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Development of a greenhouse steam-powered, self-propelled soil sterilization device

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ABSTRACT

This study aims to develop an eco-friendly, self-propelled device to sterilize greenhouses soils with pressurized, superheated steam. The innovated device sterilizes greenhouse soils directly without removing their structures. The device operates electrically with remote control and is equipped with a smart electronic system to control superheated steam temperatures. The device is an alternative to pollutant chemical and long-term solarization sterilization methods. Three forward speeds (steaming exposure periods) of the steam soil sterilizer were tested: 0.05 m s^{-1} (7s), 0.12 m s^{-1} (4s), and 0.19 (3s) m s^{-1}. Three pressurized superheated steam temperatures of 153°C (0.414 MPa), 170°C (0.689 MPa), and 183°C (0.965 MPa) were tested at three heights of the steam distributor above the soil surface: 0, 25, and 50 mm. The efficiency of controlling common fungal pathogens, nematodes, and weed seeds were estimated and compared to solarization control. The performance rates, field efficiency, and operating costs of the steam sterilizer were evaluated. The maximal control efficiencies for fungal pathogens for Fusarium oxysporum, Rhizoctonia solani, and Pythium spp. were 90.90, 92.72, and 91.37%, respectively. The highest value of nematode control efficiency was 97.73%. The maximal specific energy consumption rate was 30.96 kWh ha^{-1} at a field capacity of 0.05 ha h^{-1} with an average operational cost of 434.18 USD ha^{-1}. The cucumber yield for experimental greenhouses increases by 3.36% over control. It could be recommended to generalize using the developed sterilizer technique in greenhouses for cultivating organic crops.

Keywords: *Cucumber, Distributor, Pathogens, Remote, Super-heated, Thermal*

INTRODUCTION

Agricultural crop disease is one of the main obstacles facing the greenhouse farmers (Ghani *et al.*, 2019). Using scientific methods prevents the emergence of greenhouse diseases (Gullini *et al.*, 2022). Numerous infections or fungi within enclosed greenhouses are the cause of seed loss and seedling death (Singh *et al.*, 2020). *Fusarium, Rhizoctonia solani, and Pythium* are considered the main fungal infections that cause root rot diseases (Bodah, 2017; El-Kazzaz *et al.*, 2022). Choosing the right strategy to start controlling fungal diseases depends on preventive treatment (Daughtrey and Buitenhuis, 2020). Infection with the *Fusarium* fungus manifests as browning of the plant's roots in the first thirty days or less (Punja, 2021). Symptoms of a *Rhizoctonia solani* infection include sunken brown spots that start between the root and the stem, suffocate the stem, and eventually kill the fruit (Aghazadeh *et al.*, 2022). The tendency of the stem bearing the plant to fall off after fruiting is one sign of a *Pythium* fungal infestation (Sarkar *et al.*, 2022). Infections with *Rhizoctonia solani* and *Fusarium oxysporum* can induce wilt and root rot diseases in cucumber crops grown in greenhouses by 67.7% and 71.0%, respectively, at the post-emergence stage, which has a relative impact on productivity (Farrag and Fotouh 2010).

The results of the development of steam soil sterilization machines were studied. Gay *et al.* (2010) assembled a prototype of a self-propelled steam injection machine to disinfect open-field tomato crops from *Fusarium*. The generated steam flow rate was 500 kg h^{-1} at a pressure of 50 kPa. The results included the elimination of the *Fusarium exsporum* fungus at rates ranging from 63 to 100%. Wang *et al.* (2018) developed a mobile soil rotary steam disinfection machine that generates steam with a pressure of 0.6 MPa and a temperature of 158.86°C with a rotary working speed of 0.035 m s^{-1} for soil depth of 15 cm and consuming power of 87.78. Also, Gao *et al.* (2023) developed a vertical rotary soil tilling disinfection combine to sterilize soil using a forward speed of 0.26 m s^{-1}, and the results concluded that the soil disinfection uniformity coefficient reached 85.57%. Peruzzi *et al.* (2011) developed a self-propelled machine to disinfect the soil using steam and chemicals while using a plastic mulch film. The steam exposure time was increased by reducing the working speed to 60 m h^{-1}. The maximum soil sterilization efficiency was increased at 100 ºC for the soil surface temperature. Nishimura *et al.* (2015) evaluated the performance of a self-propelled machine equipped with a steam generator that generates superheated steam from 150 to 300 ºC at a pressure of 0.4 MPa using fuel. The machine was tested at speeds ranging from 0.3 to 1 km h^{-1}. The effectiveness of eliminating weed seeds were reached at a soil temperature of 60 ºC. Operating the machine was ineffective in the open field due to the high operating cost. Raffaelli *et al.* (2016) designed a prototype of soil fumigation from pathogens and weed seeds. A maximum temperature of 63 ºC at a depth of 25 mm with a steam dose of 2.87 kg m^{-2} was able to significantly reduce soil weed bank in the layer of 0-100 mm soil depth.

The investigated research problem is that greenhouses require periodic sterilization operations due to the frequent fungal and viral soil infections. The use of chemical methods is the most common and harmful

(Daughtrey and Buitenhuis, 2020). Soil chemical sterilization had many environmental and health disadvantages, in addition to its high cost. Applying chemical sterilization to the soil prevents the cultivation of medicinal and aromatic crops (Namdeo, 2018). Soil solar sterilization requires warm weather for a long period of 6-8 weeks and completely evacuates the greenhouse (Mormile *et al.*, 2016). Steam sterilization is the most successful method of sterilizing greenhouse soils but is expensive in small greenhouses (Dietrich *et al.*, 2020; Gullino *et al.*, 2022). Using fuel-powered steam boilers to sterilize greenhouses generates gas emissions that pollute the environment (Khattak *et al.*, 2016; Srivastava *et al.*, 2020). Therefore, the idea was given to design a self-propelled steam device that runs on electricity to directly sterilize the greenhouse soil. The quick and efficient steaming direct procedure with no chemical residues allows the soil steam sterilizer device to overcome the shortcomings of both chemical and solarization methods (Gay *et al.*, 2010). The developed steam sterilizer is more cost-effective and environmentally friendly compared to traditional solarization methodology (Gullino *et al.*, 2022).

This research aims to develop and performance-evaluate an electric self-propelled steam sterilizer device to sterilize soil greenhouses from fungal pathogens and nematodes. On the other hand, reducing yield production costs and maximizing its quality with rationalization of harmful chemical pesticide using were aimed at.

MATERIALS and METHODS

Experimental procedure

The experiments were carried out at Ashmoun, Dakahlia, Egypt (latitude 31° 09′ 11″ and longitude 31° 64′ 60″) on cucumber (*Cucumis sativus*) in September 2023. Three plastic tunnel-type greenhouses were steamed, and one greenhouse for control was sterilized by solarization. This site was chosen due to the presence of a history of bacterial and fungal infections. The greenhouse soil was plowed and leveled in preparation for steaming before planting. The area of one greenhouse is 405 m^2, with dimensions of 9 x 45 m. Each greenhouse was divided into 40 plots; every plot had an area of 9 m^2 with dimensions of 1×9 m. The total number of experimental plots was 135, with a total area of 1215 m^2. The experimental greenhouse structures weren't removed, unlike the solarized control greenhouse. Three variables were tested in a completely randomized block design (RCBD) with five replicates. Three levels of forward speeds for the self-propelled steam soil sterilizer in exchange for steaming exposure periods (FS) [0.05 m s^{-1} (7 sec), 0.12 m s^{-1} (4 sec), and 0.19 m s^{-1} (3 sec)] were tested. A delay period of 2 seconds has been added to the forward speeds at an operating distance of 0.25 m using the flashing button within the remote control. Three temperatures of pressurized super-heated steam (ST) were tested: 153°C (0.414 MPa), 170°C (0.689 MPa), and 183°C (0.965 MPa). Three heights (H) of the truss steam distributor above the ground (zero level; 25 and 50 mm) were tested. All experiments were tested using a steam discharge rate of 0.04 L s^{-1}.

General description

The self-propelled device sterilizes the soil with pressurized, superheated steam to eliminate fungal pathogens and nematodes directly. The treated infected greenhouse soil surface layer disinfects due to drying up the pathogens. Solarization requires around two weeks to solarize the soil by covering it with plastic and mulching tools over the top 5 cm of the ground. The temperature can reach 42 to 60°C, though this varies greatly from place to place. The developed device works with electrical energy without any polluting gas emissions. The device's geometric dimensions were designed to suit small and medium greenhouses, as shown in Figures 1 and 2. The developed device generates steam using a pressure steam boiler made of thick steel to withstand high pressures. The boiler is mechanically secured with an overpressure relief valve to avoid explosion. The boiler is electrically secured with an electric pressure sensor to cut off the electric current when the mechanical valve is blocked. The device is well insulated from electric shocks due to the use of wooden insulators in the base of the device and electrical insulating paint. The device generates superheated steam with a maximum temperature of 183°C and pressures up to 0.965 MPa. The total width of the device is 1 m to fit the greenhouse entrance, while the actual operating width is 0.75 m. The height of the device is 1.16 m. The device is self-propelled and operates with a remote control. The sterilizer is a tricycle for easy maneuvering in tight spaces. The device's net weight is 175 kg, which does not affect the soil's compressibility. The steam height above the soil surface can be controlled from 0 to 50 mm. The steam generator was insulated using glass wool fiber lining to prevent heat leakage and minimize consumed power. The device is equipped with a transmission DC motor that runs on a speed control circuit. The device operates using a 220-volt, 50-Hz alternating current. The device also works with a 5-kilowatt diesel electrical generator that is installed outside the greenhouse to avoid polluting with combustion exhaust. The steam soil sterilization device consists of the following parts, as shown in Figures 1 and 2.

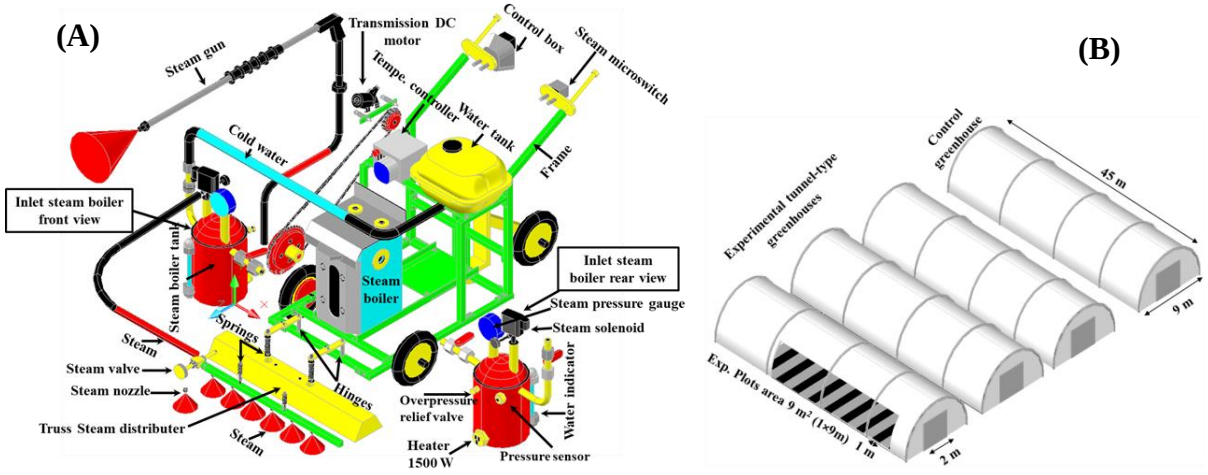

Figure 1. *(A) Isometric view of the self-propelled steam soil sterilizer and (B) The experimental plastic tunnel-type greenhouses.*

A light frame is designed from 30 mm hollow square-section tubes of 3 mm thick iron, as shown in Figure 1A. The frame is durable to resist shocks and vibrations during operation. The frame was assembled with screws without welding for ease of maintenance. The device is rear-steering to ensure front stability for steaming. A solid wheel type with a diameter of 270 mm was installed axially, as shown in Figure 2A No. 9. The front wheels are installed at a distance of 280 mm from the frame to maintain balance. The right front wheel is equipped with a gear (42 teeth) to front-tow the device (Figure 2 A and C). The rear wheel is mounted on a cylindrical axis 300 mm long and 381 mm in diameter, equipped with an internal shaft to turn the device (Figure 2A, No. 6). The rear wheel is mounted on a U-shaped holder with a 10 mm thickness and 10 mm width to resist shocks (Figure 2C). A pair of solid handles was installed to guide the device (Figure 2A, No. 15). The frame base is lined with a plywood base for electrical insulation, as shown in Figure 1A. Safety factors were taken into account when designing the device, in agreement with Yonter and Houndomougbo (2022); Alkan and Gugor (2024).

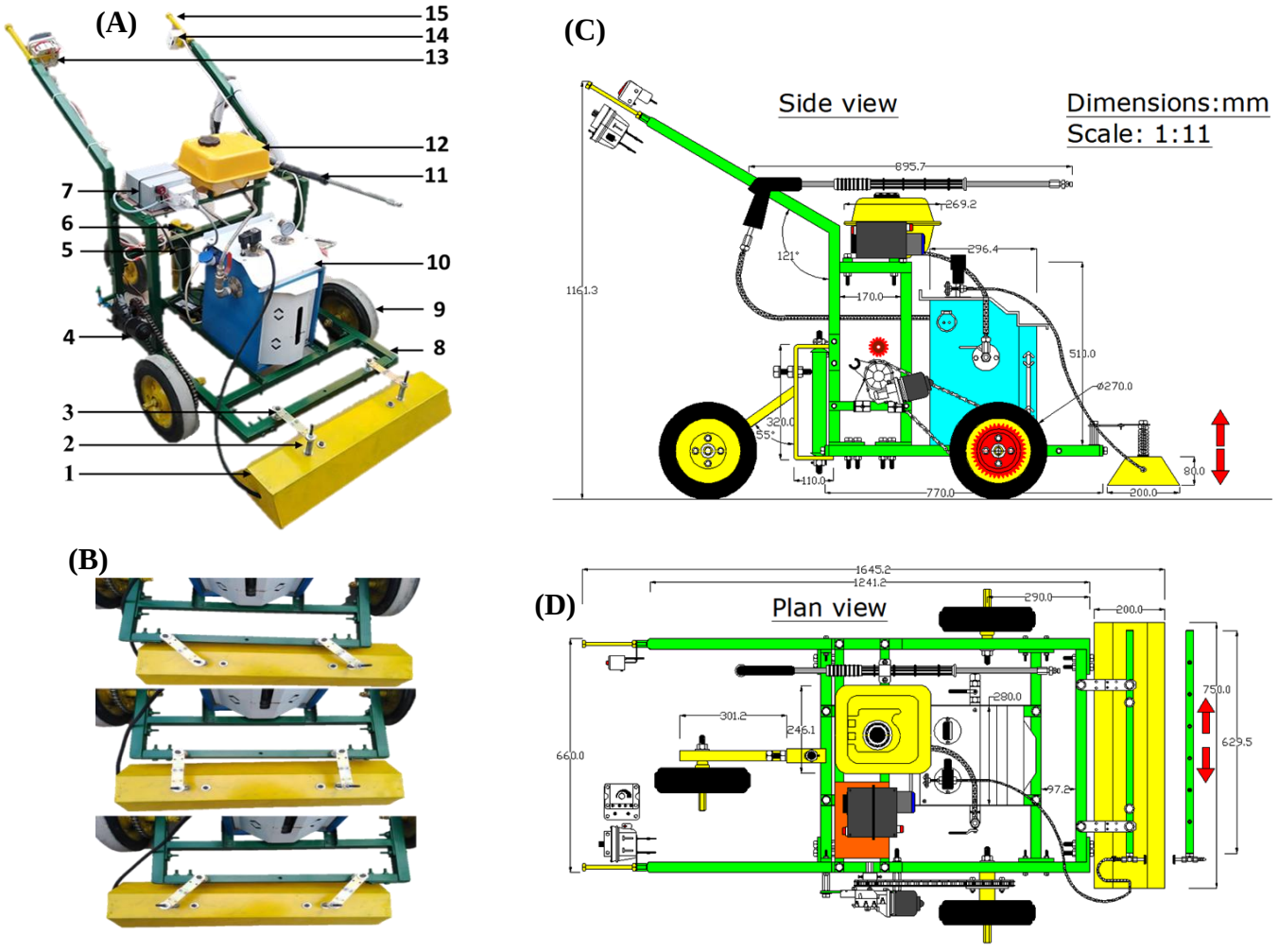

Figure 2. *(A) The self-propelled steam soil sterilizer (1-steam distributor; 2-spring holder; 3-rotary hinges; 4-DC transmission motor; 5-thermocouble sensor; 6-rear wheel spindle; 7-thermocontroller; 8-frame; 9-front wheels; 10-steam generator unit; 11-steam gun; 12-water tank; 13-control box; 14-steam microswitch; 15-handle), (B) steam distributor positions, (C) Side view of the 2D geometric of a soil steam sterilizer device and (D) plan view of the 2D geometric of a soil steam sterilizer device.*

The pressurized steam generation unit consists of a steam boiler, a water tank, and, as shown in Figure 2A, No. 10 and 12. The water tank is made of rust-resistant galvanized sheet and is provided internally with a filter to trap impurities (Figure 2A, No. 12). The steam boiler is connected to the water tank using a thermal hose with a diameter of 12.7 mm. The steam boiler converts water into pressurized steam and directs it to the steam distributor (Figure 2A, No. 10) (El-Sayed and El-Hameed, 2017). The steam boiler consists of an outer body made of coated, electrical insulating galvanized sheet, as shown in Figure 1A. The steam boiler internally contains a cylindrical tank made of galvanized iron with a thickness of 20 mm to resist large pressures (Figure 1A). The boiler's inner tank is lined with glass wool to insulate the boiler thermally and saves power. The inner diameter of the steam boiler tank is 250 mm, and its height is 330 mm, as shown in Figure 1A. The steam boiler is supplied with a thermo-resistant glass water indicator (Figure 1A). The boiler's inner tank is connected from the right side with a 12.7-mm-diameter pipe connected by a valve to the 7-liter water tank (Figure 1A). The inner tank boiler lefting tube is connected by a valve and connected to the steam gun (Figure 2A, No. 11). The steam gun is used to sterilize narrow places, pots, and the interior walls of the greenhouse. The steam gun is made from galvanized iron tubes with a thickness of 2 mm, a length of 1 meter, and a diameter of 10 mm. The steam gun is equipped with a front nozzle with a diameter of 1.5 mm to distribute the steam in the form of a cone shape (Figure 1A). The steam gun is well thermally insulated with a thick layer of heat-resistant polyethylene to protect operators' hands from overheating. A spiral copper electrical heater with an internal tungsten coil (1.5 kW and 220 V) was inserted in the boiler inner tank base (Figure 1A). An electrical solenoid was used to control the outlet steam from the boiler automatically (Figure 1A). The steam solenoid is operated automatically by a thermo-controller (Figure 2A, No. 7). A mechanical safety valve was used to protect the steam boiler explosion and relieve overpressures up to 0.965 MPa, as shown in Figure 1A. The steam distribution unit directs the pressurized superheated steam directly to the surface of the soil, as shown in Figure 2B. The steam distribution unit consists of a truss shape made of galvanized sheet with a thickness of 1 mm and geometric dimensions (Figure 2 C and D). The operating width of the steam distributor is 750 mm. The steam distributor height over the soil surface ranged from 0 to 50 mm. The steam distributor prevents steam leakage and directs it to a soil area of 0.15 m^2. A square-section pipe (630 mm in length) that contains six copper nozzles (1 mm in diameter) was used to distribute steam in a cone shape (Figure 1A). The steam square-section pipe is connected axially to a copper valve to control the steam discharge rate, as shown in Figure 1A. A pair of twin hinges was used to direct the steam distributor axially on the right and left sides (Figure 2A, No. 3). Two 130-mm-long spring spiral guides were utilized to adjust the steam distributor's height and absorb shocks (Figure 2A, No. 2). A DC-type electric motor within speed-reducer gears was used to fit the slow process of soil sterilization (Figure 2A, No. 4). Forward speeds were slow to allow the steam to penetrate the surface layer of the soil efficiently, as listed in Table 1. The transmission motor has a large withdraw torque of 29-60 N m, and its specifications are listed in Table 1. The motor is mounted laterally using guides and a tensioner to tighten the transmission chain (Figure 2D).

A driving 14-teeth gear was installed on the transmission motor, versus a 42-teeth gear on the right front wheel axle, as shown in Figure 2C. A control box was used to control the motor speeds (Figure 2A, No. 13). The transmission motor is controlled remotely by an infrared remote control circuit for easy operation of the device, as shown in Figure 3E.

Table 1. *Forward speeds for the steam sterilizer device and the used steam specifications.*

Transmission motor specifications		**Motor gear speed (14 teeth), rpm**	**Wheel gear speed (42 teeth), rpm**	**Linear forward speeds, m s^{-1}**	**Consumed power, Amp.**
Rating voltage	12 V	10	3.33	0.05	1
Rating power	50 W	25	8.33	0.12	2.5
Torque	29-60 N m	40	13.33	0.19	4
Net weight	1400 g m	Forward speeds: 0.18, 0.43, and 0.68 km h^{-1}			

Superheated steam Temp., ^{o}C	Pressure, MPa	Specific enthalpy, kcal kg^{-1}	Specific volume, m^{3} kg^{-1}	Specific heat, kcal (kg ^{o}C)$^{-1}$	Viscosity, mPas
153	0.414	664.008	0.183	0.657	0.014
170	0.689	661.211	0.243	0.621	0.147
183	0.965	664.008	0.183	0.657	0.151

A smart electronic circuit was equipped with the device to automatically control the operation, as shown in Figure 3A. A digital thermo-controller attached to a thermocouple was used to set the steam temperature automatically (Figure 2A, No. 5 and 7). The thermocouple sensor is inserted into the outlet upper pipe attached to the electrical solenoid. The measured temperature is displayed on the thermo-controller digital screen (Figure 3D). The settled temperature of outlet steam is controlled using the touch buttons on the digital thermo-controller LCD screen (Figure 3D). The thermo-controller is connected to a 16-amp contactor to transfer the electrical load of the steam boiler (Figure 3B). The digital thermo-controller unit is supplied with an outer plug connected to the electrical steam solenoid, as shown in Figure 3A. A direct micro-switch is mounted on the left device handle to operate the steam solenoid directly (Figure 3C). A control box was installed on the right handle to control forward speeds (Figure 3E). A dimmer was used as a speed regulator switch with the controlling box (Figure 3E). A triple switch on the right side of the control box is used to disconnect and operate the motor at two speeds: fast (right side) and slow (left side), and a disconnect (middle), as shown in Figure 3E. A left triple switch on the left side was used to operate the changeable speeds from dimmer (Figure 3 E). A 12-volt, 16-amp relay is used to connect the control box's electrical loads (Figure 3A). An infrared receiver unit is connected to the relay's magnetic coil terminals to remotely control the device forward (Figure 3E). The positive electrical current is transmitted remotely to the transmission motor through the attached

relay by the remote control, as shown in Figure 3A. To operate the self-propelled sterilizer device, the forward speed is selected using the dimmer in the electrical control box. The forward speed is chosen according to the severity of the injury and the condition of the soil. The left key in the control box is turned to the right. The transmission motor is controlled remotely by pressing the remote control. The electrical steam boiler is operated using a side button installed in it, as shown in Figure 3A. The digital thermo-controller button is switched, and the desired temperature is selected from 100 to 183ºC. The solenoid steam socket is connected to the thermo-controller outer plug. Each temperature corresponds to a specific pressure that can be read on the pressure gauge, as shown in Figure 3B. The steam boiler takes a period of preparing time (20 minutes, approximately) to reach the required temperature. The height of the truss steam distributor above the ground is adjusted using the screw guides as needed. Sterilization operations are carried out by passing the device side by side inside the greenhouse.

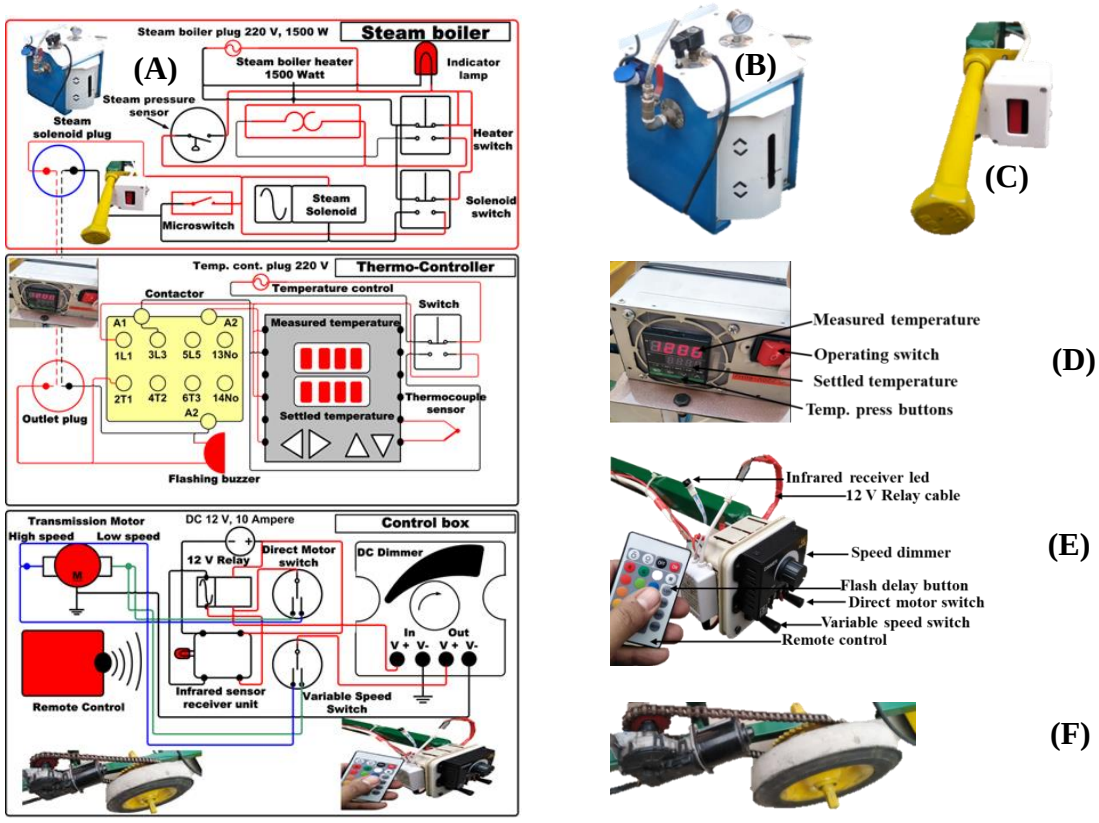

Figure 3. *Electrical wiring circuit for the self-propelled steam sterilizer device. (A) Electrical wiring diagram for steam soil sterilizer; (B) Steam generator unit; (C) Steam micro-switch; (D) Thermo-controller; (E) Control box for the self-propelled steam soil sterilizer device; and (F) Transmission motor.*

The self-propelled soil steamer sterilizer device evaluation

The soil texture of the experimental greenhouses had been analyzed within a depth of 0-600 mm of the soil surface layer, according to Carter and Gregorich (2007). The testing location had a clay-loam soil structure that consisted of 22.14% sand, 45.05%

silt, and 32.81% clay. To determine the soil surface temperatures (SST, ºC) after treatment directly, three thermo-sensors connected to a data logger were used. Each thermal sensor is installed inside a vertical tube and implanted in the soil at a depth of 200 mm. The temperature sensors were distributed evenly along the operating width of the steam sterilizer to measure the soil temperature. Five random samples were collected from each experimental plot at depths of 0-100 and 100-200 mm and placed in plastic bags 24 hours after steaming treatments. The fungal pathogen CFU (colony-forming unit) and nematode populations were estimated before and after the sterilization procedure. To determine the sterilizer device efficiency, a comparison was made between the solarized control greenhouse and the steamed experimental greenhouse. One gram of soil was taken from the treated random samples before and after steaming treatment. A soil suspension was made and diluted, and then 1 ml of the solution was transferred to petri dishes. The samples were inserted in petri dishes with agar medium (NA) and incubated at a temperature of 25 ± 2 °C for 72 hours. A dilution percentage was chosen according to the colonies forming the unit's appearance. The colonies forming unit (Cfu g^{-1}) for the main common pathogen infections (*Fusarium Oxysporum, Rhizoctonia Solani,* and *Phytium spp.*) were recorded according to the methodology of Masago *et al.* (1977). To estimate the number of nematode populations (NP) per 100 g of soil, the samples were ground and sieved, then diluted with water. The soil suspensions were filtered with fine sieves (< 2 mm) according to the methodology of Seinhorst (1962). The control efficiency (Cη) for fungal pathogens (FCη) and nematode infections (FCη) was determined according to Equation (1) (Mao *et al.*, 2016).

$$C\eta = \frac{X_1 - X_2}{X_1} \times 100 \quad (1)$$

Where; $C\eta$: control efficiency, %; X_1: the pathogens forming colonies CFU g^{-1} or the nematode population number in untreated plots; %; and X_2: the pathogens forming colonies CFU g^{-1} or the nematode population number in the treated plots.

The soil weed seed bank (SB) was determined according to Chejara *et al.* (2019). Samples were taken from experimental plots at depths of 0-100 and 100-200 mm to estimate SB by sieving before and after treatments. The cucumber crop yield was estimated for the experimental greenhouses compared to the control. Cucumber was planted directly in mid-September after the steaming sterilization for the experimental greenhouses until harvested in mid-February. Cucumber was planted in the control greenhouse at the end of October after the solarization sterilization and harvested at the end of April. The chemical and physical properties of soil samples before and after sterilization were estimated at depths of 0-200 mm, according to Ngakou *et al.* (2008). Soil-steaming self-propelled sterilizer device performance was estimated. The field efficiency and actual field capacity were estimated according to Kepner *et al.* (1978). The specific energy consumption rate (SE) was determined as presented in Equation (2), according to Culpin (1986). Operating costs (OC) for operating the steam sterilizer were estimated in Equation (3), according to Hunt (1983).

$$SE, kWh\ ha^{-1} = \frac{Consumed\ power\ kW\ h}{Actual\ field\ capacity, ha\ h^{-1}} \quad (2)$$

$$OC, USD\ ha^{-1} = \frac{Device\ hourly\ cost\ USD\ h^{-1}}{Actual\ field\ capacity, ha\ h^{-1}} \quad (3)$$

Statistical analysis

The statistical analysis programs COSTAT (version 2019) and IBM SPSS (version 2020) were used. The mean average values and standard deviation of the measurements for the tested variables were statistically analyzed. Significance tests were conducted at a level of $P \leq 0.05$ for the tested variables. The ANOVA analysis was conducted to assess the difference between the means of the tested factor levels. Linear-type regression analysis was performed to study the association between a continuous outcome variable and a continuous covariate.

RESULTS AND DISCUSSION

Soil surface temperatures

The experiments were conducted in September, when the average daily temperature was 25.60ºC and the relative humidity was 0.65%, according to the Meteorological Unit Data. As listed in Table 3, the average measured soil surface temperatures (SST) for the experimental plots after treatment were recorded. Solar sterilization temperatures do not exceed 60°C when covered with plastic at maximum solar radiation at noon, which is less than half the temperature measured by exposure to steam, 140°C, which leads to the elimination of fungal pathogens. Figure 4A illustrates, the sterilizer device forward speeds (FS) increment is comparatively opposite to the SST. The maximum measured soil surface temperature (SST) was 155.69ºC at the lowest forward speed (FS) of 0.05 m s^{-1}, and the highest temperature of superheated steam used (ST) was 183ºC. The lowest value of SST was 93.50ºC recorded at the maximum level of FS of 0.19 m s^{-1}, and the lowest ST was 153ºC, as shown in Figure 4A. As shown in Figure 4B, there is a directly proportional relationship between ST and SST at different levels of superheated steam heights (H). The highest value of SST was 137.17ºC at H of 0 mm, and ST was 183ºC. The minimal value of SST was 107.48ºC at H of 50 mm, and ST was 153ºC. The measured SST decreased by 25.04 and 29.75%, respectively, at the maximum ST of 183ºC and the lowest H of 0.0 mm, and vice versa, at the lowest ST of 153ºC and the highest H of 50 mm, as shown in Figure 4B. As mentioned in Table 3, there is a high significant probability at the $P \leq 0.05$ level for the SST measurement, the main factors, and the interaction between them. Statistically, a linear regression Equation of SST was obtained, as illustrated in Equation 4.

$$SST, ºC = -249.229\ FS\ (m\ s^{-1}) + 0.913\ ST\ (ºC) - 0.0384\ H\ (mm)\ (R^2 = 0.899) \quad (4)$$

In order to anticipate the required measurement result and determine the performance rate of the developed device, the regression equation is applied with varying levels of coefficients based on the fungal infection state and varying levels of device adjustment.

The measured soil surface temperature after treatment decreased by 14.92 and 38.89%, respectively, at the maximum ST of 183ºC and the lowest FS of 0.05 m s^{-1}, and vice versa, at the lowest ST of 153ºC and the highest FS of 0.19 m s^{-1}. The percentage decrease in measured soil surface degrees was relatively small at low forward speeds compared to high speeds. Soil temperature fluctuations are due to the fact that the steam flow rate coincides inversely with the increase in the forward speed of the steam sterilizer, in accordance with Runia and Greenberger (2004). The steam penetration ratio into the interstitial soil pores increases in direct proportion to the soil surface temperature, in accordance with Raffaelli *et al.* (2016). The rate of transferred heat quantity increases with a lower height of emitted steam to the soil surface, in agreement with Mormile *et al.* (2016).

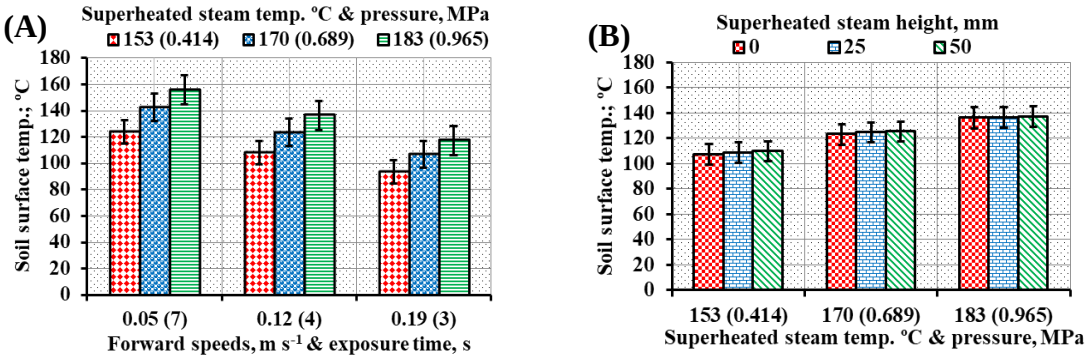

Figure. 4. *The soil surface temperatures at the effect of (A) forward speeds (exposure times) and the superheated steam temperatures; and (B) superheated steam temperatures and the steam heights.*

Fungal pathogens control efficiency

Figure 5A displays an inversely proportional correlation between sterilizer forward speeds (FS) and the efficiency of controlling fungal pathogens (FCη) with the steam temperatures (ST). The highest values for controlling fungal pathogen efficiencies FCη were (90.90, 92.72, and 91.37%), respectively, for *Fusarium oxysporum (Fus. Ox.), Rhizoctonia solani (Rhiz. S.), and Pythium* spp. *(Pyt.* spp.*)*, at the lowest FS of 0.05 m s^{-1} and the highest ST of 183ºC, as shown in Figure 5A. Figure 5A illustrates the FCη lowest values of (66.11, 79.42, and 75.61%), respectively, for *Fus. Ox., Rhiz. S., and Pyt. spp.*, at the maximum FS of 0.19 m s^{-1} and the lowest ST of 153ºC. The FCη values for control greenhouse were (47.11, 49.55, and 45.53%), respectively, as shown in Figure 5A. Figure 5B illustrates an inversely proportional correlation between the ST and FCη at the different levels of H. The maximum values for FCη were (84.01, 88.64, and 85.70%), respectively, for *Fus. Ox., Rhiz. S., and Pyt. spp.*, at the minimum H of 0 mm and the highest ST of 183ºC, as shown in Figure 5B. The minimal values for FCη were (75.97, 84.58, and 80.31%) for *Fus. Ox., Rhiz. S., and Pyt. spp.,* respectively, at the maximum H of 50 mm and the lowest ST of 153ºC, as shown in Figure 5B. The FCη values for the control greenhouse were (47.11, 49.55, and 45.53%), respectively, as shown in Figure 5B. The average mean values and the standard deviation for soil fungal pathogen infections before and after steam treatment are indexed in Table 2. Statistically, there is a high significance effect at a probability of $P \leq 0.05$ for the FCη, the main factors, and the interaction

between them, as listed in Table 2. The linear regression formulas for fungal pathogen efficiencies for the steam sterilizer were obtained and illustrated in Equations 5 to 7.

Fus.Ox FCη, % = - 128.373 FS + 0.568 ST - 0.0219 H (R^2= 0.897) (5)

Rhiz. S. FCη, % = - 56.184 FS + 0.552 ST + 0.0460 H (R^2= 0.896) (6)

*Pyt. spp.*FCη, % = - 67.889 FS + 0.540 ST - 0.0038 H (R^2= 0.897) (7)

Table 2 displays the CFU of the different fungal pathogens before and after the thermal treatment with steam and the solarized control. There are highly significant differences that confirm the efficiency of the steam sterilizer device compared to solar sterilization. The efficiency of controlling fungal pathogens in the soil for the control decreased by rates of (43.79, 43.17, and 45.84%) and (36.9, 39.09, and 40.17%), respectively, from the maximum control values for *Fus. ox., Rhiz. s.,* and *Pyt.* spp. for the experimental greenhouses, as shown in Figures 5A and B. The efficiency of controlling fungal pathogens in experimental greenhouses increased at the highest steam exposure time (lower forward speeds) of the steam soil sterilizer device. The superheated steam was used oppositely to the saturated steam despite the higher heat transfer capacity than superheated steam due to it easily penetrating the soil pores using superheated steam and being free of water, which can raise soil humidity when the temperature drops due to condensation, creating an active environment for fungal pathogens. The efficiency of fungal pathogen control increases proportionally with an increase in the duration of soil steaming exposure. Superheated steam eliminates fugal pathogens and disinfects the soil directly in a quick, safe, and economical manner, with the agreement of Raffaelli *et al.* (2016). Increasing the exposure time and temperature of the steam increases the sterilization efficiency. Reducing steam height increases the penetration of dynamically pressurized superheated steam into the fungal-infected soils. There were significant differences between the control and experimental greenhouses. This significant effect is due to raising the treated soil temperatures above the lethal range for pathogens thermal potential range, 70ºC, in agreement with Gay *et al.* (2010), Aghazadeh *et al.* (2022), and El-Kazzaz *et al.* (2022).

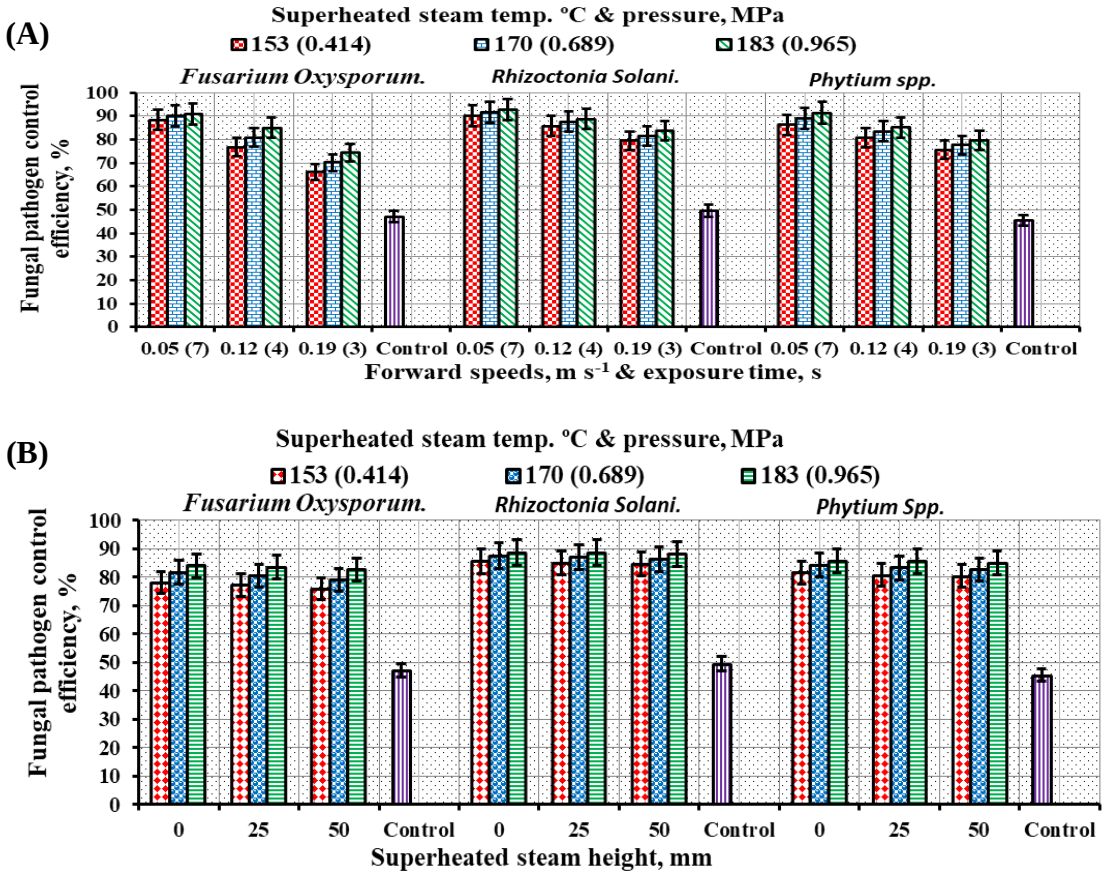

Figure 5. *The fungal pathogen control efficiency at the effect of (A) forward speeds (exposure times) and superheated steam temperatures and (B) superheated steam heights and steam temperatures.*

Table 2. *Mean values and standard deviations of the fungal pathogen CFU of soil samples and the fungal control efficiencies before and after soil thermal treatments.*

Factors		Fus. ox.1, CFU g^{-1}	Fus. ox.2, CFU g^{-1}	Rhiz. s 1, CFU g^{-1}	Rhiz. s 2, CFU g^{-1}	Pyt. spp 1, CFU g^{-1}	Pyt. spp. 2, CFU g-1	Fus. Ox., FC η %	Rhiz. S., FC η %	Pyt. Spp., FC η %
FS, m s^{-1}	0.05	216±36^{a}	22±5^{a}	210±16^{a}	18±2^{a}	839±112^{a}	93±23^{a}	89.77	91.48	88.88
	0.12	228±36^{a}	44±12^{b}	217±24^{a}	28±4^{b}	849±61^{a}	143±17^{b}	80.83	87.31	83.11
	0.19	236±31^{b}	70±13^{c}	212±12^{a}	39±4^{c}	848±91^{a}	190±26^{c}	70.15	81.59	77.58
ST,°C	153	237±34^{a}	56±26^{a}	204±12^{a}	31±10^{a}	848±80^{a}	163±42^{a}	77.04	85.06	80.85
	170	214±28^{a}	42±17^{b}	220±25^{a}	29±9^{b}	830±93^{a}	138±42^{b}	80.33	86.89	83.36
	183	229±39^{b}	39±20^{c}	214±11^{b}	25±8^{c}	859±95^{a}	126±46^{c}	83.37	88.42	85.35
H, mm	0	232±32^{a}	44±20^{a}	214±24^{a}	28±10^{a}	811±87^{a}	132±44^{a}	81.22	87.24	83.81
	50	220±37^{a}	45±24^{b}	211±15^{a}	28±9^{b}	861±99^{a}	144±44^{b}	80.36	86.84	83.17
	25	228±36^{a}	48±23^{b}	213±14^{a}	29±10^{b}	864±73^{b}	151±48^{c}	79.16	86.29	82.58
Control		230±30	108±44	219±24	109±29	833±96	379±54	47.11	49.55	45.53
LSD 0.05		11.487	2.154	9.358	1.229	41.191	7.201	0.259	0.134	0.172
P value		0.0007***	0.0013**	0.00***	0.0001***	0.00***	0.00***	0.001**	0.00***	0.0031**
R^2		0.754	0.879	0.394	0.860	0.517	0.843	0.898	0.798	0.797

Where: FS: forward speeds, m s^{-1}; ST: superheated steam temp.,°C; H: steam height, mm; *Fus. ox., Rhiz. S., and Pyt.* spp. *1&2: Fusarium oxysporum, Rhizoctonia solani,* and *Pythium* spp. pathogens in soil before and after treatment, CFU g^{-1}; FCη: fungal control efficiencies for the pathogens, %; R^2: determination factor; P: probability at (P ≤0.05). $^{a-d.}$ the means with no common subscript within each column differed significantly (P≤ 0.05).

Nematode control efficiency in greenhouse

As demonstrated in Table 3, the average nematode population decreased significantly after treatment with a steam soil sterilizer. As shown in Figure 6 A and B, the highest values of nematode control efficiency NCη using steam sterilization were 97.73 and 92.12%, respectively, at the lowest FS of 0.05 m s^{-1}, the lowest H of 0 mm, and the highest ST of 183ºC. Also, the lowest values of NCη using steam sterilization were 75.88 and 85.28%, respectively, at the highest FS of 0.19 m s^{-1}, the highest H of 50 mm, and the lowest ST of 153ºC. Nematode control efficiency is inversely proportional to the sterilizer forward speeds and steam height at various steam temperatures. The nematode control efficiency for the control greenhouse decreased to 49.13%, as shown in Figures 6A and B. The linear regression analysis for NCη was determined as presented in Equation 8.

$$NC\eta, \% = -100.204\ FS + 0.596\ ST - 0.0095\ H \quad (R^2 = 0.896) \tag{8}$$

As listed in Table 3, there is a high significant effect at a probability of $P \leq 0.05$ for the nematode control efficiency. Nematode knot aggregations are eliminated significantly due to direct exposure to the lethal heat using pressurized superheated steam (Mao *et al.*, 2016). The nematode elimination ratio in control decreased due to the heat is not being enough to affect them (39ºC) in the solar sterilization, in agreement with Runia and Greenberger (2004).

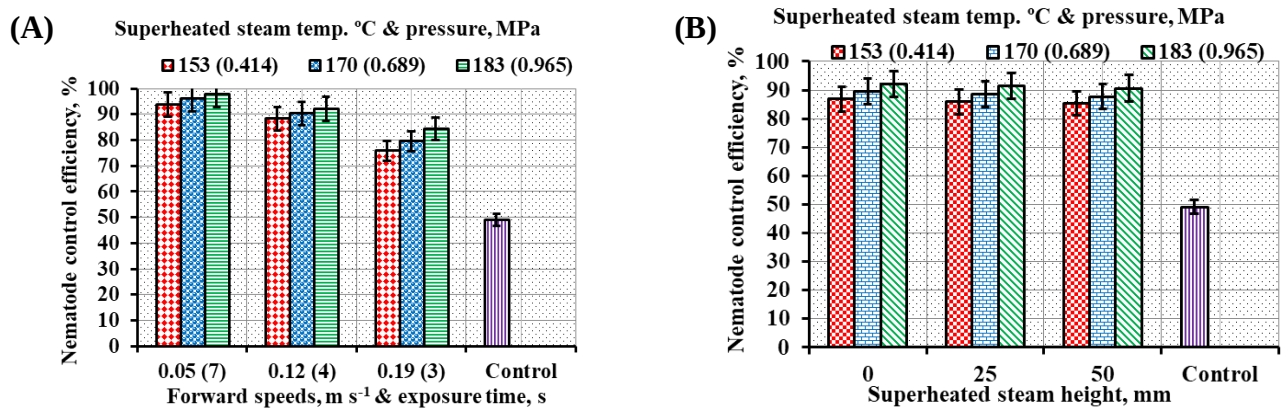

Figure 6. *The nematode control efficiency at the effect of (A) forward speeds and superheated steam temperatures and (B) superheated steam heights and superheated steam temperatures.*

Table 3. *Mean values and standard deviations of the measured soil surface temperatures and the nematode populations before and after soil thermal treatment.*

Factors		SST, °C	NP1, No./100g soil	NP2, No./100g soil	NC η %
FS, m s^{-1}	0.05	140.8±13.25^{a}	293±35^{a}	12±5^{a}	95.87
	0.12	122.76±11.74^{b}	281±31^{ab}	55±14^{b}	79.93
	0.19	105.98±10.06^{b}	276±40^{b}	28±5^{c}	90.26
ST,°C	153	108.63±12.76^{a}	287±31^{a}	40±23^{a}	86
	170	124.36±14.91^{b}	281±40^{a}	32±19^{b}	88.62
	183	136.55±15.88^{c}	281±37^{a}	24±16^{c}	91.44
H, mm	0	124.09±18.57^{a}	285±29^{a}	30±21^{a}	89.49
	50	122.22±18.79^{b}	281±38^{a}	32±20^{ab}	88.68
	25	123.23±18.57^{c}	283±40^{a}	34±21^{b}	87.89
Control		33± 2.5	280±39	138±22	49.13
LSD 0.05		0.242	16.874	2.702	0.191
P value		0.00***	0.0005***	0.00***	0.013*
R^2		0.899	0.495	0.860	0.898

Where: FS: forward speeds, m s^{-1}; ST: superheated steam temperature, °C; H: steam height, mm; SST: soil surface temperature, °C; NP1&2: nematode populations in soil before and after treatment, No. /100g soil; NC η: nematode control efficiency, %; R^2: determination factor; P: probability at (P ≤0.05). $^{a-d.}$ the means with no common subscript within each column differed significantly (P≤ 0.05).

Weed seed bank

As demonstrated in Table 4, the soil seed weed bank reduction ratio for the experimental greenhouses increased significantly compared to the control greenhouse. The overall mean average of the variables interaction was determined. The most infested Experimental plots with weeds were selected to estimate the weed seed bank reduction ratio. The superheated steam usage led to the atrophy of weed seeds present in the surface layer of the soil, in agreement with Peruzzi *et al.* (2011). Reducing the soil weed seed bank leads to reducing weed control costs, in agreement with Daughtrey and Buitenhuis (2020). Using a steam sterilizer makes it possible to dispense with the need for mulching plants in the greenhouse, which saves production costs and increases quality, in agreement with Nishimura *et al.* (2015) and Raffaelli *et al.* (2016).

Table 4. *Weed seed classification before and after three weeks of treatment.*

Weeds classification	Narrow-leaved weeds No. m^{-2}			Broad-leaved weeds, No. m^{-2}		
	Phalaris minor L.	*Lolium temulentum* L.	*Poa annua* L.	*Lathyrus hirsutus* L.	*Medicago polymorpha* L.	*Cichorium endivia* L.
Exp. 1	211	119	88	68	57	42
Exp. 2	37	27	15	19	17	11
Con. 1	215	120	75	55	63	44
Con. 2	89	44	31	23	26	19
SB Exp. RT,%	82.46	77.31	82.95	72.06	70.18	73.81
SB Con. RT %	58.60	63.33	58.67	58.18	58.73	56.82

Where: Exp.; Con. 1&2: total main average of experimental and control greenhouses seed bank before and after 3 weeks from treatment; SB Exp. RT: experimental greenhouse weed seed bank reduction ratio, %; SB Con. RT: Control greenhouse weed seed bank reduction ratio, %.

Crop yield

The crop yield of the *Belgino* cucumber variety was collected after the end of the loop for the experimental and control greenhouses. The average productivity of the three experimental greenhouses was 4 tons. Each greenhouse contained 800 plants, with an average productivity of 5 kg per plant. The yield of the control greenhouse decreased to 3.87 tons as a result of the delay in the planting date and the emanation of *Fusarium* wilt and root rot diseases. The cost of fungal disease control in the control greenhouse increased to 200 USD as a result of the use of chemical fungicides. Solar sterilization was not sufficient to disinfect the soil. The cost of plastic mulching for soil solarization was 203 USD. The cost of steaming a single greenhouse using the new device was 32.25 USD. The use of sterilizer devices led to a saving of 88.50% on the cost of solar sterilization. Steam sterilization led to an increase in crop yield of 3.36% compared to the control treatment.

Soil chemical properties

The device can be used in a variety of settings, and because of the moderate fall temperatures, it is best to utilize it around September. When the treatment is applied throughout the winter at low temperatures, the steam temperature can be regulated. Given that clay soil is particularly vulnerable to fungal infections, the treatment was applied to it. The soil chemical analysis before and after steam and solar sterilization treatments for testing greenhouses is listed in Table 5. The percentage of available nutrients in the steam-treated soil increased relatively as a result of increasing soil moisture content, in accordance with Dietrich *et al.* (2020). The relative increase in available soil nutrients reduced fertilizer requirements for minerals by 2% for steam sterilization and 1% for solar sterilization, in the agreement with Ngakou *et al.* (2008).

Table 5. *Chemical analysis for the experimental and control greenhouses before and after sterilization.*

Chemical analysis	EC, dSm^{-1}	OM, $g\ kg^{-1}$	pH	N, %	P, ppm	K, ppm	Fe, ppm	Mn, ppm	Zn, ppm
Experimental before	1.17	13.43	7.44	0.09	27.03	280.14	30.55	18.39	7.03
Experimental After	1.98	14.55	7.47	0.11	28.09	285.05	31.15	19.05	7.55
Control before	1.15	12.95	7.34	0.08	28.13	280.22	30.28	18.78	6.98
Control after	1.23	13.22	7.39	0.12	27.15	282.33	31.15	18.98	7.01

Where: EC: Electrical Conductivity; OM: Organic Matter.

Self-propelled steam sterilizer evaluation performance

The field efficiency of the self-propelled steam soil sterilizer increased to 0.95% as a result of less time lost due to malfunctions. The actual field capacities of the soil steam sterilizer were 0.013, 0.03, and 0.05 ha h^{-1}, respectively, at the different forward speeds of the device. Field capacity decreased due to the long time required for sterilization. Specific energy consumption rates reached 77.85, 42.67, and 30.96 kWh ha^{-1}, respectively, at the device forward speeds. The operating cost of the

self-propelled soil sterilizer is 769.23, 333.33, and 200 USD ha^{-1}, respectively, at the sterilizer device forward speeds.

CONCLUSION

Utilizing the self-propelled steam soil sterilizer device in greenhouses was highly significant compared to solar sterilization. Optimum sterilization levels were achieved at the lowest device forward speed of 0.18 km h^{-1} at a steam exposure time of 7 sec. Setting the steam distributor height to zero and the steam temperature to 183°C (0.965 MPa) achieved the maximum results for disinfecting soil fungal pathogens. Fusarium wilt diseases were eliminated up to 90.90% using the developed sterilizer. The highest fungal control efficiencies for *Rhizoctonia solani and Pythium* spp. fungi were 92.72 and 91.37%, respectively. The root rot infections were significantly decreased. The nematode infestation rate decreased to 2.27% by using the developed sterilizer. The soil bank of weed seeds decreased significantly for experimental greenhouses over control. Soil properties improved positively, and the availability of soil nutrients increased. The experimental greenhouse yield increased by 3.36% over the control. The quality of cucumber yield was significantly improved by using the device. The device's average power consumption was 50.49 kWh ha^{-1} at an average field capacity of 0.031 ha h^{-1}. The average operating cost was 434.18 USD ha^{-1}. The new device can be recommended for small greenhouse owners to save on production costs and maintain crop quality.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

This research work was conducted in cooperation with all authors equally in terms of the idea, conducting experiments, writing the research, and reviewing it in its final form.

ETHICS COMMITTEE DECISION

This article does not require any Ethical Committee Decision.

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