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Target-Size-Dependent Application of Electrostatic Techniques for Pest Management in Greenhouses

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Abstract: Two new electrostatic devices were developed to manage greenhouse insect pests. One was an electrostatic insect catcher (EIC) to trap small flying pests, and the other was an arc-discharge zapper (ADZ) to kill larger insects emerging from soil beds. The EIC consisted of negatively charged insulated conductor plates (NIPs) and grounded conductor plates (GCPs), which were alternately arrayed in parallel at defined intervals. The ADZ had the same framework as the EIC, except that the NIPs were replaced with negatively charged non-insulated iron plates (NNPs). The EIC formed a non-discharging electric field between the NIP and GCP to create an attractive force to capture insects. By contrast, the ADZ formed a discharge-generating electric field between the NNP and GCP that killed insects. The EIC was effectively applied to small pests, such as whiteflies, thrips, leaf miners, winged aphids, and shore flies, that can pass through the conventional insect-proof nets installed on greenhouse windows. The ADZ was effective for adult houseflies emerging from pupae in soil beds. Our electrostatic devices are useful for controlling insect pests of different sizes.

Keywords: arc discharge zapper; electrostatic insect catcher; green peach aphid; housefly; physical control; shore fly; tomato leaf miner; western flower thrips; whitefly

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1. Introduction

Electrostatic techniques have been developed to precipitate airborne biotic and abiotic nuisances (such as airborne fungal spores, flying insect pests, pollen grains causing pollinosis, and tobacco smoke particles) in various environments [1]. The major electrostatic principle used in these approaches is the formation of an electric field. An electric field is the space surrounding an electric charge that exerts a perceptible force on another electric charge [2]. A negative charge is supplied to a conductor by connecting it to a direct current (DC) negative voltage generator (NVG). An NVG is a booster that enhances an initial voltage (12 V) to a desired voltage using a transformer and Cockcroft circuit integrated into a voltage generator [3]. Using this enhanced voltage, an NVG draws negative charge (free electrons) from a ground and supplies it to a conductor linked to the voltage generator. Negative charge accumulates on the conductor and generates an electric field in the surrounding space. If a grounded conductor is placed inside the electric field, the negative charge on the charged conductor polarizes the grounded conductor positively by electrostatic induction [4]. Eventually, the opposite charges on the conductor and grounded conductor form a dipolar electric field in the space between them. In this study, based on this electrostatic theory, we constructed two different physical tools to control insect pests.

First, we produced a device to capture flying insect pests in a dipolar electric field. Kakutani et al. [5] proposed such a device using an insulated metal wire and a non-insulated, grounded metal net. They tested it on the vinegar fly, *Drosophila melanogaster* Meigen (Diptera, Drosophilidae). A negative charge on the insulated wire pushed negative electricity (free electrons) out of the fly body and onto the grounded metal net. Eventually, the fly became positively electrified and was drawn to the negatively charged, insulated wire. They referred to this phenomenon as "discharge-mediated positive electrification of an insect."This method worked because of the highly conductive nature of the cuticle layer of the insect body [6–10]. The same group found that the mechanism is effective for many insect species (across 8 orders and 15 genera) [11]. Building on this idea, our electric-field-based insect-capturing device employed a pair of identical metal plates: one was insulated with a soft polyvinyl chloride resin and linked to a continuous-charge voltage generator, while the other was noninsulated and linked to a grounded line. The use of the two parallel metal plates enabled an even pole distance (the distance between the two plates) to be created over the entire surface of the plates, which was expected to have the same attractive force for target insects at any location along the plate. More importantly, an insulative coating on the charged metal plate would effectively prevent accidental electrocution of workers.

Next, a device was produced to kill insects via an arc discharge. This concept was originally used to manage the rice weevil, *Sitophilus oryzae* Linnaeus (Coleoptera: Curculionidae), a warehouse pest that nests in stored rice [12,13]. In previous studies, two identical conductors (metal nets or plates) were placed in parallel at a defined interval to form a dipolar electric field between them. One conductor was linked to an NVG, and the other was linked to a grounded line. Because the negatively charged conductor was not insulated, the negative charge on the conductor was discharged toward the insect when it entered the electric field (the space between the two conductors). Insects were killed by the strong impact of the discharge [12,13]. However, because of the high risk of electrocution with this system, it was essential to furnish the device with an insulation guard. Thus, in our arc-discharge-based device reported herein, we used a pulse-charge-type voltage generator, which is commonly used in electric fences to repel wild animals. Electric fences are ubiquitous and essential in modern agriculture. Accidents in association with agricultural electric fences are very rare [14]. Although unintentional human contact with electric fences occurs regularly, it causes little more than temporary discomfort [14].

A total of six pest species were targeted and tested with two devices that had different body sizes; these are listed in Table S1. All pests in the small- and middle-size groups were able to pass through a conventionally woven "insect-proof" net (1–1.5 mm mesh size) installed on the windows of greenhouses. Most greenhouse plants are vulnerable to direct attacks by these pests as well as serious infections caused by viral, bacterial, and fungal pathogens that are carried by these vectors. In particular, whiteflies, thrips, and aphids transmit viral pathogens: tomato yellow leaf curl virus [15,16], tomato spotted wilt tospovirus [17,18], and cucumber mosaic virus [19], respectively. Shore flies in the middle-sized group were also able to pass through the net and transfer rhizosphere fungal pathogens (*Verticillium dahliae* and *Fusarium oxysporum* f. sp. *radicis-lycopersici*) [20,21]. Vinegar flies have been targeted as a potential vector of various bacterial and fungal pathogens [22]. The most problematic pest in our greenhouses was the viruliferous whitefly. Tomato plants suffer from viral diseases every year in our greenhouses [23], whereas other pests seldom cause problems. Thus, the establishment of a reliable control method for whiteflies was extremely important in the present study.

Although houseflies in the large size group were not able to pass through the net, they were frequently transferred to greenhouse soil beds from cattle manure used for fertilization [24]. Cattle manure is the major organic fertilizer in our greenhouse cultivation system and is typically applied once or twice each year. Unfortunately, it frequently contains the larvae of houseflies, and therefore adult flies frequently emerge during plant cultivation. Houseflies can transmit pathogenic *Escherichia coli* O157 [25,26], causing food poisoning in people who ingest foods contaminated with this pathogen. *E. coli* O157 is originally present in the intestines of cattle and sheep, where it does not cause disease [25–27]. However, housefly larvae develop in animal feces [25], and the microbes they ingest remain viable in their excreta; consequently, they carry and disseminate *E. coli* for several days [25] and thus pose a threat to public health [28–30]. Therefore, the management of adult houseflies that emerge from underground is of critical importance.

In an effort to give greenhouse managers/researchers flexibility in what tool would be best for their current situation, we designed the two devices mentioned above. The main distinction between the two devices is that one features an iron plate that is covered with a soft polyvinyl chloride resin and linked to a continuous-charge type voltage generator; the other is not insulated and is linked to a pulse-charge type voltage generator. We call the former the electrostatic insect catcher (EIC) and the latter the arc-discharge zapper (ADZ). These works are unique challenges to develop new physical methods for pest control, and the newly devised apparatuses possess simple structures, allowing ordinary greenhouse workers to fabricate or improve them for their own requirements and exert prominent control functions to target insect pests.

2. Materials and Methods

2.1. Insects

Adult whitefies (*B. tabaci*), vinegar flies (*D. melanogaster*), western flower thrips (*F. occidentalis*), wingless female green peach aphids (*M. persicae*), and pupae of houseflies (*M. domestica*) and tomato leaf miners (*L. sativae*) were purchased from Sumika Technoservice (Hyogo, Japan). Pupae of greenbottle flies (*L. sericata*) were purchased from the Japan Maggot Company (Okayama, Japan). Although vinegar fly *D. melanogaster* and greenbottle fly *L. sericata* were not pests of greenhouse plants, they were added as supplements to the medium- and large-size groups, respectively.

Houseflies and greenbottle flies were reared on a certified diet (MF; Oriental Yeast Co., Ltd., Tokyo, Japan) [31] in a closed 30 mL transparent acrylic vessel. The rearing was conducted in a growth chamber (25 ± 0.5 °C, 12 h photoperiod, 4000 lux) from the egg to adult stages. Pupae found in the medium were individually transferred into fresh medium in a 20 mL vial for isolation, and the vial mouth was covered with gauze. The sexes of adult flies that emerged from the pupal stage were determined based on the sexual dimorphism of their external morphology [32,33]. For immobilization, adult houseflies and greenbottle flies were anesthetized by CO_2 exposure according to a method described previously [34]. The vials containing insects were placed in a non-vacuum glass desiccator (jar capacity: 5 L) into which CO_2 gas (Air Water West Japan Inc., Osaka, Japan) was continuously introduced at 10 kg/cm^2 for 4–5 min. The air in the desiccator was simultaneously exhausted from an exhaust port on the desiccator lid. The introduction of CO_2 was stopped when all insects were anesthetized. In the CO_2 treatment, all of the anesthetized flies awoke within 5 min. These immobilized flies were used in the experiments.

Adult vinegar flies were reared on blue medium (Wako Pure Chemical, Osaka, Japan) under the above conditions, and newly emerged adults (15–24 h after eclosion) were used as active flies for experiments. The whiteflies were reared on 10-day-old kidney bean (*Phaseolus vulgaris* L. 'Nagauzura-saitou') seedlings [35] in a phytotron (22–34 °C). Adult western flower thrips and wingless adult female green peach aphids were reared on water-swollen seeds and 1-week-old broad-bean (*Vicia faba* L. "GB-Blend") seedlings in a growth chamber according to the methods of Murai [36] and Murai and Loomans [37]. Pupae of tomato leaf miners were maintained in a growth chamber until the adults emerged. Adult shore flies were collected from a hydroponic tomato greenhouse and maintained on a lawn of green algae (*Chlamydomonas reinhardtii* Dangeard). The lawn was cultured on a sponge cube soaked in hydroponic culture solution in a transparent 2 L culture bottle; the bottle opening was covered with a woven net of 0.6 mm mesh [38]. The test insects were held in a temperature-controlled growth chamber (26 ± 2 °C, 35–45% relative humidity, and a 16 h photoperiod with 4000 lux from fluorescent lamps). The hatched winged adult female green peach aphids and newly emerged adults of other test insects (whiteflies, western flower thrips, tomato leaf miners, vinegar flies, and shore flies) were collected with an insect aspirator (Wildco, Yulee, FL, USA).

Table S1 shows the mean body sizes of the insects (i.e., length from head to wing tip), where 20 adults of each species were measured.

2.2. Experimental Instrument for an Insect-Capturing Assay

2.2.1. Fabrication of the Instrument

Figure 1 shows the structure of the instrument used to capture insects. The instrument consisted of two identical iron plates (30 × 20 mm^2; thickness, 1 mm) horizontally arranged at defined separation intervals (5 or 10 mm). One plate was coated with a soft polyvinyl chloride resin for insulation (coating thickness, 2 mm; resistivity, 2 × 108 Ωcm) (Sonoda Seisakusho, Osaka, Japan) and linked to a direct current (DC) negative voltage generator (NVG) (continuous-charge type; applicable voltage, –0.1 to –10 kV) (Max Electronics, Tokyo, Japan). The voltage generator was operated by a lithium storage battery (12 V). The other plate was non-insulated and linked to a grounded line. In this instrument, the negative charge that accumulated on the surface of the charged conductor plate dielectrically polarized an insulating cover, positively on the inner surface and negatively on the outer surface [39]. The negative charge on the insulated conductor plate (ICP) generated a monopolar electric field in the surrounding space (Figure 1A). When the grounded conductor plate (GCP) entered the monopolar electric field, the negative charge on the ICP polarized it positively to form a dipolar electric field between them (Figure 1B). Any insect that entered the dipolar electric field was deprived of free electrons from its body, causing it to be positively polarized. This drew the polarized insect to the negatively charged ICP (NIP) [5].

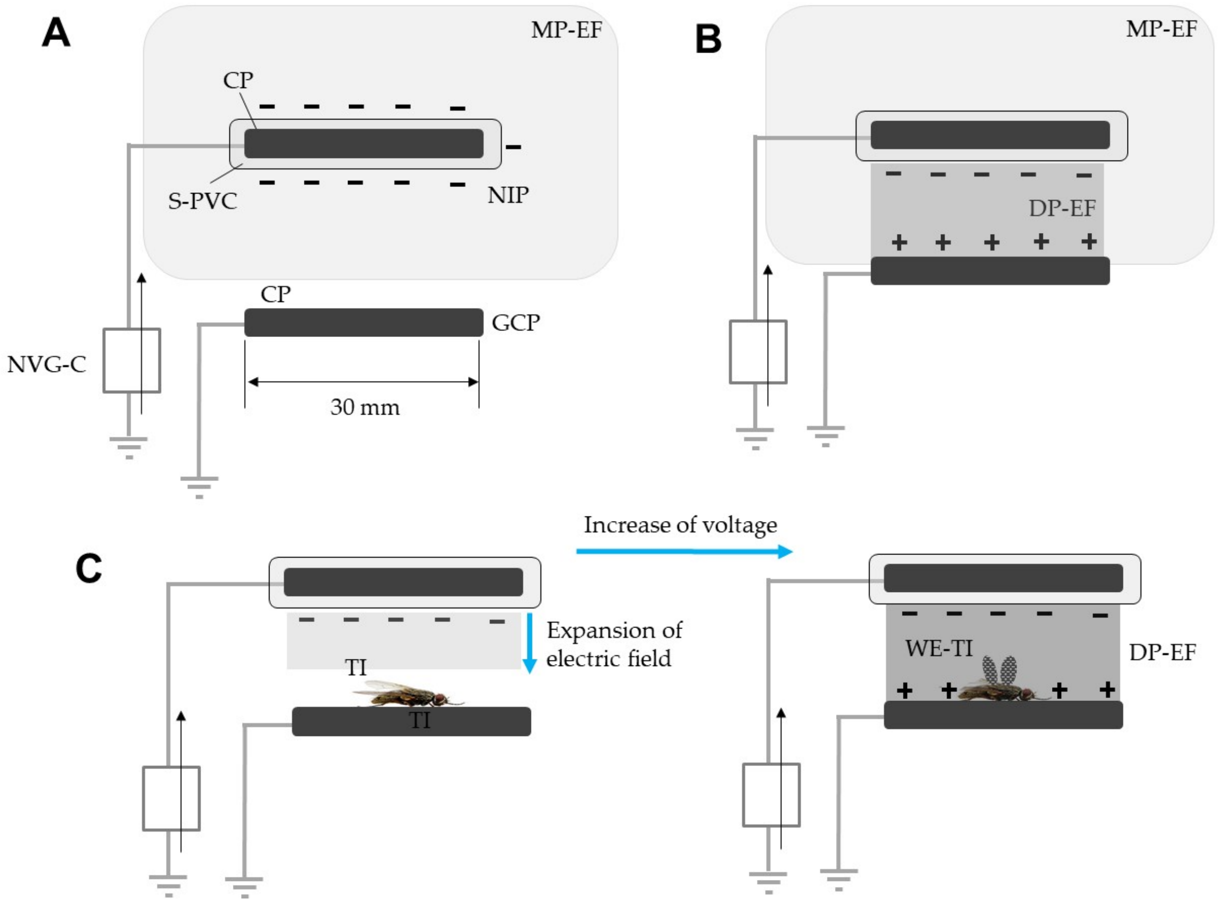

Figure 1. Structure of an experimental instrument for capturing insects and the formation of monopolar and dipolar electric fields. (**A**) Two identical conductor (iron) plates (CPs) were horizontally arranged;

the upper plate was insulated with a soft polyvinyl chloride (S-PVC) resin and linked to a negative voltage generator (continuous-charge type) (NVG-C), and the lower plate was non-insulated and linked to a grounded line (cross-sectional view). A negatively charged insulated conductor plate (NIP) formed a monopolar electric field (MP-EF) in the surrounding space. A grounded conductor plate (GCP) was located outside the MP-EF. (**B**) When the GCP entered the MP-EF, it was positively polarized by the negative surface of the NIP as a result of electrostatic induction; eventually, a dipolar electric field (DP-EF) was formed between the two plates. (**C**) Determination of the expansion of the electric field based on a wing erectness phenomenon observed with a test insect (TI) that entered the dipolar electric field. The electric field was expanded in direct proportion to the increase in the voltage applied to the insulated conductor plate. The insect lifted its wings (WE-TI) when it entered the electric field. The black arrows represent the direction of the movement of negative electricity.

2.2.2. Electric Field Expansion with an Increase in Voltage

First, we evaluated the area of the electric field generated by the NIP (its reach). Kakutani et al. [5] reported that an insect in an electric field first lifts its wings in response to the attractive force of the conductor and is then drawn to it by an increase in the applied voltage. In the present study, we adopted this wing erectness phenomenon as a sign that an insect had encountered a field. We placed two rectangular polypropylene (insulator) spacers (length: 20 mm; width: 3 mm; height: 5 mm) at both ends of the GCP to create a separation interval of 5 mm between the NIP and GCP. As the monopolar electric field produced by the NIP was expanded by an increase in the voltage applied (Matsuda et al. 2006), we placed a test insect (an adult whitefly) onto the GCP and raised the voltage gradually until the insect lifted its wings. At that point, we considered that a dipolar electric field was formed between the NIP and GCP (Figure 1C). In addition, we fabricated the instruments at 6 to 10 mm intervals and determined the voltage that formed the dipolar electric field between the two plates at these interval settings, using the wing erectness method mentioned above.

2.2.3. Insect-Capturing Assay

Next, we ran an experiment using the instrument with two plates spaced by a 5 mm interval. The ICP was negatively charged at different voltages (0.1 to 10 kV). Test insects (without respect to their sex) belonging to the small- and middle-size groups (Table S1) were transferred individually onto the GCP using an insect aspirator. Because adult houseflies and greenbottle flies were too large to transfer that way, they were immobilized by CO_2 anesthetization and then gently transferred onto the GCP with bamboo forceps. The edges of the forceps were covered with rubber caps. After the flies awoke from anesthesia, the voltage was applied. Twenty insects were used for each species and each voltage to determine the rate of capture at a given voltage.

2.3. Experimental Instrument for Exposing Insects to an Arc Discharge

2.3.1. Fabrication of the Instrument

Figure 2 shows the second experimental instrument used to expose an insect to an arc discharge. The instrument consisted of two identical iron plates (30×20 mm^2; thickness, 2 mm) horizontally arranged at a defined interval. One plate was non-insulated and linked to a pulse-charge-type NVG (pulse interval, 1 s; usable voltage, −10 kV) (Suematsu Denshi, Kumamoto, Japan), and the other plate was linked to a grounded line. The voltage generator was operated by a lithium storage battery (12 V) powered by a solar panel. In this instrument, the pole distance determined the occurrence of arcing. In the first experiment, the GCP was lifted gradually and settled at the position where the arcing by the NNP occurred (Figure 2). At this position, a dipolar electric field was formed between the NNP and GCP, and arcing occurred [40]. In this instrument, pulsed arcing occurred continuously in the electric field at an interval of 1 s.

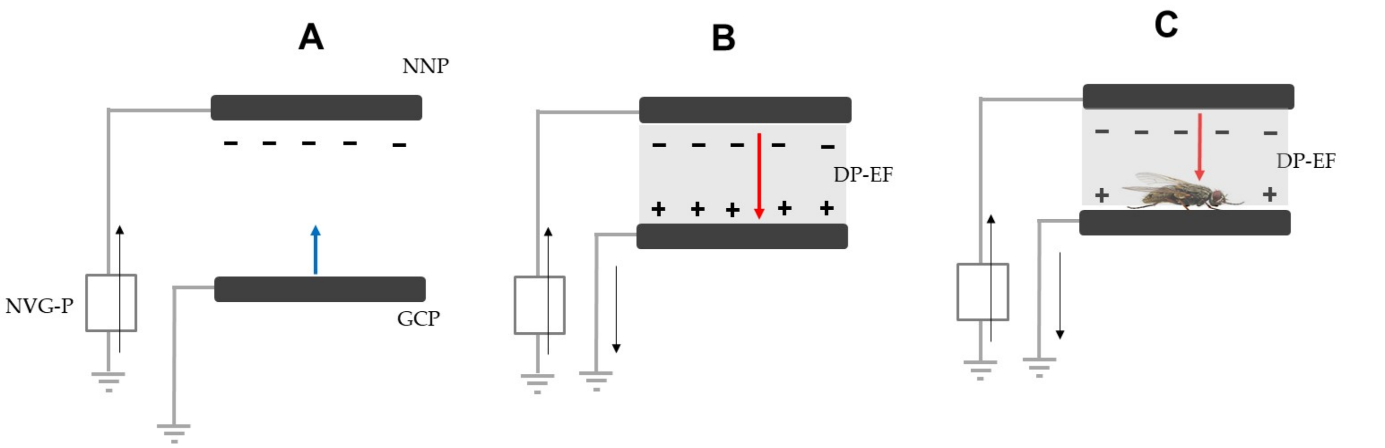

Figure 2. (**A**, **B**) Schematic representation of arc-discharge generation by an experimental instrument. The instrument consisted of a negatively charged non-insulated conductor plate (NNP) linked to a negative voltage generator (pulse-charge type) (NVG-P), and a grounded conductor plate (GCP). The GCP was lifted gradually (blue arrow) (**A**) and settled in a position that caused an arcing (red arrow) by the NNP (**B**), where a dipolar electric field (DP-EF) was formed between the two plates to positively polarize the GCP. In this position, the pulsed arcing continuously occurs at an interval of 1 s. The arcing was preferentially directed to an insect that was located on the GCP (**C**).

2.3.2. Exposure of Insects to an Arc Discharge

Next, we introduced insects into an electric field in which pulsed arcing occurred continuously to examine whether the arcing was preferentially directed toward them (Figure 2). Small- and intermediate-sized insects were individually transferred onto the GCP of the charged instrument with an insect aspirator; large ones were first immobilized as described above. We examined whether preferential arcing was dependent on the body size of the insect. We used 20 insects from each species. We measured the weight of insects before and after they were subjected to arcing to estimate the loss of body water due to the arcing treatment.

2.4. Construction and Practical Application of the EIC and ADZ

2.4.1. Construction of the EIC and ADZ

Next, the practical application of each device was tested (Figure 3). The two devices were constructed on an identical framework, namely, the NIPs and GCPs or NNPs and GCPs were alternately arrayed in parallel at an interval of 5 mm in the EIC and ADZ, respectively. The NIPs and NNPs were linked to a continuous- and pulse-charge-type voltage generator, respectively. In both devices, the plates were fixed with two polypropylene props that were pierced into the holes on both ends of the plates, and the separation interval between the plates was created using polypropylene cylindrical spaces with a height of 5 mm.

2.4.2. Insect-Capturing Assay

An insect-capturing assay was conducted in a closed cabinet (2 m^3) placed in a greenhouse (Figure 4A). In this experiment, the EIC (30 × 30 cm^2) was furnished with a yellow board to attract phototactic insects to the vicinity of the device (Figure 4B). A yellow board was prepared by coloring a thick piece of paper with a watercolor paste (Turner Color Works Ltd., Osaka, Japan). Its Munsell hue/value/chroma index [41] was 7Y8.5/11 (yellow), which corresponded to the coloration of a commercially available yellow sticky trap (Horiver yellow trap; Arysta LifeScience Corp., Tokyo, Japan). The coloration of the yellow board was measured using an RGB-1002 color analyzer (Sato Shoji Inc., Kanagawa, Japan). Whiteflies were used as a model insect for phototactic insects. Two yellow-boarded EICs, two commercial yellow sticky traps of the same size as the EIC, and two potted tomato

(*Solanum lycopersicum* cv. Momotaro Fight) plants (1-month-old seedlings; 40 cm high from the pot bottom to the plant top) were placed on the concyclic points at regular intervals, and a vessel containing 20 whiteflies was placed at the central point of a circle. In this experiment, 24 and 48 h after the insects were released, we counted the number of test insects that had been captured by the EICs and sticky trap plates, the number of test insects that had reached the plant, and the number of test insects that remained in the vial or on the walls and ceiling of the cabinet. The experiments were conducted separately and repeated five times.

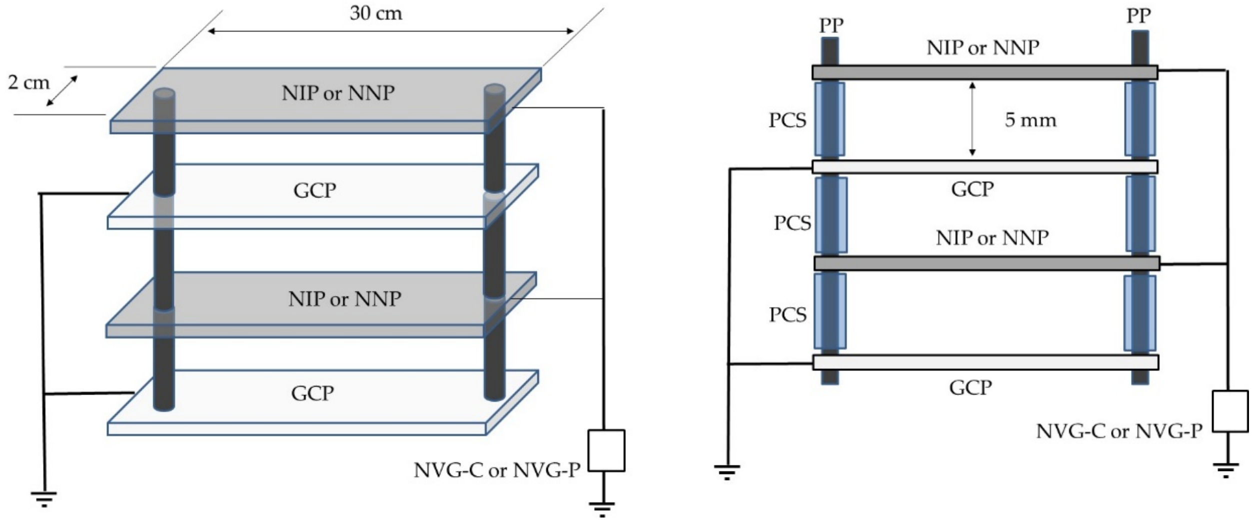

Figure 3. Schematic representation of an identical framework for an electrostatic insect catcher (EIC) and arc-discharge zapper (ADZ). The devices consisted of identical conductor (iron) plates, polypropylene props (PPs), polypropylene cylindrical spacers (PCSs), and a negative voltage generator. Negatively charged insulated conductor plates (NIPs) and grounded conductor plates (GCPs) or negatively charged non-insulated conductor plates (NNPs) and GCPs were arranged in parallel at an interval of 5 mm to fabricate the EIC and ADZ, respectively. The plates were fixed with the PCSs, which were poked into the holes on both sides of the plates, and the separation intervals between the plates were made by the PCSs that passed through the PPs. The EIC and ADZ were linked to the continuous-charge and pulse-charge types of negative voltage generators (NVG-C and NVC-P, respectively).

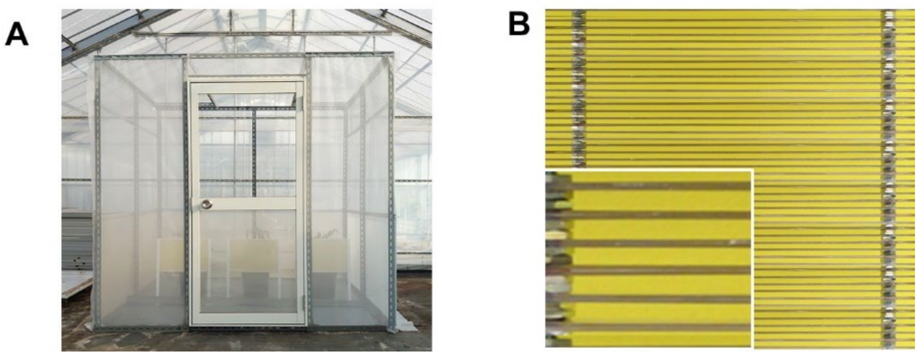

Figure 4. (**A**) A closed, small, cubic cabinet placed inside a greenhouse for conducting an insect-capturing assay. (**B**) An electrostatic insect catcher (EIC) furnished with a yellow board to attract phototactic insect pests. The insert in B shows an enlarged part of the EIC.

2.4.3. Arc-Discharge Exposure Assay

The ADZ was applied to kill adult houseflies that emerged from pupae in the soil bed of a greenhouse. In this test, we utilized the strong impact of the arc discharge to strike houseflies that climbed on to the apparatus. For this purpose, we set the plates of the ADZ vertically and placed them on a plastic grid (30 × 30 cm^2; 20 mm height) that consisted of multiple cells (Figure 5A). The cells provided a climbing path for the houseflies on the soil surface to the arcing site of the ADZ. In the first experiment, CO_2-anesthetized male and female houseflies were individually transferred to the bottom of the grating cells. The houseflies climbed along the wall of the cell and were subjected to the arc discharge when they reached the arcing zone, which forced them down to the bottom of the cell (Figure 5B). Due to their inherent habit of climbing upward [42], the flies continued to climb even after they were subjected to the arc discharge and knocked down to the bottom of the grating. We therefore counted the number of climbing trials until they died. In the second experiment, we transferred different numbers (25, 50, 75, and 100 adults) of anesthetized houseflies (without respect to their sex) to separate cells to create a situation in which multiple adult houseflies invaded successively. In the first round of experiments, we increased the numbers of adult houseflies stepwise from 25 to 75 in individual experiments, and the experiment was conducted once for each number of flies. In the second round, we used 100 and 110 adult houseflies and conducted the same experiment five times for each. At the end of the experiment (after 2 days), we counted the number of dead houseflies on the bottom of the cells.

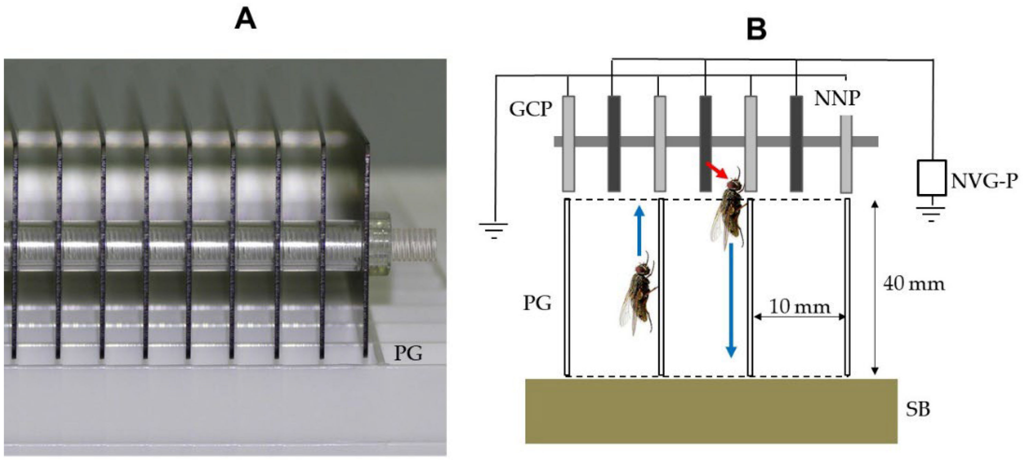

Figure 5. Photograph (**A**) and schematic representation (**B**) of an arc-discharge zapper (ADZ) placed on a plastic grating (PG). The ADZ, which consisted of negatively charged non-insulated conductor (iron) plates (NNPs) linked to a pulse-charge type voltage generator (NVG-P) and grounded conductor plates (GCPs), was placed on a plastic grating (40 mm height, 10 mm square cells). Houseflies anesthetized with CO_2 were transferred to the bottom of the separate cells of the PG placed on a soil bed (SB). After awaking from anesthesia, they climbed along the wall of the cell (blue arrow) and were subjected to an arc discharge (red arrow) from the NNP when they reached the arcing zone, then were knocked downward (blue arrow) by the strong impact of the arc discharge.

2.5. Statistical Analysis

All experiments were repeated five times, and all data are presented as means with standard deviations. The analyses were performed using the EZR software version 1.54 (Jichi Medical University, Saitama, Japan) to identify any significant differences among the results obtained under different test conditions, which are shown in the figure and table legends.

3. Results and Discussion

3.1. Construction of the EIC

3.1.1. Expansion of the Electric Field of the NIP by Increasing the Applied Voltage

The electric field of the NIP expanded as the voltage was increased; as described above, we measured the field area based on the wing erectness method (using whiteflies). Figure 6 shows the voltages required to connect the NIP and GCP with an electric field in the instruments where the intervals of the two plates were 5 to 10 mm. At a separation interval of 5 mm, the electrostatic force on the whitefly was initially detectable at around 0.5 kV, with the flies erecting their wings and seemingly bracing against the NIP attraction force. Video S1 shows this behavior. The longer separation intervals (6 and 7 mm) required higher voltages (–5 and –9.5 kV, respectively). At <8 mm, no whitefly displayed wing erectness with the application of the highest voltage (–10 kV), indicating that the electric field did not reach the GCP. Based on these results, we first settled the GCP at a position 5 mm from the NIP, at which point we were able to use a wider range of voltages (–0.5 to –10 kV). The use of a higher voltage reinforced the electric field intensity, and led to the exertion of a stronger force on the insects in the electric field.

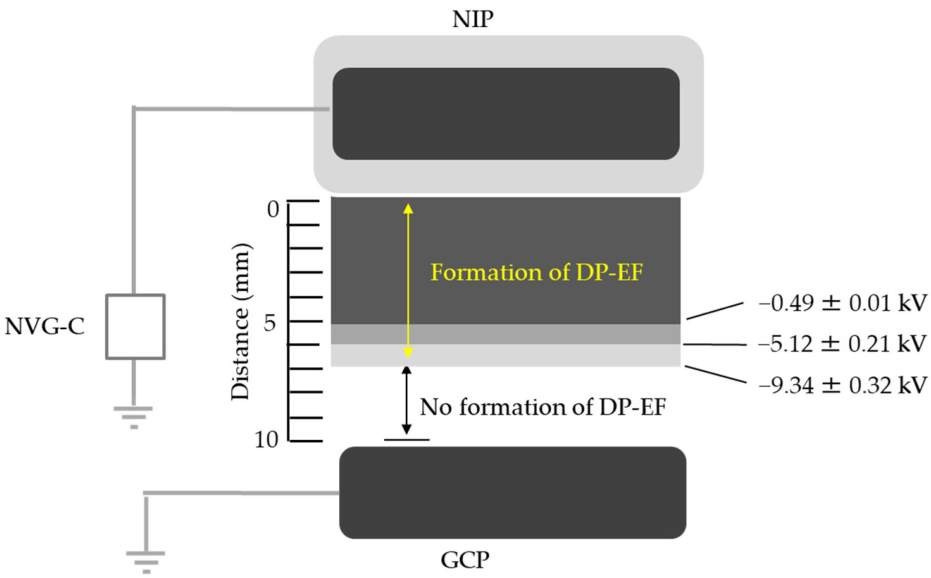

Figure 6. The voltages required to form a dipolar electric field (DP-EF) between a negatively charged insulated conductor (iron) plate (NIP) and a grounded conductor plate (GCP), which were spaced by different distances (5–10 mm). The NIP was linked to a negative voltage generator (continuous-charge type) (NVG-C) and charged with different voltages (–0.1 to –10 kV).

3.1.2. Insect-Capturing Ability

All test insects were transferred individually onto the GCP of the insect-capturing instrument that was negatively charged with different voltages (–0.1 to –10 kV). Table 1 shows the percentage of captured insects at each voltage. Higher voltages were required to capture larger insects. For example, for whiteflies (small insects) and vinegar flies (intermediate), charging at –1 and –4 kV, respectively, was sufficient to capture all insects. Videos S2A and S2B demonstrate the strong capture of an adult whitefly at –1 kV and a vinegar fly at –4 kV, respectively. At lower voltages, however, the attractive force was insufficient, and the insects ultimately escaped from the trap. All small and intermediate insects were captured at <–3.1 kV (Table 1).

Table 1. Percentage of insects captured by an experimental instrument consisting of a negatively charged insulated conductor (iron) plate (NIP) and a grounded non-insulated conductor plate (GCP) at a separation interval of 5 mm.

Test Insects *	Negative Voltage (–kV) Applied											
	0.4	0.6	0.8	1	1.2	1.6	2	3	4	6	8	10
WH	0	42.1 ± 5.3 a	100 a	100 a	100 a	100 a	100 a	100 a	100 a	100 a	100	100
WFT	0	0 b	0 b	0 b	36.8 ± 2.7 b	91.3 ± 2.2 b	100 a	100 a	100 a	100 a	100	100
TLM	0	0 b	0 b	0 b	48.6 ± 4.2 b	95.6 ± 3.2 b	100 a	100 a	100 a	100 a	100	100
SF	0	0 b	0 b	0 b	0 c	18.8 ± 2.2 c	48.3 ± 2.7 b	79.3 ± 4.9 b	100 a	100 a	100	100
VF	0	0 b	0 b	0 b	0 c	20.5 ± 5.1 c	54.6 ± 3.9 b	84.9 ± 2.8 b	100 a	100 a	100	100
GPA-w	0	0 b	0 b	0 b	0 c	0 d	68.7 ± 3.5 c	97.3 ± 4.2 c	100 a	100 a	100	100
HF-m	0	0 b	0 b	0 b	0 c	0 d	0 d	0 d	0 b	0 b	BF **	BF
GBF-m	0	0 b	0 b	0 b	0 c	0 d	0 d	0 d	0 b	0 b	BF	BF
HF-f	0	0 b	0 b	0 b	0 c	0 d	0 d	0 d	0 b	0 b	BF	BF
GBF-f	0	0 b	0 b	0 b	0 c	0 d	0 d	0 d	0 b	0 b	BF	BF

* Refer to Table 1 for the abbreviations of insect names. Insect species are ordered from top (smallest) to bottom (largest) according to their body sizes. ** bridge is formed by an inset body between the NIP and GCP. Twenty insects were used for each voltage and each species. The means ± standard deviations were calculated from five experimental replicates. The different letters (a–d) within a column indicate significant differences ($p < 0.05$) according to Tukey's test.

The attractive force of the instrument (5 mm interval) was sufficient to draw large insects (houseflies and greenbottle flies) to the NIP at >–8 kV. However, their capture was considered abnormal because a bridge was established between the opposite poles by the insect body, which was large enough to touch both poles (Figure 7A) (Video S3A). In this case, the flies formed a direct route for the electric current to flow between the opposite poles. The current flow erased the surface accumulation of negative charge (i.e., loss of attractive force) and eventually caused the insulating coating to break down.

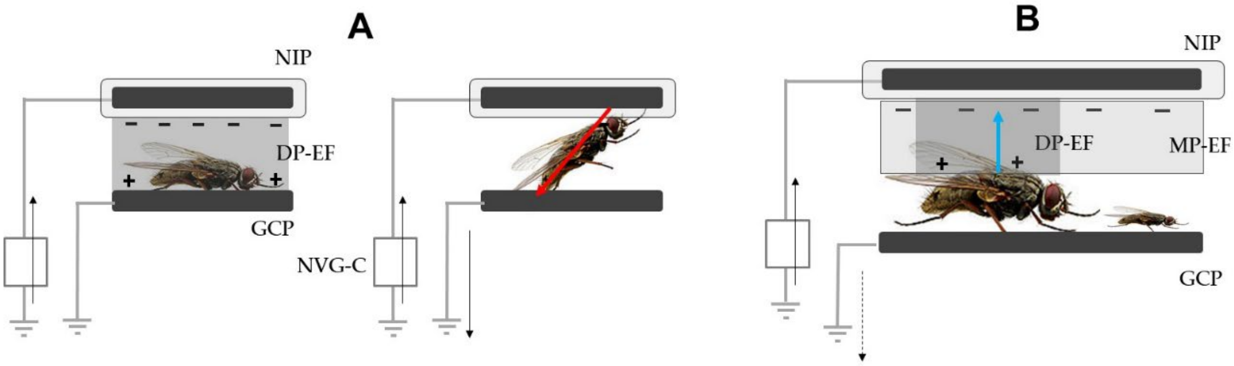

Figure 7. (**A**) Formation of an insect body bridge between the negatively charged insulated conductor plate (NIP), which was linked to a negative voltage generator (continuous-charge type) (NVG-C), and the grounded conductor plate (GCP). The electric current (red arrow) moved over a direct route (i.e., the insect body) between the two plates. (**B**) Formation of an insect-mediated opposite pole to the NIP. A large fly (housefly and greenbottle fly) on the GCP reached a monopolar electric field (MP-EF) to create a dipolar electric field (DP-EF) between the NIP and the fly. Eventually, the fly was positively electrified and drawn to the NIP (blue arrow). At this distance between the NIP and GCP, small insects did not reach the MP-EF and were therefore not drawn to the NIP. The solid black arrow represents the direction of movement of the negative charge (free electrons), and the dotted black arrow represents an insect-derived transient electric current caused by its positive electrification.

To solve this problem, it was essential to make the separation distance wider. A separation interval of 10 mm was wide enough to avoid this problem. At this distance, the NIP was not able to expand its monopolar electric field to the GCP even when the highest voltage (–10 kV) was applied; the expansion at –10 kV was approximately 7 mm (Figure 6). However, large flies (houseflies and greenbottle flies) reached the monopolar electric field (MP-EF) and formed a dipolar electric field between the NIP and themselves when they were located on the GCP (Figure 7B). In this situation, the flies were deprived of free electrons and became positively polarized, eventually being drawn to the NIP (Table 2). In both fly species, male flies were smaller than females, and therefore lower voltages (–8 kV) were sufficient to capture them, while a charge of –9 kV was necessary to capture female adults. Video S3B shows the successful capture of a female adult housefly at –9 kV.

Table 2. Capture of insects with different body sizes by an experimental instrument consisting of a negatively charged insulated conductor (iron) plate (NIP) and a grounded non-insulated conductor plate (GCP) at a separation interval of 10 mm.

Insects Used *	Negative Voltage (–kV) Applied						
	5	5.5	6	7	8	9	10
WH	0	0 a	0 a	0 a	0 a	0 a	0 a
WFT	0	0 a	0 a	0 a	0 a	0 a	0 a
TLM	0	0 a	0 a	0 a	0 a	0 a	0 a
SF	0	0 a	0 a	0 a	0 a	0 a	0 a
VF	0	0 a	0 a	0 a	0 a	0 a	0 a
GPA-w	0	0 a	0 a	0 a	0 a	0 a	0 a
HF-m	0	12.1 ± 0.5 b	78.6 ± 0.1 b	100 b	100 b	100 b	100 b
GBF-m	0	13.6 ± 0.2 b	82.3 ± 0.3 b	100 b	100 b	100 b	100 b
HF-f	0	0 a	22.2 ± 0.4 c	84.5 ± 0.6 c	100 b	100 b	100 b
GBF-f	0	0 a	24.6 ± 0.8 c	86.7 ± 0.8 c	100 b	100 b	100 b

* Refer to Table 1 for the abbreviations of insect names. Insect species are ordered from the top (smallest) to the bottom (largest) according to their body sizes. Twenty insects for each voltage and each species were used. The means ± standard deviations were calculated from five experimental replicates. The different letters (a–c) within a column indicate significant differences ($p < 0.05$) according to Tukey's test.

In addition, as shown in Table 2, not all insects in the small and medium-sized groups were captured at this separation distance because they did not reach the monopolar electric field of the NIP (Figure 7B). From these results, we concluded that it is impossible to capture all insects in the three groups using an instrument with a separation interval of either 5 or 10 mm.

3.2. Construction of the ADZ and Preferential Arcing for Insects

The NNP was able to generate pulsed arcings at an interval of 1 s toward the GCP when the separation interval between them was settled at 5 mm. In this experiment (described above), all male and female housefly and greenbottle fly adults were preferentially subjected to pulsed arcing after they were introduced to the electric field (Figure 8A). The impact produced by the arc discharge was so strong that the flies were rendered motionless by the first pulsed arcing (Video S4A). The arcing continued for a while and then stopped automatically. This automatic stoppage was due to a decline in body conductance caused by the loss of body water [43,44]. We confirmed that the insects that received continuous pulsed arcing had lost more than 50% of their body water. Small/intermediate insects did not receive preferential arcing, with arcing continuing between the two plates regardless of the presence of an insect on the G-MN (Figure 8B). Preferential arcing did not occur even when the distance between the two plates was shortened (4 and 3 mm). These results suggest that insect body size is of critical importance or receives a certain amount of electric charge. The capacitance is defined as the ability of the conductor to store or receive an electrical charge and depends on the shape and size of the conductor (i.e., larger conductors receive a larger electric charge) [45]. In our interpretation, it was essential for the conductor (the insect) to have a sufficient capacitance to receive the total electric charge released by the charged conductor (the NNP) through an arc discharge. Consequently, the capacitances of small/intermediate insects were too small to receive arcing. Accordingly, we conclude that the arc discharge method is suitable only to control houseflies.

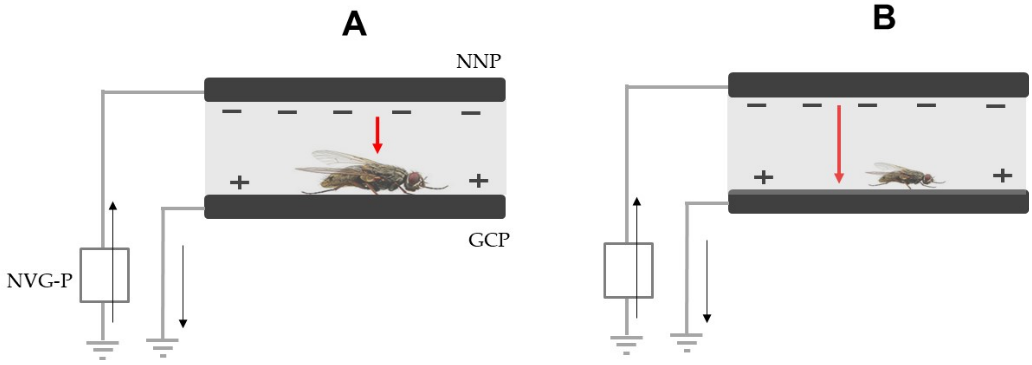

Figure 8. Schematic representation of preferential (**A**) and non-preferential (**B**) arcing to an insect in the electric field. The instrument consisted of a negatively charged non-insulated conductor plate (NNP), which was linked to a negative voltage generator (pulsed-charging type) (NVG-P), and a grounded conductor plate (GCP). (**A**) Larger insects were introduced into the electric field where a pulsed arc was generated and preferentially subjected to an arc discharge (red arrow) from the NNP. (**B**) No preferential arcing occurred to small insects, and the arcing occurred between the two plates as before. The black arrow indicates the movement of negative electricity.

3.3. Practical Application of the EIC and ADZ

Of the insects used in the present study, whiteflies and houseflies are the most intractable pests in our greenhouse for tomato cultivation [23,24], and therefore it was important to evaluate the feasibility of the new devices for these two insect pests. The EIC had the ability to capture insects that entered its electric field; however, it could not attract insects beyond a certain distance from the apparatus. This weakness was compensated for by adding a yellow-colored plate to the apparatus because many harmful flying insect pests, including whiteflies, winged aphids, leaf miners, thrips, and shore flies, are effectively attracted to yellow objects [46]. This was effective for luring distant whiteflies into the electric field of the device. The attraction-and-capture provided by the device was equivalent to a commercial yellow sticky trap (Figure 9), indicating the effectiveness of the EIC in greenhouse operations. Interestingly, whiteflies exhibited a stronger photoselectivity to the yellow-colored traps than the host tomato plant. These results strongly suggest that the EIC combined with a yellow board is useful as an on-site method to control flying phototactic insect pests in a greenhouse.

For practical use of the ADZ, we used the impact of the arc discharge to knock down adult houseflies that climbed onto the device. For this purpose, we set all of the plates vertically and placed them on a plastic grating (Figure 5A). The separate cells of the grating enabled adult houseflies on the soil surface to climb up to the arcing zone of the ADZ, as described above. As previously described, the flies repeatedly climbed up, were impacted by the arc, and eventually died. Both male and female houseflies were killed after three or four discharges (Figure 10) (Video S4B). These results indicate that the method was effective for killing adult houseflies of either sex that climbed onto the device from the soil surface.

According to our records over the past 3 years, in which flypapers (sticky paper ribbons) were suspended over the soil beds and the number of trapped houseflies were counted, their occurrence (during the 3-month summer season) was between 8 and 62 per m^2. However, this approach provided no information about how many houseflies escaped from the trap or, more importantly, how many houseflies emerged simultaneously from the soil bed. In the second experiment in a greenhouse, we directly applied adult houseflies to the ADZ to set up an acute situation in which adult houseflies (in this case, 25–110 adults) simultaneously emerged from underground pupae and successively invaded the ADZ. In the preliminary application of the 25–75 houseflies, all flies were detected as dead bodies on the bottom of the grating (Table 3). Moreover, in five repeated applications of 100 and

110 adult houseflies, we confirmed that the newly developed device was able to kill all houseflies even when 100 flies invaded successively (Table 3), whereas one or two flies escaped from the device in the case of 110 houseflies. These results indicate that if the number of synchronously emerging adult houseflies does not exceed 100, the ADZ would be able to effectively cope with successive invasions by multiple houseflies.

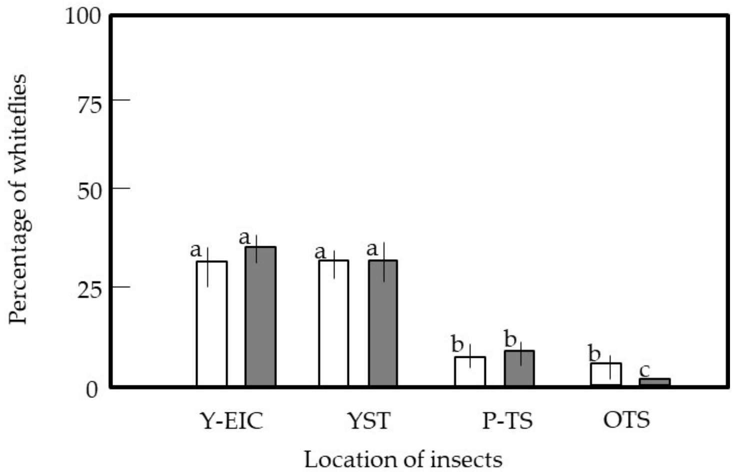

Figure 9. Assay of the preferential attraction of whiteflies to a yellow-colored electrostatic insect catcher (Y-EIC), a yellow sticky trap (YST), and a potted tomato seedling (P-TS), which were placed in concyclic positions at equal distances. A vessel containing test insects was placed at the central position of a circle. Adult whiteflies were used as test insects. In all experiments, the destinations of test insects were recorded 1 day (open) and 2 days (gray column) after their release. OTS represents other places, such as in the vial or on the floor, wall, and ceiling of the cabinet. Twenty insects were used in each experiment, and the means and standard deviations were calculated from five replicates of the experiments. The letters a–c in each vertical column indicate significant differences ($p < 0.05$) according to Tukey's test.

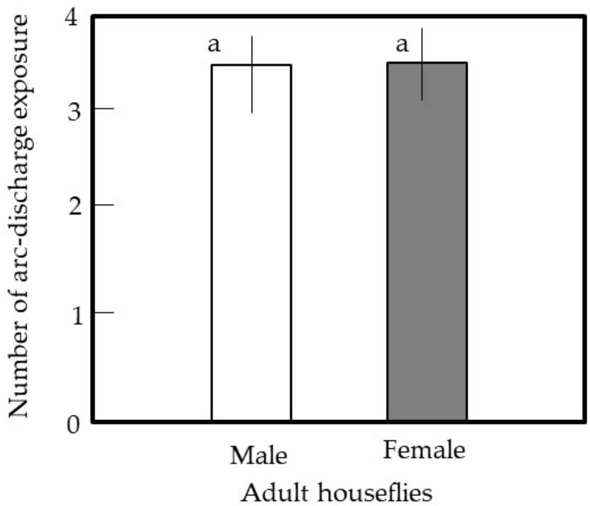

Figure 10. Number of arc-discharge exposures required to kill adult houseflies that climbed up to the arc discharge zapper (ADZ). The flies climbed along the wall of the cell of the grating placed beneath the ADZ and were subjected to the arc discharge when they reached the arcing zone of the device. They were knocked down to the bottom of the cell. The flies attempted several climbing trials and were exposed to repeated arc discharges until they died. Twenty insects were used in each experiment, and the means and standard deviations were calculated from five replicates of the experiments. The letter "a" in each vertical column indicates no significant difference ($p < 0.05$) according to Tukey's test.

Table 3. Evaluation of the capability of the arc discharge zapper (ADZ) used to control successive invasions of adult houseflies.

Number of Adult Houseflies Used [a]	Number of Dead Houseflies on the Bottom of the Grating	Number of Houseflies that Escaped from the ADZ
25	25	0
50	50	0
75	75	0
100	100	0
	100	0
	100	0
	100	0
	100	0
110	98	2
	100	0
	99	1
	99	1
	98	2

[a] Adult houseflies anesthetized by CO_2 were placed in separate cells of the grating. These flies climbed along the wall of the grating and reached the arcing zone of the ADZ, where they were subjected to arcing from the negatively charged non-insulated conductor plate (NNP), and then were knocked down to the bottom of the grating.

The two unique devices devised in this study (the ADZ and EIC) to manage greenhouse insect pests are both simple and easy to fabricate. The ADZ is slightly easier to fabricate and was operated safely using a pulse-charge-type voltage generator. However, its application is restricted to larger insect pests, such as houseflies. These pests are too large to pass through a conventional insect-proof net, but they are typically introduced to greenhouses as larvae in manure. Housefly management may therefore be a specific problem limited to greenhouses that utilize cattle manure. By contrast, the invasion of small flying insect pests that can pass through insect nets is common in ordinary open greenhouses. The EIC had a higher utility value for managing harmful insect pests, such as whiteflies, thrips, aphids, leaf miners, and shore flies, which are common pests. More importantly, its insect-trapping function was strengthened by adding a yellow-colored plate, which attracted insects that were some distance from the device. The EIC requires insulation of its charged metal plates; for this, we used a soft polyvinylchloride resin. Unfortunately, the coating had to be applied by a professional producer, and it will therefore be essential to prepare a substitutable coating method if the device is to be produced by greenhouse workers. Several commercially available electrostatic dissipative (ESD) materials covering the range of desired resistivities are potential candidates for insulating charged metal plates. The identification of a suitable ESD tape would make it possible to reconstruct the ADZ into an EIC merely by applying it to the metal plate for charging, because the devices share the same framework.

4. Conclusions

We constructed two electrostatic devices with a common framework to manage greenhouse insect pests. The key difference between the two devices was the presence or absence of an insulation coating on the metal plates used for charging. The charged insulated metal plates generated an electrostatic force to trap small flying insects, while the charged non-insulated metal plates generated an arc discharge to kill adult houseflies that emerged from underground pupae. Both devices are simple to fabricate and could be used as a new physical tool for physical pest management in greenhouse crop production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13010125/s1. Table S1: Average body sizes (from head to wing edge) of the adult insects tested, Video S1: Lifting of the wings of an adult whitefly placed on a grounded conductor (iron) plate (GCP) facing the negatively charged insulated conductor plate (NIP) of an insect-capturing instrument, Video S2: Capture of an adult whitefly (A) and vinegar fly (B) with a negatively charged insulated conductor plate (NIP) at –1 and –3 kV, respectively, Video S3: (A) Bridge formation between a negatively charged insulated conductor plate (NIP) and a grounded conductor plate (GCP) (5 mm interval) by an adult female housefly at a –8 kV-charge. (B) Capture of an adult female housefly with the NIP (–9 kV-charge), which was positioned 10 mm from the GCP, Video S4: (A) Arc-discharge to an adult female housefly located on a grounded conductor plate (GCP) facing a negatively charged non-insulated conductor plate (NNP). (B) The removal of a housefly from the bottom of the cylinder by the strong impact of an arc discharge

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