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Effectiveness of integrated solarization technology in managing soil-borne pathogens and weeds in citrus seedlings under greenhouse conditions

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Abstract

Solarization Technology utilizes solar radiation to kill soil-borne pests, diseases, and weeds in an environmentally and eco-friendly way. In this study, we assessed the efficacy of integrating solarisation with sticky traps on two potting mixtures (sawdust and soil) for three Citrus species (*Citrus sinensis*, *C. reticulata,* and *C. limon*). Eight treatments were tested viz., non-solarized sawdust, non-solarized soil, solarized soil, solarized soil with sticky traps, non-solarized soil with sticky traps, non-solarized sawdust with sticky traps, solarized sawdust, and solarized sawdust with sticky traps, each replicated thrice and were arranged in a randomized complete block design (RCBD). Thirty sterilized seeds of each Citrus species were sown per treatment and monitored for one year in 2019. Analysis of variance (ANOVA) revealed a significant difference in weed control between the treatments at $p \leq 0.05$. Tukey's post hoc test showed weed growth differences between treatments with sawdust and ones with soil as media. More weeds grew in non-solarized soil (32%), compared to non-solarized soil with sticky traps (30%), solarized soil with sticky traps (21%), solarized soil (17%), and treatments with sawdust media did not allow weed growth (0%). A Kruskal Wallis test revealed a significant effect of treatments on the survival percentage of *Citrus* seedlings ($X_2 = 36.008$, df = 7, $p < 0.001$), mean of chewed leaves ($X_2 = 20.850$, df = 7, $p = 0.004$) and percentage levels of low chlorophyll ($X_2 = 21.073$, df = 7, $p = 0.004$) at the $p \leq 0.05$ level. Highest number of Citrus seedlings with folded leaves were observed in non-solarized sawdust with sticky traps (mean rank = 119.50), followed by non-solarized soil with sticky traps (112.22), and solarized sawdust (107.69), while the lowest in non-solarized sawdust (90.96), solarized soil (90.91), non-solarized soil (88.25), solarized sawdust with sticky traps (85.44) and lastly solarized soil with sticky traps (82.54). *Citrus* seedlings with sawdust media were observed to be nitrogen deficient (Mean ranks 118.43 - 141.63). Solarized soil with sticky traps had the least number of *Citrus* seedlings with leaf miner symptoms (Mean rank = 12.50). Therefore, solarized soil with sticky traps was the most suitable treatment for the control of soil-borne pathogens. Treatments with sawdust media effectively stopped weed growth while those with solarized soil media reduced their growth. Integration of sticky traps was very pivotal in the management of whiteflies and other honey dew secreting insects. We recommend a similar study under field conditions.

Keywords: Integrated-solarization-technology; Greenhouse; Soil-borne-pests; Diseases

1. Introduction

Development of sustainable agricultural methods by manipulating soil microbiota using soil and crop management practices is a basic tactic for improving crop production and management of plant diseases (Van Bruggen, 1995); (Yan *et al.*, 2022). Solarization as the name implies, utilizes solar energy and involves use of a layer of clear polythene or plastic to cover moist potting mix, in order to raise the potting mix temperatures for the control of soil-borne pests and

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diseases (Katan, 1976); (Krueger & Mcsorley, 2012). Where the term "potting mix" is used here, it can also be taken to include separate mix components and soil. Solarization is applied in the nursery potting mixes or their components. It is widely carried out by either steam sterilization (pasteurization) or by the use of fumigants (Augmentation of Soil Solarization Effects by Application of Solar-Heated Water,1989). However, these two techniques (steam sterilization and fumigants) are cumbersome. Steam sterilization requires a ready source of heat like fuel wood, charcoal. If continuously used, the forest cover which is aimed at mitigating climate change may end up being depleted. Conversely, fumigants are also not very reliable as they lead to water pollution, death of beneficial soil microorganisms and leave pesticide residues in tissues of food crops like fruits and vegetables which hinders their acceptability on the premium markets regulated by the European Union (Sturz & Christie, 2003). Solarization is applied mostly in dry season during very hot weather. It may also be applied in dry and short rainy season inside green house. It can take place in nursery beds, fields for weeding, greenhouses and is beneficial in a number of ways which include but not limited to the following:

Disease control by increasing temperatures to between 40 and 60 °C in potting mix during solarization which can greatly reduce or eradicate soil-borne diseases. Duration of exposure plays an important part in the control of such diseases, as the longer the high temperatures are maintained, the less is the likelihood that disease propagules will survive. Some of soil-borne pathogens so far investigated elsewhere that have been controlled by solarization include: *Fusarium oxysporium f.sp dianthi* (Fusarium wilt of carnations), *Meloidogyne spp*. (root knot nematodes), *Phytophthora spp*., *Pythium spp*., *Rhizoctonia solani* (damping-off and root rot pathogens), *Sclerotium rolfsii* (basal rot), and *Verticillium dahlia* (wilt disease).

Effective weed control which results into successful control of many annual and perennial weeds. Research shows that winter weeds are generally the most sensitive, while summer weeds are usually more resistant. Susceptibility is further influenced by both the soil type and moisture content. Based on work done elsewhere, weeds from the following genera have been effectively controlled by soil solarization: *Amaranthus spp.*, *Cynodon*, *Datura*, *Digitaria*, *Ipomoea*, *Oxalis*, *Solanum*, Sorghum, and others. This method of weed control provides an alternative to herbicide usage in the nursery, reducing the cost of hand-weeding pots and repeated chemical applications that are hazardous to the environment.

Increased growth response whereby plants grown in solarized potting mix soon after treatment have often benefited from improved seed germination, better stand establishment, improved plant height, early crop maturity, and increased yield (both fresh and dry weights). In Darwin, increased plant height and earlier flowering were observed in trials on tomato plants. Such increased growth responses are thought to be due primarily to the increase in soil nutrient availability, as a result of the breakdown of soil organic material. Concentrations of nitrogen increase with solarization. Whereas concentrations of Potassium, Phosphorous, Magnessium, Calcium, Chlorine, and sodium increase with solarization in some situations with a decrease in others. Concentrations of micronutrients are not clearly understood with solarization which calls for further studies.

There are 5 factors that need to be remembered when envisaging use of solarization technology:

- Transparent, not black, polyethylene plastic should be used, as this transmits most of the solar radiation.
- Solarization should be carried out during periods of high temperature and intense solar radiation (Krueger & Mcsorley, 2012).
- The mix should be kept moist during solarization period in order to improve heat conduction within the mix. The resting spores of plant pathogens are more sensitive under such conditions.
- The thinnest plastic possible should be used, as it is both cheaper and somewhat more effective in heating. Both 25 micron and 50 micron thick clear plastic can be used. The plastic sheeting should be kept in place for as long as possible. The plastic reduces the evaporation of soil moisture thus imitating a miniature green house.
- Using two layers of clear polyethylene plastic increases temperatures above those achieved with only a single layer of clear plastic. A fifteen centimeter air space between the two layers is currently recommended but this optimum distance has not been fully investigated. A metal frame to support the second layer of plastic is ideal. This second layer acts as added insulation, trapping the heat more effectively.

It is justified that there is no any current environmentally friendly approach tested and applied for managing the following illustrated biotic challenges (see Fig. 1A-I) hampering production of *Citrus* seedlings in the green house of the National Forestry Resources Research Institute, Kifu, Mukono, Uganda. This has resulted into production of seedlings struggling with pests and diseases and which consequently hampers their quality and productivity. There are also high costs on inorganic pesticides and fungicides which are hazardous to both human health and the environment when used repeatedly. The illustrations in Fig. 1A-I show some of the biotic challenges of Citrus production observed at NaFORRI in 2019 which our novel innovative technology described in this study intended to address.

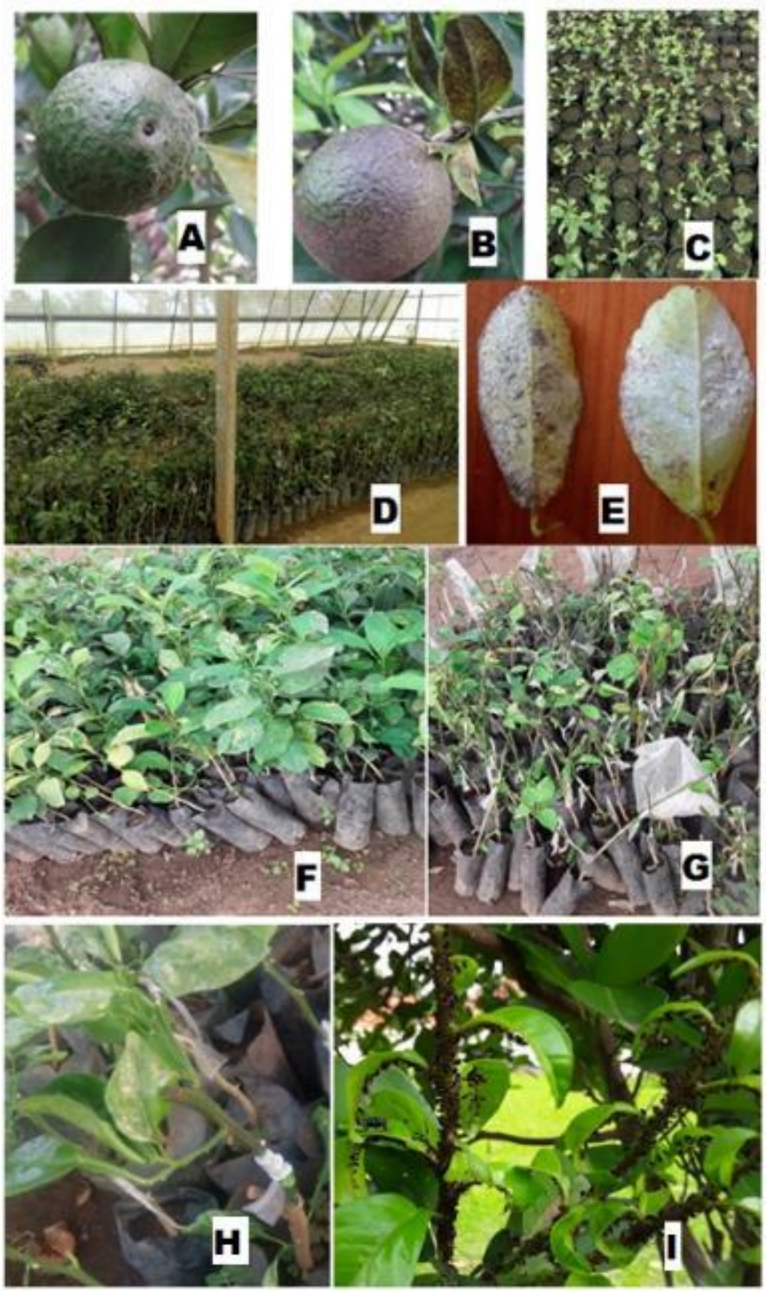

Figure 1 Biotic challenges (pests and Diseases) that our study intended to address: A- Citrus scab on Citrus fruit; B- Sooty moulds on Citrus fruit; C- Citrus scab on very young Citrus seedlings; D- Sooty moulds on Citrus seedlings; E- Citrus wooly whiteflies; F- Citrus scab on Citrus leaves; G- Citrus scab on grafted Citrus seedling leaves; H- leaf miner on grafted Citrus seedling leaves; I- aphids on leaves of mature Citrus plant (Courtesy photo of Ronald Kisekka at NaFORRI, Kifu in 2019)

2. Materials and methods

2.1. Study area

This experiment was conducted inside greenhouse located on coordinates; Longitude: E 032^{0} 45.592′, Latitude: N 00^{0} 27.224′ and elevation of 1188 m asl at the National Forestry Resources Research Institute (NaFORRI), Kifu. This is one of the Public Agricultural Research Institutes (PARIs) under the National Agricultural Research Organization (NARO) in Uganda. It is located 12 km along Kayunga-Bugerere road from Mukono Municipality.

2.2. Materials

Materials used in this study included 360 *Citrus* seeds of 3 different species (sweet orange or *Citrus sinensis*, Mandarin orange or *C. reticulata* and Lemon or sour orange or *C. limon*) sown on sawdust as their growth media (90 potted bags each of solarized sawdust with or without sticky traps and non-solarized sawdust with or without sticky traps) and 360 *Citrus* seeds of 3 different species (*C. sinensis*, *C. reticulata* and *C. limon*) sown on soil as their growth media (90 potted bags each of solarized soil with or without sticky traps and non-solarized soil with or without sticky traps), seed sterilants or sodium hypochlorite (household bleach or Jik), blue and yellow commercially available and locally fabricated sticky traps, transparent polythene sheeting (180 microns), potting bags, hand lenses, poles, nails, hammer, ropes, manila, Vaseline jelly, black marker pen, water, watering cans, the lid of a pen and punching machine.

2.3. Development and testing different innovative approaches of IST for the control of soil-borne pathogens and weeds in *Citrus* species under GHC

2.3.1. Solarization of growth media

Figure 2 Steps of solarisation used in the experiment. A- Assembling of platform for supporting potting bags; B- aligning of potting bags in the platform; C- Thorough watering of potting media in the potting bags; D- covering of some of the potting media in the potting bags with transparent polythene for solarisation to happen leaving out controls; E- water droplets as a result of solarisation in a miniature greenhouse formed.

The following procedures were applied in the implementation of an experiment involving both solarized or non-solarized sawdust and soil integrated with both commercially available and locally fabricated blue and YST. There was setting up a platform for supporting the potting bags. This was made using eucalyptus poles, nails, and a hammer as illustrated in Fig. 2A below.

There was an assembling of potting bags with either soil or sawdust. These were firmly held on the platform above by ropes as demonstrated in Fig. 2B above.

2.4. Experimental design on the assembled platform

The platform was divided into three blocks which at the same time acted as the replicates (Block 1= Replicate 1, Block 2= Replicate 2, Block 3= Replicate 3). In these blocks, there were eight treatments which were assigned letters $T_{1\text{-}8}$, representing different treatments as shown below: T_1 = non-solarized sawdust, T_2 = solarized soil, T_3 = non-solarized soil, T_4 = solarized soil integrated with sticky traps, T_5 = non-solarized soil integrated with sticky traps, T_6 = non-solarized sawdust integrated with sticky traps, T_7 = solarized sawdust and T_8 = solarized sawdust integrated with sticky traps. The experimental design was laid on-station inside NaFORRI's greenhouse in an RCBD as illustrated in the table 1 below:

Table 1 Illustration of an Experimental design for our innovated integrated solarization Technology being investigated in this study

T	**BLOCK 1 = REPLICATE 1, n = 30**	**BLOCK 2 = REPLICATE 2, n = 30**	**BLOCK 3 = REPLICATE 3, n = 30**	**Sizes (n_1....n_8)**
T_1	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	90
T_2	BLOCK 1 = REPLICATE 1, n = 30	BLOCK 2 = REPLICATE 2, n = 30	BLOCK 3 = REPLICATE 3, n = 30	90
	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	
T_3	BLOCK 1 = REPLICATE 1, n = 30	BLOCK 2 = REPLICATE 2, n = 30	BLOCK 3 = REPLICATE 3, n = 30	90
	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	
T_4	BLOCK 1 = REPLICATE 1, n = 30	BLOCK 2 = REPLICATE 2, n = 30	BLOCK 3 = REPLICATE 3, n = 30	90
	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	
T_5	BLOCK 1 = REPLICATE 1, n = 30	BLOCK 2 = REPLICATE 2, n = 30	BLOCK 3 = REPLICATE 3, n = 30	90
	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	
T_6	BLOCK 1 = REPLICATE 1, n = 30	BLOCK 2 = REPLICATE 2, n = 30	BLOCK 3 = REPLICATE 3, n = 30	90
	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	
T_7	BLOCK 1 = REPLICATE 1, n = 30	BLOCK 2 = REPLICATE 2, n = 30	BLOCK 3 = REPLICATE 3, n = 30	90

	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	
T_8	BLOCK 1 = REPLICATE 1, n = 30	BLOCK 2 = REPLICATE 2, n = 30	BLOCK 3 = REPLICATE 3, n = 30	90
	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	$S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1$ $S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2$ $S_3 S_1 S_2 S_3 S_1 S_2 S_3 S_1 S_2 S_3$	
Total sample size (N)				720

In the design, S_1, S_2, S_3 were the different *Citrus species* tested in the experiment (S_1= sweet orange a.k.a *C. sinensis*; S_2= Mandarin orange a.k.a *C. reticulata* and S_3 = Lemon or sour orange a.k.a *C. limon*); n_1, n_2, n_3…………n_8 were the sample sizes of 3 different replicates of the different treatments ($T_{1\text{-}8}$). The replicates were at the same time serving as the blocks in the experiment.

There was minimization of extraneous sources of variation and this involved the following steps: (a) Pre-sowing treatment of *Citrus* seeds by soaking them in a seed sterilant particularly Sodium hypochlorite (household bleach or Jik) to remove possibilities of seed-borne pathogens, (b) replication, (c) randomization, (d) making the soil and sawdust uniform by separately mixing them thoroughly well, and (e) selection of a site with even distribution of light in the green house where the experiment was laid.

There was thorough wetting of the soil and sawdust in their potting bags as shown in Fig. 2C above. This was followed by cutting and covering the selected treatments with double layered transparent polyethylene of 180 microns leaving out treatments without covered transparent polyethylene which were used as the controls in the experiment as demonstrated in Fig. 2D above. The entire experiment was left to stand for 8 weeks, the recommended optimum duration during solarization process. There was induction of heat which created water vapour on the surfaces of transparent polythene sheeting to form a miniature green house as shown in Fig. 2E above.

The transparent polyethylene was then removed and the potted soil and sawdust were thoroughly wetted with tap water using watering cans. However, it should be noticed that a germination test which involves soaking *Citrus* seeds in sterile water and choosing only sunk ones was not performed. This implies that survival percentage of *Citrus* seedlings was not fundamental to be considered among the important criteria for assessing the best performing (recommended) treatments in the designed experiment. The *Citrus* seeds of different species were sown in the order as guided by the experimental design (layout) in table 1 above.

There was immediate integration of two each of locally fabricated and commercially available yellow and BST in the experiment to avoid any cross infection by incoming insects which tend to prefer tender leaves due to their softness for easy piercing by their mouth parts. The local traps were mounted immediately next to the commercially available insect sticky traps of the same colour in all treatments of the experiment where they were integrated for easy comparison of their efficacy in capturing insects and/or other pests important in *Citrus* production indoor.

2.5. Pre-sowing treatment of seeds with Sodium hypochlorite

Seeds of *Citrus species* were first pre-treated before sowing to eradicate possibilities of seed-borne pathogens. This was done by dipping them for fifteen minutes in a solution of 3.85% m/v Sodium hypochlorite and distilled water in a ratio of 1:7.

2.6. Sowing *Citrus* seeds in potted soil and sawdust under GHC

Sowing of three species of *Citrus* (*C. sinensis*, C. *reticulata* and *C. limon*) was done on 18th June 2019. This followed removing of white transparent polyethylene from the solarized potted soil and sawdust on 17th June 2019 after eight weeks of solarization and watering thoroughly the entire experiment. The *Citrus* seeds were sown in a RCBD. This was achieved by making small holes in potted soil and sawdust using a lid of pen, inserting one seed in each and covering with a thin layer of soil or sawdust which was twice the smallest diameter of the *Citrus* seed. From one treatment to another, there was sterilization of the lid of pen used in creating holes in the middle of the potting bags by dipping it in household bleach (sodium hypochlorite) before being reused to avoid contamination. Watering of pots was done regularly only in the morning hours to avoid overwatering and to give more time for the soil and sawdust to dry in order to avoid high humidity during prolonged hours of the night, a factor which could promote infection by damping-off pathogens like *Pythium*, *Phytophthora*, *Rhizoctonia*, *Fusarium* and others.

2.7. Integration of sticky traps in the experiment

Locally fabricated and commercially available blue and yellow sticky traps (YST) were integrated in the solarized and non-solarized potting media in the designed experiment on 21st June 2019, only three days after sowing *Citrus* seeds and clearly before their germination. This intended to monitor any incoming insects or pests some of which are known vectors of different pathogens like damping-off (fungus gnats), *Citrus* greening (Asian Citrus psyllids), Citrus scab (psyllids), sooty moulds (all honey dew secreting insects) and many others. Young tender leaves are very soft and hence highly prone to infestation by insects which further prompted pre-emergence mounting of sticky traps in the experiment as an innovative approach of the IST that aimed at regulating flying insects or pests.

2.8. Innovative approach of developing locally fabricated sticky traps as one tactic in IST

Yellow and blue coloured manila were cut into rectangular cards with dimensions of 26 cm by 10 cm. The cards were divided into quadrats using black marker pen on both sides. They were then perforated by a punching machine to create three holes and one hole at the top and bottom respectively to imitate the commercially available sticky traps. Colourless or transparent and odourless vaseline or petroleum jelly was smeared on both surfaces of the rectangular cards as the adhesive or attractant for insects leaving a small area on top for easy handling.

2.9. Determining the efficacy of commercially available and locally fabricated blue and yellow insect sticky traps as integral innovative approaches in IST under GHC

Efficacy of different traps was assessed by mounting ten traps each of the locally fabricated and commercially available blue and YST in another on-station greenhouse containing severely infested seedlings of *Citrus* with high population of insects and other pests (Fig. 3B). The sticky traps were installed in a zig-zag pattern and these were monitored for pest populations on a weekly basis using a hand lens (Fig. 3A). There was no counting of all insects on the entire trap but counting the insects was made only in a vertical column that is 1 inch (2.5 cm) wide on both sides of the trap which gave results that represented the entire trap as according to Heinz *et al*., 1992. The obtained insect numbers were scored using an arbitrary scale of 0-4 during assessment of pest populations on different sticky traps for comparison purposes as according to Boll *et al*., 2002. Average scores were then computed and used to evaluate the comparative performance of the different insect sticky traps.

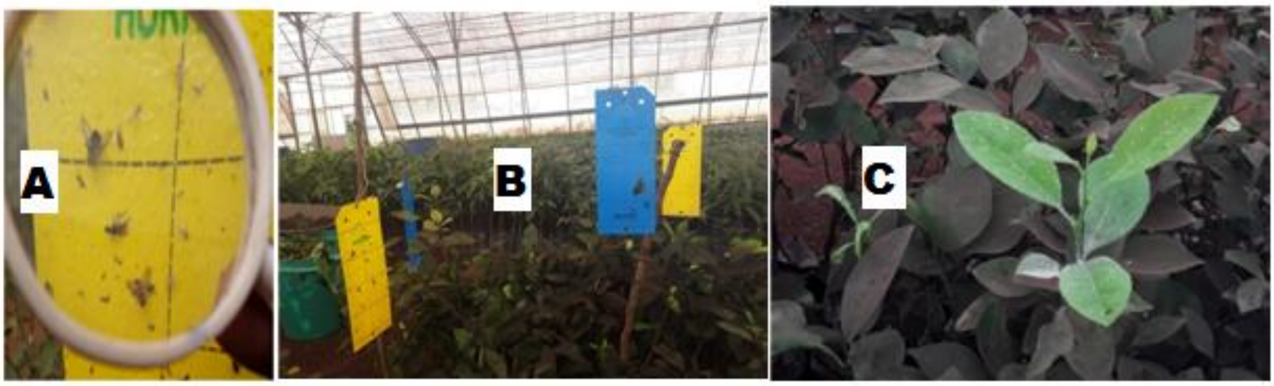

Figure 3 A- Hand lens used in magnification of insects on commercially available YST prior to their scoring and identification; B- Experimental set-up for comparing the efficacy of commercially available versus locally fabricated sticky traps in regulating high abundance of insects on infected Citrus seedlings under GHC; C- Citrus having high population of insects on which assessment of accuracy of insect sticky traps was done

2.10. Determining the effectiveness of different treatments of IST in managing soil-borne pathogens and weeds under GHC

There was assessment of the performance of the germinating *Citrus* seeds by taking relevant measurements for example survival percentage, pests and disease incidences (folded leaves, chewed leaves, leaf miner symptomatic plants and whiteflies infested *Citrus*) and percentage of *Citrus* seedlings with low chlorophyll levels. Weed specimens were also collected (Fig. 5) from different treatments of IST, identified and quantified using magnifiers like hand lens (Fig. 3A) and microscope.

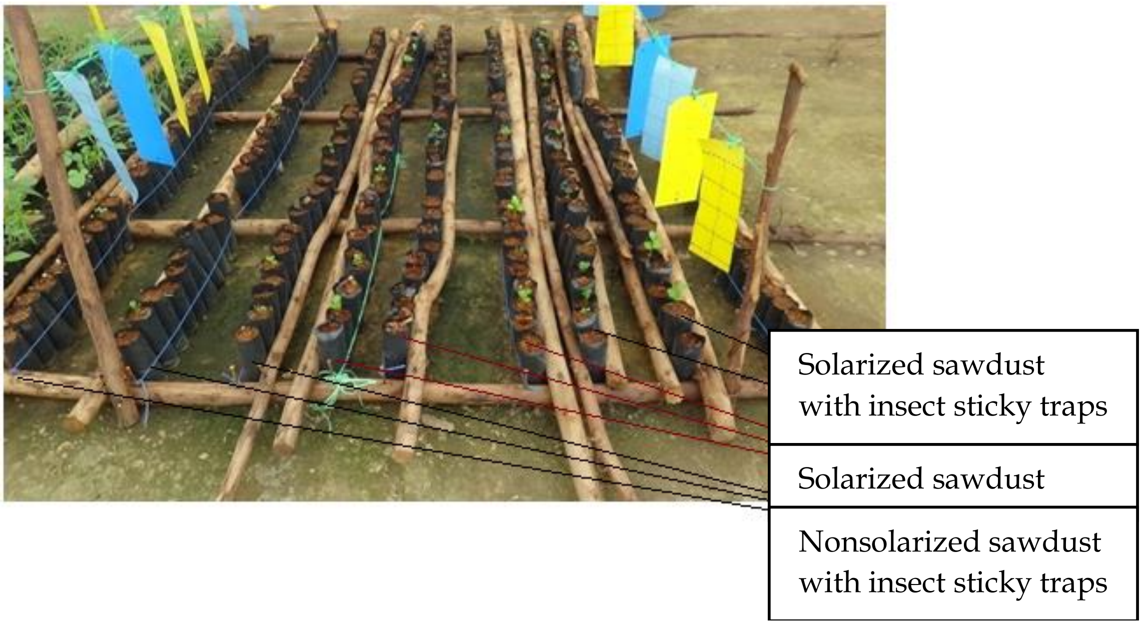

Figure 4 Demonstration of resistance to weeds by some of the treatments with sawdust in their design in the ISE conducted under GHC

Figure 5 Some of the collected weed specimens from some treatments in the ISE for establishment of their populations and subsequent identification

2.11. Data Analysis

Data analysis was carried out using SPSS software. Logarithmic transformation was performed on data to qualify it for some parametric tests. For data that violated the assumptions of normality, nonparametric tests like a Kruskal Wallis test was used to determine the mean ranks of performance of different treatments under different assessment criteria. Modeling the influence of treatments and replication on the percentage survival and healthy of *Citrus* seedlings grown under GHC was done using regression analyses.

3. Results and discussions

3.1. Effectiveness of different treatments in the IST in managing soil-borne pathogens

Data violated the assumptions for normality, homoscendasticity for example the homogeneity of variance test (with p > 0.05) justifying use of a nonparametric test during analysis. Data was then analyzed using a Kruskal Wallis test which revealed a significant effect of treatments on the: (a) survival percentage of *Citrus* seedlings (X_2 = 36.008, df = 7, p = 0.000), (b) average number of chewed leaves (a biotic factor) (X_2 = 20.850, df = 7, p =0.004) and (c) percentage levels of low chlorophyll (an abiotic factor) (X_2 = 21.073, df = 7, p =0.004) at the p ≤ 0.05 level of significance. However, this was not the case on the: (a) number of folded leaves (a biotic factor) (X_2 = 11.426, df = 7, p =0.121), (b) number of dried leaves (a biotic factor) (X_2 = 4.339, df = 7, p =0.740), (c) number of whiteflies (a biotic factor) (X_2 = 0.867, df = 2, p =0.648) and (d) leaf miner (a biotic factor) (X_2 = 1.320, df = 7, p =0.988) at the p ≤ 0.05 level of significance. The average survival performance of *Citrus* seedlings in all the 8 treatments assessed in the integrated solarization experiment (ISE) was 31.88% with a standard error of 2.02. This low average survival performance was probably attributed to the nitrogen deficiency syndrome in all the treatments within the experimental layout of IST which had undecomposed sawdust in their design. Also, the omission of performance of a germination test on *Citrus* seeds prior to their sowing in the experiment explains the low survival rate. The average survival performance of 31.88% translated into an average survival frequency of 9.58 out of every 30 *Citrus* seedlings with a standard error of 0.61. The overall average pest abundance was 0.46 with a standard error of 0.17. On average, only 1.00 *Citrus* seedling had damping-off, 1.80 *Citrus* seedlings had folded leaves, 0.60 *Citrus* seedlings had dried leaves, 0.71 whiteflies existed, 3.50 leaf miner existed and on average, the low percentage chlorophyll levels were on 11.01 *Citrus* seedlings. From mean plots and mean ranks, the non-solarized sawdust with sticky traps had the highest survival rate (mean rank = 171.05) although *Citrus* seedlings exposed to this treatment were nitrogen deficient and their leaves expressed patent symptoms of low chlorophyll levels. The non-solarized soil with sticky traps had the second highest survival rates of *Citrus* seedlings (mean rank = 138.92). These were followed by treatments of non-solarized soil (mean rank = 138.77) and solarized soil (mean rank = 128.75). Then solarized sawdust (mean rank = 103.00) although this treatment equally had *Citrus* seedlings with leaves expressing nitrogen deficiency symptoms. Solarized sawdust integrated with sticky traps (mean rank = 100.52) and treatment with non-solarized sawdust (mean rank = 95.50) followed, however, nitrogen deficiency was still a constraint in these two treatments as well. Finally, solarized soil integrated with sticky traps had the lowest survival percentage (mean rank = 87.50) but in the most ideal health condition (status) that is to say with pests and disease-free *Citrus* seedlings which forms a fundamental criterion for the assessment of the best recommended treatment(s) in the entire experimental layout of the IST demonstrated in this study. The nitrogen deficiency syndrome is an abiotic condition that was universal in all treatments that had undecomposed sawdust (sawdust in its raw form) in their design. However, as time lags happened, sawdust started decomposing and chlorotic leaves of some *Citrus* seedlings attained normal green colour (see Fig. 6). Another cause of low survival percentages is presumed to be the exclusion of a germination test on the *Citrus* seedlings which were sown in the entire experiment. There existed a probability or likelihood that the treatment of solarized soil integrated with sticky traps got majority of unviable *Citrus* seeds and this negatively impacted their survival performance during the assessment. Consequently, the survival performance of *Citrus* seedlings was neglected among the criteria for assessment of the best recommendable treatment(s) due to the aforementioned justification. In this study, the choice was exclusively made based on performance in the health status of *Citrus* seedlings under different treatments. Analyses of the health status of seedlings revealed that treatment 6 (T_6) of non-solarized sawdust with sticky traps (mean rank = 119.50), treatment 5 (T_5) of non-solarized soil with sticky traps (mean rank = 112.22), and treatment 7 (T_7) of solarized sawdust (mean rank = 107.69) had the highest number of *Citrus* seedlings with folded leaves in that descending order. These were followed by treatment 1 (T_1) of non-solarized sawdust with mean rank 90.96, treatment 2 (T_2) of solarized soil with mean rank = 90.91, treatment 3 (T_3) of non-solarized soil with mean rank 88.25, treatment 8 (T_8) of solarized sawdust with sticky traps with mean rank 85.44 although the *Citrus* seedlings in all the treatments with sawdust in their design had leaves expressing nitrogen deficiency symptoms rendering them to be horrific choices. Finally and very important to notice, treatment 4 (T_4) of solarized soil integrated with sticky traps had the lowest number of *Citrus* seedlings with folded leaves (mean rank = 82.54) which forms one of the basic criteria for its suitability as the best treatment. Treatment 8 (T_8) of solarized sawdust with sticky traps had the highest number of *Citrus* seedlings with dried leaves (mean rank = 96.73). This was followed by three other treatments which had negligible and almost equal number of *Citrus* seedlings with dried leaves (treatment 4, T_4 of solarized soil integrated with sticky traps with mean rank 93.96, treatment 3, T_3 of non-solarized soil with mean rank 93.12 and treatment 5, T_5 of non-solarized soil integrated with sticky traps with mean rank 92.25). Other two treatments followed the latter with almost the same number of *Citrus* seedlings with dried leaves (treatment 7, T_7 of solarized sawdust with mean rank 88.39 and treatment 2, T_2 of solarized soil with mean rank 86.17). In this category, treatments 6 (T_6) of non-solarized sawdust integrated with sticky traps and 1 (T_1) of non-solarized sawdust had the lowest number of *Citrus* seeds with dried leaves with mean ranks 81.83 and 74.31 respectively. For leaf miner which is well known to cause significant damage and economic losses in *Citrus* seedlings, treatments 3, 2, 8, 1 and 7 had the highest number of

Citrus seedlings with leaf miner symptoms in that descending order with mean ranks 17.17, 16.50, 16.33, 15.17 and 14.00 respectively. On the other hand, treatments 6 (T_6) of non-solarized sawdust with sticky traps), 4 (T_4) of solarized soil with sticky traps and 5 (T_5) of non-solarized soil with sticky traps had the lowest number of *Citrus* seedlings expressing leaf miner symptoms in that descending order with mean ranks of 13.67, 12.50 and 12.33 respectively. This formed a second important criterion upon which the best recommended treatment(s) were chosen since leaf miner is a pest of significant importance on the productivity of *Citrus* seedlings both in green house and field conditions. This implies that treatments of non-solarized soil with sticky traps, solarized soil with sticky traps and non-solarized sawdust with sticky traps were the best in regulating leaf miner in *Citrus* seedlings in that order. However, since the non-solarized sawdust integrated with sticky traps equally supported *Citrus* seedlings with leaves expressing nitrogen deficient symptoms, then treatments of non-solarized soil with sticky traps and solarized soil with sticky traps are the best two treatments recommended for managing leaf miner in *Citrus* farming and under GHC. Chewing is another symptom of insect attack in *Citrus* which was assessed in this study and it is as a result of insects with chewing mouth parts imposing damage on leaves. This results into defoliation and consequently poor productivity of *Citrus* seedlings. Analysis of data revealed that treatments 4 (T_4) of solarized soil with sticky traps, 8 (T_8) of solarized sawdust with sticky traps and 6 (T_6) of non-solarized sawdust with sticky traps were the best three treatments for regulating insects with chewing mouth parts in causing damage to *Citrus* seedlings with mean ranks of 66.70, 81.25 and 84.26 respectively in that ascending order. The most horrible treatments in regulating the chewing damage symptoms of *Citrus* leaves were 3 (T_3), 5 (T_5), 1 (T_1), 2 (T_2) and 7 (T_7) in that order with mean ranks of 99.27, 101.48, 107.10, 109.04 and 121.87 respectively. It is therefore from this analysis that solarized soil with sticky traps is the best recommended treatment with regard to managing damage in *Citrus* seedlings caused by insects with chewing mouthparts. Whiteflies are known as sap-sacking insects which consequently lead to loss of plant vigor. They prefer lower surface of leaves for their rest and feed. Whiteflies tend to secrete honey dew, a substrate for growth of a black fungus known as sooty molds on leaves, stems and other surfaces of seedlings resulting in reduced photosynthesis. The analysis revealed only three treatments that had the highest number of *Citrus* seedlings with whiteflies. These are treatments: 3 (T_3) of non-solarized soil, 2 (T_2) of solarized soil, and 1 (T_1) of non-solarized sawdust with mean ranks of 9.50, 7.17 and 7.17 respectively. This therefore confirms that the integration of sticky traps is pivotal in the management of whiteflies and other honey dew-secreting insects since all the treatments where they were observed lacked sticky traps in their design. Nitrogen is a well-known nutrient that is very fundamental in the synthesis of chlorophyll in the leaves of plants. This gives them the normal conciliatory green colour. Analysis of data revealed that treatments: 1 (T_1) of non-solarized sawdust, 8 (T_8) of solarized sawdust with sticky traps, 3 (T_3) of non-solarized soil, 2 (T_2) of solarized soil, 6 (T_6) of non-solarized sawdust with sticky traps and 7 (T_7) of solarized sawdust had the highest percentage of *Citrus* seedlings expressing low chlorophyll levels which is reflected by their high mean ranks of 141.63, 137.48, 120.67, 119.82, 118.43 and 114.65 respectively. On the other hand, treatments: 4 (T_4) of solarized soil with sticky traps and 5 (T_5) of non-solarized soil with sticky traps had the lowest number of *Citrus* seedlings with low chlorophyll levels in their leaves with mean ranks of 100.62 and 110.70 respectively. Generally, treatments with sawdust resulted into *Citrus* seedlings with low chlorophyll levels in their leaves. This is because they had low organic matter as they were used in their undecomposed forms. If sawdust is to be used as a potting media, it is highly recommended to mix NPK, urea, DAP, or CAN in a ratio favouring higher Nitrogen compared to other nutrients in all sawdust containing treatments demonstrated in this study for better results. Alternatively, organic fertilizers like animal manure, green manure, plant compost can be mixed with sawdust before being used for *Citrus* seedlings production. Several previous studies revealed that solarization can also be integrated with a wide range of organic amendments, such as composts, crop residues, green manures and animal manures and inorganic fertilizers to increase the pesticidal effect of the combined treatments (*Ramirez-Villapudua, 1987*, n.d.);Gamliel, 1993b; Gamliel, 1993a; Chellemi *et al*., 1997). Alternatively, sawdust should be left to stand for a longer period to give enough time for decomposition before sowing *Citrus* and/or any other seeds when used as the potting media. This would be intended to provide enough organic matter to enable growth of Citrus seedlings with high growth vigour. This argument is supported by findings from previous studies like “Augmentation of Soil Solarization Effects by Application of Solar-Heated Water,” 1989 who had suggested that adding suitable organic residues to the soil may enhance the benefits of solarization. Studies by Ramirez-Villapudua and Munnecke, 1985 and Chellemi *et al*., 1997 also supported the hypothesis by “Augmentation of Soil Solarization Effects by Application of Solar-Heated Water,” 1989; 一般社団法人日本リウマチ学会, 2019 and hence in agreement with our own recommendation of allowing decomposition of sawdust prior to sowing *Citrus* seeds since both aim at enhancing organic matter in the different potting media.

Figure 6 Initially chlorotic/ Nitrogen-deficient Citrus seedling (see encircled) turning green due to decomposition of sawdust potting media

Ramirez-Villapudua and Munnecke, 1985; Chellemi *et al*., 1997 portrayed that both solar heating alone and cabbage amendments reduced soil-borne populations of *Fusarium oxysporum f. sp. conglutinans*, but these treatments were not as effective as the combination of the two treatments. They indicated that a tarp is necessary not only to increase the temperature of soil to critical levels, but also to trap fungitoxic gases coming from cabbage amendments. Greenberger *et al*., 1987 had suggested that suppressiveness in solarized soils may result from a shift in microbial populations in favour of heat-resistant antagonists. This factor and the possibility of chemical breakdown products from green manure residues may provide an even wider variety of additional interactions leading ultimately to the control of many soil-borne pathogens under conditions that are currently considered to be marginal for the effective practice of solarization. From analysis made in this study concerning chlorophyll concentration (levels) in leaves of *Citrus* seedlings under different treatments, it was imperative that treatment 4 (T_4) of solarized soil with sticky traps supported the highest number of *Citrus* seedlings with leaves expressing normal chlorophyll levels which is very fundamental in their photosynthetic abilities and consequently productivity compared to treatment 5 (T_5) of non-solarized soil with sticky traps and other treatments. Five out of six analyses made regarding the health status (a fundamental criterion used in their assessment) of *Citrus* seedlings sown in 8 different treatments concur that treatment 4 (T_4) of solarized soil integrated with sticky traps is the best recommendable treatment in the raising of pests and disease-free *Citrus* seedlings of high growth vigour under GHC.

3.2. Effect of different treatments in the IST on growth of weeds

Solarized sawdust, solarized sawdust with sticky traps, non-solarized sawdust and non-solarized sawdust with sticky traps demonstrated to be the best treatments for managing weeds among all the treatments tested in the ISE as they never supported growth of any weeds (their weed frequency (WF) was 0, (see Fig. 7 and Fig. 8). In contrast, all the treatments with soil in their design demonstrated some degree of weed growth with solarized soil having supported growth and consequently survival of the lowest percentage of weeds, i.e. only 17% (with WF of 116). This was followed by solarized soil with sticky traps which supported growth of 21% weeds (with WF of 138), non-solarized soil with sticky traps that supported growth of 30% weeds (with WF of 198), and lastly non-solarized soil which supported growth of the highest percentage of weeds, i.e. 32% (with WF of 216)(Fig. 7 and Fig. 8). Solarized soil mostly supported growth of *Setaria viridis* (WF = 28), followed by *Cynodon dactylon* (a.k.a Couch grass; Family Poaceae) (with WF of 18), and *Euphorbia hirta* (a.k.a Asthma-plant; Family Euphorbiaceae) (WF = 17). The least supported weed species by solarized soil included: *Commelina benghalensis* (a.k.a *wandering jew;* Family Commelinaceae) (WF = 7), *Abelmoschus esculentus* (a.k.a Okra weed*; Family* Malvaceae) (WF = 7), *Amaranthus spp.* (a.k.a pigweed or dodo; Family Amaranthaceae) (WF = 5), *Chenopodium album* (a.k.a Empunika (Rukiga), lamb's quarters, melde, goosefoot, manure weed, fat-hen and Pigweed; Family Amaranthaceae) (WF = 4), *Epimedium spp.* (a.k.a Horny Goat Weed or Barren wort plant*; Family* Berberidaceae) (WF = 2), *Chromolaena odorata* (a.k.a Efugwe (Rukiga); Family Asteraceae or Compositae) (WF = 2), *Sida cordifolia* (Family Malvaceae) (WF = 2), *Lactuca serriola* (a.k.a **Wild Lettuce;** Family Asteraceae) (WF = 2), *Senna occidentalis* (Omwitajoka (Rukiga), 'au'auko'i in Hawaii, septic weed, coffee senna, coffee weed, Mogdad coffee, negro-coffee, senna coffee, Stephanie coffee, stinking weed or styptic weed; Family Fabaceae or Leguminosae) (WF = 1), *Aerva lanata* (WF = 1) and *Galinsoga parviflora* (a.k.a guasca (Colombia), mielcilla (Costa Rica), galinsoga (New Zealand), gallant soldier, quick weed, and potato weed (United Kingdom, United States); Family Asteraceae). Non-solarized soil supported growth of more *Setaria viridis* (a.k.a Wild millet, Bottle grass, Green bristle grass, Green foxtail or Pigeon grass; Family Poaceae) (WF = 53), followed by *Chenopodium album* (WF = 52), *Euphorbia hirta* (WF = 17), *Cyperus rotundus* (coco-grass, Java grass, nut grass, purple, nut sedge or purple nutsedge, red nut sedge, Khmer kravanh chruk; Family Cyperaceae) (WF = 16), *Cynodon dactylon* (WF = 14), *Amaranthus spp.* (WF = 12), *Abelmoschus esculentus* (WF = 10), *Commelina benghalensis* (WF = 7), *Aerva lanata* (WF = 6), *Epimedium spp.* (WF = 5), *Bidens pilosa* (a.k.a Black jack; Family Asteraceae) (WF = 5), *Sida cordifolia* (WF = 3), *Ageratum houstonianum* (a.k.a ageratum, billygoat crofton, billygoat weed, blue billy goat weed, blue top, bluemink, bluetop, dark bluetop, floss flower, flossflower, garden ageratum, goatweed, invading ageratum, Mexican ageratum, Todd's curse, tropic ageratum; Family Asteraceae) (WF = 3), *Chromolaena odorata* (WF = 2), *Senna occidentalis* (WF = 2), *Galinsoga parviflora* (WF = 2), *Calliandra spp.*, *Solanum nigrum* (a.k.a Nightshade/ Ensugga/ or blackberry *nightshade/* black nightshade; Family Solanaceae), *Ageratum conyzoides* (Namirembe (Luganda), billy goat-weed, chick weed, goatweed, whiteweed, ageratum, invading ageratum, chickweed, adwolo (Lango), kimavi cha kuku (Kiswahili), gathenge (Kikuyu); Family Asteraceae) (WF = 1). Non-solarized soil with sticky traps supported the growth of more *Setaria viridis* (WF = 55), followed by Bahunika (Rukiga) (WF = 42), *Cynodon dactylon* (WF = 22), *Euphorbia hirta* (WF = 19), *Amaranthus spp.* (WF = 13), *Cyperus rotundus* (WF = 9), *Ageratum conyzoides* (WF = 8), *Commelina benghalensis* (WF = 7), *Epimedium spp.* (WF = 5), *Ageratum houstonianum* (WF = 4), *Abelmoschus esculentus* (WF = 3), *Sida cordifolia* (WF = 2), *Aerva lanata* (Family Amaranthaceae), *Bidens pilosa*, *Euphorbia heterophylla* (fire plant, painted *euphorbia*, Japanese poinsettia, desert poinsettia, wild poinsettia, fire on the mountain, painted leaf, painted *spurge*, milkweed, and kaliko plant; Family Euphorbiaceae) (WF = 1) (see Fig. 9). Related field experiments by Katan, 1976 found that mulching for four to five weeks resulted in a significant reduction in both the incidence and severity of Verticillium wilt in eggplant. Additionally, the eggplants showed an increased growth response with an increase of 38 percent in plant height and a 26 percent increase in plant stand compared with non-mulched plots. They also observed almost complete control of several weed species in the mulched plots. Their findings agree with the findings in our study which revealed that solarization regulated weed growth as shown in Figures 7, 8, and 9.

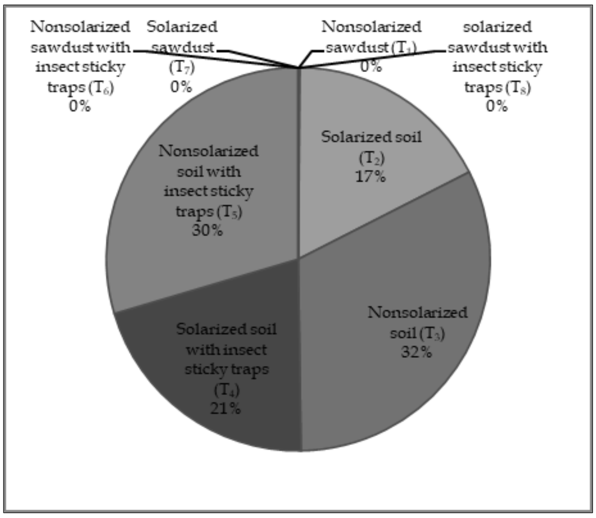

Figure 7 Pie-chart showing survival percentage of weeds in all the treatments of the ISE conducted under GHC

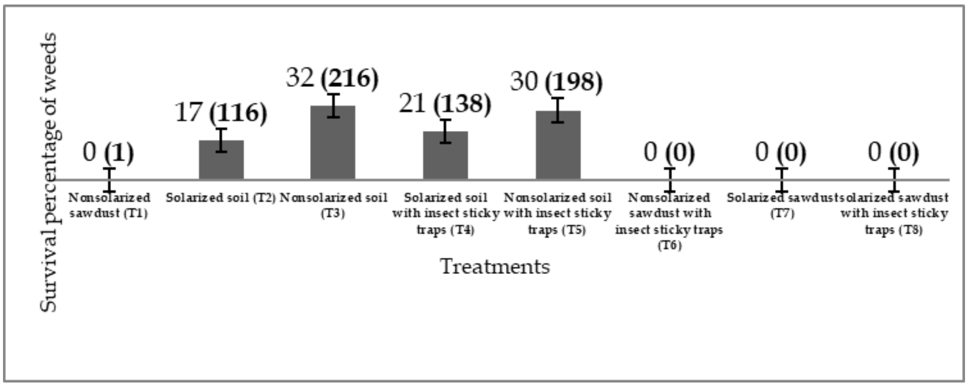

Figure 8 Percentage of weeds in the different treatments of ISE. In parentheses are frequencies of the weeds (WF) in different treatments

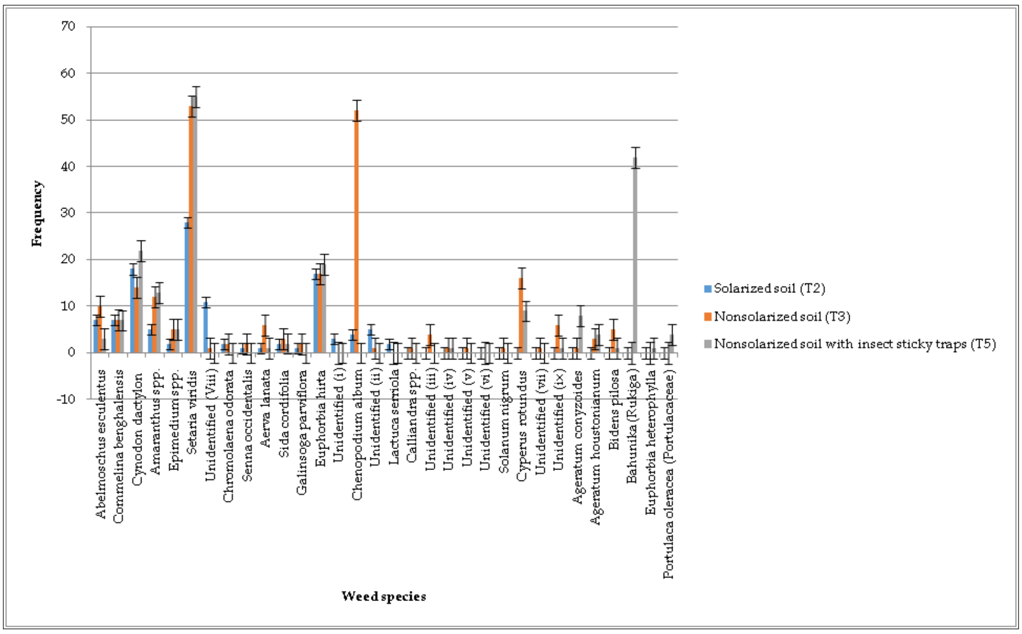

Figure 9 Frequency (WF) of different weed species in some of the treatments in the ISE that demonstrated weed growth

3.3. Modeling influence of treatments and replication on the percentage survival and healthy of *Citrus* seedlings grown under GHC in the IST

Data violated the assumptions of normality and was logarithmically transformed. Using the regression analyses, it was revealed that:

The degree of correlation between replicate numbers (R), treatments (T) and the Log_{10} of percentage (%) survival of *Citrus* seedlings (Y_1) was moderately positive. That is to say there was a moderate positive correlation (r = 0.48) between:

Replicate numbers (R) and the Log_{10} of survival percentage of *Citrus* seedlings (Y_1) grown under GHC.

Treatments (T) and the Log_{10} of survival percentage of *Citrus* seedlings (Y_1).

It was also revealed that 23.2% ($R^2 = 0.232$) of the Log_{10} % survival of *Citrus* seedlings (Y_1) can be explained by both the replicate numbers (R) and treatments (T). Overall, the model applied is significantly good enough (p = 0.000) in predicting the Log_{10} % survival of *Citrus* seedlings (Y_1) at the $p \leq 0.05$ level of significance in the entire experimental layout involving IST under GHC. Treatments (T) had no significant contribution ($p = 0.503$) to the % survival of *Citrus* seedlings (Y_1) at the $p \leq 0.05$ level of significance. On the other hand, replicate numbers (R) had a significant contribution ($p = 0.000$) to the Log_{10} % survival of *Citrus* seedlings (Y_1) at the $p \leq 0.05$ level of significance. The regression equations for this model are presented in the form Y=a+bX as illustrated below:

Y=a+bX, where, Y = dependent variable, X = independent/ predictor variables, a = constant, b = y-intercept. Thus,

Y_1=0.937+0.294R……………………………………………… (Equation I)

Y_1=0.937-0.0094T……………………………………………… (Equation II)

Y_1 = Log_{10} (% survival of *Citrus* seedlings), R = Replicate No., T = Treatments.

The degree of correlation between replicate number (R), treatments (T) and the number of *Citrus* seedlings with chewed leaves (Y_2) was of a weak positive nature. That is to say there was a weak positive correlation ($r = 0.129$) between:

Replicate number (R) and the number of *Citrus* seedlings with chewed leaves (Y_2) grown under GHC.

Treatments (T) and the number of *Citrus* seedlings with chewed leaves (Y_2).

It was also revealed that only 1.7% ($R^2 = 0.017$) of the number of *Citrus* seedlings with chewed leaves (Y_2) can be explained by both the replicate numbers (R) and treatments (T). Overall, the model applied is not significantly good enough ($p = 0.206$) in predicting the number of *Citrus* seedlings with chewed leaves (Y_2) at the $p \leq 0.05$ level of significance in the entire experimental layout involving IST under GHC. Treatments (T) had no significant contribution ($p = 0.100$) to the number of *Citrus* seedlings with chewed leaves (Y_2) at the $p \leq 0.05$ level of significance. Replicate numbers (R) also had no significant contribution ($p = 0.504$) to the number of *Citrus* seedlings with chewed leaves (Y_2) at the $p \leq 0.05$ level of significance. The regression equations for this model are also presented in the form Y=a+bX as illustrated below:

Y=a+bX, where, Y = dependent variable, X = independent/ predictor variables, a = constant, b = y-intercept. Thus,

Y_2=0.859-0.038T……………………………………………… (Equation III)

Y_2=0.859-0.044R……………………………………………… (Equation IV)

Where, Y_2 = number of *Citrus* seedlings with chewed leaves, R = Replicate No., T = Treatments.

The degree of correlation between replicate number (R), treatments (T) and the number of *Citrus* seedlings with folded leaves (Y_3) was of a weak positive nature. That is to say there was a weak positive correlation ($r = 0.181$) between:

Replicate number (R) and the number of *Citrus* seedlings with folded leaves (Y_3) grown under GHC.

Treatments (T) and the number of *Citrus* seedlings with folded leaves (Y_3).

It was revealed that only 3.3% ($R^2 = 0.033$) of the number of *Citrus* seedlings with folded leaves (Y_3) can be explained by both the replicate numbers (R) and treatments (T). Overall, the model applied is significantly good enough ($p = 0.042$) in predicting the number of *Citrus* seedlings with folded leaves (Y_3) at the $p \leq 0.05$ level of significance in the entire experimental layout involving IST under GHC. Treatments (T) had no significant contribution ($p = 0.785$) to the number of *Citrus* seedlings with folded leaves (Y_3) at the $p \leq 0.05$ level of significance. Replicate numbers (R) had a significant contribution ($p = 0.012$) to the number of *Citrus* seedlings with folded leaves (Y_3) at the $p \leq 0.05$ level of significance. The regression equations for this model are also presented in the form Y=a+bX as illustrated below:

Y=a+bX, where, Y = dependent variable, X = independent/ predictor variables, a = constant, b = y-intercept. Thus,

Y_3=2.657+0.018T……………………………………………… (Equation V)

Y_3=2.657-0.470R……………………………………………… (Equation VI)

Where, Y_3 = number of *Citrus* seedlings with folded leaves, R = Replicate No., T = Treatments.

The degree of correlation between replicate number (R), treatments (T) and the number of *Citrus* seedlings with leaves expressing low percentage levels of chlorophyll (Y_4) was of a moderate positive nature. That is to say there was a moderate positive correlation ($r = 0.519$) between:

Replicate number (R) and the number of *Citrus* seedlings with leaves expressing low percentage levels of chlorophyll (Y_4) grown under GHC.

Treatments (T) and the number of *Citrus* seedlings with leaves expressing low percentage levels of chlorophyll (Y_4).

It was revealed that 26.9% ($R^2 = 0.269$) of the number of *Citrus* seedlings with leaves expressing low percentage levels of chlorophyll (Y_4) can be explained by both the replicate numbers (R) and treatments (T). Overall, the model applied is also significantly good enough ($p = 0.000$) in predicting the number of *Citrus* seedlings with leaves expressing low percentage levels of chlorophyll (Y_4) at the $p \leq 0.05$ level of significance in the entire experimental layout involving IST under GHC. Treatments (T) had no significant contribution ($p = 0.552$) to the number of *Citrus* seedlings with leaves expressing low percentage levels of chlorophyll (Y_4) at the $p \leq 0.05$ level of significance. Replicate numbers (R) had a significant contribution ($p = 0.000$) to the number of *Citrus* seedlings with leaves expressing low percentage levels of chlorophyll (Y_4) at $p \leq 0.05$ level of significance. The regression equations for this model are also presented in the form Y=a+bX as illustrated below:

Y=a+bX, where, Y = dependent variable, X = independent/ predictor variables, a = constant, b = y-intercept. Thus,

Y_4=-8.130+0.207T…………………………………………… (Equation VII)

Y_4=-8.130+9.104R…………………………………………… (Equation VIII)

Where, Y_4 = number of *Citrus* seedlings with leaves expressing low percentage levels of chlorophyll, R = Replicate No., T = Treatments. Previous studies had ascertained effect of solarization on yield and their benefits to general crop performance. The occurrences of these benefits in moderate temperature conditions provide hope for the future. In light of increased reductions of pesticides, threats of ground water pollution, and the everlasting need to control a wide range of soil-borne pathogens and pests, the science of solarization provides many possibilities for improved yield.

Krueger & Mcsorley, 2012 summarized the effect of soil solarization on yield. In certain instances these yield benefits were infinitive since the crops in un-solarized soil were totally destroyed by the pathogens (Jacobsohn *et al*., 1980; Stapleton *et al*., 1987). These studies also ascertained that increases in yield by solarization may depend upon a variety of factors: damage resulting from the disease being controlled, inoculum potential, and efficacy of control, compensation by neighboring plants, and the phenomenon of increased growth response (Katan, 1976). Perhaps more important, solarization may also improve quality with increases of yield (一般社団法人日本リウマチ学会, 2019; Chellemi *et al*., 1997; Yücel *et al*., 2007).

4. Conclusions and recommendations

For effective monitoring, inspection and mitigation of insects, pests or vector populations in *Citrus* seedlings under GHC, use of commercially available sticky traps is more recommended compared to locally fabricated sticky traps due to the former's fabulous performance. However, in order to improve on the performance of locally fabricated sticky traps, there should be use of comparable blue and yellow-coloured manilar, cardboards, glass, wood, plastic cups, plastic sheets, trap boards, empty milk cartons, red apple spheres or any other surfaces without any divergence in colour from that of commercially available sticky traps for developing locally fabricated sticky traps as any variation in colour makes the locally fabricated traps insensitive to insects hence making them unable to attract and regulate high insect populations. For yellow sticky traps for instance, about 550 – 600 nm wave length is highly attractive to many insects. Additionally, the strength of the adhesive or glue to be used in developing locally fabricated sticky traps should be checked since petroleum jelly or Vaseline proved to be too fragile to capture larger insect populations. Of the two types of commercially available sticky traps which were experimented in this study, yellow sticky traps were more effective in monitoring, inspecting, mitigating and regulating insect populations by trapping a wide range of insects having the photo tactic character and fondness towards yellow color compared to blue sticky traps. Consistent use of well-maintained sticky traps is also an important tool for helping to determine whether treatments are warranted, the timing of applications and the effectiveness of previous control options. To reduce costs, traps can be homemade and reused. Boards painted bright yellow (e.g. with Rustoleum Yellow No. 659 or Rust-Oleum 659 or Safety Yellow) can be coated with clear polybutene material (e.g. Stickem or Tanglefoot). These adhesive must be washed-off using commercial solvents before recoating traps for reuse. This can be time consuming and messy. An alternative adhesive composed of one part petroleum jelly (e.g. Vaseline) or mineral oil mixed with one part household detergent can be used, however, some insects escape this material, and it may drop off boards under hot conditions unless applied thinly. Periodic cleaning or replacement of traps is essential to maintain the sticky surface. Although solarization of potting media (sawdust and soil) gave good results in raising non-symptomatic *Citrus* seedlings under GHC, integrating them with sticky traps preferably yellow coloured ones gave better domino effect and solarized soil when integrated with sticky traps surpassed solarized sawdust integrated with the same in view of the fact that the latter had inadequate organic matter since it was used before decomposition culminating into production of high percentage of *Citrus* seedlings that expressed low chlorophyll levels. According to results of this study, both solarized and non-solarized sawdust whether integrated with sticky traps or not were superb potting media that could be used for effectively managing soil-borne pathogens and several weed species. However, when sawdust is to be used in either non-solarized or solarized form, it should be either allowed to fully decompose under aseptic conditions (without microbes) or be aseptically mixed with one of the inorganic fertilizers like Nitrogen, Phosphorous, Potassium (NPK), diammonium phosphate (DAP), triammonium phosphate (TAP), urea or CAN in a ratio favouring higher Nitrogen compared to other nutrients for better results. Alternatively, organic fertilizers like animal manure, green manure, plant compost can be mixed with sawdust before being used for *Citrus* seedlings production using the recommended doses and ratios as directed by experts before integrating it with sticky traps and subsequently sowing *Citrus* seeds. The results of this study validated some of the treatments (innovative approaches) demonstrated in the IST as very fundamental tools applicable for the management of soil-borne pathogens and weeds in *Citrus* seedlings grown under GHC and form an effective ingredient to the Integrated Pest Management recipe. This intended to minimize overreliance on synthetic chemicals and hence would promote production of healthy *Citrus* seedlings using environmentally friendly, cost-effective and ecologically sound technologies and practices since no any chemicals were used during the course of implementing the Integrated Solarization Experiment which generated data analyzed in this study.

Compliance with ethical standards

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Disclosure of conflict of interest

Authors have declared that no competing interests exist.

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