Development of a field weed control device using hot air

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Abstract: The aim of this study is to evaluate the performance of a hot air weed control prototype. This study was done in Egypt at the Al-Serw Agricultural Research Station, Damietta Governorate. Also, the study aimed to evaluate the effect of the device on plant damage and soil weed seed bank content as well as evaluate the prototype's mechanical and economic performance. The electrical energy is considered as an alternative source of power for the weed control device. Hot air temperatures, flow rates, and exposure times are automatically controlled using electronic units such as thermocouples, speed controls, digital timers, and infrared motion sensors. The field tests were carried out at 0.28, 0.56, and 0.83 m s^{-1} of tractor forward speed levels, with air temperature levels of 750°C, 850°C, and 950°C and hot air flow rate levels of 0.035 and 0.045 m^3 s^{-1}. The main results indicated that using tractor forward speed of 0.28 m s^{-1}, air temperature of 950°C, and air flow rate of 0.045 m^3 s^{-1} achieved the optimal value of weed control efficiency of 91.45%, the higher decrement in weed seed bank in the soil surface layer of 76.93%, the higher plant damage of 10.83%, higher field capacity of 0.33 ha h^{-1}, consumed energy of 156.76 kWh ha^{-1} and operating costs of 124.32 \$ ha^{-1}.

Key words: weed control; thermal weeding; onion.

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1 Introduction

One of the most intriguing ways of safeguarding public health is to protect the environment from toxic pesticide residues that affect microorganisms, plants, and water. Chemical herbicides are hazardous to human and animal health as well as to the environment. The weeds didn't only reduce the yield, but also reduced the quality of the crops and had some toxic effects. In addition, some species of weeds secrete toxic substances (Mesnage et al., 2014; Qasem, 2017). Therefore, weeds compete with the growing crop for the main sources of growth like light, food, and water (Damalas and Eleftherohorinos, 2011; Kaur et al., 2018). As a result, non-chemical treatments such as flame, infrared radiation, hot water, steaming, hot air, and other approaches were required because they had a direct influence on weed elimination and weed seed reduction in the soil (Rask and Kristoffersen, 2007; Peerzada and Chauhan, 2018). Thermal weeding is a weed elimination technique that uses several types of electromagnetic radiation. Thermal prototypes can be classified into two categories based on how they operate: (a) direct heating (flaming, hot air, hot water, steaming, infrared) and (b) indirect heating (microwave, electrocution, laser, and ultraviolet radiation) (Ascard et al., 2007; Rask and Kristoffersen, 2007). Despite their effectiveness, some thermal methods are considered environmental pollutants as a result of the burning of

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large quantities of fuel. There is a limited amount of scientific research on thermal weeding (Bajwa et al., 2015). Thermal control is a suitable and feasible option for weed control on both organic and conventional farms (Datta and Knezevic, 2013). When compared to mobile steam sterilization for intensive and comprehensive cultivation, the weed control approach with hot air treatment offers several benefits, including a 10% to 20% reduction in energy use (Ascard et al., 2007). Furthermore, using hot air to control weeds enhances the yield of potatoes, tomatoes, and radish tubers (Runia et al., 2007). Moreover, when temperatures reach 60°C, the thermal control causes nucleic acid denaturalization in weed cells as well as necrosis damage to the weed tissue (Júnior et al., 2019).

Thermal weed control using hot air destroys the cell structure by allowing moisture and heat to be transferred between weed cells more quickly (Bauer et al., 2020). Besides, Hansson and Ascard (2002) found that thermal weed control treatments are more effective on young weeds than older ones. Also, they found that controlling large weeds (6 leaf stage) at 0.4 m s^{-1} of tractor speed uses energy more than 2.7 times as much as controlling small weeds (2 leaf stage) at 0.35 m s^{-1} of tractor speed (Coleman et al., 2019). As a result, Piron et al. (2011) found that using temperatures ranging from 1300°C to 1900°C for thermal flame methods were more successful and advantageous for weed control during early crop growth stages, although only 300°C to 600°C could reach the soil and weeds. In the flame method, the tractor is typically run at 0.56 to1.67 m s^{-1} to achieve an effective working width of 2 to 6 meters, resulting in work rates of 0.4 to 3.6 ha h^{-1} (Rifai et al., 2002). When designing a thermal weeding machine, keep in mind that it should be as effective as possible while avoiding heat damage to the growing crop. Sometimes, heat treatment may cause harm to crops depending on their stage of growth (Stepanovic et al., 2016; Peruzzi et al., 2017). Spagnolo et al. (2019) developed a weed control prototype with a 1.4 m structure installed at the end of the heat transfer nozzles to improve heat retention and extend the time that weeds are exposed to heat. Mechanical weeders, which are a form of row crop weeders, are the most advanced weeding techniques. The most advanced intra-row weeders use sensors and robotics (Shamkuwar et al., 2019). Furthermore, Peruzzi et al. (2017) stated that the smart intra-row flaming machines with the intelligent smart weeding technique are suitable for non-competitive heat-tolerant row crops such as onion and garlic. It is possible to rely on weed control systems using thermal control systems such as the use of flames, fire, hot water, steam, and freezing to control weeds directly without leaving chemical residues or pesticide traces in both soil and water. Thermal control methods are one of the selective methods used in precision farming because they control only the area where the weeds are found and improve the soil's properties by reducing the content of weed seed banks (Scavo and Mauromicale, 2020). Weeds are a severe challenge to agricultural efficiency, causing significant losses in crop yield. Therefore, it is not possible to rely on a specific method of weed control, but rather, several methods must be combined to increase the effectiveness of the control in the so-called integrated weed control systems (Monteiro and Santos, 2022). Because mechanical or chemical weed control methods lead to long-term weed resistance, more effective weed control methods, such as utilizing hot air, must be used.

Different traditional weed control methods vary, whether mechanical or chemical, and these methods differ among themselves in terms of the efficiency of weed control. Methods of mechanical weed control include the use of tractor-mounted harrowing machines or self-propelled harrowing machines. The use of mechanical methods does not constitute a high level of efficiency in controlling broad-leaved weeds because it controls weeds only in the surface soil layer without affecting the content of the soil bank of weed seeds, unlike the thermal methods of weed control, which are characterized by their effectiveness to control weeds (Peruzzi et al., 2017; Machleb et al., 2021). Weed control by hot air is an effective and direct method to eliminate weeds. Weed control by hot air has a positive effect on broad-and narrow-leaved weeds that reproduce vegetatively only (i.e., without rhizome). One of the most significant advantages of using hot air is that it eliminates the need for an intermediary such as steam weed control machines, which need large attached water tanks in addition to consuming a large amount of energy and fuel, which increases environmental pollution. One of the disadvantages of using hot air is that cultivated plants are exposed to partial damage to the vegetative system as a result of weather conditions only during winds, as well as their weak ability to eliminate weeds with rhizomes. Otherwise, it is an ideal method when compared to other costly weed management methods, whether mechanical, chemical, or biological (Morselli et al., 2022).

The objective of this study is to evaluate the performance of a hot air weed control prototype. Second, study the prototype's effects on crop damage and soil seed banks.

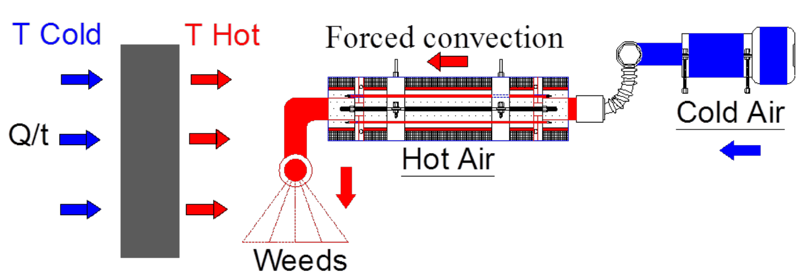
2 Materials and methods

2.1 Study location

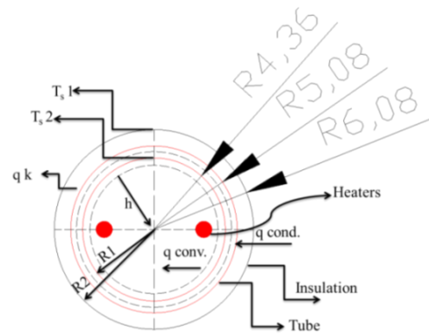
The hot air weed control prototype was tested at the El-Serw Agriculture Research Station, Damietta governorate, Egypt (latitude 41′31°- 30′31°N, and longitude 81′31°- 18′31°E), during 2020 and 2021 winter seasons. The climatological information of the experimental sites was provided by the professional wireless weather station model ACURITE, No. 01512, which monitor air temperature (°C), air relative humidity (%) and wind speed (m s^{-1}) during the interval testing periods. During the test period, air temperatures ranged between 21°C and 17°C (a daily average of 21.05°C), with monthly average air humidity ranging between 75% and 66%. The mean wind speed was recorded to be between 3.2 and 4.1 m s^{-1} at the end of the testing period. The prototype was evaluated at three tractor forward speed levels (S) of 0.28, 0.56, and 0.83 m s^{-1}, which corresponded to a time of 6, 4, and 2 s of exposure to hot air, respectively. Also, it was tested at hot air temperature levels (T) of 750°C, 850°C, and 950°C and hot air flow rate levels (Fr) of 0.035 and 0.045 m^3 s^{-1}. A factorial experiment in complete randomized block design was used to arrange the experimental plots. In total, 18 plots (plot area equals 30 m^2, with every plot having 5 rows of 10 m long and 0.6 m wide) of onions (*Allium cepa L.*) were cultivated and tested in five replicates of the experiments. Pre-laboratory experiments were carried out to calibrate the weed control prototype to adjust its height over growing plants and apply thermal treatments through field experiments. Laboratory tests included testing the device in the laboratory on different weed samples to determine the levels of hot air temperatures and its flow rate.

2.2 Theoretical considerations

The weed control device was designed to use hot air that based on the theory of heat exchangers. Heat is transferred by two mechanisms in the prototype condition: first, via conduction from the tungsten inlet coil for the tubular heaters; and second, by forced convection through the outlet, blowing air into the final distribution nozzles over the weeds, as illustrated in Figure 1: (Nakayama and Park, 1996).



(a) path of forced convection heat transferred



(b) cross section area of the heating tube generator (dimension: cm).

Figure 1 Hot air prototype heat transfer specifications include

$$q_{cond.} = \frac{K\,A(T_{Hot} - T_{Cold})}{d} \quad (1)$$

$$q_{\,conv.} = h_c\, A\, (T_s - T_a) \quad (2)$$

Where: $q_{\,cond.}$: conduction heat transfer, W; K: material thermal conductivity, W m^{-1} K^{-1}; A: cross sectional area, m^2; T_{Hot}: higher temperature °C; T_{cold}: higher temperature °C; d: material thickness, m; $q_{\,conv.}$: heat transferred by unit time, W; h_c: convective heat transfer coefficient of the process, W m^{-2} K^{-1}; T_s: temperature surface, °C; Ta: temperature air, °C.

$$Q = cp.\ dT.\ m/t \quad (3)$$

Where: Q: mean heat transfer rate, kJ s^{-1}; m/t= mass flow rate, kg s^{-1}; cp: specific heat capacity, kJ kg^{-1} °C^{-1}; dt: change in temperature of the fluid (air), °C.

The optimum thickness of thermal insulation was calculated using Equation 6, which is defined as the thickness at which the total resistance is high and the heat loss is low. $T(r) = T_o + \frac{\dot{q}}{4k}(r_o^{\,2} - r_i^{\,2}) - \frac{\dot{q}}{2k} r_o^{\,2} \ln\frac{r_o}{r_i}$ (4)

$$R_{tot} = \frac{\ln(r_o/r_i)}{2\,\pi\,k} + \frac{1}{2\,\pi\,r_o\,h} \quad (5)$$

$$r_c = \frac{k}{h} \quad (6)$$

Where: T(r) : Tube temperature distribution, °C; $R_{\,tot}$: total resistance per unit length of tube; Rc: critical radius of the thermal insulator, m (0.02 m) (R2; Figure 1, b); k: heat transfer factor, W m^{-1} K^{-1}; h: coefficient of heat load between insulation and air, h: 5 W m^2 K^{-1}; q: heat transfer rate, W; (T_s1: outer surface temperature, °C; T_s2: inner surface temperature, °C; Figure 1, b); To: temperature at axis, °C; r_o: outer radius, m; r_i: inner radius, m (R1, Figure 1, b).

Basing on the design considerations of heat transfer equations and their practical application, the appropriate diameter, thickness, and length of the heat generator tubes was used, as shown in Figure (1, b). Also, the optimal diameter of the thermal insulator and the number of heaters were chosen according to mathematical equations.

2.3 Specifications of hot air weed control prototype

The thermal weed control prototype works by blowing hot air between the planted rows during the critical period for growing plants during the first month after planting, to improve the ability of the planted crops to compete against weeds for light, nutrition, and water. The prototype frame was designed for facilitating its use by attaching to the three-point hitch of the tractor (Figure 2, No. 7). A major safety factor was taken into account when designing the frame to resist different stresses. The frame has been assembled by a laser cutting machine for easy maintenance and storage. The design of the frame took into account the engineering dimensions and the center of gravity for comfort in maneuvering, rotation, and achieving maximum balance. The frame was equipped with three adjustable cranes to facilitate the storage and preservation of electrical parts while observing the good electrical insulation, as shown in Figure 2, No. 6. The frame of the prototype is made of 4 mm-thick steel, and the tubes of the hot air pumping unit are made of 4 mm-thick stainless steel. The device's balance is adjusted by calculating the center of gravity with a large safety factor. All electrical components of the device were isolated using electrical insulators and grounding. A model was also designed for easy maneuvering and handling of different crops while using it for weed control, taking into account all engineering factors related to crops such as plant height and cultivation systems. The machine's general specifications are shown in Figures 2 & 3 and Table 1.

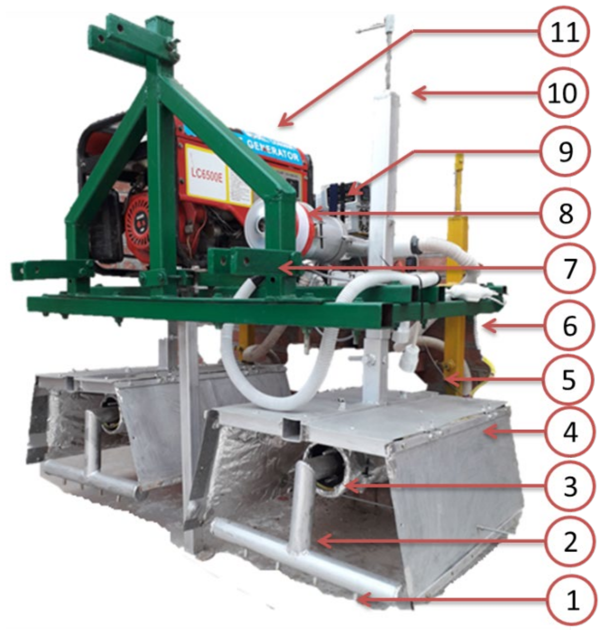
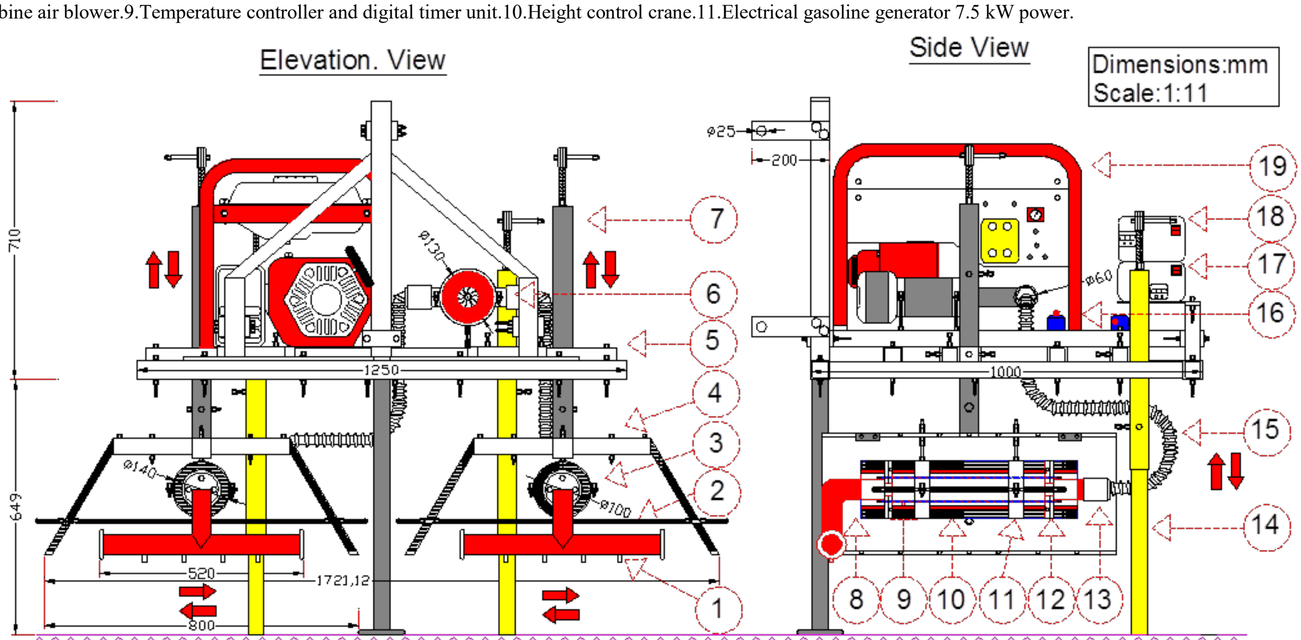


Figure 2 Hot air weed control prototype components.

1.Hot air nozzles. 2.Outlet hot air tube. 3.Hot air generator. 4.Insulator shield. 5.Thermocouple cable. 6.Frame lifter crane.7.Three- point hitch. 8.Turbine air blower.9.Temperature controller and digital timer unit.10.Height control crane.11.Electrical gasoline generator 7.5 kW power.



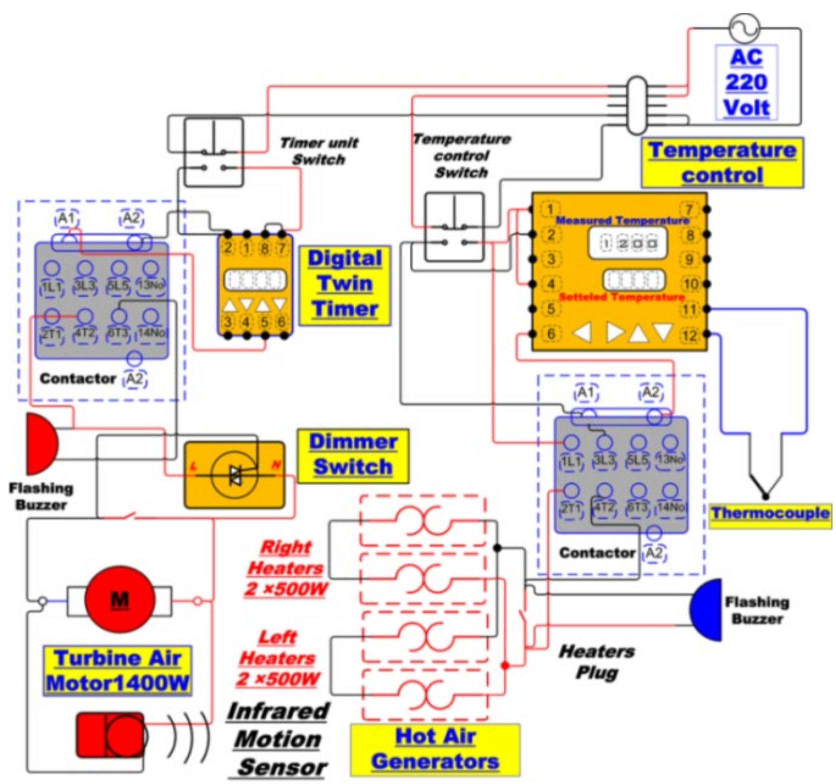
1.Hot air distributor. 2.Angled control tensioner. 3.Hot air generator. 4.Insulator shield. 5 .Frame. 6 .Turbine air blower. 7.Adjustable crane.8.Outlet hot air tube.9.Dual tubular heaters (500 W). 10.Insulator. 11. Hot air tube holders. 12.Inside flange. 13.Inlet cold air collar. 14.Frame holder cranes.15.Cold air hose.16.Air motor dimmer.17.Digital timer unit.18.Temperature controller.19.Gasoline generator 7.5kW.

Figure 3 Hot air weed control prototype schematic diagram (Dimensions: mm)

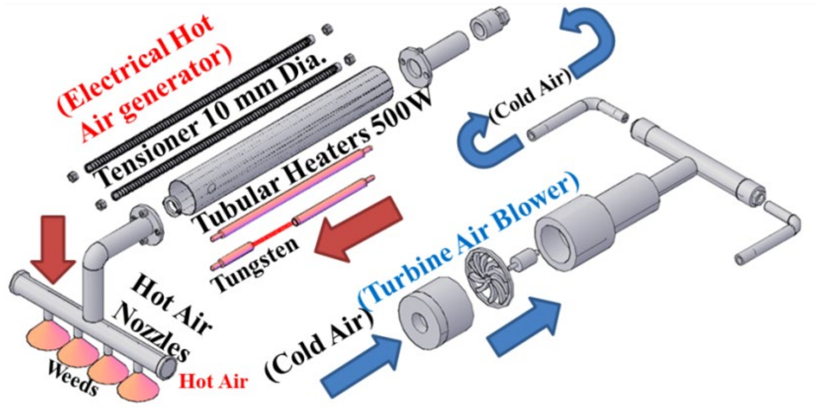
Table 1 Hot air weed control prototype specifications

Hot air weed control device		Electrical generator	
Dimensions	1250;1000 and1356 mm (Long, width and height)	Model	Lincoln LC 6500 E Chinese
Operation width	Up to 1720 mm	Standby power	7 kW
Net mass	223 kg	Rated voltage	220 V
Air temperatures	Up to 950°C	Frequency	50-60HZ
Air flow rate	Up to 0.045 $m^3 s^{-1}$	Speed	15.708-18.850 $m s^{-1}$
Used tractor	Kubota 58.840 kW	Phase	Single phase
Forward speeds	0.28 to 0.83 $m s^{-1}$	Engine	(4.781kW) 3600 RPM

The main components of the prototype thermal machine were investigated as follows: First, the hot air thermal generators consisted of two units. Each unit consists of a 101.6 mm diameter steel tube with a length of 550 mm and has two fixed linear tube heaters (500 W) inside, as shown in Figure 3, No. 9. Every tube was flanged on both sides and connected to another 50.8 mm tube that was connected to the hot air distributor. Also, each hot air distributor had four copper nozzles (cone type, 10 mm dia.) to plough the flaming hot air directly over the weeds (Figure 2, No.1). In addition, the thermal generators were externally insulated by a layer of glass wool to avoid thermal leakage (Figure, No. 10) and protects the growing crops from damage. In addition, an articulated galvanized insulator shield is lined from the inside with a layer of glass wool to permanently seal the flow of hot air above the treatment area. However, every articulated angled isolator shield was provided with a latitude tighter shaft to adjust its coverage area. Besides, each thermal shield was hung using a manual crane with a lateral slider to control the thermal unit height and operation width over weeds as required, as shown in Figure 2 (No. 7). As well, a turbine air blower from the compressed-type and its specifications listed in Table 2 was gathered to plough the air with different flow rates, which were connected by flexible polyethylene hoses to the inlet thermal generator tubes (Figure 2, No. 8). The exposure air flow rate was controlled by an electrical dimmer to control the fan rotation speed (Figure 3, No. 16).



(a) Electronic unit



(b) Electrical circuit

Figure 4 An electronic circuit

Table 2 Turbine air blower specifications

Electrical specifications			
Power	1400 W	Frequency	50-60 HZ
Rotation speed	335.104 m s^{-1}	Inlet coil	From copper
Using current	10 A	Air flow	Max. 58 L s^{-1}
Voltage	220 V	Noise level	dB

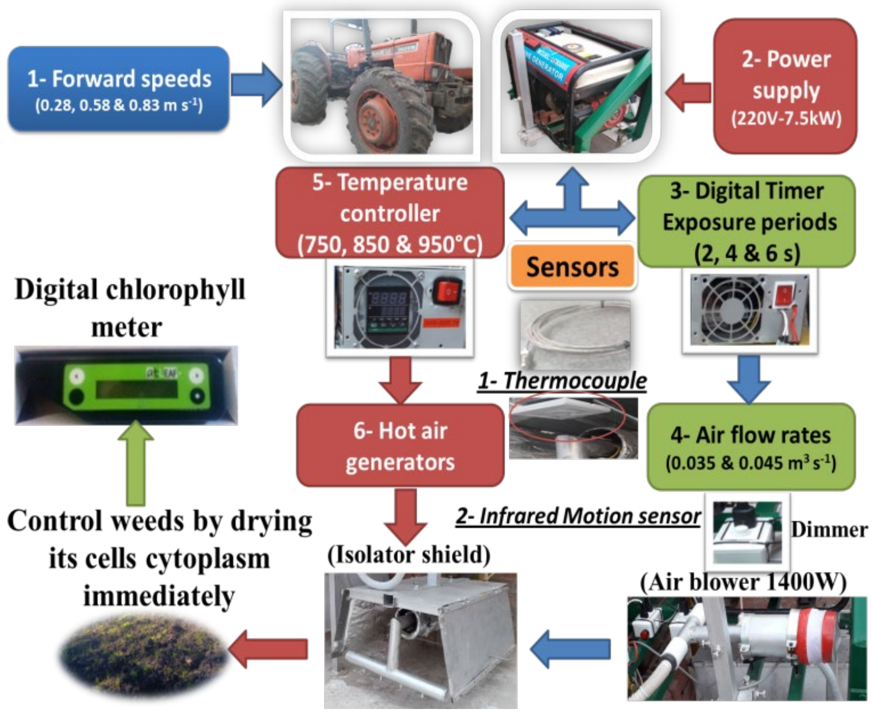


Figure 5 Flowchart of thermal hot air weed control prototype variables, the automatic control devices, and sensors

An electronic circuit has been integrated into the hot air weed control prototype to smartly control and facilitate field operations (Figure 4, a). The power source was first selected based on the total electrical load. The thermal hot air generators have a pair of tubular heaters with inlet tungsten coils that need about 2 kW (Figure 4, b). The prototype was attached to a suitable electronic temperature controller with a thermocouple sensor to control the operating temperature up to 950°C (Figure 5). The temperature controller had two LCD screens, one for measuring the temperature and the other for adjusting the hot air temperatures using the thermocouple sensor

(Figure 4, a and 5). An electrical contactor was also utilized to protect the electrical circuit from overload current, with a flashing buzzer to indicate that hot air was flowing. In addition, the electrical circuit was included with a 1400W turbo electrical blower and its dimmer (Figure 5). Besides, a digital twin timer unit for adjusting the exposure time for the treatment was integrated to synchronize air flow rates with the tractor's forward speeds, as shown in (Figure 5). Infrared motion sensors were also added through the hot air generator circuit to connect-disconnect the electrical signal to the air blower through movement and stop the air flow during field turns to save energy consumption, as shown in Figure 5. As illustrated in Figure 6, the programming system has been done for the hot air temperature control during the thermal control process.

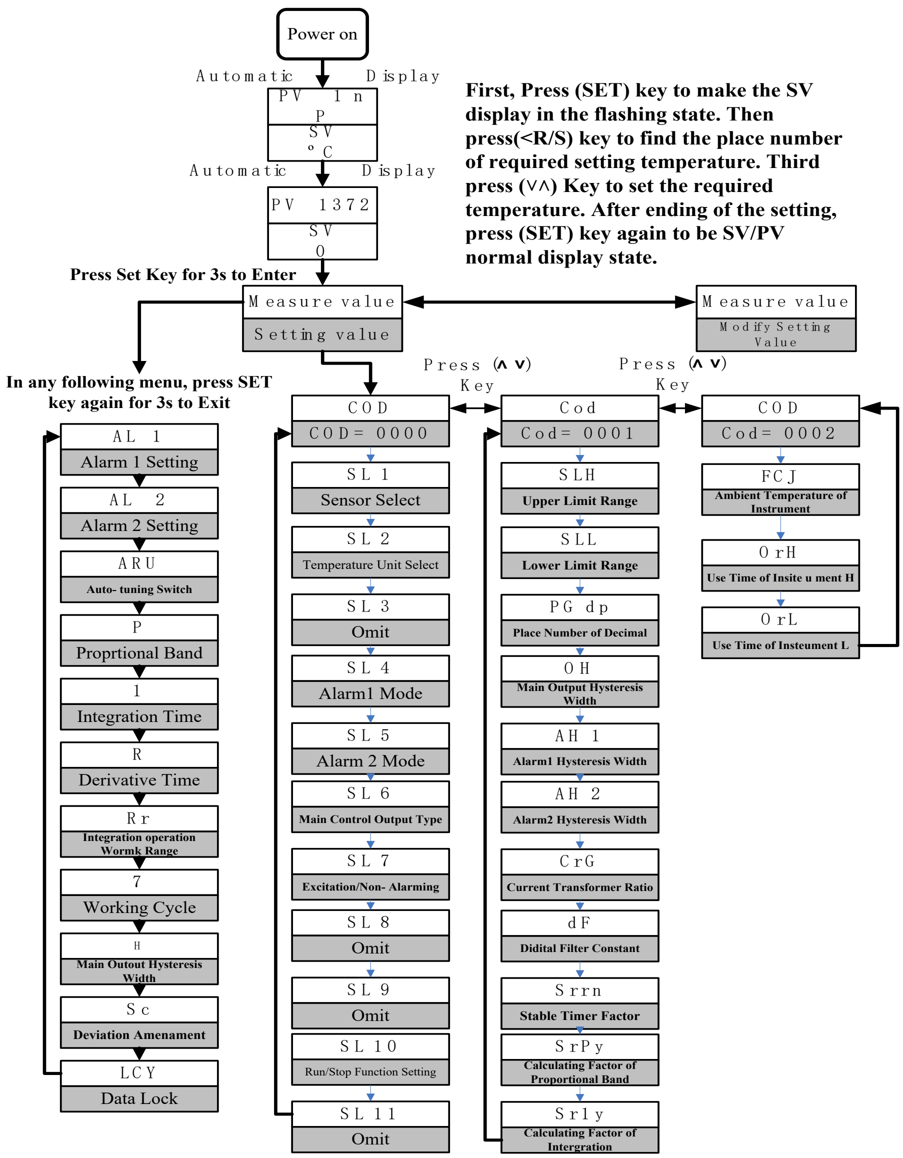


Figure 6 Operation program procedure of the temperature controller

2.4 Mechanical performance of the hot air weed control prototype

The weed control efficiency (WCE), chlorophyll level (Ch), crop damage, and soil weed seed bank were estimated to determine the hot air weed control prototype's performance. Tractor-mounted harrowing machine was used as a traditional method for comparison. After onion sowing, four permanent quadrates of (0.5 × 0.5 m) were marked in each plot to determine the weed number and biomass. At two and four weeks, weed density was measured, and weed dray data was measured and divided into two categories: broad and narrow-leaved for determining dry weight. Weeds were cut at ground level and washed with water before been dried in an oven at 70°C for 48 hours and weighed. A random sample was taken from one square meter of each experimental plot during the growing season as fresh weight (g m^{-2}). According to Tajuddin (2006), only weed biomass was determined from 0.1 m^2 of the remaining areas, excluding quadrate areas, at crop harvest stage. ISA, (2009) employs the following formula to calculate the weed control efficiency of WCE. During the growth season, a random sample of one square meter of each experimental plot was taken as a fresh weight (g m^{-2}).

The weed control efficiency (WCE) was calculated at three different times: after treatment, 1, 5, and 30 days of thermal treatment (ISA, 2009).

$$\mathrm{WCE} = \frac{\mathrm{WD_c} - \mathrm{WD_t}}{\mathrm{WD_c}} \times 100\ \% \qquad (7)$$

Where: WD_c and WD_t (weed m^{-2}) are weed density in control and hot air treated plots, respectively.

While the weed chlorophyll level (Ch) was measured before and after treatment with a digital chlorophyll meter (model *Atleaf PN/0131*), it was estimated after 1, 3 and 7 days from weeding treatment. Ten readings of chlorophyll were taken before and after the treatment at different intervals at 12 p.m. For the controls, the average of the collected readings from the middle of the completely extended top sheet of five weed plants from each square was determined with three replicates (Galon et al., 2019).

$$\mathrm{Ch} = \frac{\text{Weed leaves chloropyll percentage after treatment, mg cm}^{-2}}{\text{Weed leaves chloropyll percentage before treatment, mg cm}^{-2}} \times 100\ \% \qquad (8)$$

According to Anonymous (1994), plant damage was calculated as shown in Equation 9:

$$Crop\ damage, \% = \frac{\text{Number of damaged plants after treatment}}{\text{Total plants number before treatment}} \times 100, \% \qquad (9)$$

The soil weed seed bank was estimated before planting. The content of the soil weed bank was determined at the soil layers of 0–100 and 110–200 mm. The density of soil seed banks was estimated using the sieving method according to Price et al. (2010).

The mechanical performance of the developed prototype was evaluated by measuring the fuel consumption (F); the prototype field efficiency (*Fe*); and field capacity (*FC*) according to Kepner et al. (1982). According to Hunt (1983), the specific energy consumption (*CE*) was estimated as presented in Equation 10.

$$CE = \left(\frac{Fs \times \rho_f \times C.V}{3600}\right) \times \left(\frac{427 \times \eta_{th} \times \eta_m}{75 \times 1.36 \times FC}\right) + EPkWh\ ha^{-1} \qquad (10)$$

Where: *CE*: prototype consumed energy, (kWh ha^{-1}); *Fs*: fuel consumption rate, (L h^{-1}); ρ_f : density of fuel, kg L^{-1}, (for diesel = 0.85 kg L^{-1}); *C.V*: calorific value of fuel, (kcal kg^{-1}); 427: thermal-mechanical equivalent, (kgm $kcal^{-1}$); η_{th}: thermal efficiency of the engine, assumed 40% for diesel engine; η_m: mechanical efficiency to engine, assumed 80% for diesel engine; *Fc*: actual field capacity, ha h^{-1}.

$$Ep = I * V * \eta * cos\varphi / 1000\ \text{kWh} \qquad (11)$$

Where: *EP*: electrical consumed power under different machine loads, kW h; I: line current strength in Amperes; *V*: potential difference (voltage) being equal to 220 V; η : mechanical efficiency assumed as 80 %; *cos φ*: power factor was taken as 0.7.

The specific energy consumption (kWh ha^{-1}) for each treatment could be calculated using the Equation 12.

$$\text{Specific energy consumption} = \frac{\text{Consumed power (kWh)}}{\text{Prototype field capacity (ha h}^{-1}\text{)}} \qquad (12)$$

In addition, the operating cost was calculated using Hunt's (1983) Equations 13 and 14.

$$C = \frac{P}{h}\left[\frac{1}{a} + \frac{I}{2} + T + r\right] + (W.e) + \frac{m}{144}\ \text{USD h}^{-1} \qquad (13)$$

Where: *C*: hourly cost, USD h^{-1}; P: price of the prototype, USD; h: yearly working hours, h $year^{-1}$; *a*: life expectancy of the prototype, year; I: interest rate per year;

T: tax overheads ratio; r: repair and maintenance ratio; W: power of motor, kW; e: hourly cost per kWh.; m: the monthly average wage, USD; 144: the monthly average working hours.

$$Operating\ cost = \frac{Prototype\ \ hourly\ cost,\ (USD\ h^{-1})}{Actual\ field capacity\ (hah^{-1})} USD\ ha^{-1} \quad (14)$$

2.5 Soil physical and chemical properties

Physical and chemical properties of the surface soil layer (0.0–30, 30-60 and 60-90 cm) were determined according to Wilde et al. (1985). As shown in Table 3, the soil texture of the experimental plots was clay loam.

Table 3 Soil mechanical and chemical analysis of the experimental site

Mechanical analysis				Chemical analysis			Available nutrients					
Sand, %	Silt, %	Clay, %	Texture	OM	PH	EC Mmhos cm^{-1}	N, %	P, ppm	K, ppm	Fe, ppm	Mn, ppm	Zn, ppm
22.05	31.44	46.51	Clay loam	1.66	7.44	1.14	0.09	28.04	290.39	32.55	19.22	5.0

Note: *OM:* organic matter content; *pH*: acidity of soil suspension; *EC*: electrical conductivity, dSm^{-1}.

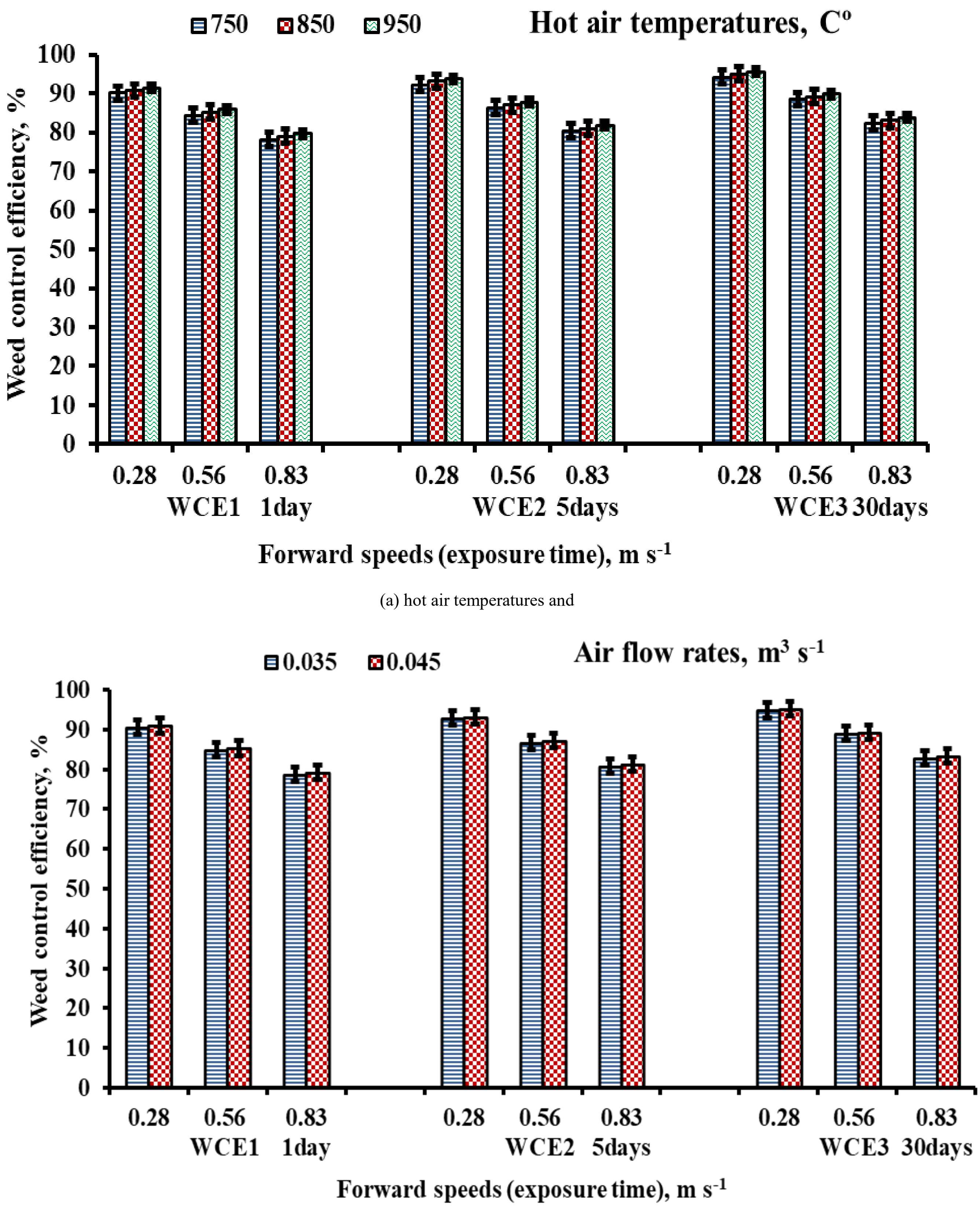
2.6 Statistical analysis

The SPSS program version (2019) was used to analyze the data statistically. Also, the analysis of variance (ANOVA) with probability ($P < 0.01$) was estimated for weed control evaluations. On the other hand, the prototype's mechanical and economic evaluations were estimated with probability ($P < 0.05$). The linear regression analyses were performed to determine the thermal prototype control's most effective factors and also the interaction between the tested factors. The regression computed model is estimated using the following formula: Y = a x1 + b x2 + c x3, where Y is the determined measurement, a, b, and c are linear regression coefficients, and x1, 2, and 3 are tested factor levels.

3 Results

3.1 Weed control evaluation

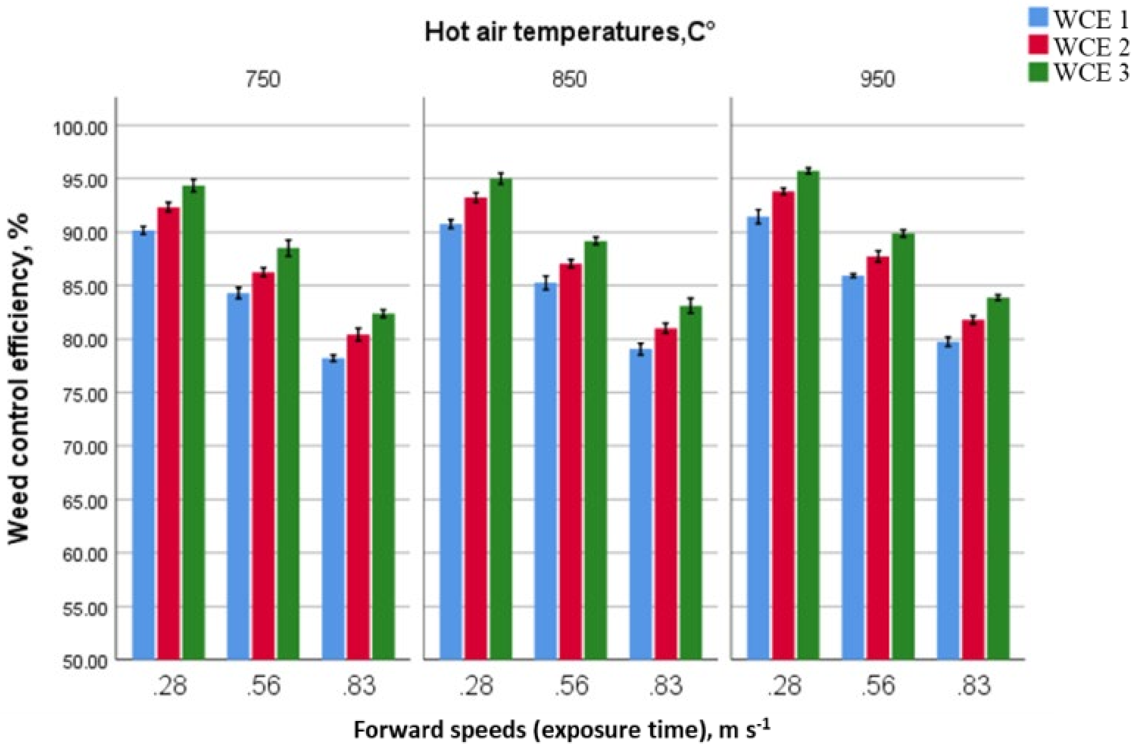
Table 4 shows the average values of the treated weed species in control and experimental plots after 30 days of hot air treatment at the site of the experiments during the testing seasons. The prototype had the greatest effect on narrow-leaved weeds, with the type *Polypogon monspeliensis L*. having the highest percentage of weed emergence rate of 18.55%. On the other hand, the control treatment of *Emex spinosus L.* had the lowest proportion of weed emergence at 3.61% (Table 4). After 30 days of treatment, the measured percentages of weeds categorized in experimental plots treated with hot air dropped to high percentages, ranging from 92.66 to 92.93 for narrow-leaved weeds. When compared to the control plots, the rate of emergence of broad-leaved weeds in the experimental plots treated with hot air was decreased from 70.92% to 82.25%. The effect of forward speeds (exposure times of 6, 4, and 2 s) on the weed control efficiency (WCE) (after treatment 1, 5 and 30 days) was described at different hot air temperatures and flow rates (T and Fr) in (Figure 7a & b). The maximum values of WCE (WCE1 = 1, WCE2 = 5 and WCE3 = 30 days) were 91.45%, 93.81%, and 95.75%, respectively, at 0.28 m s^{-1} of tractor forward speed (S), 950°C of hot air temperature (T), and 0.045 m^3 s^{-1} of hot air flow rate (Fr). Meanwhile, the lowest values of WCE were WCE1 = 78.21, WCE2 = 80.43, and WCE3 = 82.23%, at 0.83 m s^{-1} of S, 750°C of T, and 0.035 m^3 s^{-1} of Fr. Increasing the prototype's forward speed has an inverse relationship with weed control efficiency. Weed control efficiency is increased when the forward speed is decreased. As a result, after 30 days of treatment, when the weeds entirely lost their moisture content as a result of the direct plasmolysis process of their cells, the highest percentage of weed control efficiency was obtained, as shown in Figure 7.



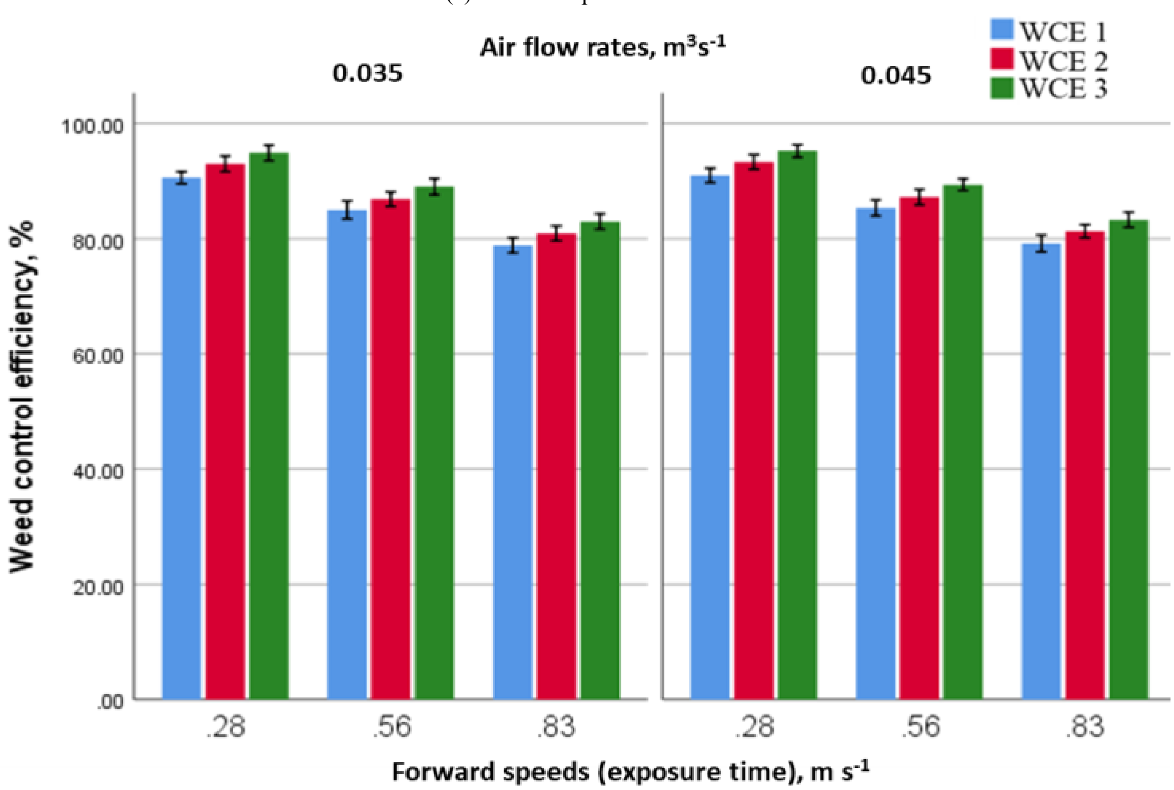
(a) hot air temperatures and

(b) air flow rates

Figure 7 The effect of forward speed on weed control efficiencies (WCE1, 2, and 3) (after 1, 5 and 30 days) at various

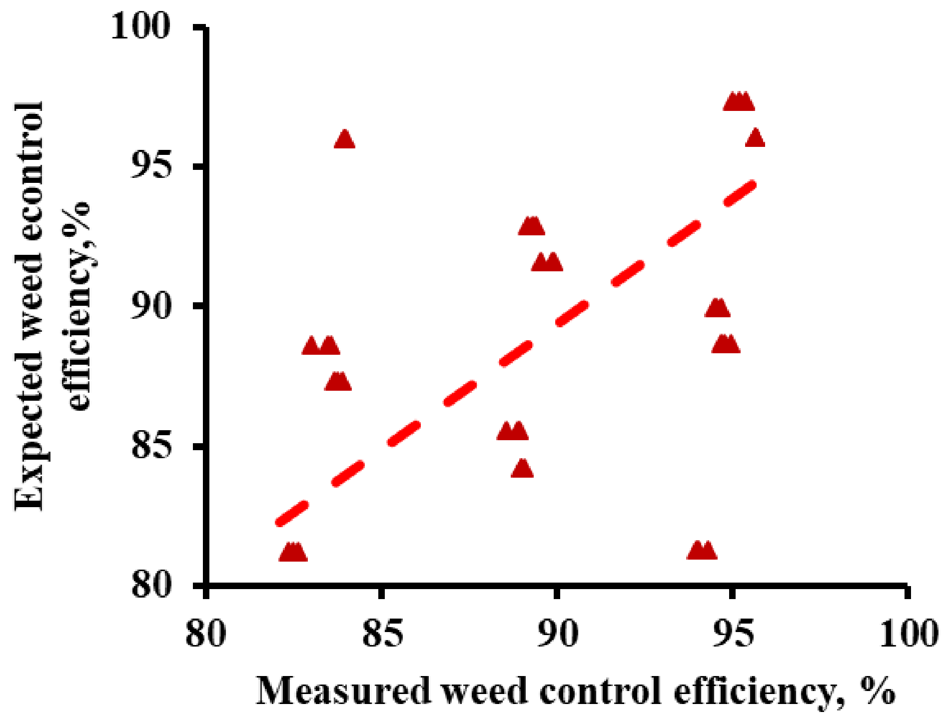


(a) hot air temperatures

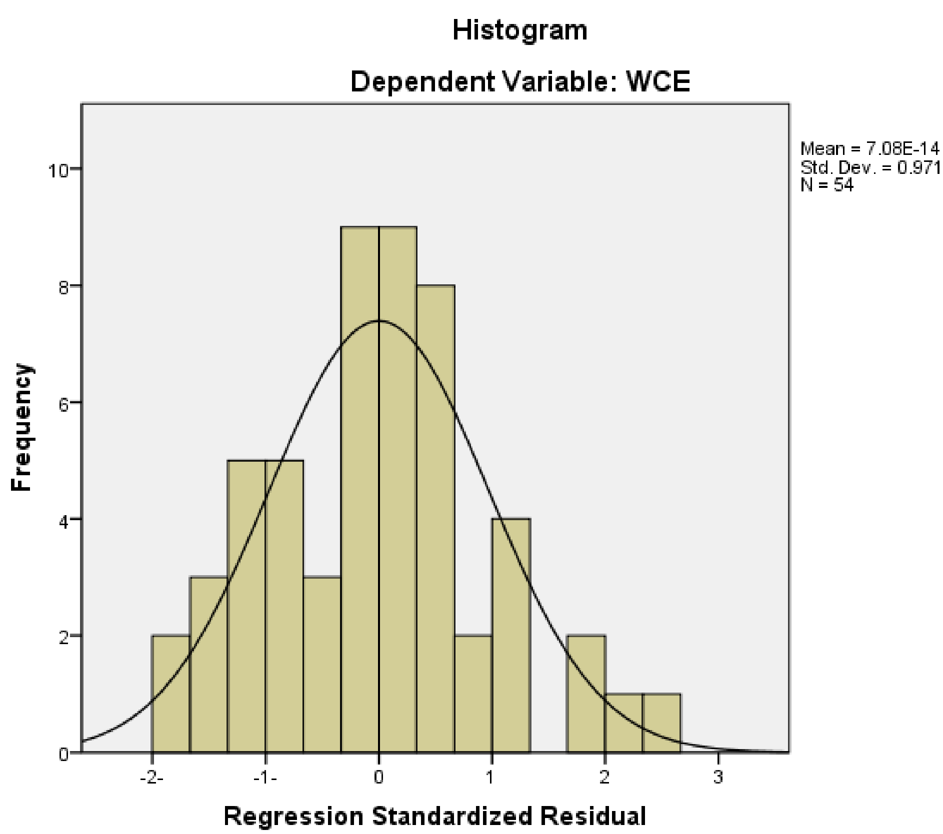


(b) flow rates

Figure 8 The effect of forward speeds on weed control efficiencies (WCE1, 2, and 3) (after 1, 5 and 30 days) at various hot air temperatures and flow rates, with a detailed comparison of the effect of temperature and air flow rate on weed control efficiency



(a) The relationships between the measured weed control efficiency and the expected percentage at the end of the tested period (30 days)



(b) the normality test for the weed control efficiency after 30 days

Figure 9 The relationships between the measured weed control efficiency and the expected percentage

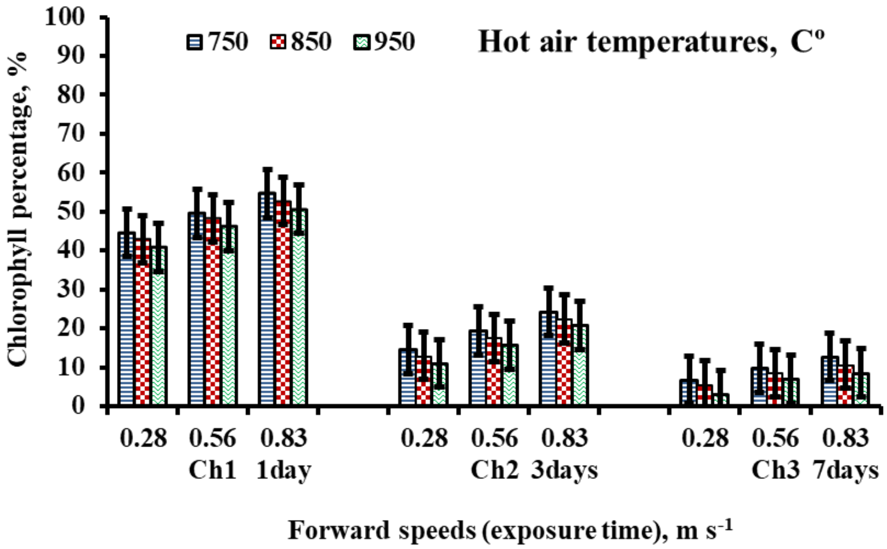
Table 4 The average values of weed species during testing seasons in control and experimental plots after 30 days of hot air treatment

Weed species	Weeds, %	Weed density, weed m^{-2}	Weed dry biomass, g m^{-2}	Weeds, %	Weed density, weed m^{-2}	Weed dry biomass, g m^{-2}
The narrow-leaved weeds		Control plots			Exp. plots after 30 days	
Polypogon monspeliensis L.	18.55	54.22	121.95	1.31	3.82	8.60
Phalaris minor L.	15.54	33.45	75.26	1.14	2.45	5.51
Lolium temulentum L.	14.21	31.55	70.98	1.17	2.59	5.83
Avena sterilis L.	13.25	30.05	67.61	1.18	2.68	6.03
The broad-leaved weeds		Control plots			Exp. plots after 30 days	
Sonchus oleraceus L.	12.11	29.51	66.39	2.15	5.24	11.79
Rumex dentatus L.	9.55	28.44	64.01	2.16	6.43	14.47
Chenopodium album L.	5.02	27.56	62.01	3.42	18.78	42.26
Coronopus squamatus L.	4.22	25.25	56.81	3.34	19.98	44.96
Mulva parviflora L.	3.94	23.33	52.49	2.03	12.02	27.05
Emex spinosus L.	3.61	22.94	51.62	1.05	6.67	15.01

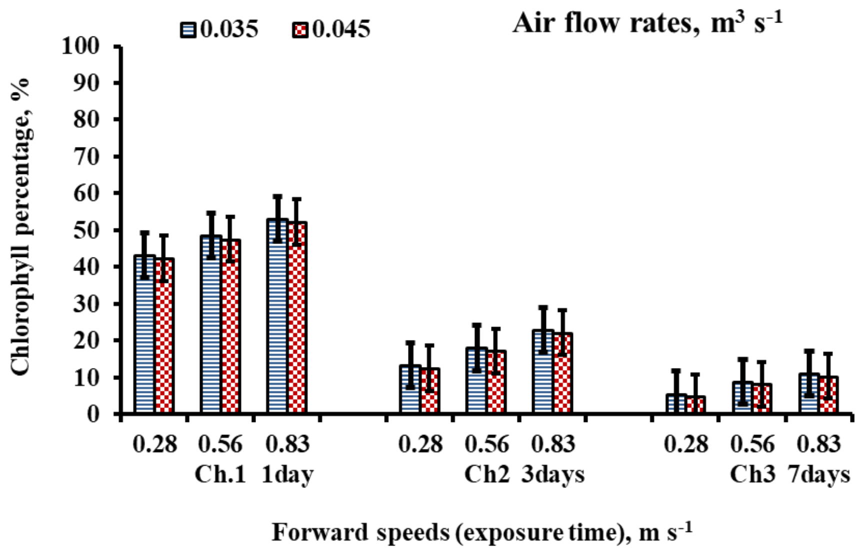
The maximum control efficiency was 95% by using the hot air weed control prototype. As shown in Figure 8a, the effect of 950ºC hot air temperature was highly significant among the other hot air temperatures, because this temperature excelled in weed control and completely stopped its vegetative growth at the end of the testing period. Figure 8b, indicates the increase in the effect of a 0.045 m^3 sec^{-1} air thrust rate at the lowest rate, resulting in the largest positive significant percentage in weed control efficiency. On the other hand, the speed factor had the opposite effect on weed control efficiency, i.e., high speed, short time of weed exposure to treatment, and was exposed to the hot air rates, thus increasing the forward speed reduces weed control efficiency.

Figure 8 (a, b) shows a detailed comparison of the effects of hot air temperatures and their effects on the weeding rates at different time periods after treatment. At the highest temperature of 950°C, it is clear that the elimination of weeds through the plasma of their cells, losing the water stored inside them, leads to their destruction, as the measured fresh weight gradually decreases as a result of the effect of treatment with hot air. The maximum weed control efficiency, increased relatively with the maximal exposure time of hot air at the lowest forward speed of 0.28 m s^{-1}. Figure 8 depicts the inverse relationship between prototype forward speeds and weed emergence levels after treatment. Weed growth rates have increased again as a result of the rapid forward speed and inadequate efficiency of weed control. The interaction between the air flow rate and temperature is shown in Figure (8 a), demonstrating that the higher air flow rate (0.045 m^3 s^{-1}) is better than the lower air flow rate. As demonstrated in Figure (8b), the air exposure rate increment with the highest hot air temperature had a significant effect on the weed control efficiency and vice versa for the rate of weed emergence levels.

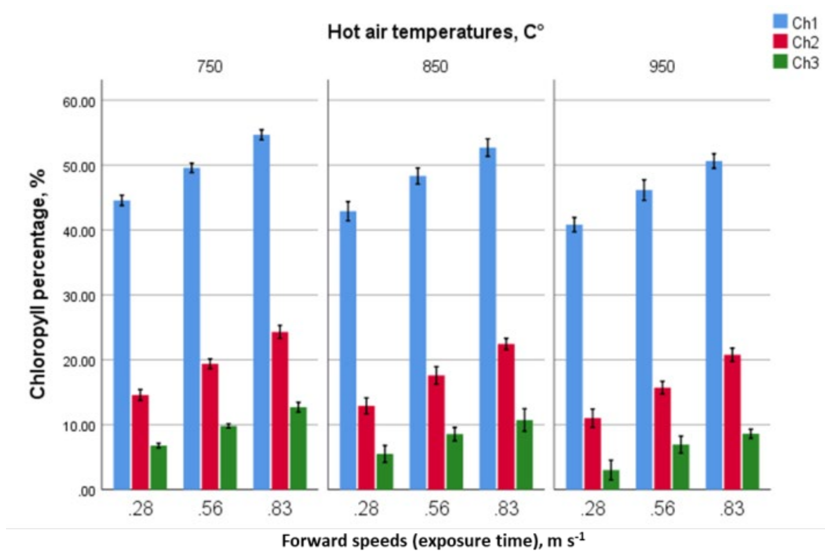
The relationships between the measured weed control efficiency and the expected percentage at the end of the tested period, as well as the frequency of the normality test for the measured weed control efficiency, are displayed (Figure 9, a & b). The trend line on the curve shows an increase in the efficiency of weed control with the random distribution of the measured values and the emergence of a significant effect between the measured and expected values for the weed control efficiency in the experiment period.



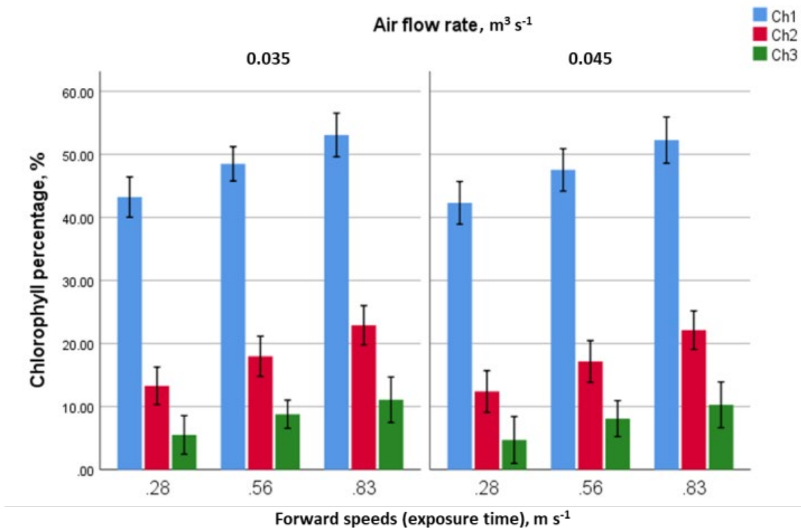
(a) at different hot air temperatures



(b) air-flow rates



(c) a detailed comparison of the effect of temperature at each measurement



(d) the interaction of forward speed with the rate of air flow

Figure 10 The effect of forward speed on the weed chlorophyll percentages (Ch1,2 and 3) after the thermal treatment for 1,3, and 7 days

Furthermore, the chlorophyll percentages (Ch 1, 2 & 3) were illustrated in Figure (10 a & b), which has a proportional direct relationship between different levels of tractor forward speeds (S). The maximum value of chlorophyll (Ch) was recorded for Ch3 = 12.71% (after 7 days) at 0.83 m s^{-1} of S, 750°C of T, and 0.035 m^3 s^{-1} of Fr. While the lowest value of Ch for the Ch3 = 3.03% (after 7 days) was observed at 0.28 m s^{-1} of S, 950°C of T and 0.045 m^3 s^{-1} of Fr.

The most significant decrease in the measured chlorophyll rate from the experimental sectors treated occurred after one week of treatment, when most of the weeds turned yellow, photosynthesis and metabolism stopped, indicating the efficiency of the developed air model in lighting them. The minimum measured chlorophyll was obtained at 0.28 m s^{-1} of forward speed, 950 °C of air temperature, and 0.045 m^3 s^{-1} of hot air flow rate, as shown in Figure (10, a & b). A detailed comparison of the effects of hot air temperatures at each interval following treatment is shown in Figure 10c. The measured chlorophyll is decreasing throughout the first week after treatment, which gives an opportunity for cultivated plants to excel in growth and competition with weeds by water absorption and nutrients. The effect of hot air on narrow and broad-leaved weeds after being exposed to treatment leads to the cessation of photosynthesis and metabolism, resulting in their death shortly after treatment. Figure (10, d) shows the measured interaction between forward speed and air utilization rate. Following treatment, low rates of the measured chlorophyll were detected, indicating that the weeds' leaves were becoming dry and leading to their death.

Table 5 General linear regression equations for weed control.

				Value = a (S) + b (T) + c (Fr)					
Equation				Coefficients					
		A			b			c	
WCE1,2&3 (%)	-15.948	-16.271	-15.883	0.0707	0.0724	0.0737	830.482	853.026	869.307
Ch1,2&3 (%)	21.521	19.181	11.408	0.022	0.00084	-0.0032	420.341	152.709	108.186
Statistical values		R^2			C.V			P	
WCE 1,2&3 (%)	0.8995	0.7996	0.152	0.133	0.175	0.175	0.0**	0.0**	0.0*
Ch1,2&3 (%)	0.7964	0.7965	0.667	1.73	4.182	4.182	0.0**	0.0*	0.0**

Note: Where S: tractor forward speed, m s-1; T: hot air temperature, °C; (a, b& c): constants; Fr: hot air flow rate, m3 s-1; WCE1, 2&3: weed control efficiencies after treatment of 1,5 and 30 days, %; Ch1,2&3: weed chlorophyll percentages after treatment of 1,3 and 7 days, %; R2: coefficient of determination; C.V: coefficient of variation. P: probability < 0.01.

Statistically, the significance level was set at 0.99% for the various measured weed control efficiencies and chlorophyll listed in Table 5. In addition, the simple power regression equations were applied to correlate the change in WCE and Ch with the change in the tested variables of all treatments (Table 5). The linear regression equations that appear in Table 5 were shown to have the possibility of obtaining the true value when compensating for any level of the specified factor. According to the statistical results of the correlation analysis between the treatments, it was indicated that the main factor (forward speed) is the most significant, followed by the hot air temperatures and air flow rates. The interaction between forward speed (S) and hot air temperature (T), as well as the interaction between forward speed (S) and hot air flow rate (Fr), were both highly significant.

3.2 Plant damage

The results of the average total percentages of all damaged plants relative to the total number of plants grown on the experimental site after treatments using the hot air weed control prototype during the two experimental seasons were estimated. The results indicated that the maximum percentage of damaged plants after heat treatment was 10.83% of the total plants cultivated at (S = 0.83 m s^{-1}, T = 950ºC and Fr = 0.045 m^3 s^{-1}). The lowest percentage of crop damage was 3.55% at (S = 0.28 m s^{-1}, T = 750ºC, and Fr = 0.035 m^3 s^{-1}). Crop damage occurs when a tractor makes turns or deviates from the path between cultivated plants, causing mechanical damage. The damage rate can be increased by the wind speed during experimental treatment application. The percentage of damaged plants has decreased as a result of using a thermal insulation system that prevents heat leaking to the cultivated plants.

3.3 Soil seed bank for weeds

Laboratory experiments have been conducted using the hot air weed control model before planting and plowing. Laboratory experiments were conducted on the ability of weed control treatments using hot air on soil samples containing weed seeds, using different hot air temperatures with different air flow rates.

Table 6 Weed seed bank density using thermal hot air prototype at an experimental site.

Weeds classification	Weeds Seed bank before treatment, g m^{-2}		Weed seed bank after treatment, g m^{-2}		Weeds seed bank reduction ratio, %	
	0-100 mm	110-200 mm	0-100 mm	110-200 mm	0-100 mm	110-200 mm
The narrow-leaved weeds *Polypogon monspeliensis L.*	130.55	71.80	30.31	22.05	76.78	69.89
Phalaris minor L.	522.11	187.96	120.44	80.68	76.93	57.08
Lolium temulentum L.	224.56	121.86	80.09	30.58	64.33	74.91
Avena sterilis L.	715.55	350.62	230.68	175.91	67.76	49.83
The broad-leaved weeds *Sonchus oleraceus L.*	100.54	61.33	31.12	21.01	69.05	65.74
Rumex dentatus L.	85.35	70.44	30.22	15.84	64.59	77.51
Chenopodium album L.	125.45	74.23	40.13	30.24	68.01	59.26

The field experiments included determining the tractor's forward speeds in relation to other factors such as air temperatures and air flow rates on the soil seed bank. The average results of random samples were collected from the experimental site at two different depth levels, ranging from 0–100 mm and 110–200 mm. The hot air prototype's various factor levels were installed at 0.28 m s^{-1} for forward speed, 950ºC for air temperature, and 0.045 m^3 s^{-1} for air flow rate, because these levels are the most efficient in terms of weed control. The prototype was put at a height of 100 mm above the soil surface to tighten hot air distribution directly over the pores of the soil surface. Table 6 lists the different weed seed species that were used in the study area, whether narrow or broad-leaved weeds. The results show that the use of weed control prototype by hot air to reduce the seed bank in the soil content within a 200 mm depth results in a significant difference. The weed seed bank was reduced by 76.93% of its soil weed seed content due to the application of hot air up to 950ºC, depending on the type of weed. The prototypes' thermal isolation using glass wool layers and distribution of hot air nozzles resulted in a significant weed bank reduction ratio at the experimental site.

3.4 Mechanical performance evaluation

The relationships between forward speed (S) and prototype field efficiency (Fe) and field capacity (FC) were illustrated at the different hot air temperatures (T) and air flow rates (Fr) in (Figure 11 a, b, c, and d). Due to covering a greater area in less time, both FC and Fe increased with increasing S at different rates of T and Fr. The maximum Fe (92.45%) and FC (0.33 ha h^{-1}) values were observed at 0.83 m s^{-1} of S, 950°C of T, and 0.045 m^3 s^{-1} of Fr. The minimum values of Fe (84.46%) and FC (0.1 ha h^{-1}), were recorded at 0.28 m s^{-1} of S, 750°C of T, and 0.035 m^3 s^{-1} of Fr.

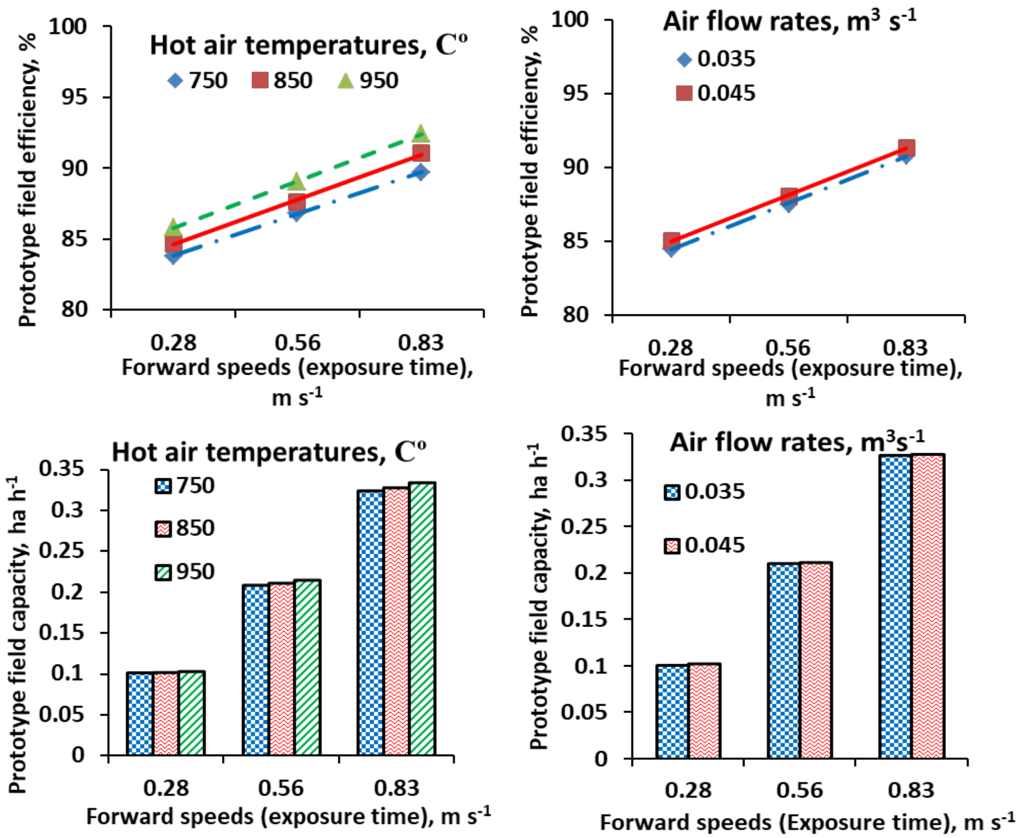
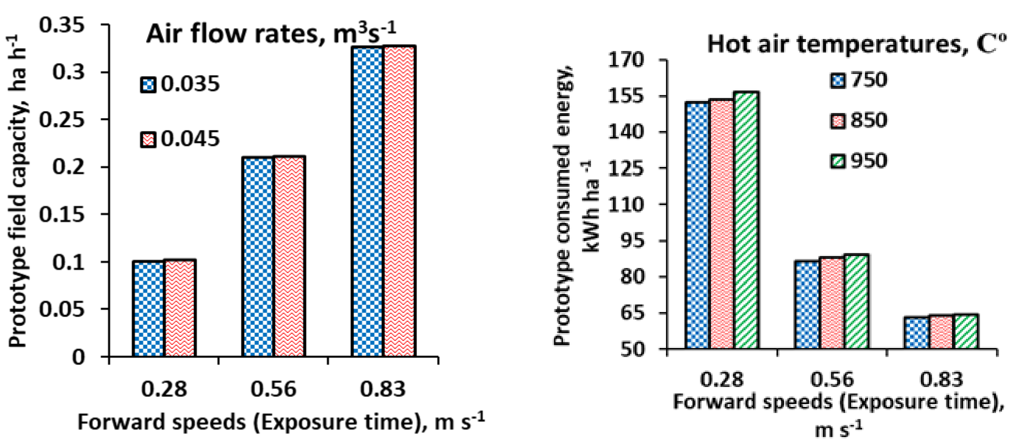


Figure 11 The effect of forward speeds on (a & b) prototype field efficiency and (c & d) prototype field capacity at different hot air temperatures and air flow rates.



(a) hot air temperatures (b) air flow rates

Figure 12 The effect of forward speeds on the prototype's consumed energy at the various (a) hot air temperatures and (b) air flow rates

Table 7 The statistical analysis of the hot air prototype's performance

Equation	Value = a (S) + b (T) + c (Fr) Coefficients			Statistical values		
	A	b	C	R^2	C.V	P
Fm, (L h^{-1})	0.803	0.000685	9.256	0.8169	8.01	0.0***
Ft, (L h^{-1})	2.140	0.00324	31.231	0.8938	0.857	0.0***
Fe, %	15.742	0.0609	674.014	0.8956	0.247	0.0***
FC, (ha h^{-1})	0.408	-0.00313	-0.272	0.8999	0.306	0.0**
CE, (kW h ha^{-1})	-153.445	0.140	1681.177	0.8996	0.916	0.0**
C, (USD ha^{-1})	-144.204	0.111	1461.719	0.8999	0.255	0.0*

Note: Where S: tractor forward speed, m s^{-1}; T: hot air temperature, C°; (a, b& c): constants; Fr: hot air flow rate, m^3 s^{-1}; Fm: gasoline generator fuel consumption, L h^{-1}; Ft: tractor fuel consumption, L h^{-1}; Fe: prototype field efficiency, %; FC: prototype field capacity, ha h^{-1}; CE: prototype consumed energy, kWh ha^{-1}; C: Economic cost, USD ha^{-1}; R^2: coefficient of determination; C.V: coefficient of variation; P: probability < 0.05 (95%).

Furthermore, the maximum value of consuming energy (CE) for the thermal prototype was 156.76 kWh ha^{-1} at 0.28 m s^{-1} of S, 950°C of T, and 0.045 m^3 s^{-1} of Fr, as shown in Figure (12 a & b). However, the minimum value of CE was 63.53 kWh ha^{-1} at 0.83 m s^{-1} of S, 750°C of T and 0.035 m^3 s^{-1} of Fr, as shown in Figure 12 a & b. As well, at a maximum of (S, T, and Fr) values, the generator (Fm) and tractor (Ft) had the highest fuel consumption of 1.69 and 5.86 L h^{-1}, respectively. The lowest values of Fm (1.11 L h^{-1}) and Ft (4.61 L h^{-1}) were recorded at the lowest levels of the tested variables. The statistical analysis of the regression equations revealed that high significance for the forward speeds was followed by hot air temperatures and flow rates, as shown in Table 7. In addition, there were significant relationships between the forward speed levels, hot air temperatures, and air flow rates.

3.5 Cost analysis

The hot air prototype lowered weed control costs by over 90%, from 234.38 USD ha^{-1} for control plots using traditional weed control methods to 39.083 USD ha^{-1} on average. The probability and linear regression equation used to estimate the total operating cost for various tested variables are shown in Table 7. The hourly cost of prototype operation is about 15 USD h^{-1}, including the costs of fuel consumption and maintenance. However, using only hot air as a heat transfer medium in the weed control process is cheaper than using fuels such as flame weed control machines or steam weed control machines.

4 Discussion

The proposed control method is scientifically dependent on exposing the weed cell's cytoplasm and drying it promptly. The highest rate of weed control efficiency was achieved by using a tractor forward speed of 0.28 m s^{-1} and a duration of hot air flow of 6 s, and more than 90% of the total weed control in relation to the treated unit area were acquired in agreement with the results of Ascard (1998).

The results of the experiments are consistent with previous studies (Bertram, 2002; Rifai et al., 2002; Kristoffersen et al., 2007; Bajwa et al., 2015), with regard to the illustration of the relationship between the age of growing weeds and the percentage of elimination, especially at the beginning of the cultivated crop age. Logically, weed control with a slow forward speed early in the weed's life cycle kills the weeds directly because their types are similar at this age, whether they have narrow or broad leaves. The factor of hot air temperatures, which reached flaming temperatures of up to 950°C, was directly applied to thermal control, which had a positive effect on improving agricultural soil, as indicated by prototype testing results in reducing the soil seed bank.

The acquired results were similar to previous studies that used a flaming weeding machine, with a width of 1 m and a speed of 0.14 –56.81 m s^{-1} at the 2–4 leaves weed growth stage (Ascard, 1998). Also, the results gained during testing the prototype were better than those obtained by Hansson and Mattsson (2003), and Kempenaar and Spijker (2004) for a hot water weeding machine. Also, the prototype's results were in line with Kerpauskas et al. (2006). They destroyed about 98% of the weed shoots by using damp water steam in an onion field. Moreover, the prototype's results were better than those were obtained by Hansson and Ascard (2002) and Kempenaar and Spijker (2004) for hot water weeding machines. On the plus side, the use of extremely high temperatures resulted in the relative heating of the top layer of agricultural soil, which holds the weed seed bank. The obtained results for the tested hot air prototype were substantial when compared to those results when measuring the rate of periodic weed emergence after heat treating in that manner.

In addition, the rate of weed emergence was inversely proportional to the hot air temperature used. Weed emergence did not exceed 20% after three weeks, which is a very small percentage when compared to the control treatment. Chlorophyll levels fall due to an increase in thermal exposure time during weed control treatments. There is an increase in thermal exposure to reduce moisture content in weed cells and stop photosynthesis processes through immediate exposure to the cytoplasm of weed cells. As a result, the acquired results were consistent (Tajuddin, 2006; Stepanovic et al., 2016). Kang (2001) stated that the flame weed control rate had a higher operating efficiency (0.14 ha h^{-1}). Practically, the design and distribution of the air nozzles were suitable in terms of the volume of pushing air that was controlled electronically for the treatment of weeds, with the use of 0.045 m^3 s^{-1} being the most efficient.

Whereas, the greater the amount of thermally concentrated air pushed over the weeds, the greater the percentage of weeds being destroyed was increased, and vice versa in terms of emission rate. However, with agreement of the experimental results of, the increased forward speed during weed treatment could be attributed to significantly enhanced efficiency and field capacity, and vice versa for the energy consumed due to increased fuel consumption at higher speeds (Shamkuwar et al., 2019). On the other hand, the most efficient variables were used to achieve the maximum values of hot air temperature and flow rate. The energy efficiency of the hot air prototype was quite similar to that of Astatkie et al. (2007) results, which reported the high energy efficiency of hot water, infrared, and open flame thermal units operating at 2.5 km h^{-1}. Also, Manjunatha et al. (2015) found the field performance of the rotary prototype at 2.5 km h^{-1} with a rotational speed of 210 rpm.

Using the hot air weed control prototype, the maximum percentage of crop damage was approximately 10.83%. This percentage was lower than when using direct thermal weeders, such as the flame weeder. While Ulloa et al. (2011) reported that using a flame weed control weeder led to the highest rates of apparent injury to the maize crop, the rate of loss in dry matter and the largest loss in the crop and its components were 7%-12% due to burning, where a large percentage of the crop was affected in its different stages of growth. The crop damage decreased using the hot air weed control prototype due to the use of hot air nozzles that were completely isolated with shields lined with glass wool to prevent heat transfer leakage.

The utilization of a separate electrical source to supply the necessary power for the hot air weed control machine has led to a reduction in fuel use rates and increased both efficiency and field capacity. In addition, the field experiments on reducing the consumed energy were close to the results of Bond and Grundy (2001). On the contrary, the use of traditional thermal methods, such as the use of steam or flame, requires a thermal medium, unlike the use of air alone. Because propane and butane fuels were used as heat energy mediums, these methods were extremely polluting for the environment, resulting in high costs and a negative impact on soil and plants (Shamkuwar et al., 2019).

It's clear that measured results included that the highest consumed power was 156.76 kWh ha^{-1} while the operating costs ranged from around 124.32 USD ha^{-1} with 59.35 t ha^{-1} of onion yield productivity. The determined results for net yield productivity may be attributed to the extended exposure durations to treating weeds with hot air, which reduced the chances of weeds emerging and hence enhanced crop yields. The prototype's economic evaluation results were in agreement with Ascard et al. (2007) finding that weed control machines have a positive impact on the yield-to-weeds increase ratio. The interest in using electrical control means in the design of the weed control machine by hot air was led to save effective energy and thus reduce fuel consumption rates due to the use of motion sensors that prevent the hot air flow when turns and in the absence of weeds. The results of the study by Deng et al. (2010) agreed with the obtained results using the high-tech electronics for the weed control machines. As a result, it advises that the usage of this sort of machine be expanded, as it is environmentally beneficial and well-suited to the present trend of clean organic agriculture.

5 Conclusion

Except for some types of rhizome weeds, the study's objectives were satisfied, which were to include weed control largely by employing a clean, non-polluting, and highly successful method of controlling most types of weeds in the surface layer. In addition to the low cost of thermal weed control in comparison to energy consumption due to the use of generating electricity energy rather than an intermediate for burning, such as other thermal control methods like flame or steam. In addition, the prototype achieved a positive improvement in the agricultural soil properties as a result of reducing the content of the weed seed bank. In addition, the prototype achieved a positive improvement in the soil properties as a result of reducing the weed seed bank content. The weed control prototype was efficiently working at 0.28 m s^{-1} of forward speed with 950°C of hot air temperature and a 0.045 m^3 s^{-1} air flow rate. For the highest forward speed of 0.83 m s^{-1} and the highest consumed power of 156.76 kWh ha^{-1}, the field efficiency and capacity were 92.45% and 0.33 ha h^{-1}, respectively. In addition, the weed seed bank decreased by 76.93%, while crop damage reached a maximum of 10.83%. Furthermore, the prototype operating costs varied by about 124.32 USD ha^{-1} with the onion crop yield productivity of 59.35 t ha^{-1} over the control by an increment ratio of 41.03% at the optimum variant levels of (0.28 m s^{-1}, 950°C, and 0.045 m^3 ha^{-1}). Moreover, these technologies for environmental weed control machines are a good option instead of using harmful chemical herbicides and weed control machines that use flames or steam.

Conflict of interest

The authors have no conflict of interest with anyone.

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References

Anonymous. 1994. Description of the visual 0–100 rating scale. *Canadian Weed Science Society*, Canada, 8-10 March.

Ascard, J. 1998. Comparison of flaming and infrared radiation techniques for thermal weed control. *Weed Research (Print)*, 38(1): 69-76.

Ascard, J., P. E. Hatcher, B. Melander, and M. K. Upadhyaya. 2007. Thermal weed control. In *Non-chemical Weed Management: Principles, Concepts and Technology*, eds. M. K. Upadhyaya, and R. E. Blackshaw, ch. 10, 155-175. CAB International, North American.

Astatkie, T., M. N. Rifai, P. Havard, J. Adsett, M. Lacko-Bartosova, and P. Otepka. 2007. Effectiveness of hot water, infrared and open flame thermal units for controlling weeds. *Biological Agriculture & Horticulture*, 25(1): 1-12.

Bajwa, A. A., G. Mahajan, and B. S. Chauhan. 2015. Nonconventional weed management strategies for modern agriculture. *Weed Science*, 63(4): 723-747.

Bauer, M. V., C. Marx, F. V. Bauer, D. M. Flury, T. Ripken, and B. Streit. 2020. Thermal weed control technologies for conservation agriculture—A review. *Weed Research*, 60(4): 241-250.

Bertram, A. 2002. Optimizing thermal prototypes for pre-emerging flaming. In *Proc. of the 6th International Symposium on Fruit, Nut and Vegetable Production Engineering*, 205-210. ATB Potsdam, Germany, 11-14 September.

Bond, W., and A. C. Grundy. 2001. Non-chemical weed management in organic farming systems. *Weed Research*, 41(5): 383–405.

Coleman, G. R. Y., A. Stead, M. P. Rigter, Z. Xu, D. Johnson, G. M. Brooker, S. Sukkarieh, and M. J. Walsh. 2019. Using energy requirements to compare the suitability of alternative methods for broadcast and site-specific weed control. *Weed Technology*, 33(4): 633-650.

Damalas, C. A., and I. G. Eleftherohorinos. 2011. Pesticide exposure, safety issues, and risk assessment indicators. *International Journal of Environmental Research and Public Health*, 8(5): 1402-1419.

Datta, A., and S. Z. Knezevic. 2013. Flaming as an alternative weed control method for conventional and organic agronomic crop production systems: a review. In *Advances in Agronomy*, *vol.118*, ed. D. L. Sparks, ch. 6, 399-428. Elsevier, Science Direct.

Deng, W., L. Chen, Z. Meng, G. Wu, and R. Zhang. 2010. Review of non-chemical weed management for green agriculture. *International Journal of Agricultural and Biological Engineering*, 3(4): 52-60.

Galon, L., F. J. M. Basso, L.Chechi, T. P. Pilla, C. O. Santin, M. A. M. Bagnara, M. B. Franceschetti, C. T. Castoldi, G. F. Perin, and C. T. Forte. 2019. Weed interference period and economic threshold level of ryegrass in wheat. *Bragantia*, 78(3): 409-422.

Hansson, D., and J. Ascard. 2002. Influence of developmental stage and time of assessment on hot water weed control. *Weed Research*, 42(4): 307–316.

Hansson, D., and J. E. Mattsson. 2003. Effect of air temperature, rain and drought on hot water weed control. *Weed Research*, 43(4): 245-251.

Hunt, D. 1983. *Farm Power Machinery Management*. 8th ed. Ames: Iowa State University Press.

ISA. 2009. *Agronomic Terminology*. 5th ed. New Delhi, India: Indian Society of Agronomy, Indian Agricultural Research Institute.

Júnior, F. W. R., M. A. Scariot, C. T. Forte, L. Pandolfi, J. M. Dil, S. Weirich, C. Carezia, J. Mulinari, M. A. Mazutti, G. Fongaro, L. Galon, H. Treichel, and A. J. Mossi. 2019. New perspectives for weeds control using autochthonous fungi with selective bioherbicide potential. *Heliyon*, 5(5): e01676.

Kang, W. S. 2001. Development of a flame prototype. *Transactions of the ASAE*, 44(5): 1065-1070.

Kaur, S., R. Kaur, and B. S. Chauhan. 2018. Understanding crop-weed-fertilizer-water interactions and their implications for weed management in agricultural systems. *Crop Protection*, 103: 65-72.

Kempenaar, C., and J. H. Spijker. 2004. Weed control on hard surfaces in The Netherlands. *Pest Management Science*, 60(6): 595-599.

Kepner, R. A., R. Bainer, and E. L. Barger. 1982. *Principles of Farm Machinery*. 3rd ed. West part, Connecticut, USA: AVI pub.

Kerpauskas, P., A. P. Sirvydas, P. Lazauskas, R. Vasinauskiene, and A. Tamosiunas. 2006. Possibilities of weed control by water steam. *Agronomy Research*, 4: 221-225.

Kristoffersen, O. P., A. M. Rask, and S. U. Larsen. 2007. Non-chemical weed control on traffic islands: a comparison of the efficacy of five weed control techniques. *Weed Research*, 48(2): 124-130.

Machleb, J., G. G. Peteinatos, M. Sökefeld, and R. Gerhards. 2021. Sensor-based intrarow mechanical weed control in sugar beets with motorized finger weeders. *Agronomy*, 11(8): 1517.

Manjunatha, K., M. Anantachar, and V. Palled. 2015. Optimization of operational parameters for development of tractor operated rotary prototype. *Green farming International Journal of Applied Agricultural & Horticultural Sciences*, 6(1): 211-214.

Mesnage, R., N. Defarge, J. S. Vendômois, and G. E. Séralini. 2014. Major pesticides are more toxic to human cells than their declared active principles. *BioMed Research International*, 2014: 179691.

Monteiro, A., and S. Santos. 2022. Sustainable approach to weed management: The role of precision weed management. *Agronomy*, 12(1): 118.

Morselli, N., F. Ottani, M. Puglia, S. Pedrazzi, P. Tartarini, and G. Allesina. 2022. Experimental analysis of effective energy dosage in hot air weeding. *Sustainable Energy Technologies and Assessments*, 54: 102799.

Nakayama, W., and S. H. Park. 1996. Conjugate heat transfer from a single surface-mounted block to forced convective air flow in a channel. *ASME Journal of Heat and Transfer*, 118(2): 301–309.

Peerzada, A. M., and B. S. Chauhan. 2018. Thermal weed control: History, mechanisms, and impacts. In *Non-Chemical Weed Control*, eds. K. Kabran, and B. S. Chauhan, ch. 2, 9-31. Elsevier, Science Direct: Academic Press.

Peruzzi, A., L. Martelloni, C. Frasconi, M. Fontanelli, M. Pirchio, and M. Raffaelli. 2017. Machines for non-chemical intra-row weed control in narrow and wide-row crops: a review. *Journal of Agricultural Engineering*, 48(2): 57-70.

Piron, A., F. van der Heijden, and M. F. Destain. 2011. Weed detection in 3D images. *Precision Agriculture*, 12(5): 607-622.

Price, J. N., B. R. Wright, C. L. Gross, and W. R. D. B. Whalley. 2010. Comparison of seedling emergence and seed extraction techniques for estimating the composition of soil seed banks. *Methods in Ecology and Evolution*, 1(2): 151-157.

Qasem, J. R. 2017. A survey on the phytotoxicity of common weeds, wild grown species and medicinal plants on wheat. *Allelopathy Journal*, 42(2): 179-194.

Rask, A. M., and P. Kristoffersen. 2007. A review of non-chemical weed control on hard surfaces. *Weed Research*, 47(5): 370-380.

Rifai, M. N., T. Astatkie, M. Lacko-Bartosova, and J. Gadus. 2002. Effect of two different thermal units and three types of mulch on weeds in apple orchards. *Journal of Environmental Engineering and Science*, 1(5): 331-338.

Runia, W. T., J. Janse, R. Maaswinkel, and L. P. G. Molendijk. 2007. Effect of soil treatment with hot air (Cultivit) on crop development of squash. *Applied Plant Research. Gelderland, The Netherlands, Wageningen University and Research,* Report: 3250074700.

Scavo, A., and G. Mauromicale. 2020. Integrated weed management in herbaceous field crops. *Agronomy*, 10(4): 466.

Shamkuwar, S. V., S. S. Baral, V. K. Budhe, P. Gupta, and R. Swarnkar. 2019. A critical study on weed control techniques. *International Journal of Advances in Agricultural Science and Technology*, 6(12): 1-22.

Spagnolo, R. T., A. Oldoni, T. V. Custódio, Â. V. dos Reis, and A. L. T. Machado. 2019. Conceptual design of a thermal weed control machine. *Ciência Rural*, 49(3): e20180673.

Stepanovic, S., A. Datta, B. Neilson, C. Bruening, C. Shapiro, G. Gogos, and S. Z. Knezevic. 2016. The effectiveness of flame weeding and cultivation on weed control, yield and yield components of organic soybean as influenced by manure application. *Renewable Agriculture and Food Systems*, 31(4): 288-299.

Tajuddin, A. 2006. Design, development and testing of engine operated weeder. *Agricultural Engineering Today*, 30(5&6): 25-29.

Ulloa, S. M., A. Datta, C. Bruening, B. Neilson, J. Miller, G. Gogos, and S. Z. Knezevic. 2011. Maize response to broadcast flaming at different growth stages: Effects on growth, yield and yield components. *European Journal of Agronomy*, 34(1): 10-19.

Wilde, S. A., R. B. Corey, J. G. L. Yer, and G. K. Voigt. 1985. *Soil and Plant Analysis for Tree Culture*. 3rd ed. New Delhi, India: Oxford and IBH Publishing Co.