 30⁰C and 33⁰C. They are categorized as mesophiles. However population densities of *Aspergillus* and *Penicillium* remained relatively high following solarization and increased to the levels higher than present in non-solarized soil. Stapleton and DeVay, (1982) reported that the fungi most frequently isolated were thermotolerant *Aspergillus* and *Penicillium* species from the experiments they conducted. *Fusarium* population increased in fumigated soil at 6 weeks of solarization, this could be due to the low temperatures experienced during this period or due to the fact that fumigation inhibits the multiplication of *Fusarium* for a limited period, in this case 6 weeks.

Disease incidence of *Fusarium* root rot of bean plants was significantly reduced in the mulched soil. The percentage of diseased plants at 5WACE from emergence dropped

from 89% in the untreated blocks to 38% in the solarized ones. The results obtained in the experiment agree with the findings of Pullman *et al.*, 1981 and Garber and Houston, 1966 who demonstrated that soil heating at sub lethal temperatures impaired the ability of some soil borne plant pathogens to penetrate the plant and cause plant disease. This probably indicates that solar heating causes an alteration in the soil microflora, which involves a biological control in addition to the thermal effect on the soil borne pathogens. However Moorman, 1982 showed that wilt disease incidence in eggplants caused by *Verticillium* did differ significantly between solarized (black polythene) and unmulched soils.

The plastic mulches improved growth of bean plants. The plants from the mulched soil had a larger leaf area, more flowers, more pods and higher bean yield. This is in agreement with the findings of Sarhan, (1990) who reported improved growth in broad beans grown in solarized soil. The findings also confirm the results of Moosa *et al.*, 1985 on the effects of soil mulching on growth of watermelon, who reported that soil mulching speeded up the release of nutrients available in the soil for plant use. The increased plant growth response in solarized soil may be a result of the control of soilborne pathogens and weeds and the release of mineral nutrients from the soil. Stapleton and DeVay, 1983 obtained similar results and reported that the increase in plant growth can also be attributed to the alteration of the soil microbiota to favour antagonists of plant pathogens as well as improved physicochemical conditions of the soil. The populations of *Actinomycetes* increased during the 8 week period and these could have been antagonistic to the plant pathogens.

An increase in seed yield of bean in solarized soil could be due to the effective control of weeds and plant pathogens. Weeds, when present in a field, strongly compete with the crop for light, water and mineral nutrients.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The conclusions derived from the study are as follows:

- Clear plastic mulch is effective in the control of mesophilic soil borne pathogens and weeds. The high temperatures generated under the mulch are lethal to the soil pests.
- Black plastic mulch is effective in controlling weeds only. The black plastic mulch promotes germination of weeds and then blocks light from reaching the plants thereby killing the plants.
- Fumigation is effective in controlling small seeded weeds, and suppresses weeds with large seeds or propagules as in the case of *Cyperus* and *Oxalis latifolia*.
- Fumigation reduces population of microorganisms in the soil, both pathogenic and beneficial.
- Covering moist soil with plastic mulches improves the nutritional status of the soil, the concentration of nitrogen increases.
- Plastic mulching of the soil improves the yield of crops. The crop grows in a weed and disease free environment and this allows the plant to grow vigorously.

6.2 Recommendation

- ❑ Soil solarization should be carried out from August to October to take advantage of the hot dry weather conditions required to raise the soil temperatures to levels, which are lethal to soilborne pests.
- ❑ Clear plastic mulch should be used for the control of mesophilic soilborne plant pathogens and weeds. Clear plastic can be used for controlling problem weeds such as *Cyperus*.
- ❑ Soil should not be cultivated after solarization, because untreated soil from deep down will be brought to the surface thereby contaminating the solarized soil with pathogens and weed seeds.

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APPENDICES

Appendix 1: Effect of solarization on weed density in tray experiment

Appendix 1.1 Analysis of Variance for *Bidens pilosa* 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	4.2244	1.4081	2.10	0.171
Trt	3	20.1650	6.7217	10.02	0.003
Error	9	6.0400	0.6711		
Total	15	30.4294			

Appendix 1.2 Analysis of Variance for *Galinsoga parviflora* 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	3.013	1.004	0.88	0.485
Trt	3	22.889	7.630	6.71	0.011
Error	9	10.227	1.136		
Total	15	36.130			

Appendix 1.3 Analysis of Variance for *Elusine indica* 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	7.5320	2.5107	3.01	0.087
Trt	3	21.8948	7.2983	8.76	0.005
Error	9	7.4951	0.8328		
Total	15	36.9219			

Appendix 1.4 Analysis of Variance for *Oxalis latifolia* 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.7441	0.2480	1.62	0.253
Trt	3	3.0693	1.0231	6.67	0.012
Error	9	1.3810	0.1534		
Total	15	5.1943			

Appendix 1.5 Analysis of Variance for *Cyperus* 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.6780	0.8927	2.95	0.091
Trt	3	1.6807	0.5602	1.85	0.208
Error	9	2.7232	0.3026		
Total	15	7.0819			

Appendix 1.6 Analysis of Variance for Other Weed Species 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.0228	0.3409	0.98	0.443
Trt	3	8.9208	2.9736	8.59	0.005
Error	9	3.1168	0.3463		
Total	15	13.0605			

Appendix 1.7 Analysis of Variance for Total Weed Counts 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.8277	0.6092	1.71	0.233
Trt	3	56.2643	18.7548	52.74	0.000
Error	9	3.2005	0.3556		
Total	15	61.292			

Appendix 1.8 Analysis of Variance for *Bidens pilosa* 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.6889	0.2296	0.49	0.696
Trt	3	37.7238	12.5746	26.98	0.000
Error	9	4.1943	0.4660		
Total	15	42.6069			

Appendix 1.9 Analysis of Variance for *Galinsoga parviflora* 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.2414	0.7471	0.89	0.485
Trt	3	24.7976	8.2659	9.79	0.003
Error	9	7.5969	0.8441		
Total	15	34.6359			

Appendix 1.10 Analysis of Variance for *Elusine indica* 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.837	0.612	0.85	0.500
Trt	3	39.3064	13.1021	18.24	0.000
Error	9	6.4665	0.7185		
Total	15	47.6100			

Appendix 1. 11 Analysis of Variance for *Oxalis latifolia* 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.7951	0.5984	1.91	0.199
Trt	3	2.6220	0.8740	2.79	0.102
Error	9	2.8214	0.3135		
Total	15	7.2385			

Appendix 1.12 Analysis of Variance for *Cyperus* 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.8784	0.2928	1.02	0.428
Trt	3	4.5741	1.5247	5.32	0.022
Error	9	2.5787	0.2865		
Total	15	8.0312			

Appendix 1.13 Analysis of Variance for Other weed species 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.4552	0.1517	0.29	0.832
Trt	3	18.2958	6.0986	11.63	0.002
Error	9	4.7185	0.5243		
Total	15	23.4695			

Appendix 1.14 Analysis of Variance for Total weed counts 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.619	0.540	0.80	0.526
Trt	3	88.030	29.343	43.36	0.000
Error	9	6.090	0.677		
Total	15	95.739			

Appendix 1.15 Analysis of Variance for *Bidens pilosa* 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.6917	0.2306	0.61	0.626
Trt	3	20.6455	6.8818	18.18	0.000
Error	9	3.4060	0.3784		
Total	15	24.7433			

Appendix 1.16 Analysis of Variance for *Galinsoga parviflora* 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.2608	0.4203	0.87	0.490
Trt	3	20.7382	6.9127	14.36	0.001
Error	9	4.3324	0.4814		
Total	15	26.3313			

Appendix 1.17 Analysis of Variance for *Elusine indica* 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.8035	0.2678	0.58	0.640
Trt	3	30.4965	10.1655	22.19	0.000
Error	9	4.1230	0.4581		
Total	15	35.4230			

Appendix 1.18 Analysis of Variance for *Cyperus* 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.83681	0.27894	3.16	0.079
Trt	3	4.41086	1.47029	16.67	0.001
Error	9	0.79399	0.08822		
Total	15	6.04166			

Appendix 1.19 Analysis of variance for *Oxalis latifolia* 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.7824	0.2608	0.90	0.478
Trt	3	0.9126	0.3042	1.05	0.417
Error	9	2.60979	0.2900		
Total	15	4.3046			

Appendix 1.20 Analysis of Variance for Other weed species 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.0500	0.3500	1.06	0.413
Trt	3	7.5278	2.5093	7.59	0.008
Error	9	2.9741	0.3305		
Total	15	11.5518			

Appendix 1.21 Analysis of Variance for Total weed counts 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.0223	0.3408	0.81	0.521
Trt	3	58.5399	19.5133	46.17	0.000
Error	9	3.8037	0.4226		
Total	15	63.3659			

Appendix 1.22 Analysis of Variance for *Bidens pilosa* 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.1090	0.0363	0.43	0.736
Trt	3	33.0325	11.0108	130.72	0.000
Error	9	0.7581	0.0842		
Total	15	33.8996			

Appendix 1.23 Analysis of Variance for *Galinsoga parviflora* 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.2311	0.4104	0.65	0.604
Trt	3	17.6472	5.8824	9.27	0.004
Error	9	5.7098	0.6344		
Total	15	24.5881			

Appendix 1.24 Analysis of Variance for *Elusine indica* 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rrep	3	0.1233	0.0411	0.93	0.466
Trt	3	16.7449	5.5816	126.14	0.000
Error	9	0.3982	0.0442		
Total	15	17.2664			

Appendix 1.25 Analysis of Variance for *Oxalis latifolia* 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.2160	0.0720	0.10	0.961
Trt	3	1.4039	0.4680	0.62	0.620
Error	9	6.7996	0.7555		
Total	15	8.4195			

Appendix 1.26 Analysis of Variance for *Cyperus* 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.0154	0.6718	2.46	0.129
Trt	3	17.2379	5.7460	21.08	0.000
Error	9	2.4535	0.2726		
Total	15	21.7068			

Appendix 1.27 Analysis of Variance for Other Weed Species at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.271	0.757	0.68	0.583
Trt	3	3.964	1.321	1.20	0.366
Error	9	9.950	1.106		
Total	15	16.186			

Appendix 1.28 Analysis of Variance for Total Weed Counts at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.271	0.757	0.68	0.583
Trt	3	3.964	1.321	1.20	0.366
Error	9	9.950	1.106		
Total	15	16.186			

Appendix 2 Analysis of Variance for Field Weed Counts

Appendix 2.1 Analysis of Variance for *Bidens pilosa* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.6404	0.5468	1.00	0.436
Trt	3	53.6390	17.8797	32.70	0.000
Error	9	4.9213	0.5468		
Total	15	60.2007			

Appendix 2.2 Analysis of Variance for *Galinsoga parviflora* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.692	0.231	1.00	0.436
Trt	3	71.685	23.895	103.59	0.000
Error	9	2.076	0.231		
Total	15	74.453			

Appendix 2.3 Analysis of Variance for *Elusine indica* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.643	0.214	1.00	0.436
Trt	3	69.849	23.283	108.65	0.000
Error	9	1.929	0.214		
Total	15	72.421			

Appendix 2.4 Analysis of Variance for *Oxalis latifolia* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.8458	0.6153	0.80	0.526
Trt	3	6.5547	2.1849	2.83	0.099
Error	9	6.9464	0.7718		
Total	15	15.3469			

Appendix 2.5 Analysis of Variance for *Cyperus* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.0535	0.3512	1.51	0.278
Trt	3	4.2728	1.4243	6.11	0.015
Error	9	2.0989	0.2332		
Total	15	7.4252			

Appendix 2.6 Analysis of Variance for Other Weed Species at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.6738	0.2246	0.68	0.586
Trt	3	2.3377	0.7792	2.36	0.139
Error	9	2.9711	0.3301		
Total	15	5.9825			

Appendix 2.7 Analysis of Variance for Total Weed Counts at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	8.622	2.874	3.36	0.069
Trt	3	244.404	81.468	95.14	0.000
Error	9	7.707	0.856		
Total	15	260.733			

Appendix 2.8 Analysis of Variance for *Bidens pilosa* at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.1206	0.0402	1.00	0.436
Trt	3	40.3321	13.4440	334.48	0.000
Error	9	0.3617	0.0402		
Total	15	40.8145			

Appendix 2.9 Analysis of Variance for *Galinsoga parviflora* at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.0448	0.0149	1.00	0.436
Trt	3	38.0133	12.6711	848.55	0.000
Error	9	0.1344	0.0149		
Total	15	38.1925			

Appendix 2.10 Analysis of Variance for *Elusine indica* at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.352	0.117	1.00	0.436
Trt	3	66.691	22.230	189.67	0.000
Error	9	1.055	0.117		
Total	15	68.098			

Appendix 2.11 Analysis of Variance for *Oxalis latifolia* at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.9969	0.3323	1.74	0.228
Trt	3	1.0990	0.3663	1.92	0.197
Error	9	1.7186	0.1910		
Total	15	3.8146			

Appendix 2.12 Analysis of Variance for *Cyperus* at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.2194	0.4065	0.91	0.472
Trt	3	1.2917	0.4306	0.97	0.449
Error	9	3.9983	0.4443		
Total	15	6.5093			

Appendix 2.13 Analysis of Variance for Other Weed Species at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.4563	0.1521	0.87	0.490
Trt	3	14.0634	4.6878	26.93	0.000
Error	9	1.5669	0.1741		
Total	15	16.0866			

Appendix 2.14 Analysis of Variance for Total Weed Counts at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.709	0.570	1.10	0.400
Trt	3	129.350	43.117	82.99	0.000
Error	9	4.676	0.520		
Total	15	135.735			

Appendix 2.15 Analysis of Variance for *Bidens pilosa* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.2189	0.0730	1.00	0.436
Trt	3	31.9893	10.6631	146.16	0.000
Error	9	0.6566	0.0730		
Total	15	32.8648			

Appendix 2.16 Analysis of Variance for *Galinsoga parviflora* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.0354	0.0118	1.00	0.436
Trt	3	50.0624	16.6875	1412.64	0.000
Error	9	0.1063	0.0118		
Total	15	50.2041			

Appendix 2.17 Analysis of Variance for *Elusine indica* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.699	0.566	1.00	0.436
Trt	3	77.579	25.860	45.67	0.000
Error	9	5.096	0.566		
Total	15	84.374			

Appendix 2.18 Analysis of Variance for *Oxalis latifolia* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.8654	0.2885	0.82	0.515
Trt	3	1.0292	0.3431	0.98	0.446
Error	9	3.1634	0.3515		
Total	15	5.0579			

Appendix 2.19 Analysis of Variance for *Cyperus* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.7524	0.2508	0.59	0.637
Trt	3	1.7876	0.5959	1.40	0.305
Error	9	3.8271	0.4252		
Total	15	6.3672			

Appendix 2.20 Analysis of Variance for Other Weed Species at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.3920	0.1307	0.32	0.813
Trt	3	11.1617	3.7206	9.04	0.004
Error	9	3.7038	0.4115		
Total	15	15.2576			

Appendix 2.21 Analysis of Variance for Total Weed Counts at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.657	0.886	3.76	0.053
Trt	3	154.598	51.533	218.83	0.000
Error	9	2.119	0.235		
Total	15	159.375			

Appendix 2.22 Analysis of Variance for *Bidens pilosa* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.2254	0.4085	1.00	0.435
Trt	3	52.2302	17.4101	42.74	0.000
Error	9	3.6663	0.4074		
Total	15	57.1219			

Appendix 2.23 Analysis of Variance for *Galinsoga parviflora* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.650	0.550	1.00	0.436
Trt	3	84.970	28.323	51.48	0.000
Error	9	4.951	0.550		
Total	15	91.571			

Appendix 2.24 Analysis of Variance for *Elusine indica* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.129	0.043	1.00	0.436
Trt	3	82.380	27.460	637.46	0.000
Error	9	0.388	0.043		
Total	15	82.897			

Appendix 2.25 Analysis of Variance for *Oxalis latifolia* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.4417	0.1472	0.76	0.546
Trt	3	11.0274	3.6758	18.90	0.000
Error	9	1.7499	0.1944		
Total	15	13.2190			

Appendix 2.26 Analysis of Variance for *Cyperus* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.1288	0.0429	0.20	0.890
Trt	3	20.5029	6.8343	32.62	0.000
Error	9	1.8858	0.2095		
Total	15	22.5174			

Appendix 2.27 Analysis of Variance for Other Weed Species at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	4.457	1.486	1.26	0.346
Trt	3	17.955	5.985	5.07	0.025
Error	9	10.625	1.181		
Total	15	33.036			

Appendix 2.28 Analysis of Variance for Total Weed Counts at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.603	0.868	1.15	0.381
Trt	3	254.475	84.825	112.31	0.000
Error	9	6.798	0.755		
Total	15	263.876			

Appendix 3 Analysis of Variance for Maximum Temperatures

Appendix 3.1 Analysis of Variance for Maximum Temperatures at Week 1 after Solarization

Source	DF	SS	MS	F	P
Re p	3	0.515	0.172	0.36	0.780
Trt	3	372.855	124.285	263.81	0.000
Error	9	4.240	0.471		
Total	15	377.610			

Appendix 3.2 Analysis of Variance for Maximum Temperatures at Week 2 after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.480	0.493	1.31	0.330
Trt	3	249.265	83.088	220.91	0.000
Error	9	3.385	0.376		
Total	15	254.130			

Appendix 3.3 Analysis of Variance for Maximum Temperatures at 3 Weeks After Solarization

Source	DF	SS	MS	F	P
Rep	3	1.423	0.474	0.47	0.713
Trt	3	312.867	104.289	102.61	0.000
Error	9	9.148	1.016		
Total	15	323.437			

Appendix 3.4 Analysis of Variance for Maximum Temperatures at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	4.432	1.477	1.48	0.285
Trt	3	560.552	186.851	187.05	0.000
Error	9	8.991	0.999		
Total	15	573.974			

Appendix 3.5 Analysis of Variance for Maximum Temperatures at 5 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	17.05	5.68	1.01	0.434
Trt	3	740.00	246.67	43.70	0.000
Error	9	50.80	5.64		
Total	15	807.85			

Appendix 3.6 Analysis of Variance for Maximum Temperatures at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.305	0.102	1.27	0.342
Trt	3	226.705	75.568	944.60	0.000
Error	9	0.720	0.080		
Total	15	227.730			

Appendix 3.7 Analysis of Variance for Maximum Temperatures at 7 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	11.96	3.99	1.57	0.263
Trt	3	660.37	220.12	86.81	0.000
Error	9	22.82	2.54		
Total	15	695.16			

Appendix 3.8 Analysis of Variance for Maximum Temperatures at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.397	0.466	2.75	0.105
Trt	3	497.197	165.732	977.69	0.000
Error	9	1.526	0.170		
Total	15	500.119			

Appendix 4 Analysis of Variance for Minimum Temperatures

Appendix 4.1 Analysis of Variance for Minimum Temperatures at 1 Week after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.002	0.334	0.73	0.562
Trt	3	69.627	23.209	50.36	0.000
Error	9	4.147	0.461		
Total	15	74.777			

Appendix 4.2 Analysis of Variance for Minimum Temperatures at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	4.592	1.531	0.45	0.724
Trt	3	104.512	34.837	10.24	0.003
Error	9	30.631	3.403		
Total	15	139.734			

Appendix 4.3 Analysis of Variance for Minimum Temperatures at 3 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.1669	0.0556	0.63	0.612
Trt	3	48.9219	16.3073	185.63	0.000
Error	9	0.7906	0.0878		
Total	15	49.8794			

Appendix 4.4 Analysis of Variance for Minimum Temperatures at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.035	0.345	2.02	0.182
Trt	3	237.735	79.245	463.12	0.000
Error	9	1.540	0.171		
Total	15	240.310			

Appendix 4.5 Analysis of Variance for Minimum Temperatures at 5 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.702	0.234	0.93	0.467
Trt	3	264.252	88.084	348.37	0.000
Error	9	2.276	0.253		
Total	15	267.229			

Appendix 4.6 Analysis of Variance for Minimum Temperatures at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.107	0.036	1.05	0.417
Trt	3	108.917	36.306	1069.12	0.000
Error	9	0.306	0.034		
Total	15	109.329			

Appendix 4.7 Analysis of Variance for Minimum Temperatures at 7 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.327	0.109	1.14	0.384
Trt	3	346.582	115.527	1208.13	0.000
Error	9	0.861	0.096		
Total	15	347.769			

Appendix 4.8 Analysis of Variance for Minimum Temperatures at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
REP	3	0.352	0.117	6.37	0.013
TRT	3	236.147	78.716	4277.38	0.000
Error	9	0.166		0.018	
Total	15	236.664			

Appendix 5 Analysis of Variance for Fungi

Appendix 5.1 Analysis of Variance for *Fusarium* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.4958	0.1653	2.19	0.159
Trt	3	26.3648	8.7883	116.37	0.000
Error	9	0.6797	0.0755		
Total	15	27.5402			

Appendix 5.2 Analysis of Variance for *Aspergillus* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.3593	0.1198	0.97	0.446
Trt	3	7.9868	2.6623	21.67	0.000
Error	9	1.1057	0.1229		
Total	15	9.4518			

Appendix 5.3 Analysis of Variance for *Penicillium* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.2001	0.0667	0.56	0.653
Trt	3	18.9934	6.3311	53.40	0.000
Error	9	1.0671	0.1186		
Total	15	20.2606			

Appendix 5.4 Analysis of Variance for Others 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.1279	0.0426	0.28	0.839
Trt	3	28.3400	9.4467	61.76	0.000
Error	9	1.3766	0.1530		
Total	15	29.8445			

Appendix 5.5 Analysis of Variance for Total Fungi 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.0068	0.0023	0.07	0.972
Trt	3	16.0161	5.3387	175.59	0.000
Error	9	0.2736	0.0304		
Total	15	16.2965			

Appendix 5.6 Analysis of Variance for *Fusarium* 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.1533	0.0511	0.61	0.624
Trt	3	26.6622	8.8874	106.41	0.000
Error	9	0.7517	0.0835		
Total	15	27.5672			

Appendix 5.7 Analysis of Variance for *Aspergillus* 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.1114	0.0371	0.23	0.874
Trt	3	16.2269	5.4090	33.32	0.000
Error	9	1.4612	0.1624		
Total	15	17.7995			

Appendix 5.8 Analysis of Variance for *Penicillium* at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.3622	0.1207	1.62	0.253
Trt	3	33.6727	11.2242	150.26	0.000
Error	9	0.6723	0.0747		
Total	15	34.7071			

Appendix 5.9 Analysis of Variance for Total Fungi at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.1657	0.0552	0.48	0.705
Trt	3	27.5902	9.1967	79.74	0.000
Error	9	1.0380	0.1153		
Total	15	28.7939			

Appendix 5.10 Analysis of Variance for *Fusarium* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.6812	0.5604	0.96	0.454
Trt	3	22.1067	7.3689	12.58	0.001
Error	9	5.2735	0.5859		
Total	15	29.0614			

Appendix 5.11 Analysis of Variance for *Aspergillus* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.6799	0.5600	0.74	0.555
Trt	3	16.9068	5.6356	7.44	0.008
Error	9	6.8201	0.7578		
Total	15	25.4068			

Appendix 5.12 Analysis of Variance for *Penicillium* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.1724	0.7241	0.94	0.461
Trt	3	7.1188	2.3729	3.08	0.083
Error	9	6.9260	0.7696		
Total	15	16.2172			

Appendix 5.13 Analysis of Variance for Other Fungi Species at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	5.8539	1.9513	2.09	0.172
Trt	3	14.8171	4.9390	5.29	0.022
Error	9	8.4012	0.9335		
Total	15	29.0721			

Appendix 5.14 Analysis of Variance for Total Fungi at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.3281	0.1094	0.73	0.560
Trt	3	7.6587	2.5529	17.04	0.000
Error	9	1.3486	0.1498		
Total	15	9.3354			

Appendix 5.15 Analysis of Variance for *Fusarium* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.7157	0.2386	0.68	0.584
Trt	3	20.1821	6.7274	19.26	0.000
Error	9	3.1431	0.3492		
Total	15	24.0408			

Appendix 5.16 Analysis of Variance for *Aspergillus* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.6682	0.2227	1.00	0.436
Trt	3	32.3532	10.7844	48.42	0.000
Error	9	2.0045	0.2227		
Total	15	35.0259			

Appendix 5.17 Analysis of Variance for *Penicillium* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.8742	0.6247	1.58	0.262
Trt	3	24.7876	8.2625	20.85	0.000
Error	9	3.5667	0.3963		
Total	15	30.2285			

Appendix 5.18 Analysis of Variance for Other Fungi Species at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	4.0820	1.3607	2.34	0.141
Trt	3	24.7898	8.2633	14.23	0.001
Error	9	5.2266	0.5807		
Total	15	34.0985			

Appendix 5. 19 Analysis of Variance for Total Fungi at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.7268	0.2423	1.20	0.364
Trt	3	7.0526	2.3509	11.64	0.002
Error	9	1.8181	0.2020		
Total	15	9.5975			

Appendix 6: Analysis of Variance for Bacteria

Appendix 6.1 Analysis of Variance for *Bacillus* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.0582	0.0194	0.03	0.991
TRT	3	9.4464	3.1488	5.48	0.020
Error	9	5.1708	0.5745		
Total	15	14.6755			

Appendix 6.2 Analysis of Variance for *Actinomycetes* at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	4.064	1.355	1.01	0.433
TRT	3	17.999	6.000	4.46	0.035
Error	9	12.094	1.344		
Total	15	34.156			

Appendix 6.3 Analysis of Variance for Other Bacteria Species at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.5506	0.5169	0.69	0.582
Trt	3	30.5760	10.1920	13.56	0.001
Error	9	6.7647	0.7516		
Total	15	38.8912			

Appendix 6.4 Analysis of Variance for Total Bacteria at 2 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.2593	0.0864	0.19	0.901
Trt	3	9.3868	3.1289	6.83	0.011
Error	9	4.1229	0.4581		
Total	15	13.7689			

Appendix 6.5 Analysis of Variance for *Bacillus* at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.039	0.346	0.35	0.793
Trt	3	5.664	1.888	1.89	0.202
Error	9	9.002	1.000		
Total	15	15.705			

Appendix 6.6 Analysis of Variance for *Actinomycetes* at 4 weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.9488	0.6496	2.00	0.184
Trt	3	9.0363	3.0121	9.28	0.004
Error	9	2.9218	0.3246		
Total	15	13.9068			

Appendix 6.7 Analysis of Variance for Other Bacteria Species at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.4343	0.8114	0.92	0.471
Trt	3	29.2914	9.7638	11.03	0.002
Error	9	7.9646	0.8850		
Total	15	39.6903			

Appendix 6.8 Analysis of Variance for Total Bacteria at 4 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.6415	0.5472	0.70	0.577
Trt	3	7.7547	2.5849	3.29	0.072
Error	9	7.0733	0.7859		
Total	15	16.4694			

Appendix 6.9 Analysis of Variance for *Bacillus* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	8.604	2.868	2.83	0.099
Trt	3	9.353	3.118	3.08	0.083
Error	9	9.118	1.013		
Total	15	27.075			

Appendix 6.10 Analysis of Variance for *Actinomycetes* at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	2.440	0.813	0.49	0.700
Trt	3	14.034	4.678	2.80	0.101
Error	9	15.051	1.672		
Total	15	31.525			

Appendix 6.11 Analysis of Variance for Other Bacteria Species at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.2777	0.4259	1.12	0.391
Trt	3	20.2533	6.7511	17.79	0.000
Error	9	3.4162	0.3796		
Total	15	24.9472			

Appendix 6.12 Analysis of Variance for Total Bacteria at 6 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.2669	0.0890	0.35	0.792
Trt	3	6.9947	2.3316	9.09	0.004
Error	9	2.3087	0.2565		
Total	15	9.5703			

Appendix 6.13 Analysis of Variance for *Bacillus* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	1.4561	0.4854	1.37	0.313
TRT	3	2.9539	0.9846	2.78	0.102
Error	9	3.1861	0.3540		
Total	15	7.5962			

Appendix 6.14 Analysis of Variance for *Actinomycetes* at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.136	0.045	0.04	0.988
TRT	3	16.442	5.481	5.06	0.025
Error	9	9.754	1.084		
Total	15	26.333			

Appendix 6.15 Analysis of Variance for Other Bacteria Species at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.0322	0.0107	0.02	0.997
TRT	3	13.3626	4.4542	7.40	0.008
Error	9	5.4199	0.6022		
Total	15	18.8148			

Appendix 6.16 Analysis of Variance for Total Bacteria at 8 Weeks after Solarization

Source	DF	SS	MS	F	P
Rep	3	0.3718	0.1239	0.43	0.737
Trt	3	6.9177	2.3059	8.00	0.007
Error	9	2.5955	0.2884		
Total	15	9.8849			

Appendix 7 Analysis of Variance for 5 Weeks After Crop Emergence

Appendix 7.1 Analysis of Variance for *Bidens pilosa* at 5 Weeks After Crop Emergence

Source	DF	SS	MS	F	P
Rep	3	54.69	18.23	0.94	0.462
Trt	3	528.19	176.06	9.05	0.004
Error	9	175.06	19.45		
Total	15	757.94			

Appendix 7.2 Analysis of Variance for *Galinsoga parviflora* at 5 Weeks After Crop Emergence

Source	DF	SS	MS	F	P
Rep	3	3.187	1.062	0.44	0.728
Trt	3	10.687	3.563	1.49	0.283
Error	9	21.562	2.396		
Total	15	35.438			

Appendix 7.3 Analysis of Variance for *Elusine indica* 5 Weeks After Crop Emergence

Source	DF	SS	MS	F	P
Rep	3	1.6875	0.5625	1.00	0.436
Trt	3	42.1875	14.0625	25.00	0.000
Error	9	5.0625	0.5625		
Total	15	48.9375			

Appendix 7.4 Analysis of Variance for *Oxalis latifolia* at 5 Weeks After Crop Emergence

Source	DF	SS	MS	F	P
Rep	3	14.688	4.896	0.83	0.510
Trt	3	28.187	9.396	1.59	0.258
Error	9	53.062	5.896		
Total	15	95.937			

Appendix 7.5 Analysis of Variance for weed fresh weight at 5 WACE

Source	DF	SS	MS	F	P
rep	3	0.5004	0.1668	0.92	0.470
trt	3	28.6245	9.5415	52.55	0.000
Error	9	1.6342	0.1816		
Total	15	30.7592			

Appendix 7.6 Analysis of Variance for Weed Dry Weight

Source	DF	SS	MS	F	P
rep	3	1.1335	0.3778	2.77	0.103
trt	3	21.1106	7.0369	51.61	0.000
Error	9	1.2271	0.1363		
Total	15	23.4712			

Appendix 8: Analysis of variance for yield components

Appendix 8.1 Analysis of Variance for Number of Flowers

Source	DF	SS	MS	F	P
Trt	3	475.00	158.33	8.15	0.003
Error	12	233.00	19.42		
Total	15	708.00			

Appendix 8.2 Analysis of Variance for Number of Pods

Source	DF	SS	MS	F	P
Trt	3	186.750	62.250	7.55	0.004
Error	12	99.000	8.250		
Total	15	285.750			

Appendix 8.3 Analysis of Variance for Number of Seeds Pod⁻¹

Source	DF	SS	MS	F	P
TRT	3	0.1875	0.0625	0.23	0.873
Error	12	3.2500	0.2708		
Total	15	3.4375			

Appendix 8.4 Analysis of Variance for Bean Yield

Source	DF	SS	MS	F	P
Trt	3	5.5724	1.8575	13.42	0.000
Error	12	1.6612	0.1384		
Total	15	7.2336			

Appendix 8.5 Analysis of Variance for bean plant fresh weight

Source	DF	SS	MS	F	P
Trt	3	1072.68	357.56	65.07	0.000
Error	12	65.94	5.50		
Total	15	1138.62			

Appendix 8.6 Analysis of Variance for bean plant dry weight

Source	DF	SS	MS	F	P
Trt	3	564.17	188.06	27.14	0.000
Error	12	83.15	6.93		
Total	15	647.32			

Appendix 8.7 Analysis of Variance for Leaf Area

Source	DF	SS	MS	F	P
Trt	3	1913822	637941	26.66	0.000
Error	12	287119	23927		
Total	15	2200941			

Appendix 9 Analysis of Variance for Disease Incidence

Appendix 9.1 Analysis of Variance for *Fusarium* incidence in Field Beans

Source	DF	SS	MS	F	P
Trt	3	1757.61	585.87	44.06	0.000
Rep	3	89.36	29.79	2.24	0.153
Error	9	119.67	13.30		
Total	15	1966.64			

Appendix 9.2 Analysis of Variance for Virus Incidence in Field Beans

Source	DF	SS	MS	F	P
Trt	3	18.528	6.176	0.76	0.543
Rep	3	110.965	36.988	4.56	0.033
Error	9	72.970	8.108		
Total	15	202.463			

Appendix 9.3 Analysis of Variance for Area Under Disease Progress Curves for *Fusarium* wilt disease

Source	DF	SS	MS	F	P
Trt/fus/	3	6.6019	2.2006	4.06	0.044
Rep	3	2.0845	0.6948	1.28	0.338
Error	9	4.8746	0.5416		
Total	15	13.5610			