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Investigation of the effectiveness of AC/DC electric current as a weed control method using NDVI technique

Hasan Sahin[a]*

[a] Department of Mechatronics School of Technical Sciences, Harran University, Sanlıurfa, Turkey.

Abstract: Due to the negative environmental effects of herbicides, restrictions are imposed in many developed countries and the transition to alternative methods is encouraged. Upon these restrictions and prohibitions, non-chemical weed control methods have been started to be developed. One of these alternative weed control methods is the electric current method.

Background: Using multiple electrodes, the mortality rates were measured by exposing the plants germinated in laboratory conditions to AC and DC currents for different periods.

Objective: In this study, the effects of direct current (DC) and alternating current (AC) on the mortality rates of plants were investigated.

Methods: By comparing the NDVI (normalized difference vegetation index) values measured before and 1 week after the plants were exposed to electrical current, the effect of AC/DC on the mortality rate was determined.

Results: While mortality was between 11% and 17% for AC, mortality occurred at a rate of 31% in plants that had 300 volts DC applied for 350 s.

Conclusions: The degrees (r) of these relationships were 79.7% and 95.7%, respectively. According to these results, mortality rates increased as the voltage increased.

Keywords: Environment; Herbicide; Electrical/Mechanical Weed Control.

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* Corresponding author: <hsahin@harran.edu.tr>

1. Introduction

Agricultural chemicals, which are widely used in agricultural activities, adversely affect the environment and human health. The difficulty of applying physical control methods has increased the interest in chemical (herbicide) use. Increasing demand for organic production and restrictions in many countries regarding the use of non-environmentally friendly agricultural chemicals has increased the interest in environmentally friendly weed control methods. Today, there are many new approaches to weed control, including artificial neural networks and robotic technologies (Monteiro et al., 2021). A sustainable and long-term strategy is required to minimize unwanted weeds grown in the agricultural field and increase crop yield (Brand et al., 2007). It is important to reduce the loss of weeds, which cause significant losses in many agricultural products such as sesame, by using non-chemical environmental methods (Lins et al., 2019). Studies have been carried out showing that the use of high technology in agricultural areas also reduces the frequency of weeds (Werle et al., 2021). Furthermore, widely using herbicides in agricultural weed control has caused undesirable plants to develop resistance to all kinds of herbicides. This has increased the orientation towards electrical/mechanical weed control methods in a electrical/mechanical weed management strategy (Khan et al., 2021). It is also important to know which method is more suitable for which weed control by comparing mechanical, physical and chemical weed control methods (Faleiro et al., 2022).

Some of the electrical/mechanical, weed control methods are the electric arc (current) method, the microwave method, hot steam, infrared, a pneumatic system, freeze-drying, and the laser cutting method, three sowing methods (Timossi et al., 2018). The electric current method is known to increase the heat of weed seeds (Nelson, 1996) in a short period, causing fading of the plant stem and leaves, and then the plants are completely biologically inactive (Wayland et al., 1975). After applying current, it is expected that the plant will weaken or mortality will occur because of the thermal effect caused by the electric current passing over the weed stem. It is seen as an alternative to chemical (herbicide) control methods because it does not leave any residue in the soil or plant (Mavrogianopoulos et al., 2000).

Alternative control methods that help determine the most economically feasible method have not yet reached the expected technological level due to incorrect comparisons (Coleman et al., 2019). New technologies, which cover alternative methods of combat, create the opportunity for field-specific weed management (SSWM) in agricultural areas by identifying undesirable plants individually and with a fast and correct intervention (Bakker et al., 2010). Site-specific control methods also allow for a fair and accurate comparison of electrical/mechanical weed control methods. Technological advances in artificial intelligence (AI) and robotics also have the potential to support ecological solutions in the IWM (integrated weed management) approach.

In a study carried out by passing electrical current at 100, 200 and 300 volts (AC) for 300, 420 and 540 seconds over one week old, germinated plants in contact with copper conducting electrodes, mortality rates were obtained between 70% and 100% (Sahin, Yalınkılıc, 2017). Scientific studies have emphasised that microwaves also have important potential in the control of various weed species (Hess et al., 2019; Sahin, 2014). However, the 2.45 GHz microwave technology used in this method has not yet reached a sufficient level in terms of economy and applicability. Besides, it is stated that the market power of these systems can be increased by saving more energy with microwave systems with weed detection technology (Brodie et al., 2012).

Electric current causes loss of cell viability in plant tissue in the areas exposed. This finding also conforms to the views of biophysicists about electrical damage to biological structures. In the electroporation method, the main target is to damage the cell membrane with a pulsed high voltage electric field. It causes damages the cell membrane and results in the death of the cell by collapsing the cell membrane. The electroporation technique applied to weed seeds is on the way to be a electrical/mechanical method for weed control (Lundensia, Persson, 2015).

A pulsed electric current is more effective than the sinusoidal current in creating damage deep in the tissues of different plants (Ivanovich, Viktorovich, 2018). In one study, a Cockroft-Walton type voltage multiplier capable of producing variable voltage for the variable load was used. The voltage multiplier provides the voltage needed for varying plant density without any additional circuits, processors, or controllers (Rona et al., 2019). It is an important fact that low DC voltages, such as 8–16 volts, increase plant vitality and quality (Gogo et al., 2016). Insufficient voltages used to kill weeds can also cause the weeds to grow and multiply by not adversely affecting them.

In experimental studies on electrical/mechanical weed control methods, it is important to accurately determine the mortality rates of plants. As far as is known, the NDVI technique is used for the first time in this study to calculate the mortality rate of weeds. The normalized difference vegetation index (NDVI) is a widely used method in determining the growth and mortality rates of plants (Rodrigues et al., 2021). The NDVI, which is based on the technique of plants with green components to reflect the energy of near-infrared wavelength and to absorb the energy of a visible red wavelength, is also a widely used method to monitor the changes in forested and agricultural areas (Arjasakusuma et al., 2018). In remote sensing systems, green plants with high biomass activity highly reflect the near-infrared wavelength. With the help of MODIS NDVI images created using this technique, the viability/mortality rates of plants can be calculated (Spruce et al., 2019). The NDVI method is also used in forest areas to monitor tree mortality rates. The use of NDVI data is a potential alternative method for creating regional tree death maps. This method is also an auxiliary method in natural resource management, forest dilution, and environmental and urbanisation activities (Schinasi et al., 2019). In the study of the analysis of the relationship between urban foliage rate and infant mortality in Philadelphia, the NDVI images derived from processed satellite data were used (Crouse et al., 2017). A similar study (Pantazi et al., 2016) based on spectral reflectance differences, used NDVI data for the rapid and accurate determination of biodiversity and spectral properties by a machine learning (ML) method, which can distinguish crops and weed species. Research on remote sensing-based solutions is becoming more common (Turner et al., 2003; Çelik, Sönmez, 2013; Çelik, Karabulut, 2013; Khare et al., 2018).

The effects of herbicides on human and animals such as bees, birds, and fishes are known. Some herbicides like phenoxy group causes cancer. However, it is the most widely used herbicide. It has been stated that triazines are associated with breast cancer, while terbuthylazine causes lung cancer (Mladinic et al., 2012). Some side effects of herbicides are deaths in non-target organisms and changing in the structure of the ecosystem and species (Solomon et al., 2013).

As the harms of herbicides are revealed and environmental awareness of humans increases, interest in non-chemical weed control methods (Banaras et al., 2020) (especially electric current and microwave) will increase. In addition, it is a known fact that long-term use of some herbicides creates resistance in weeds, making the control even more difficult (Bonow et al., 2018).

As can be seen from previous studies, many studies have been conducted on non-chemical weed control methods. Especially in studies using electric arc and microwave, more experimental studies have been included. The aim of this study is to demonstrate the usability of electric current as a non-chemical method in weed control. However, it is to investigate how alternating current (AC) or direct current (DC) application has an effect on mortality rates in plants.

2. Material and Methods

Air conditioning cabinet: To germinate the plant seeds at 20–22 °C temperature and 60-70% humidity, a temperature, humidity, and light-controlled Laborteknik IK-300 air conditioning cabinet was used.

Speed controlled conveyor belt: In the study, to simulate the movement of the tractor, a moving belt with a Power Flex 4M motor drive, whose speed ranges between 0.0099 m/s (0.03564 km/h) and 0.156 m/s (0.5616 km/h) was used.

Vertical Type Multi-Electrode Tunnel: The electrode tunnel consists of two pieces of 40 cm × 50 cm copper plates, with 30 × 30 pieces of vertically mounted copper electrodes. An electrical circuit was created by connecting the positive (+) end of the voltage regulator to one of the copper plates and the negative (–) end to the other (Figure 1).

Voltage Regulator: The voltage regulator (power supply) used in the experiment can operate between 1 and 300 volts. The power supply was 1 phase input/1 phase output, 1 kVA power input voltage range: 130 V AC/260 V AC, with an output voltage sensitivity of 220 V AC ± 2%. The DC voltage required for the DC experiments was obtained by converting the AC voltage received from the voltage regulator to DC with the help of the bridge diode circuit (Figure 2).

NDVI (normalized difference vegetation index) Meter: NVDI values before the exposure of plants to electric current and 1 week after application were measured with the TRIMBLE Green Seeker handheld device shown in Figure 3. The emission wavelengths of the device are red 660 nm, 25 nm FWHM, near-infrared 780 nm and 25 nm FWHM, and the field of view of the device is 25 cm at 60 cm or 50 cm at 122 cm.

2.1 Experimental method:

In the electric arc method, which is applied by passing an electric current over the plant body, according to equation (1), the electrical energy is converted into heat because of the electrical resistance (R) of the plant (Vincent et al., 2001).

$$E = \frac{V^2\, T_c}{R_P} \qquad (1)$$

(E), is the quantity of energy transferred to the plant body, (R_P) is the electrical resistance of the plant, (T_c) is contact time of the electrodes to the plants, and (V) is the applied voltage to the plant body.

Equation (2) shows the effective contact time of the electrodes (Vincent et al., 2001).

$$n_c = L\, W_{eff}\, D \qquad (2)$$

Here, (n_c) is the product of the number of plants that the electrodes contact instantaneously, (L) is the electrode length, (W_{eff}) is the effective electrode width and (D) is the product density (Vincent et al., 2001). The undesired plants damage because of the high temperature caused by the electric current pass through the plant body. In equation (3), the total load resistance (R_L) is equal to the sum of the resistance sums of each plant (R_P) and the ground resistance (R_S) (Vincent et al., 2001).

$$R_L = \left[\sum_{i=1}^{n_c} \frac{1}{R_P}\right]^{-1} + R_S \qquad (3)$$

Figure 1 - Vertical type multi electrodes tunnel

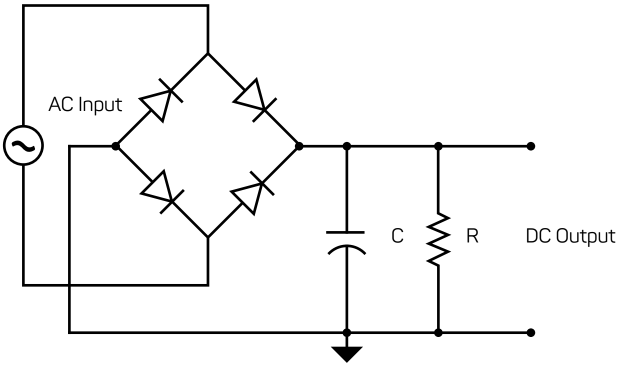

Figure 2 - A diode bridge AC/DC converter

Figure 3 - Trimble GreenSeeker handheld NDVI meter device (Trimble, 2021)

Increasing the number of electrodes that contact plants instantaneously will require increasing the generator power to be used in the application at the same rate. In Equation 3 (Vincent et al., 2001), the R_P value, which expresses the resistance of plants, varies according to plant age, plant type, amount of cellulose it contains, and plant morphology (Yudaev, 2019). The equation is transformed into equality (4) by accepting equal resistance for all plant species.

$$R_L = \frac{R_P}{n_c} + R_S \tag{4}$$

Under ideal conditions, the power produced by the transformer assumes that the weed plants have resistance values close to each other. If the energy loss caused by the transformer, the resistance can be neglected, then it can be expressed as in equation (5) (Vincent et al., 2001).

$$P = \frac{V^2}{R_L} = \frac{n_c V^2}{R_P + n_c R_S} \tag{5}$$

The plant density in the application area, will increase the total electrical resistance of the plants, but it can be neglect, as it is very small compared to the resistance of the soil. The power of the generator will be a function of the applied voltage and ground resistance as shown in equation (6).

$$P = \frac{V^2}{R_S} \tag{6}$$

2.2 AC and DC voltage application by using vertical type multiple electrodes

Barley seeds were germinated in four 20 cm × 30 cm aluminium pots (to provide electrical conductivity), one of which is the control group and the other three are samples. All of the samples were kept in the air conditioning cabinet at about 20–22°C temperature, average 1,000–1,200 lux light, and 60–70% humidity during germination and after the experimental treatment. One week old, germinated barley was subjected to 110, 220 or 300-volts DC voltage with three replicates for 150, 250 or 350 seconds with a vertical type multiple electrode method. The maximum contact of the plants to the electrodes, which are vertically mounted into the tunnel with the help of a movable conveyor belt, was attempted. Before and after application, moisture, the temperature of the soil, and the electrical current passing over plants during application were measured. Then, the same process was repeated for AC current. Before and after application, the moisture, temperature of the soil and electrical current passing over plants during application were measured. The NDVI values of the vegetation were measured and recorded before and one week after the application of current.

2.3 Statistical Analysis

In calculating the sample width of this study conducted for investigation of the effect of AC and DC voltage application on mortality rates, the power for each variable was determined by taking at least 0.80 and a Type 1 error of 0.05. The Shapiro-Wilk (n < 50) test was used to see if the continuous variables in the study were normally distributed and nonparametric tests were applied because the mortality variable was not normally distributed, and the number of observations was low (n = 9).

The effects AC-DC voltage method were examined with two-way variance analysis. For the AC-DC voltage method, the Mann-Whitney U test was calculated in comparison to mortality ratios. The Kruskal-Wallis H test was calculated for comparing mortality rates according to voltage, and Bonferroni post hoc (multiple) comparison tests were used to determine different groups. Spearman's rho correlation coefficients were calculated to determine the relationship between mortality rates, voltage level and AC-DC voltage type. The statistical significance level (α) was taken as 5% in calculations and SPSS (IBM SPSS for Windows, Ver.24) statistical software was used for calculations.

3. Results and Discussion

As shown in Table 1, no death occurred in plants that applied 110-volts DC for 150 s, 250 s and 350 s. Negative values seen in the table in 110-volt DC applications show that there is germination in plants contrary to mortality. Similarly, in previous microwave weed control studies, an increase in germination rates was observed in short-term microwave applications (Sahin, 2014). However, in 220-volt and 300-volt applications, mortality rates varying between 10% and 31% were realized in each repetition. Mortality rates increased as the duration of exposure to electric current increased. Average mortality rates were highest in 220-volt and 300-volt applications for 350 seconds.

Experimental studies conducted have the potential to make the electric current method an energy-saving tool in weed control (Yudaev, 2019). It was stated that, "the low DC voltages such as 8-16 volts increase the plant vitality and quality" (Gogo et al., 2016). Insufficient voltages used to kill weeds can also cause the weeds to grow and multiply by not adversely affecting them

In Table 2, the results of the experiment performed by applying AC voltage to the plants are given. Similar to the DC voltage results, an average of 5% increase in the germination rate of the plants was recorded in the repetitions of 110-volt applied for 150 s, 250 s and 350 s. In 200-volt and 300-volt applications, the mean recurrence mortality for the same durations was approximately 15%.

In Table 3, mortality rates obtained when 110-volt, 220-volt and 300-volt AC-DC voltages are applied to plants are compared. It was observed that there

Table 1 - In vertical type multi-electrode method, current change and mortality rates in three replicates at 110, 220 and 300 DC voltage

Voltage DC	Current(mA) min-max	Time	Temperature (T$_s$-T$_i$)	Soil moisture	Plant density	NDVI$_1$	NDVI$_2$	Mortality
Volt	mA	s	°C	%	pcs/cm^2	-	-	%
1-110	2-16.4	150	20-19	75	0.560	0.64	0.65	-1
2-110	3-19.13	250	20-20	70	0.550	0.63	0.65	-2
3-110	3-19.90	350	21-20	78	0.580	0.64	0.66	-2
1-220	2-108	150	20-19	80	0.565	0.62	0.52	10
2-220	2-100	250	21-21	77	0.585	0.63	0.48	15
3-220	2-128	350	21-20	75	0.590	0.61	0.50	11
1-300	3-236	150	21-20	73	0.580	0.64	0.47	17
2-300	2-221	250	23-21	76	0.570	0.61	0.44	17
3-300	2-252	350	23-20	81	0.550	0.66	0.35	31
Control				74	0.590	0.58	0.65	-7

DC: Direct current, mA: mili amper, NDVI: Normalized Difference Vegetation Index

Table 2 - In vertical type multi-electrode method, current change and mortality rates in three replicates at 110, 220 and 300 **AC** voltage

Voltage AC	Current(mA) min-max	Time	Temperature (T$_s$-T$_i$)	Soil moisture	Plant density	NDVI$_1$	NDVI$_2$	Mortality
Volt	mA	s	°C	%	pcs/cm^2	-	-	%
1-110	2-49.53	150	21-20	65	0.550	0.67	0.69	-2
2-110	1.5-40	250	20-19	66	0.580	0.68	0.74	-6
3-110	1.8-39.50	350	20-20	63	0.590	0.64	0.57	-7
1-220	2.5-83.40	150	20-19	62	0.575	0.62	0.49	13
2-220	1.6-90	250	20-21	60	0.565	0.61	0.47	14
3-220	2-70.50	350	20-19	65	0.595	0.50	0.39	11
1-300	2.6-182	150	21-20	63	0.585	0.69	0.58	11
2-300	2.3-135	250	22-21	61	0.570	0.64	0.50	14
3-300	3-200	350	22-20	62	0.560	0.52	0.35	17
Control				64	0.550	0.61	0.65	-4

DC: Direct current, mA: mili amper, NDVI: Normalized Difference Vegetation Index

Table 3 - Comparison of "mortality rates" according to AC-DC method and voltage

	voltage	AC					DC					*p.
		Median	Mean	Std. Dev.	Min.	Max.	Median	Mean	Std. Dev.	Min.	Max.	
Mortality Rates(%)	110 volt	-6.00	-5.00	2.65	-7.00	-2.00	-2.00	-1.67^{b}	0.58	-2.00	-1.00	0.105
	220 volt	13.00	12.67	1.53	11.00	14.00	11.00	12.00^{ab}	2.65	10.00	15.00	0.658
	300 volt	14.00	14.00	3.00	11.00	17.00	17.00	21.67^{a}	8.08	17.00	31.00	0.102
**p.		0.058					0.026					
Method *Voltage Interaction "p-value=,221" (two-way analysis of variance)												

* Significance levels according to Mann-Whitney U test results →

** Significance levels according to Kruskal-Wallis Test results ↓

a,b,c: Bonferroni Post Hoc shows the difference between Voltage Types according to multiple comparison test was no statistically significant difference between the mortality results of AC and DC voltage applied for the same durations for 110-volt ($p > 0.05$). In the 220-volt and 300-volt applications, higher mortality rates were obtained compared to the 110-volt applications. However, the difference here is due to the voltage values ($p < 0.05$). In other words, the application of AC or DC voltage did not significantly affect mortality rates for low voltages.

On the other hand, when using the DC method, a statistically significant difference was observed between the mortality rate observed according to voltage ($p < 0.05$). In other words, the level of the mortality rate was affected by the voltage level in the DC method. Here, 110 V and 300 V groups were different from each other. For the 220-volt and 300-volt AC/DC levels, mortality rates increased as the voltage increases.

Table 4 shows correlation analysis results between mortality rate and voltage and duration are given separately for AC-DC methods. According to this result, a statistically significant positive correlation was observed between mortality rate and volts in both AC and DC methods ($p < 0.05$). The degrees (r) of these relationships were 79.7% and 95.7%, respectively. According to the results, mortality rates increase as the voltage increases. Despite that, for AC and DC methods, no statistically significant correlation was observed between mortality rate and voltage ($p > 0.05$).

Figure 4 shows the mortality rates occurring at 110, 220 and 300 volts in AC and DC voltage applications with a vertical type of multi-electrode method. As shown in Figure 4, the highest mortality rates were obtained from 300 volts DC level (mean of three recurrences %22).

Figure 5 shows the mortality rates of AC/DC voltage methods for 150 s, 250 s and 350 s periods. As can be seen from Figure 5, the highest mortality rate was obtained as %30 in the application with DC voltage and 350 s duration.

Figure 6 shows the average mortality rates in the AC and DC voltage methods. Mortality rates in the DC voltage method were relatively a little higher than the AC voltage applications.

Table 4 - Correlation analysis results between “Mortality rates” and “Voltage” and Time”, separately in AC-DC Methods

		AC	DC
		Mortality rates (%)	**Mortality rates (%)**
Volt	r	0.797*	0.957**
	p	0.010	0.001
Time (s)	r	0.050	0.054
	p	0.885	0.892

*p < 0.05; ** p < 0.01; r: Spearman’s rho correlation coefficient

Figure 7 shows the mortality rates that occurred in AC and DC voltage applications for 150, 250 and 350 seconds. There was an increase in mortality rates as the voltage application time increases.

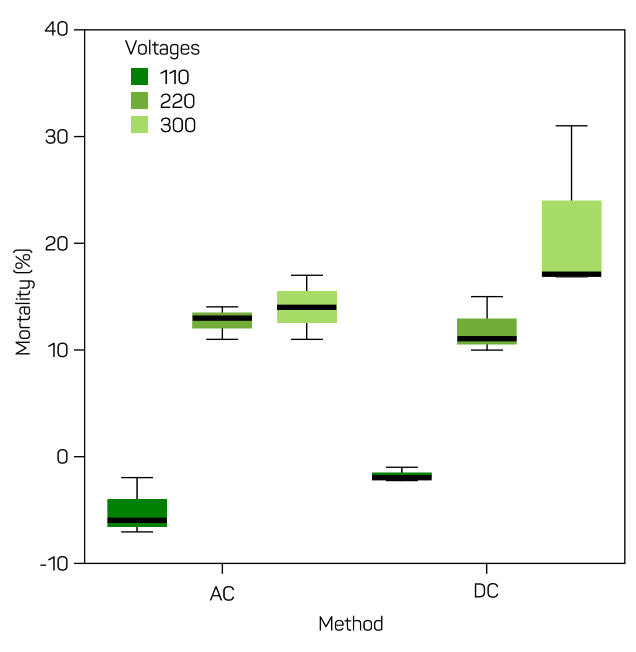

Figure 4 - The change of mortality rates according to AC/DC method and voltage levels

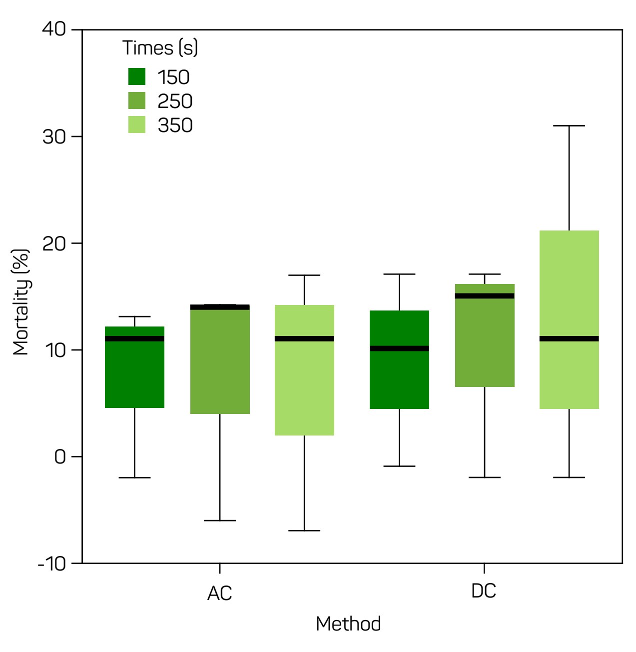

Figure 5 - The change of mortality rates according to AC/DC method and application time

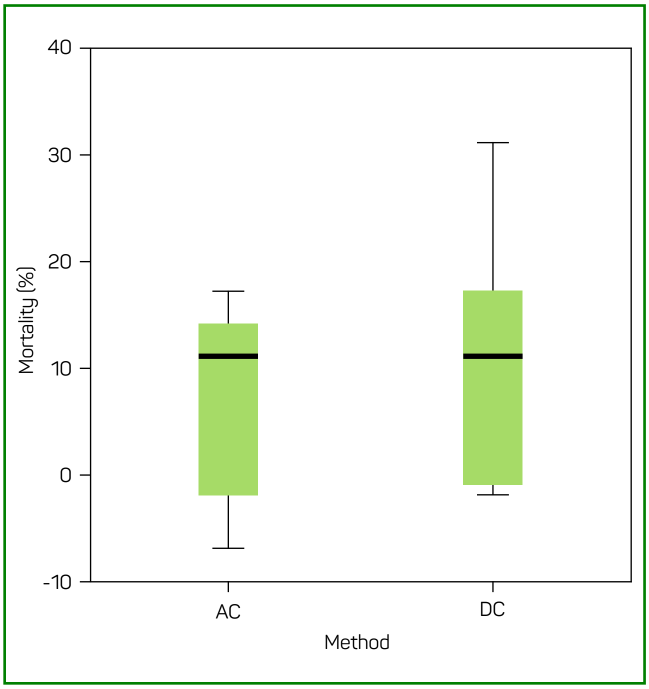

Figure 6 - The change of mortality rates according to the AC/DC method

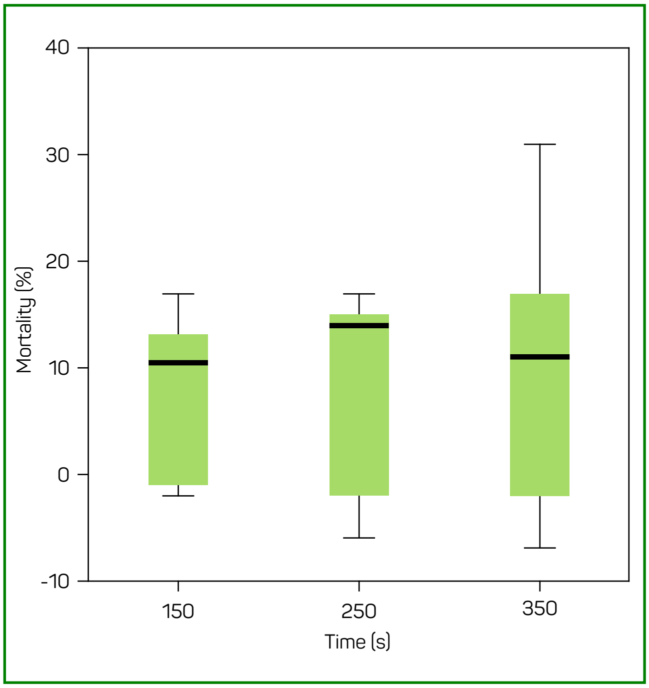

Figure 7 - Mortality rates depends voltage application time in both AC/DC method

In other words, it can be said that high mortality rates can be obtained by increasing the electric current/voltage intensity or the application time. That is, higher mortality values can be obtained by keeping the exposure time constant, increasing the voltage, or extending the exposure time by keeping the voltage constant.

As mentioned above, as seen in previous studies, low voltage or short-term microwave exposure can sometimes lead to increased germination in plants. In the vertical multi-electrode method in 110-volt DC recurrence, in contrast to mortality, there is an average 1.67% increase in germination (Wang et al., 2020). In the 110-volt AC application, an average of 5% germination rate increase was observed (Hess et al., 2018). Close results were also obtained in the microwave weed control method. A higher rate of germination was observed than the control group, which was not exposed to microwaves (Sahin, 2020; Sahin, 2014; Nelson, 1996).

As it is known, temperature, which is one of the factors necessary for seed germination, will accelerate germination up to a certain level and will restrict seed germination at higher levels (Lippmann et al., 2019; Desta, Amare, 2021).

The results show that a statistically significant positive correlation was observed between mortality rate and volts in both AC and DC methods ($p < 0.05$). The degrees (r) of these relationships were 79.7% and 95.7%, respectively. According to the results, mortality rates increase as the voltage increases. Despite that, for AC and DC methods, no statistically significant correlation was observed between mortality rate and voltage ($p > 0.05$).

The results also show that the mortality rates in (220 and 300 volts) DC voltage methods are relatively higher than the (220 and 300 volts) AC voltage applications. Among mortality rates of AC/DC voltage methods for 150 s, 250 s, and 350 s periods, the highest mortality rate was obtained in the application with (220 and 300 volts) DC voltage and for 350 s duration (17% and 31% respectively). For 150, 250, and 350 seconds, there was an increase in mortality rates as the voltage application time increases in both AC and DC volts. It can also be said that the mortality rates in the DC voltage method were relatively higher than the AC voltage applications (Sahin, 2020).

In this study, a stepped power supply with a maximum output of 300 volts was used. The effectiveness of the method increases by keeping the voltage constant and increasing the application time. However, the results show that when the appropriate voltage is applied, considering the plant density and plant growth level, it has the potential to be used against all kinds of weeds.

Since this study was carried out in laboratory conditions, it was applied by obtaining a maximum voltage of 300 volts through the regulator using 220 volts, which is the mains voltage. As understood from the results, high voltage and current values will increase the success rate in weed control. Parameters such as weed age, root and stem structure, type and soil moisture are other factors affecting the efficiency of the method.

4. Conclusions

According to the results obtained in the study, to obtain higher efficiency in weed control with electric current or microwave, it is necessary to know the physical, chemical and biological properties of the plant to which the current will be applied, as well as the plant dielectric properties.

The results obtained in the study show that AC/DC electric current has the potential to be used as a "weed control method", provided that direct current and voltage intensity are selected. It is thought that the data obtained in the study will help researchers who will work on this subject. It is expected that non-chemical alternative methods in weed control need more research and take more place on the agenda of relevant stakeholders.

Author's contributions

SH: design of the electrode tunnel, all experiments, preparation of the manuscript according to the journal writing rules, and editing works.

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