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Use of a Pair of Pulse-Charged Grounded Metal Nets as an Electrostatic Soil Cover for Eradicating Weed Seedlings

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Abstract: An electrostatic technique was developed to generate a simple physical method to eradicate weeds in crop fields. The proposed apparatus consisted of double-expanded metal nets connected to a pulse-charging type negative voltage generator and a grounded line. The two metal nets were arranged in parallel at an interval (6 mm) that caused no arc (spark) discharge between the negatively charged metal net (NC-MN) and the grounded metal net (G-MN). The paired nets were used as a soil cover to zap weed seedlings emerging from the ground. As plant seedlings are biological conductors, the seedling was subjected to an arc discharge from the upper metal net (NC-MN) when it emerged from the soil and passed through the lower net (G-MN). The discharge was strong enough to destroy the seedling with a single exposure. The arc treatment was highly effective for eradicating successively emerging mono- and dicotyledonous weed seedlings, regardless of the number of coexisting weeds or the area of the netted field. Thus, the present study provides a simple and reliable weed eradication method that could be integrated into a sustainable crop production system.

Keywords: electric field; expanded metal net; herbicide-independent method; physical weed control; pulse-charging type voltage generator; weed control

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1. Introduction

Weed control is necessary for sustainable crop production. Herbicide-based weed control has been the most commonly used method for half a century [1]. However, due to the intensive use of herbicides, many weeds resistant to major classes of herbicides have evolved [2–4]. In addition to the problem of herbicide resistance in a wide range of weed species, greater public concern about the use of chemicals for managing all classes of pests (i.e., pathogens, insect pests, and weeds) has led to the development of a non-chemical method of weed control. Biological and physical methods can be integrated into total pest management systems as an alternative to chemicals.

The use of bioherbicides is an emerging technique for weed control and sustainable agriculture [5,6]. Bioherbicides include plant-producing phytotoxins [7], allelochemicals [8], and fungal phytotoxins [9,10]. The direct application of living herbivorous insects [11,12] or fungal phytopathogens [13] is another option for biological weed control. However, little practical progress has been made because effective control is difficult to maintain, agent preparation is problematic, there are few application targets, and costs are high. The main barrier to their practical implementation is integrating individual methods into large-scale weed control systems under various environmental conditions.

The most basic conventional methods used to physically control weeds include covering the soil surface with a weeding mulch film [14,15] and mowing, flaming, and tilling practices [16]. Some studies have proposed the use of electrical [17,18] and robotic weeders [19] to reduce the labor requirements of these operations. However, the high cost of these machine weeders limits their wide use, particularly in developing countries [20]. Electrostatic techniques provide additional ways to kill weeds at the soil-emerging stage by directly exposing young seedlings to a high voltage arc (spark) discharge [17,21] generated in the space between conductors. The soil-emerging weed seedlings act as a biological conductor that receives a discharge from a charged conductor [21]. Matsuda et al. [22] successfully applied this technique to control kudzu creeping along an animal-repelling electric fence by attaching a grounded metal wire to an electrified fence wire at predefined intervals. This approach suggests that a simple electrostatic weed eradicator could be fabricated easily and inexpensively.

The objective of the present study was to provide an electric discharge-generating soil cover for practical weed management, in which a pair of charged grounded metal nets (G-MNs) were placed on a field to kill weed seedlings emerging from the soil. The framework of the apparatus is simple and easy to fabricate using commonly available materials. The main goal was to safely charge a metal net with a voltage generator, which is the only electric part of the present apparatus. A pulse-charging type negative voltage generator used for an electric fence was applied to the present system. Electric fences are used to repel wild animals and are ubiquitous and essential devices in modern agriculture. Accidents associated with agricultural electric fences are very rare [23]. Although unintentional human contact with electric fences occurs regularly, it only causes temporary discomfort [23]. Accordingly, this type of voltage generator is considered safe.

The arc discharge-exposure method was originally developed to prevent rice weevils nesting in dried rice grains [24,25]. Arcing is an electrical phenomenon generated by the movement of a high voltage-mediated negative charge in the air between opposite electric poles [26]. The intensity of the arc is determined by the voltage applied to the conductor and the distance between the opposite poles. The arc generated by the pulse-charging type voltage generator is sufficient to kill weeds effectively and quickly [22]. Thus, we developed an "electric discharge-armed weed zapper" (EDWZ) and determined the frequency of pulsed arc discharge exposure required to kill the seedlings of mono- and dicotyledonous plants. Based on these results, we evaluated the feasibility of the EDWZ for weed control and provided an experimental basis for developing an electrostatic weeding method.

2. Materials and Methods

2.1. Plant Species

Barley (*Hordeium vulgare* cv. Kobinkatagi), oats (*Avena sativa* cv. Negusaredaigi), soybeans (*Glycine max* cv. Natsunokoe), tomatoes (*Solanum lycopersicum* cv. Momotaro fight), watermelons (*Citrullus lanatus* cv. Tahiti), and sunflowers (*Helianthus annuus* cv. Konatsu) were used as model graminaceous, leguminous, solanaceous, cucurubitaceous, and asteraceous weeds, respectively. Germinated seeds of these plants were sown in a tray in soil and newly emerged seedlings were used in the experiments.

2.2. Instrument to Generate Arc Discharge between Two Metal Nets

Two identical expanded stainless nets (Okutani Wire Netting Mfg., Co., Ltd., Kobe, Japan) (Figure 1A) were used to construct the arc discharge instrument. One of the metal nets was held horizontally with a plastic clamp and linked to a solar cell-driven pulse-type negative voltage generator (pulse interval, 1 s; usable voltage, 10 kV) (Suematsu Denshi, Kumamoto, Japan) (Figure 1B), which is commonly used in electric fences to repel wild animals from crop fields. The other metal net was connected to a grounded line and placed on the horizontal platform of a laboratory scissor jack stand to vary the gap between the two nets (Figure 1C). The negative voltage generator amplified the initial voltage (12 V) to achieve the desired voltage (10 kV). The generator draws a negative charge from the ground using this voltage and supplies it to the conductor connected to the voltage generator [27]. A negative charge accumulates on the surface of the charged conductor and forms an electric field (monopolar electric field) in the surrounding space (Figure 1D). If the grounded conductor is placed inside the electric field, the negative charge on the charged conductor pushes negative electricity (free electrons) out of the grounded conductor by electrostatic induction [28]. The grounded conductor becomes positively electrified, and opposite charges on the nets form a dipolar electric field (Figure 1E). The positively electrified grounded conductor acts as a recipient pole for the negative charge released from the negatively charged conductor via the arc discharge (Figure 1E). Thus, arcing occurs when a dipolar electric field forms between the oppositely charged conductors. In this experiment, the G-MN was brought closer to the negatively charged metal net (NC-MN) by gradually raising the jack platform to determine the longest distance (from the NC-MN) that would cause an arc discharge (arcing distance).

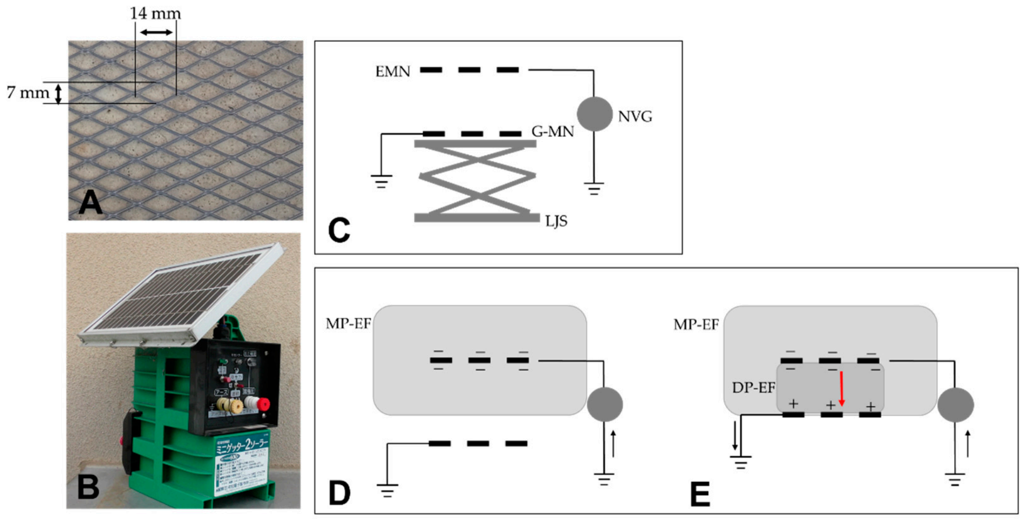

Figure 1. Experimental apparatus generating arc discharge. (**A**) Expanded stainless net with diamond-shaped 2 mm mesh connected to a voltage generator and grounded line. (**B**) Pulse-type voltage generator equipped with a solar panel and storage battery. (**C**) Configuration of the instrument (cross-sectional view), which consisted of two identical expanded metal nets (EMNs): one was maintained in a horizontal position and connected to a negative voltage generator (NVG), while the other was connected to a grounded line and placed on the horizontal platform of a laboratory jack stand (LJS) such that its height could be adjusted relative to the grounded metal net (G-MN). (**D**,**E**) Schematic representation of the monopolar electric field (MP-EF) surrounding the negatively charged metal net (**D**) and the dipolar electric field (DP-EF) formed between the two metal nets (**E**). The G-MN was moved closer to the charged upper metal net by gradually raising the jack platform. Arc discharge (red arrow) occurred when the G-MN entered the MP-EF and formed the DP-EF between the two metal nets. This distance was denoted as the arcing distance. The black arrow represents the movement direction of the negative charge.

2.3. Construction of the EDWZ

We fabricated the EDWZ using two expanded metal nets (30 × 30 cm^2). As the NC-MN caused arcing toward the G-MN when the distance between them was 5 mm (Figure 2A), the G-MN was set at a distance of 6 mm (non-arcing distance) by placing a square 6 mm high polypropylene frame (insulator) between the nets (Figure 2B). The EDWZ was placed on soil in a tray in which seeds had been sown. Arcing occurred preferentially toward a plant seedling when it reached the NC-MN electric field (Figure 2B).

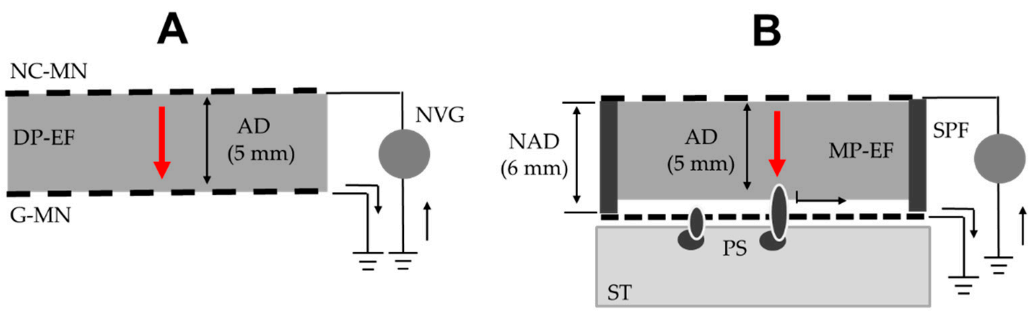

Figure 2. Schematic representation of the experimental instrument used to eradicate weed seedlings emerging from the ground (cross-sectional view). The expanded upper metal net was connected to a pulse-type negative voltage generator (NVG) and the lower net was connected to a grounded line. (**A**) Arc discharge occurred between the two metal nets, which were parallel to each other and separated by 5 mm (arcing distance, AD). A dipolar electric field (DP-EF) formed between the two nets. (**B**) The instrument was fabricated by placing a square polypropylene frame (SPF) (6 mm in height) between the NC-MN and G-MN to maintain a non-arcing distance (NAD) and set on soil in a tray (ST) containing sown plant seeds. Arcing occurred toward a plant seedling (PS) when it reached the MP-EF of the NC-MN. The black arrow represents the ground-to-ground movement of negative electricity. The red arrow represents the movement of electricity (arcing) through the air.

2.4. Assay of Damages on Plant Seedlings Caused by Arc-discharge Exposure

Arc discharge exposure seriously damages the targets exposed to the arcing [22,29]. In the present study, the plant seeds were sown in a soil tray to determine the arc discharge exposure frequency required to kill the seedlings. The sound associated with arc discharge exposure [21,22] was recorded using a sound-level meter (Sato Tech, Kanagawa, Japan) throughout the entire experiment. A sound profile was generated on a chart to count the number of arc discharge sounds using a spectrum analyzer integrated into a sound-level meter. Twenty seedlings of each plant species were used, and the experiment was repeated five times. In addition, we recorded a video of monocotyledonous (barley) and dicotyledonous (tomato) seedlings subjected to arc discharge to demonstrate the effect on the seedling.

2.5. Practical Application of the EDWZ to Control Weed Seedlings Emerging in a Crop Field

A 1 m^2 EDWZ was constructed for practical use. Multiple EDWZs were connected with electrical wire (Figure 3A) and used to cover different areas (1 × 6–20 m^2) in the field. All EDWZs were operated by a single voltage generator and a ground line. Before starting the apparatuses, the soil covering the top surface of the G-MN was leveled off to avoid exposure of the soil to an arc discharge (leveling-off-soil operation) (Figure 3B). Experiments were conducted at 18 locations in the crop field for 3 months between April and October in 2021 and 2022.

In the study area (Nara Prefecture, Japan), the seedlings of many weeds appear in April and grow vigorously. The present experimental period included the rainy (June–July) and high-temperature (July–September) seasons. At the end of each month, we assessed the weed community that appeared in the region adjacent to the area covered by the apparatuses. The Pl@ntNet application [30] was used to identify weed species.

2.6. Statistical Analysis

Each experiment was replicated five times, and all data are presented as mean and standard deviation. Tukey's test was performed using EZR software (ver. 1.54; Jichi Medical University, Saitama, Japan) to detect differences among the various conditions. A *p*-value < 0.05 was considered significant.

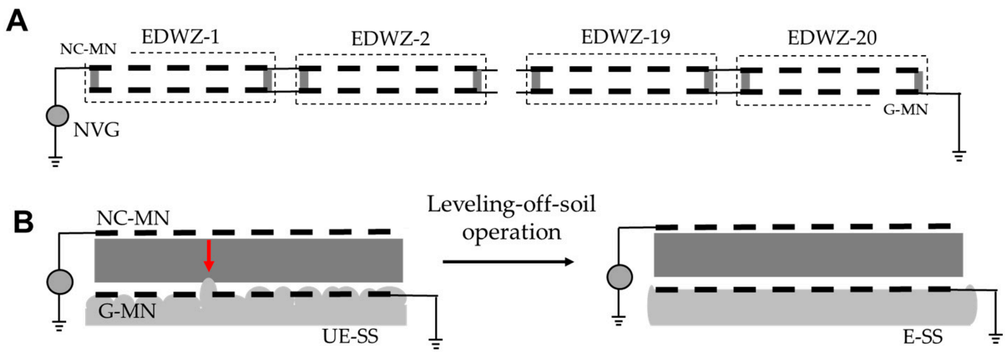

Figure 3. Application of multiple electric discharge-armed weed zappers (EDWZs) to a crop field. (**A**) Connection between the negatively charged metal nets (NC-MNs) of 20 EDWZs (EDWZ 1–20) and one pulse-charging type negative voltage generator (NVG), and between 20 grounded metal nets (G-MNs) and a grounded line, using an electric wire. (**B**) Soil covering the top surface of the G-MN was leveled off to transform the uneven soil surface (UE-SS) into an even soil surface (E-SS); undesirable arcing (red arrow) of this soil portion was thus evaded.

3. Results and Discussion

3.1. Determination of Arcing Distance

A negatively charged conductor creates an electric field in the surrounding space, which widens as the voltage applied is increased [26]. In the present study, the −10 kV metal net generated a 5 mm wide electric field and ejected an arc (spark) to the G-MN (Figures 1E and 2A). Based on this result, we designed an electrostatic soil cover consisting of two metal nets arranged in parallel at an interval of 6 mm (Figure 2B). This arrangement made it possible to achieve a distance between the NC-MN and G-MN at which arcing did not occur between them; instead, arc discharge was directed toward a seedling that emerged from the soil and extended 1 mm over the G-MN (Figure 2B). Thus, the EDWZ preferentially killed juvenile plant seedlings emerging from the soil.

3.2. Ability of the EDWZ to Eradicate Mono- and Dicotyledonous Plant Seedlings

The negative voltage generator produced arc discharges at an interval of 1 s. A sound was created at the time of the pulsed arc discharge, i.e., a sonic boom caused by the shock wave from the high-speed electrons moving within the electric field. The intensity of this sound reflected the impact of the shock wave produced by the arc discharge. Previous studies have reported that a pulsed arc discharge produces a force that can destroy the apical tissue of kudzu vines [22] and prompts flight by adult houseflies [29]. In this study, we examined how much arcing was required to kill plant seedlings that entered the NC-MN arcing area. Figure 4 shows the typical profiles of the sound(s) generated by arc discharges targeting the same monocotyledonous (barley) (A) and dicotyledonous (tomato) (B) seedlings during the experimental period (7 days).

The results indicated that the monocotyledonous plants were subjected to several arc discharge exposures (Figure 4A). The monocotyledonous plants first developed coleoptile tissue, which was destroyed by the first exposure (Video S1A). The lower part of the epicotyl remained alive and elongated continuously despite damage to the apical region. However, subsequent discharges destroyed the newly developed epicotyl. Repeated discharges overcame regrowth and killed the seedling. In contrast, the growth of dicotyledonous seedlings was halted after the first arc discharge exposure (Figure 4B). The arc discharge struck the dicotyledonous seedling's hypocotyl hook, which separated the hypocotyl hook from the epicotyl and halted further growth (Video S1B). Figure 5 shows the number of arc discharges required to kill the seedlings of mono- and dicotyledonous plants. There was no significant difference in the number of arcings required to kill the monocotyledonous and dicotyledonous plant seedlings, although there was a significant difference between the mono- and dicotyledonous plants. Thus, the results suggest that the EDWZ is a practical way to eradicate weed seedlings emerging in a crop field.

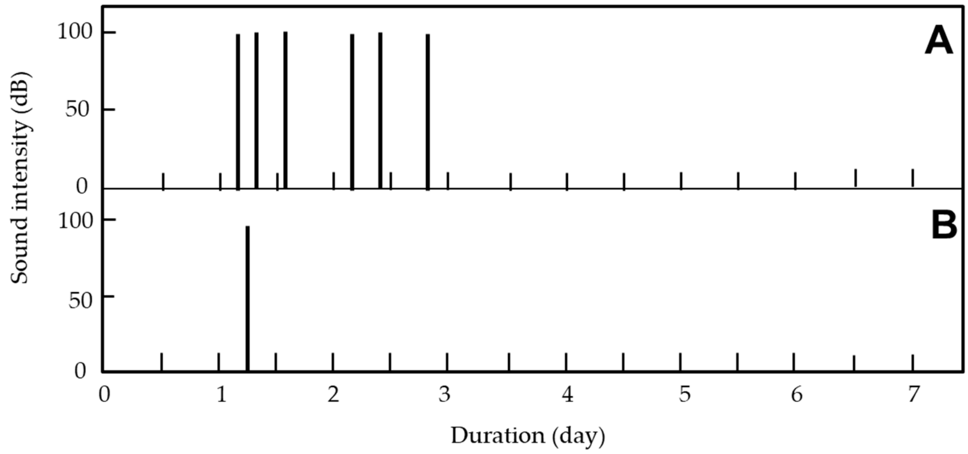

Figure 4. Profile of sound(s) generated by arc discharge(s) produced by the electric discharge-armed weed zapper (EDWZ) targeting barley (monocotyledon) (**A**) and tomato (dicotyledon) (**B**) seedlings.

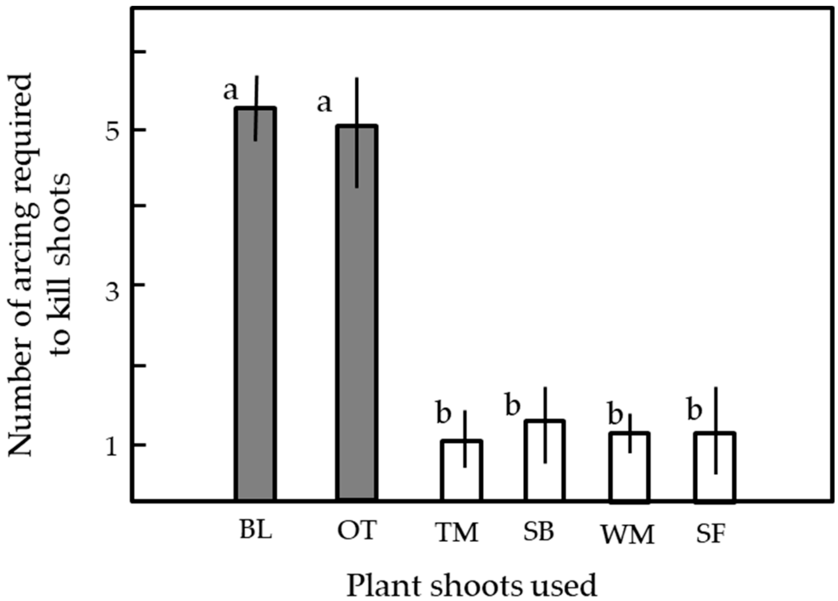

Figure 5. Eradication of elongating mono- and dicotyledonous plant seedlings via exposure to arcing generated by the negatively charged metal net of the electric discharge-armed weed zapper. Barley (BL) and oat (OT) were used as model monocotyledonous weeds, and tomato (TM), soybean (SB), watermelon (WM), and sunflower (SF) served as dicotyledonous weeds. Twenty seedlings were used for each plant species. Mean and standard deviation values were calculated from five experimental replicates. Different letters (a, b) in each vertical column indicate significant differences ($p < 0.05$) according to Tukey's test.

3.3. Practical Application of the EDWZ

3.3.1. Successful Grounding of the EDWZ

A prerequisite for the normal functioning of the EDWZ is successful grounding, which allows the collection of a negative charge from the ground by the voltage generator. The charge is then sent back to the ground. In a laboratory experiment, we inserted the grounded line plug of the voltage generator into the ground-contact outlet of a wall socket, which was equipped with a conductive pipe. The pipe was driven into the earth to a minimum depth of 8 feet (about 2.5 m) to protect against fire caused by electricity leakage [31]. It was necessary to ground the voltage generator and the grounded line during the field experiments because the dried surface layer of the field increased ground resistance (earth resistance), which impeded current flow to the ground [32]. The manufacturer of the pulse-charging type voltage generator used here recommends driving a 50 cm long iron stake into the ground. The apparatus produced pulsed arc discharges at all 200 points tested in the crop field.

Plant seedlings with roots growing in wet ground are electrically grounded such that they are exposed to an arc discharge when they enter the NC-MN electric field, even if the G-MN is not equipped [21]. The surface layer of the ground soil is easily dried by a change in weather conditions. The dried soil layer was less conducive to intercepting the current flow from the arc discharge-exposed seedling. This is an important factor with respect to suppressing arcing from the NC-MN to a weed seedling. The G-MN was set to ensure a stable ground for the target seedling, regardless of any change in the weather. Seedlings that passed through the G-MN acted as intermediate poles and were subjected to an arc discharge from the NC-MN because of their conductivity. The electricity was eventually transferred to the seedling, and then to the ground, via the G-MN by a two-step arc discharge (Figure 2B) [22].

3.3.2. Leveling-Off of Soil for Preferential Arcing of Plant Seedlings

Wet soil is conductive and acts as an opposite pole receiving a negative charge from the NC-MN if the soil reaches the electric field (Figure 2A) [21]. To avoid undesirable arcing between the NC-MN and the ground, soil that projected over the top surface of the G-MN was leveled off to ensure that arcing to the weed seedlings passed through the G-MN and reached the NC-MN electric field (Figure 2B). The leveling-off of soil was easily achieved by sliding a flat-edge plate over the surface of the G-MN; successful leveling-off was confirmed by the lack of arcing and weed seedlings within the netted area.

3.3.3. Effects of a Change in Weather on EDWZ Functioning

Changes in the weather during the outdoor experiment were of concern. The voltage generator used in the present study was an all-weather generator; therefore, the effect of climate conditions on the generation of arc discharges by the NC-MN was an important consideration. The change in vapor concentration (relative humidity) in the air was the most important factor affecting the generation of arc discharges. Air conductivity changes in response to changes in the water vapor concentration (relative humidity) in the air: air conductivity is higher (i.e., more electricity is transferred) under conditions of higher relative humidity [33]. This implies that, under high humidity conditions, seedlings were exposed to arc discharges with larger amounts of electric current. Accordingly, highly humid conditions promoted effective arc discharge exposure treatment [21,22]. Seedlings that became wet because of rain or morning dew were more susceptible to arc discharge due to the increased conductivity of the wet plant body [21,22]. Temperature changes did not affect the generation of arc discharges by the apparatus. In fact, the EDWZ was not affected by changes in diurnal temperature even when the temperature change increased from 12 °C to 46 °C (at the ground level of 1 cm) over a period of several days in August.

3.3.4. Practical Application of the EDWZ for Weed Control in Crop Fields

The most important characteristic of the apparatus used in this study was that arc discharges were generated toward the seedling nearest to the NC-MN, suggesting that arcing occurs at a point on the charged metal net regardless of the net size or the number of seedlings reaching the electric field. It was possible to increase the size of the charged metal net for practical use. Multiple EDWZs were easily connected by linking their NC-MNs to a voltage generator and connecting the G-MNs to a grounded line (Figure 3A). However, we were concerned that expanding the apparatus would delay exposure to the arc discharge because of the tremendous increase in the number of targeted weed seedlings. The voltage generator generated 60 arcs/min, i.e., 86,400 arcs per day. Theoretically, this means that the EDWZ can treat approximately 85,000 seedlings per day if all of the targets are dicotyledons, and approximately 14,000 seedlings if they are all monocotyledons. In our preliminary survey, the average density was 328.9 ± 85.4 weeds/m^2, suggesting that the voltage generator could treat weeds emerging in a 50–280 m^2 area. These provisional calculations encouraged us to apply the EDWZ for weed control. Ultimately, we fabricated 20 EDWZs because of budget limitations.

We conducted field experiments to demonstrate the practicality of the apparatus. The results indicated that the EDWZs functioned continuously during the experiments. In fact, the emergence of weed seedlings was completely suppressed in all 18 locations, where 6–20 apparatuses were combined to cover different areas. Figure 6 shows two examples of successful applications. Figure 6A–C show where the 20 EDWZs were placed initially (A) and where they were placed after 3 months (B). The results indicate that the apparatuses completely suppressed the emergence of seedlings, and the post-experiment survey indicated that no weed seedlings remained beneath the nets (Figure 6C). Figure 6D,E show the application of six EDWZs, which achieved the complete suppression of weed emergence. We concluded that the EDWZ is a promising tool to eradicate weed seedlings and achieve weed control in crop fields.

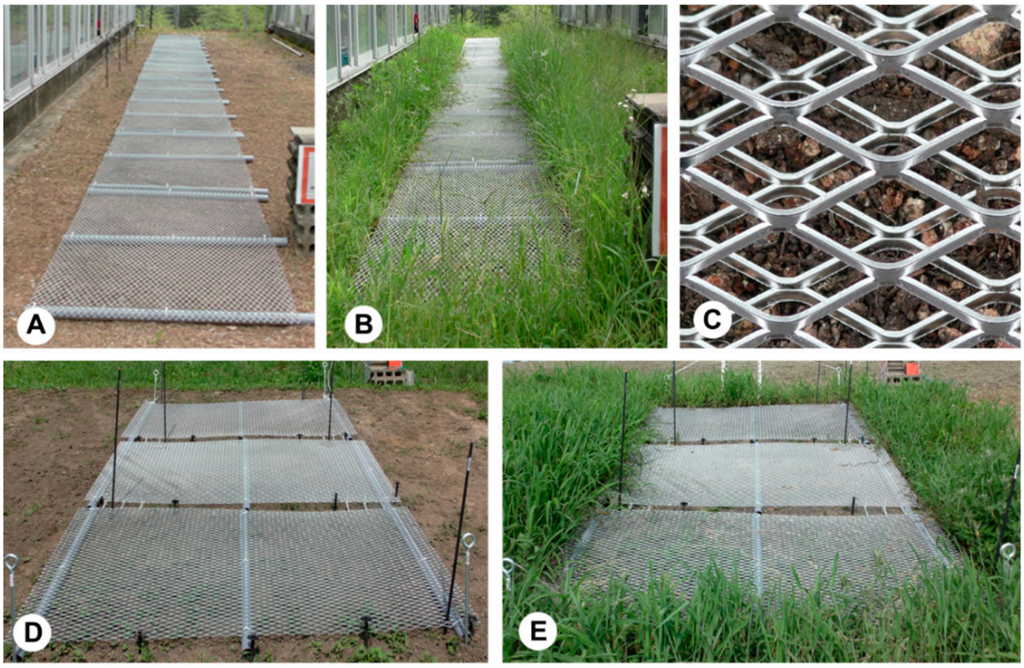

Figure 6. Photograph showing the sustainable functionality of the electric discharge-armed weed zapper (EDWZ). (**A**–**C**) Suppression of weed emergence using a soil cover consisting of 20 connected EDWZs at the start of experiment (**A**) and after 3 months (**B**,**C**). The image in C is an enlargement of the image in B. (**D**,**E**) Suppression of weed emergence by six connected EDWZs at the start of the experiment (**D**) and after 3 months (**E**). No weeds appeared in netted areas, while numerous weeds emerged and grew in areas adjacent to those covered by the apparatus.

To identify the weeds that were controlled, we designated an adjacent control plot where we analyzed the weed population of the soil seedbank. Our survey indicated that several weed species appeared seasonally during the experimental period, including four kinds of dicotyledonous weeds and six monocotyledonous species (Table 1).

Table 1. List of Identified Weeds [a].

Types of Cotyledon	Common Name	Scientific Name
Dicotyledons	Chickweed	*Stellaria media* (L.) Vill.
	Narrow-leaved Vetch	*Vicia sativa* L. subsp. *nigra* (L.) Ehrh.
	Philadelphia Fleabane	*Erigeron philadelphicus* L.
	White Clover	*Trifolium repens* L.
Monocotyledons	Green Bristlegrass	*Setaria viridis* (L.)P. Beauv
	Southern Crabgrass	*Digitaria ciliaris* (Retz.) Koel
	Indian Goosegrass	*Eleusine indica* (L.) Gaertn
	Annual Bluegrass	*Poa annua* L.
	Shortawn Foxtail	*Alopecurus aequalis* Sobol.
	Wild Oat	*Avena sativa* L.

[a] Weeds growing in the area adjacent to the test locations covered by the electric discharge-armed weed zappers.

We have proposed a unique electrostatic weed eradicator. Due to its simple structure, it can be fabricated inexpensively using common materials without requiring any special construction skills. The use of a pulse-charging voltage generator, which has been typically used for electric fences to repel wild animals, reduced the total production cost. The voltage generator was operated by a solar panel-powered storage battery; therefore, it was not necessary to equip the apparatus with electric wiring. This low-cost equipment should be acceptable to many farmers for use as a weed management tool. Moreover, the apparatus is weatherproof such that it can be operated outdoors for extended periods. Importantly, a successful arc discharge depends on the conductivity of the weeds, and all weeds entering the electric field are targeted for eradication, regardless of their biological characteristics. In summary, we have developed a promising new tool for physical weed management.

Despite the prominent weed seedling-eradicating ability of the present apparatus, we have some problems regarding its practicality. The important problems may be identifying how to adequately treat weeds in a crop field that are adjacent to crop plants without harming the crop and how to apply the apparatus to a curved place, such as raised beds, where crops are cultivated. Because weed seeds germinate throughout the year, another problem is how long the apparatus would need to stay in place. Once the system is installed, it may be more difficult to do some farming by tractor. In addition, existing weed populations or perennial weed species are problematic to the present system. Despite these questions, this system could be very useful in specific cropping situations. Some future research to deal with these issues could continue to improve this method.

4. Conclusions

The electrostatic weed eradicator presented here is a newly developed device to kill weed seedlings emerging from crop fields via arc discharge. The convex part of an expanded metal net ejects discharge sparks toward seedlings in any location. The arc discharge treatment can target the tallest emerging weed seedlings with a high accuracy. The present study describes a simple physical herbicide-independent weed management approach for sustainable crop production systems.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agronomy13041115/s1. Video S1: Arc discharge from the negatively charged metal net (NC-MN) and the electric discharge-armed weed zapper (EDWZ) affecting barley (monocotyledon) (A) and tomato (dicotyledon) seedlings (B), respectively.

Author Contributions: Conceptualization, H.T. and Y.M.; methodology, Y.M. and Y.T.; software, Y.M.; validation, H.T., Y.M., K.S., S.-i.K. and Y.T.; formal analysis, Y.M. and Y.T.; investigation, Y.M. and Y.T.; resources, Y.M.; data curation, Y.T.; writing—original draft preparation, H.T.; writing—review and editing, Y.M. and Y.T.; visualization, Y.M.; supervision, H.T.; project administration, Y.M. All authors have read and agreed to the published version of the manuscript.

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