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Review

An Electrostatic Pest Exclusion Strategy for Greenhouse Tomato Cultivation

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Abstract: Electrostatic devices generating an electric field (EF) are promising tools for greenhouse tomato cultivation. In these devices, an EF is generated in the space surrounding an insulated conductor (IC) that is charged by a voltage generator. Thus, a physical force is exerted on any insect that enters the EF, as a negatively charged IC (NC-IC) pushes a negative charge (free electrons) out of the insect body. The insect is polarized positively to be attracted to the NC-IC, and a grounded metal net (G-MN) repels the insect. This dual function of the apparatus (insect capture and repulsion) is the core of the electrostatic pest-exclusion strategy. In this study, we applied various innovative EF-based devices to evaluate their efficacy in greenhouse tomato cultivation. Our objective was to determine the optimal apparatus for simple, inexpensive construction by greenhouse workers. The results of this study will contribute to the development of sustainable pest-management protocols in greenhouse horticulture.

Keywords: attractive force; electric field; electric field screen; leaf miner; phototactic insect; repulsive force; shore fly; thrips; whitefly

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1. Introduction

In horticulture, insecticide-free greenhouse crop cultivation is a non-chemical component of integrated pest management (IPM). This approach has been a major focus for achieving sustainable pest control because it reduces the occurrence of insecticide-resistant pests and addresses public pesticide concerns. The main obstacles to the practical implementation of non-chemical pest control systems are the application of individual methods to an integrated pest control system at scales larger than the test experiments, and under variable environmental conditions [1]. Physical techniques have potential as effective supplementary measures against an unlimited range of targets under diverse conditions. Electrostatic techniques are useful to generate physical barriers as the first step in a pest management strategy for prevention, avoidance, monitoring, and suppression of pest populations (the PAMS approach) [2].

Because electrostatic phenomena are less susceptible to biological and environmental influences, physical pest control measures based on electrostatics are promising under variable environmental conditions. For example, an electric field (EF) is defined as the space surrounding an electric charge within which a perceptible force can be exerted on another electric charge [3]. Thus, EF-based devices have been developed as a stable method for trapping or repelling insect pests. In these devices, the EF is generated in the space surrounding a conductor that is negatively charged [4,5]. To produce attractive or repulsive forces within the EF, the release (discharge) of a negative charge from the charged conductor must be suppressed by covering the conductor with an insulating material such as polyvinylchloride (PVC). An EF will also form in the space surrounding a positively charged insulated conductor. Pairing oppositely charged insulated conductors at a definite interval forms a double-charged dipolar electric field (DDEF) [5]. A single-charged dipolar electric field (SDEF) is formed by placing a negatively charged insulated conductor (NC-IC) and a grounded metal net (G-MN) within the EF, facing each other [5]. The strength of the force thus generated is determined according to the strength or intensity of the EF, which is optimized by controlling the voltage applied to the insulated conductor and the distances between the charged insulated conductor and the G-MN, and between the oppositely charged paired insulated conductors (pole distance). In the SDEF and DDEF, the generated force is sufficiently strong that insects that enter the EF cannot escape the trap. In this study, we examined the efficacy of various apparatuses that produce SDEF and DDEF for EF-based pest control by using video recordings. These apparatuses have simple structures and are easily constructed by using inexpensive common materials and a voltage generator [5]. Our objective was to provide basic data for the application and development of electrostatic techniques for pest control.

Greenhouse tomatoes have several insect pests including the whitefly (*Bemisia tabaci* [Gennadius] [Hemiptera: Aleyrodidae]) [6–10], green peach aphid (*Myzus persicae* [Sulzer] [Hemiptera: Aphididae]) [6,7], western flower thrips (*Frankliniella occidentalis* [Pergande] [Thysanoptera: Thripidae]) [6,7,10], tomato leaf miner *(Liriomyza sativae* Blanchard [Diptera: Agromyzidae]) [8,10,11], and shore fly (*Scatella stagnalis* [Fallén] [Diptera: Ephydridae]) [6,7]. In this study, we evaluated the performance of various electrostatic pest control devices by using some of these pests. The results of this study will contribute to the development of feasibly EF-based pest control apparatuses for greenhouses.

2. SDEF-Based Capture-and-Kill Insect Trap

2.1. Fabrication of the Device

The first step in EF production is to charge an insulated conductor by using a voltage generator. In this study, we used a voltage generator powered by a rechargeable lithium storage battery to enhance an initial voltage (12 V) to a desired voltage within the range 1–20 kV by using an integrated Cockcroft circuit [12] and an integrated transformer. Negative and positive voltage generators were used to charge an insulated conductor negatively and positively, respectively (Figure S1) [5]. Thus, the voltage-enhanced negative voltage generator collects negative electricity from a ground and supplies it to a conductor linked to the voltage generator (Figure S1A). Negative charge accumulates on the surface of the conductor; an insulating PVC tube with a resistivity of 10^9 Ωcm prevents the conductor from releasing surface charge (i.e., discharge). The surface charge of the conductor polarizes the insulating cover dielectrically: negatively on the outer surface and positively on the inner surface [13]. Finally, a negative surface charge on the insulated conductor generates an EF in the space surrounding it (Figure S1B). By contrast, a positive voltage generator pushes free electrons from the linked insulated conductor to a ground, positively charging the outer surface of the conductor (Figure S1C), which in turn positively charges the insulating coating through dielectric polarization (Figure S1D) [13]. Thus, negative and positive charges on the surface of an insulating coating each produce an EF in their surrounding space.

When a grounded non-insulated conductor is placed within an EF produced by the charged insulated conductor, free electrons in the grounded conductor are pushed to the ground by the negatively charged insulator surface. As a result, the grounded conductor facing the charged insulated conductor becomes positively charged through electrostatic induction [14]. Opposite charges on these two conductors form dipoles in the original EF to produce the SDEF (Figure 1A). In this study, the SDEF was produced by opposing a charged insulated iron wire and a stainless-steel G-MN consisting of 1.5 mm mesh (Figure 1A) or a charged insulated (soft PVC-membrane-coated) iron plate to a grounded non-insulated iron plate (Figure 1B).

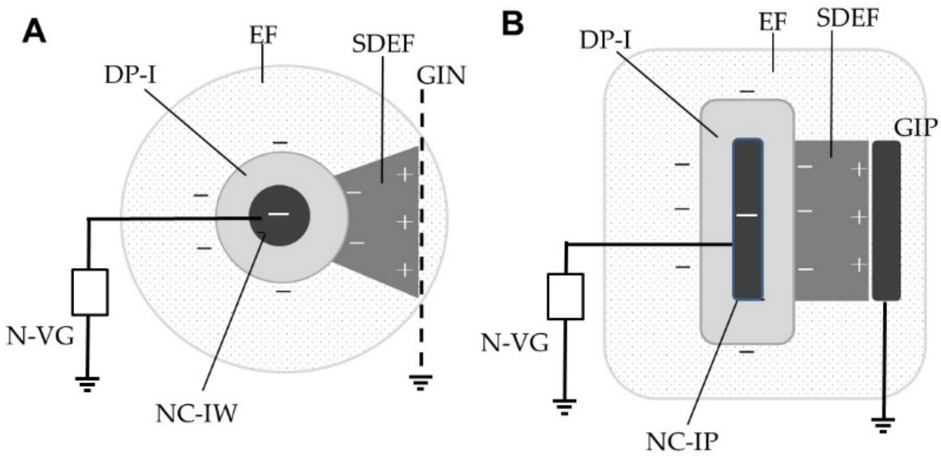

Figure 1. Single-charged dipolar electric field (SDEF) produced within an EF produced by a negatively charged insulated conductor (NC-IC) by opposing a charged insulated iron wire to a grounded metal net (**A**) or a charged insulated iron plate to a grounded non-insulated iron plate (**B**). N-VG, negative voltage generator; DP-I, dielectrically polarized insulator with negative charge on its surface; EF, electric field; NC-IW, negatively charged iron wire; NC-IP, negatively charged iron plate; GIN, grounded iron net; GIP, grounded iron non-insulated plate [5].

2.2. Insect Capture through Discharge-Mediated Positive Electrification

In the SDEF, the negative charge of the NC-IC has a repulsive force to an insect entering the EF and pushes free electrons out of the insect body to the ground (Figure 2A), positively electrifying the insect such that it is attracted to the NC-IC (Figure 2B) [15,16]. During this process, free electrons are released from the insect body due to the conductivity of its outer protective cuticle [17–21]. As an example, Video S1 shows four adult insects (whitefly, green peach aphid, western flower thrips and tomato leaf miner fly) being blown into the space between the G-MN and the NC-IC, which consists of insulated iron wire, followed by its successful attraction to the NC-IC.

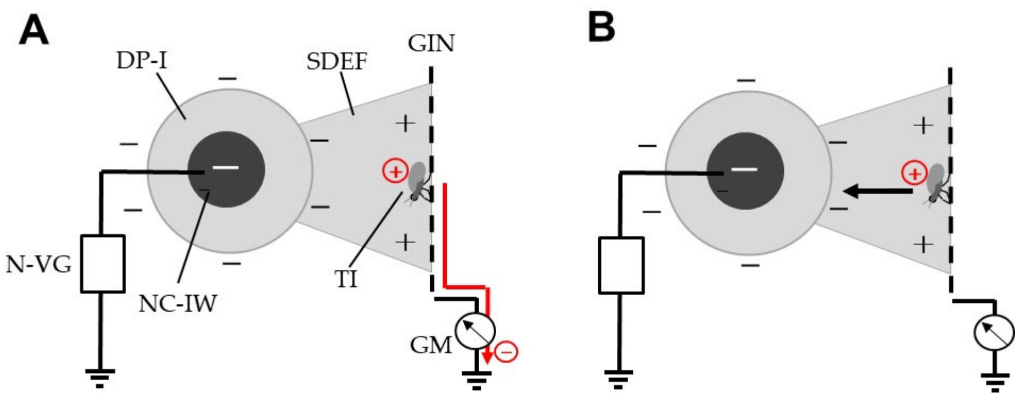

Figure 2. Schematic representation of insect capture showing discharge-mediated positive electrification of an insect in an SDEF. The SDEF was produced within the EF of an NC-IC. Free electrons were ejected out of the insect body, producing positive electrification (**A**), and the positively electrified insect was attracted to the NC-IC (**B**). Red arrow indicates the direction of free electron movement. Black arrow indicates the direction of the force attracting the positively electrified insect to the negatively charged insulated conductor. N-VG, negative voltage generator; DP-I, dielectrically polarized insulator with negative charge on its surface; NC-IW, negatively charged iron wire; GIN, grounded iron net; GM, galvanometer; TI, test insect [5].

The force required to attract an insect to the NC-IC is directly proportional to the increase in the voltage applied to the insulated conductor. More importantly, free electrons that are pushed out of the insect body are recorded as a transient electric current by a galvanometer integrated into the grounded line (Figure 2). Using 15 insect species (8 orders, 15 families, 15 genera; body length, 0.8–5.1 mm), we examined the voltages showing a 100% capture rate for each test insect (Figure 3A) [22]. The test insects were individually transferred onto the EF-side surface of the G-MN by using an insect aspirator to examine the attraction of the insect to the NC-IC. We detected a linear correlation between body size and the voltage applied to the insulated conductor, indicating that higher voltages were required to capture larger insects. The relationship between insect body size and the electric current released from the insect upon its attraction to the NC-IC is shown in Figure 3B. In this experiment, the insulated conductor was charged at −13.1 kV to obtain a 100% capture rate for all tested insect species. The results indicated that larger insects released larger electric currents upon attraction to the NC-IC.

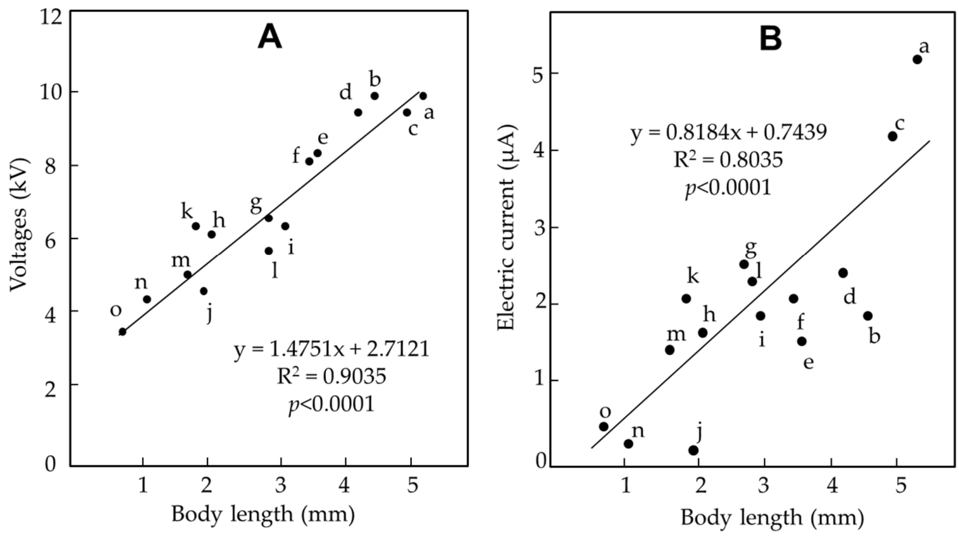

Figure 3. Relationships between insect body size and minimum voltage for 100% insect capture (**A**) and insect body size and the magnitude of the insect electric current at −13.1 kV (**B**). a, German cockroach; b, rice weevil; c, green rice leaf hopper; d, greenhouse shore fly; e, adzuki bean weevil; f, red flour beetle; g, Asian tiger mosquito; h, green peach aphid; i, common clothes moth; j, bathroom fly; k, western flower thrip; l, oriental termite; m, tomato leaf miner fly; n, book louse; o, whitefly [22].

The force generated in the EF is fundamentally influenced by the applied voltage and pole distance, with longer distances requiring higher voltages. Table 1 shows the voltages required to capture all test insects for a range of distances between the NC-IC and G-MN.

Table 1. Voltage (−kV) required to capture all test insect pests at different pole distances in the single-charged dipolar electric field (SDEF).

Insect Pests Tested	Pole Distance (mm) [a]		
	5	7	10
Whiteflies	2.7	4.2	6.2
Green peach aphids	3.2	4.5	6.5
Western flower thrips	4.2	6.3	7.3
Tomato leaf miner flies	3.6	5.1	6.2
Shore flies	4.8	5.9	7.5

[a] Distance between the charged insulated conductor wire and grounded metal net.

2.3. Insect Death Caused by the Release of Free Electrons during Continuous Capture by the NC-IC

The field strength of the SDEF is determined by the applied voltage and pole distance. Uneven pole distance can occur as a structural fault in the field produced by the NC-IC (insulated iron wire) and G-MN (Figure 1A). By contrast, the dipolar field produced by a pair of identical iron plates has an even distance along the entire face of the plate pair (Figure 1B), such that current generation from the insect can be examined without positional influence. By using this apparatus and the adult housefly *Musca domestica* (Linnaeus) (Diptera: Muscidae), which is sufficiently large to generate significant electric current, we traced current generation by the housefly throughout the capture process [23,24], from its attraction to the NC-IC (Figure 4A) to its confinement to the charged plate (Figure 4B). Figure 4C shows a typical profile of the electric current generated by the adult housefly. The total amount of electric current generated by the housefly is a crucial factor in its survival.

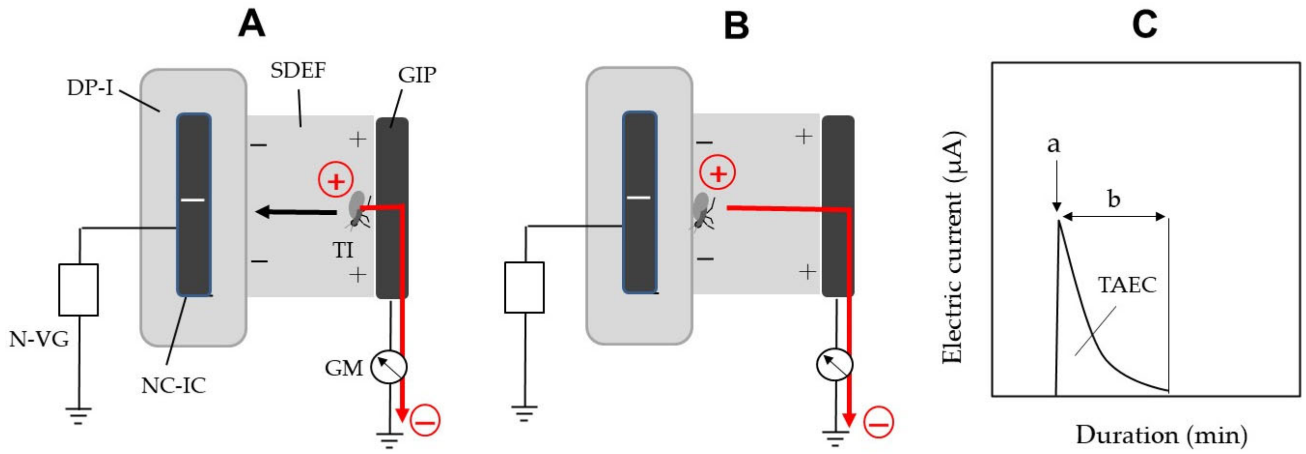

Figure 4. (**A**,**B**) Schematic representation of electric current generation by an insect upon its attraction to an insulated iron plate (NC-IC) (**A**) and during subsequent confinement to the charged plate (**B**). Red arrow indicates the direction of movement of free electrons pushed out of the insect body by the NC-IC. Black arrow indicates the direction of the attractive force drawing the positively electrified insect to the negatively charged insulated conductor. (**C**) Typical profile of electric current generated by an insect placed on the grounded iron plate. Arrows 'a' and 'b' indicate electric current produced by the insect upon its attraction to the negatively charged insulated iron plate and during subsequent confinement to the charged plate, respectively. The total amount of electricity released from the fly was calculated as the total amount of electric current (TAEC) (μA min) generated by the fly, according to the area bounded by the x-axis and the plotted curve of generated current. Abbreviations are provided in Figure 1.

In this experiment, all flies that were transferred to the grounded plate were captured by the NC-IC at <−8 kV, such that no flies escaped from the trap. An example of current discharge for a range of applied voltages (−8 to −15 kV) is shown in Figure 5. In this experiment, we examined changes in the magnitude of electric current and duration of current generation among the different voltages. Higher voltages produced a large initial current peak with a short duration. At higher voltages 14 to −15 kV), the flies died before current generation ended; we calculated the lethal amount of electric current (AECD) as 120 μA min for adult houseflies, with little variation among individual houseflies (Figure 5A–C). At lower voltages, current generation ended before the AECD was reached, and the flies remained alive for 2–6 h during the confined stage (Figure 5D–F). We released the flies from the trap by switching off the voltage generator before they died, and then examined the degree of damage to the flies, which was sufficient to kill all flies within 3 days after their release from the trap.

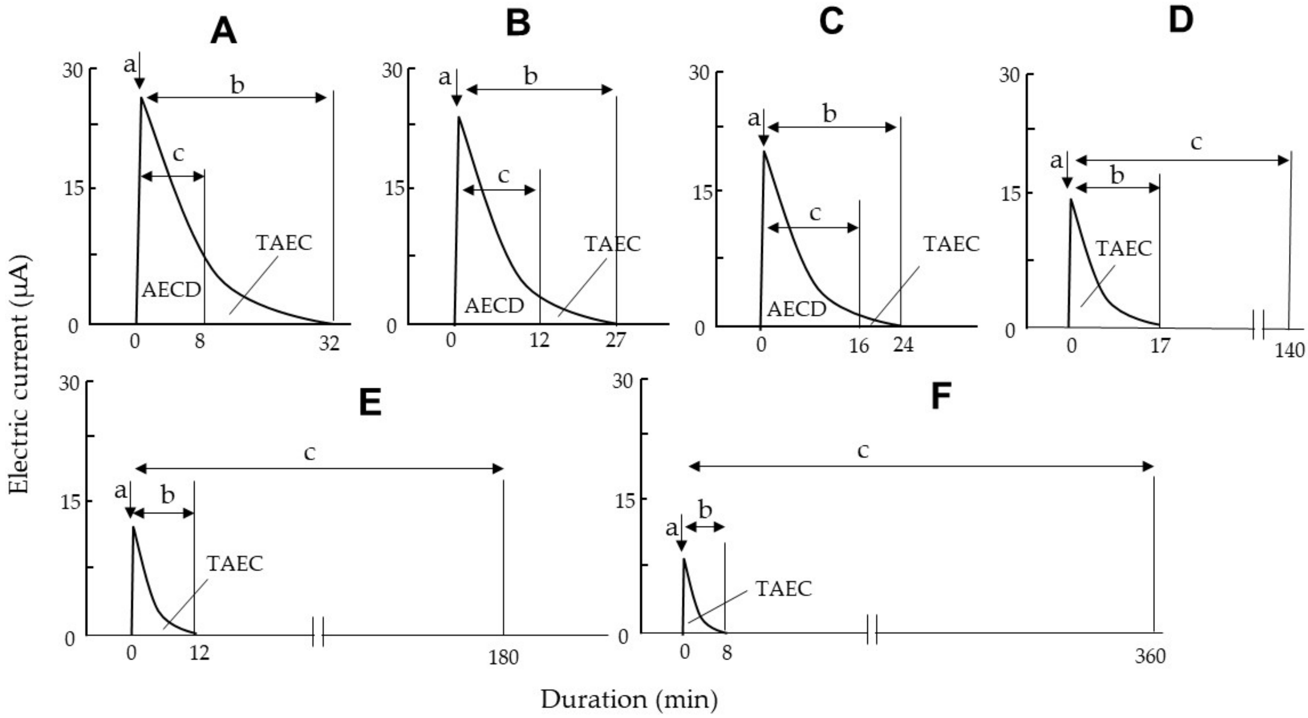

Figure 5. Typical profiles of electric current generated by an adult housefly placed on a grounded iron plate in a negatively charged insulated conductor (an insulated iron plate, NC-IP) with voltages of −15 (**A**), −14.5 (**B**), −14 (**C**),−12 (**D**), −10 (**E**), and −8 kV (**F**). Arrows 'a' and 'b' indicate the electric current produced by the fly upon attraction to the NC-IP and the subsequent electric current generated by the captured fly, respectively. The total amount of electricity released from the captured fly was determined as the total amount of electric current (TAEC; μA min) generated by the fly, calculated as the area bounded by the x-axis and the profile curve of current generation. Arrow 'c' indicates the time until death of the captured fly. The total amount of electric current (AECD) until fly death was also calculated [24].

Thus, discharge-mediated positive electrification effectively trapped insects within the SDEF and killed them through the loss of electricity from the insect body. These results demonstrate that the SDEF-generating trap-and-kill device can be used as an insect trap for physical pest control. Kakutani et al. [22] reported that all insects of 15 species tested were successfully killed during capture by the same apparatus. The target pests for greenhouse tomatoes mainly include whitefly, thrips, winged and wingless aphids, leaf miners, and shore flies. These insects can pass through a conventional, woven, insect-proof net with a mesh size of approximately 1.5 mm. The application of the SDEF apparatus described in this section can kill insects at low applied voltages (−1 to −4 kV) and within a short period of time (1–2 h) [24]. These results strongly support the use of this apparatus for non-chemical greenhouse pest control.

2.4. Fabrication of an Electrostatic Soil Cover (ESC) to Trap Emerging Adult Leaf Miners

The first SDEF-producing device applied for pest control was an ESC designed to trap adult tomato leaf miners emerging from underground pupae [11]. Leaf miner larvae hatch from eggs deposited on the leaf surface, where they eat leaf tissues, and then fall to the ground and crawl under the soil to pupate; the adult flies emerge and oviposit eggs on a host plant. This life cycle allows persistent infestation of greenhouse tomatoes [25]. The ESC was developed to cover soil beds in a greenhouse; its structure (Figure 6A) consists of two sets of iron rods welded to an iron frame. The first set is coated with a PVC membrane and linked to a voltage generator to supply a negative charge to the iron rods, whereas the second remains uninsulated and is linked to a ground line. Each set of iron rods is offset in a zigzag pattern to form the SDEF between the iron rods (Figure 6B). The ESC was placed on a soil bed to capture adult leaf miners at a voltage of −4 kV as they emerged from the soil surface and jumped into the space of the ESC [11]; the successful operation of the ESC is shown in Video S2.

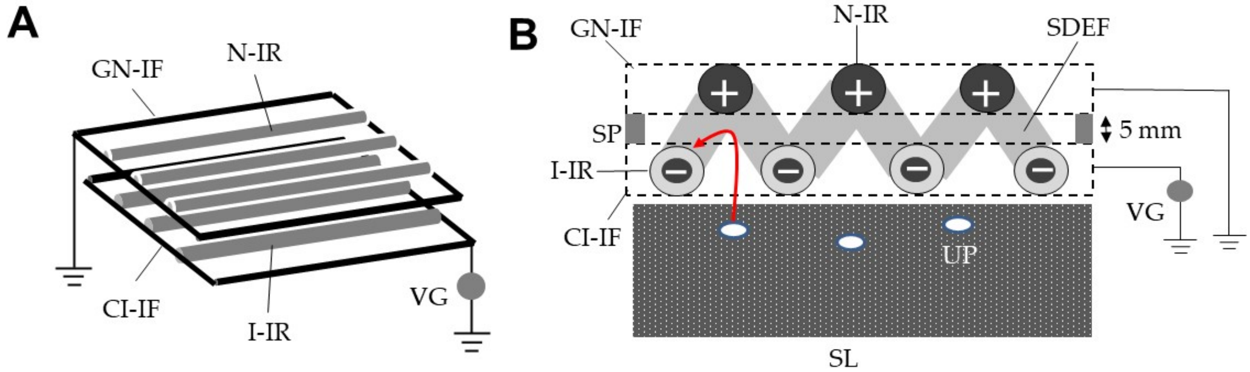

Figure 6. Diagram of an electrostatic covering (EC) to capture adult tomato leaf miner flies emerging from underground pupae (**A**) and an SDEF formed between negatively charged, insulated iron rods and grounded, non-insulated iron rods (cross-sectional view) (**B**). Red arrow indicates the path of a leaf miner that emerged from a pupa in a soil. GN-IF, grounded non-insulated iron frame; CI-IF, charged, insulated iron frame; N-IR, non-insulated iron rod; I-IR, insulated iron rod; VG, voltage generator; SDEF, single-charged dipolar electric field; SP, spacer, UP, underground pupa; SL, soil. [11].

3. Single-Charged Dipolar Electric Field Screen (SD Screen)

3.1. Avoidance of the SDEF by Insects

In a previous study, we examined the ability of an SDEF-producing apparatus to capture whiteflies [26]. Eventually, whiteflies that were placed on the EF-side surface of the G-MN were strongly attracted to the NC-IC, which consisted of an insulated iron wire (Figure 7A), whereas those placed on the outside surface of the net inserted their antennae in the SDEF and avoided entering it (Figure 7B).

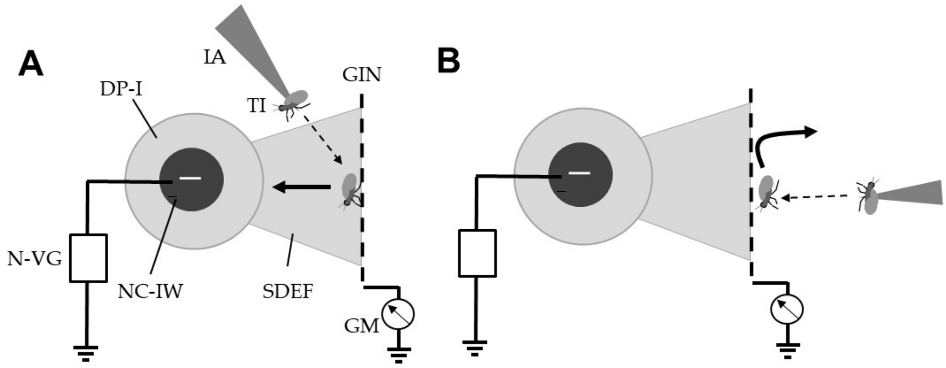

Figure 7. Schematic representation of insect capture (**A**) and repulsion (**B**) after insect placement on the electric field-side and outside surface of the grounded metal net, respectively. Solid straight and curved arrows indicate the paths of an insect transferred along the dotted line from an insect aspirator (IA). Abbreviations are provided in Figure 2.

Matsuda et al. [27] detected this peculiar action in a total of 13 orders, 45 families, and 62 genera of the arthropods, which was considered the result of inherently hesitant behavior. In the present study, we attempted to clarify the mechanism through which insects avoid an SDEF. Newland et al. [28] reported that adult cockroaches were suitable for examining antennae responses to a monopolar EF. Therefore, we used the Turkestan cockroach *Shelfordella lateralis* Walker (Blattodea: Blattidae) as a model insect [29].

In this experiment, the SDEF was formed by arranging the NC-IC (insulated iron plate) and G-MN in parallel at an interval of 10 mm (SDEF-producer, SDEFP) (Figure 8A), and a square surrounded by four SDEFPs was used to examine insect avoidance behavior (Figure 8B). The electric current generated by antenna insertion into the EF was recorded by a galvanometer integrated into the ground line (Figure 8C), and the distance of antenna insertion into the EF was measured from images obtained from a video recording (Figure 8D).

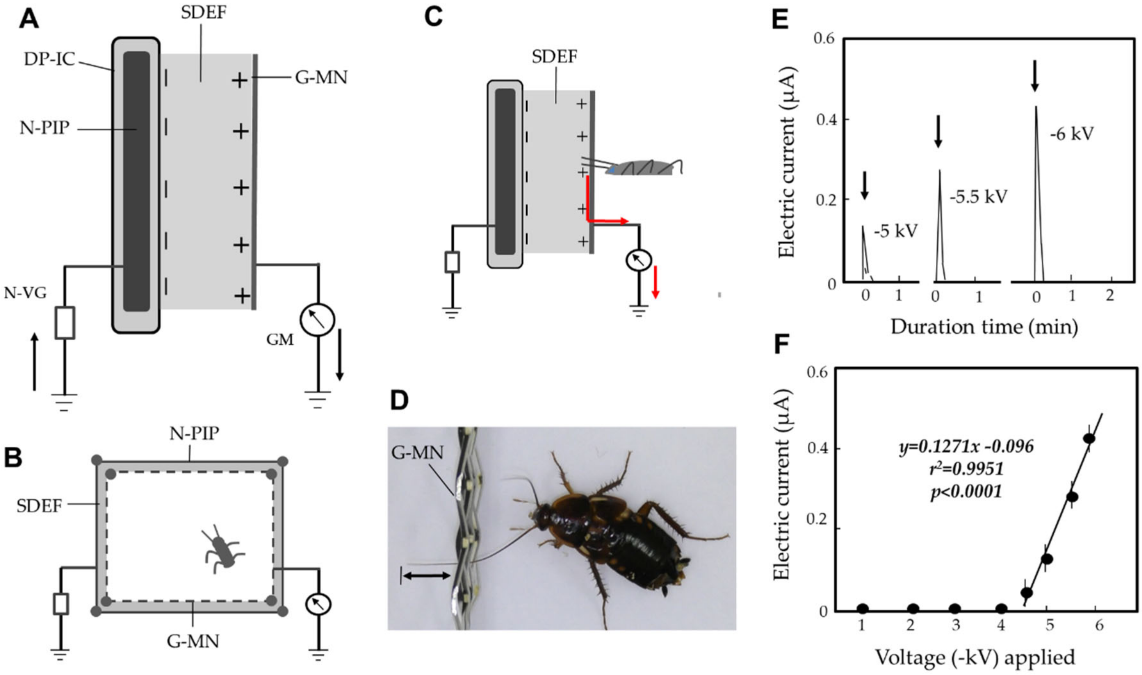

Figure 8. (**A**) Schematic representation of an SDEF producer (SDEFP) in cross-sectional view. (**B**) A square surrounded by four SDEFPs was used to examine insect avoidance behavior (bird's-eye view). (**C**) Flow of a transient electric current (red arrow) from an insect that inserted its antennae into the EF. (**D**) Insertion of the antennae by cockroaches into the EF of the SDEFP charged at a voltage of −4.5 kV. Arrow indicates the distance of antenna insertion from the G-MN (stainless steel). (**E**) Profiles of transient electric currents from discharges of adult Turkestan cockroaches that inserted their antennae into the EF of an SDEFP negatively charged with different voltages. (**F**) Relationship between the applied voltage and magnitude of the transient electric current. Means and standard deviations were calculated from five repetitions of the experiments. DP-IC, dielectrically polarized insulator coating with negative charge on outer surface; N-PIP, negatively charged PVC-insulated iron plate; N-VG, negative voltage generator; SDEF, single-charged dipolar electric field; G-MN, grounded metal (stainless steel) net; GM, galvanometer [29].

We determined the magnitude of the transient electric current produced upon antenna insertion into the SDEF, which was negatively charged at a range of voltages. At −5 to −6 kV, a transient electric current was generated as soon the antennae were inserted 1–2 mm inside the SDEF; its magnitude increased linearly with the applied voltage (Figure 8E,F). The current flow from the insect to the ground was essential for positive polarization of the insect, i.e., for it to be subjected to the attractive force of the NC-IC. We concluded that higher voltages pushed more negative electrons out of the insect antenna, increasing the positive charge on the insects and their attraction to the oppositely charged insulated plate [29].

A schematic of the events leading to insect avoidance of the SDEF is shown in Figure 9. The initial event was the insertion of the antennae into the space (Figure 9A1)). Then, a discharge from the insect indicated positive electrification of its body. The 1.5 cm G-MN mesh was narrow, such that one or both antennae inevitably touched the G-MN upon insertion; free electrons in the touched region were pushed out toward the ground via the G-MN (Figure 9A2). The tip of the antenna was positively charged and then attracted to the opposing charge of the N-PIP (Figure 9A3). As shown in Video S3, the insect pulled its antennae back reflexively and moved backward (Figure 9A4). It is likely that the positively polarized antennae attracted free electrons from the air [30] to restore the original neutral state after the antennae were withdrawn from the SDEF (Figure 9A4).

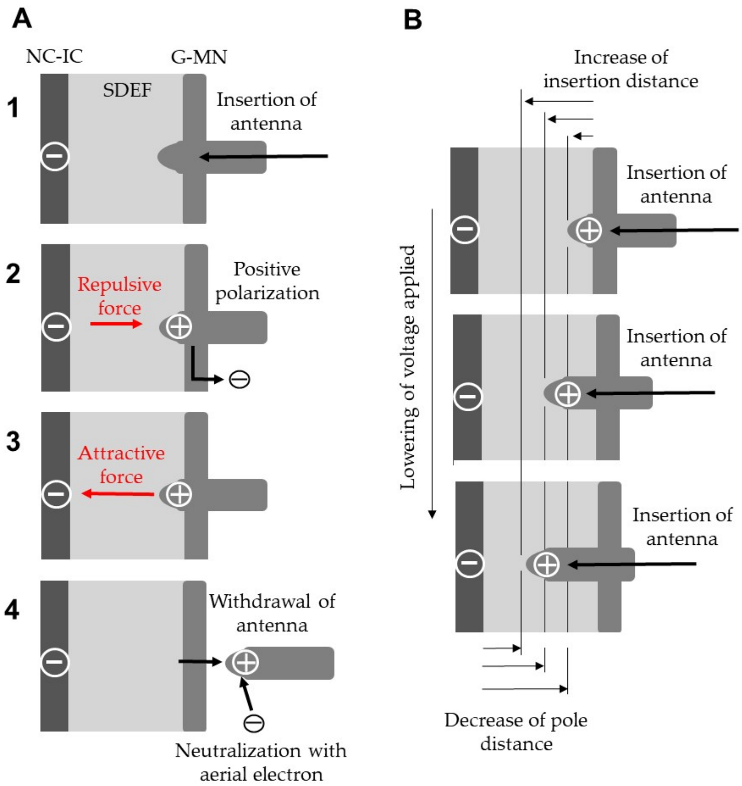

Figure 9. (**A**) Schematic representation of the electrostatic and biological events causing an insect to avoid entering an SDEF. (**B**) Relationship between applied voltage, antennae insertion distance within the SDEF, and pole distance (interval between the NC-IC and the tip of the antenna touching the G-MN) [29].

The voltage applied to the apparatus influenced the effect on insect antennae inserted into the SDEF; antennae that touched the G-MN were positively polarized, temporarily opposing the charge of the N-PIP (Figure 9B). Lowering the voltage applied to the N-PIP reduced the potential difference between the poles (charged plate and antenna tip), which reduced the range of repulsive force from the NC-IC, allowing deeper insertion of the antennae. When the tip of an antenna reached a point with sufficient field intensity, the antenna was subjected to an attractive force from the NC-IC, causing the insect to withdraw its antennae reflexively (Figure 9B). These findings support our hypothesis that the cockroach perceived an attractive force applied to its antennae through electron removal as they were inserted into the SDEF.

3.2. Fabrication of the SD Screen and Practical Application in Greenhouse Pest Control

Based on the avoidance of the SDEF by a wide range of insects, we developed a new EF-based apparatus to repel insect pests: the SD screen (Figure 10A,B) [15]. This device was designed to be installed on the lateral windows of a greenhouse (Figure 10C) [6]. In our experiments, eight SD screens were linked to a negative voltage generator operated by a solar panel and storage battery (Figure 10D).

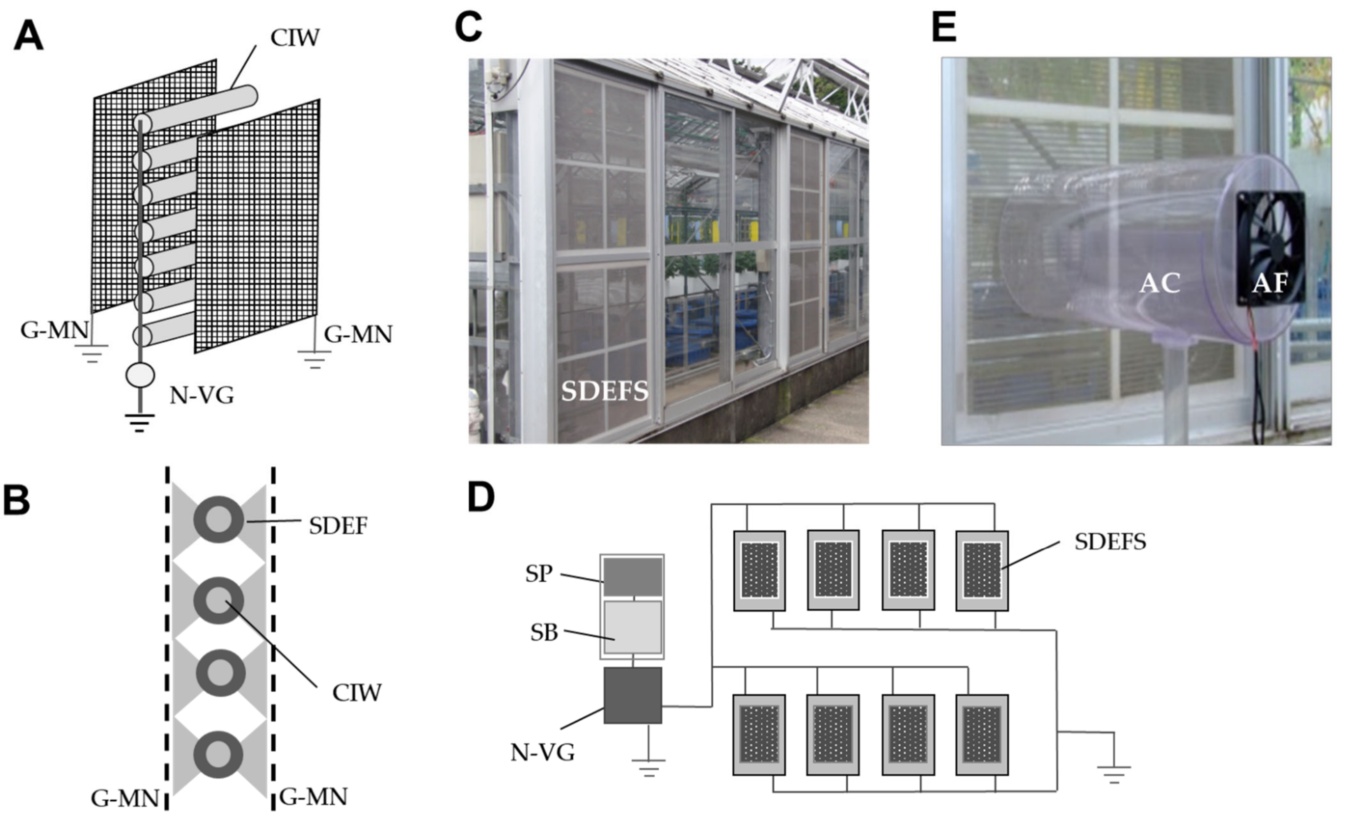

Figure 10. (**A**,**B**) Structure of a single-charged dipolar electric field screen (SD screen) (**A**) and its cross-sectional view (**B**). (**C**) SD screens installed on the lateral windows of a greenhouse. (**D**) An electric circuit to link the EF screens to a voltage generator operated by a solar panel and storage battery. (**E**) Acrylic cylinder with an axis fan for observing the behavior of insects reaching the net of the SD screen. G-MN, grounded metal net; CIW, charged insulated iron wire; N-VG, negative voltage generator; SD-EFS, single-charged dipolar electric field screen; SP, solar panel; SB, storage battery; AC, acrylic cylinder; AF, axis fan.

Most serious greenhouse tomato pests can pass through a conventional insect-proof net. Some such pests, including aphids, thrips, and whiteflies transmit viral pathogens such as the cucumber mosaic virus [31], the tomato spotted wilt tospovirus [32,33], and the tomato yellow leaf curl virus [34,35]; shore flies transfer rhizosphere fungal pathogens such as *Verticillium dahliae* and *Fusarium oxysporum* f. sp. *radicis-lycopersici* [36,37]. Therefore, we examined the functionality of greenhouse-installed SD screens in repelling these pests.

To test insect avoidance, we designed a method to trace the behavior of insects that reached a G-MN with a mesh size of 1.5 mm, which is similar to that of a conventional insect net, within the SD screen. An electric fan was installed at one end of a transparent acrylic cylinder (length, 40 cm; diameter, 30 cm); the opposite end was placed against the screen net (Figure 10E). Adult test insects (whiteflies, thrips, winged aphids, and shore flies) were released individually into the cylinder as the fan produced wind speeds varying from 0.5 to 5 m/s toward the screen. Individual release of the insects was necessary because all insects remained motionless on the cylinder wall at wind speeds of >0.5 m/s. The SD screen captured all insects at a voltage of −4.2 kV (Figure 11). Three insect behaviors were recorded in these experiments: passing through the screen, leaving the net without entering the screen, and being drawn inside the screen and captured by the NC-IC (insulated iron wire).

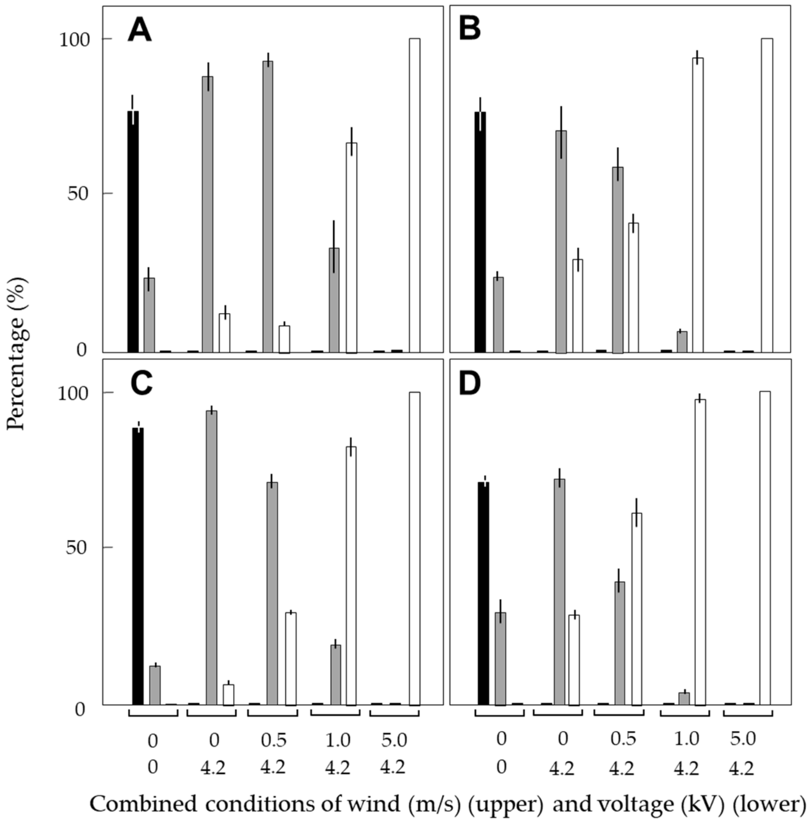

Figure 11. Behavior of adults of shore flies (**A**), western flower thrips (**B**), green peach aphids (**C**), and whiteflies (**D**) reaching the screen net under different wind speed and voltage conditions. Black, gray, and white columns represent insects passing through the screen, removed without entering the screen, and drawn to the NC-IC, respectively. We used 20 insects for each voltage. Data are means and standard deviations of three replications [6].

The first experiment was conducted under windless conditions. When the screen was not charged, insects rested or walked on the net for 2–5 s and then passed through the screen. By contrast, when the screen was charged, insects on the net inserted their antennae into the screen and then flew away without entering. These results indicate that the insects sensed the SDEF by using their antennae and avoided entry. The strong attraction of the NC-IC drew some insects inside the screen after they probed it with their antennae. This compulsory attraction was more frequent when the insects were subjected to wind (<0.5 m/s). Importantly, the screen captured all insects when they were pushed inside the screen at the maximum wind speed of 5 m/s (Figure 11A–D).

In conclusion, the function of the SD screen was mainly to repel insects reaching the G-MN under windless or weak wind conditions, and also to capture insects that were forcibly pushed inside the screen under stronger wind speeds. This dual function makes the SD screen a practical pest control approach for greenhouse tomato cultivation. Importantly, the properly charged SD screen prevented pests from entering the greenhouse via screen-guarded windows.

3.3. Practical Implementation of the SD Screen

For our laboratory experiments, an insulated conductor wire was easily fabricated by passing a metal wire through a soft PVC tube. However, outdoor application of the device for long periods can lead to severe deterioration including discoloration, deformation, and cracking due to changes in temperature, humidity, and ultraviolet irradiation, which may significantly affect the practical implementation of the SD screen.

In SD screens that are marketed for pest control (Sonoda Seisakusho Co., Ltd., Osaka, Japan), the conductors are coated with PVC resin, such that the screens can operate outdoors for long periods without deterioration [38]. At large scales, such as that installed at the Osaka Prefectural Research Institute of Environment, Agriculture and Fisheries (Figure 12A,B), these screens are constructed by welding multiple iron wires to an iron frame, coating them with PVC resin, and placing a grounded metal net on both sides of the screen. The net on the indoor side has a large mesh size to enhance wind permeability, and the insulator coating the conductor of the SD screen can be white or yellow for insect photo-selectivity.

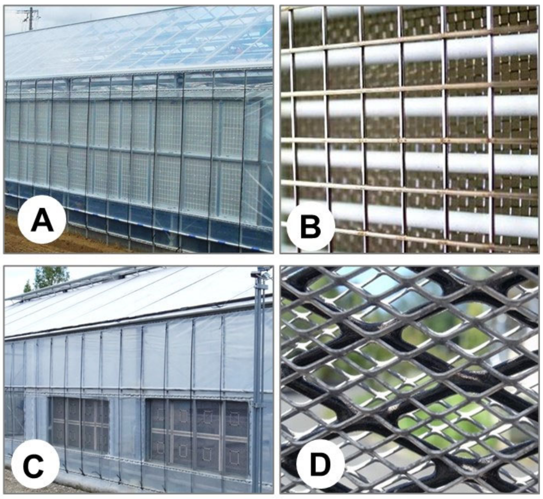

Figure 12. (**A**,**B**). Practical application of an SD screen (Sonoda Seisakusho Co., Ltd. Osaka, Japan.) in a greenhouse facility. Photographs were obtained from the Osaka Prefectural Research Institute of Environment, Agriculture and Fisheries. (**C**,**D**) Commercial EF screens (Navec Co., Ltd. Aichi, Japan) installed on the lateral windows of a greenhouse at the Faculty of Agriculture, Kindai University [38].

Another SD screen design (Panasonic Environmental Systems and Engineering Co., Ltd., Osaka, Japan) consists of a G-MN (stainless steel net with diamond-shaped mesh) placed on either side of an insulated conductor formed by coating expanded iron with black PVC resin (Figure 12C,D). This device is weatherproof, for stable outdoor use over long periods.

3.4. Modification of the SD Screen to Construct an Electrostatic Insect Sweeper (EIS)

The EIS (Figure 13A) (Sonoda Seisakusho Co., Ltd. Osaka, Japan) consists of an SD screen wound around a cylindrical PVC pipe (Figure 13B,C). It contains an integrated non-grounded circuit to produce an SDEF in the space between the NC-IC and G-MN, eliminating the need for a ground line [7]; it is easy to operate in a greenhouse (Figure 13D). The EIS directly traps pests such as whiteflies and aphids (wingless) that frequently rest on the leaf surface. This device was developed for supplementary use in a greenhouse equipped with an SD screen; however, it is also useful for unscreened greenhouses and can significantly decrease insect populations on cultivated plants through routine application.

The optimal voltage applied to the EIS varies according to the size of the target pest; whiteflies and western flower thrips are captured at a voltage of 0.8 kV, whereas green peach aphids, tomato leaf miners, and shore flies are captured at 1 kV. Insects are easily trapped by gently stroking the host leaf with the EIS (Figure 13E). This method is particularly useful for whitefly trapping because they remain on the leaf surface for long periods (Figure 13F). Thus, pest entry into a greenhouse equipped with SD screens on lateral windows can be completely prevented, and pests that enter via the unscreened doorway can be eliminated by using the EIS at the initial stage of invasion.

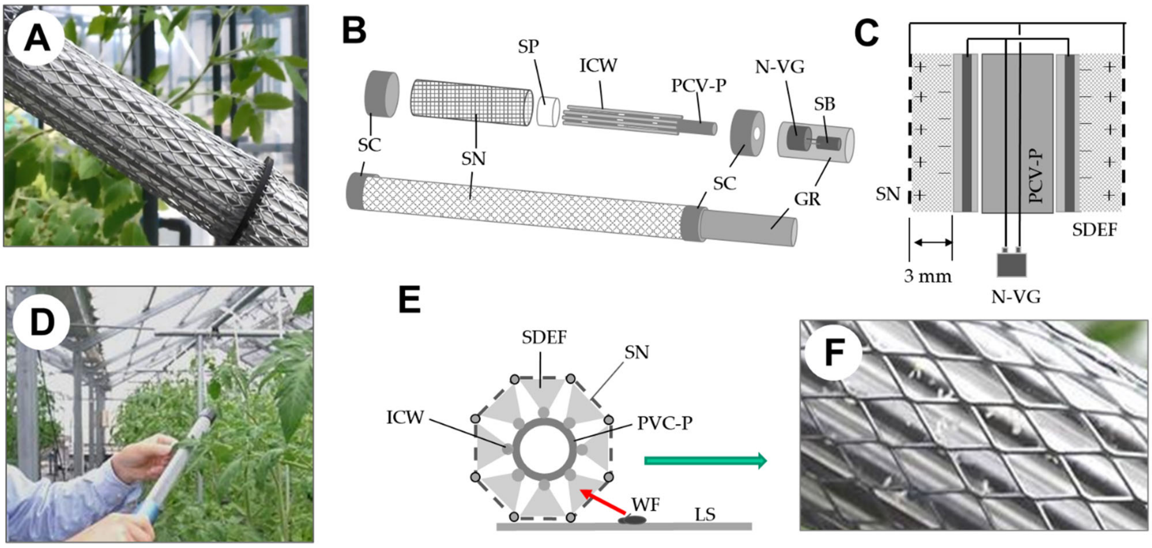

Figure 13. (**A**) Electrostatic insect sweeper (EIS) used to trap insects resting on greenhouse tomato leaves. (**B**) Schematic representation of the EIS structure. (**C**) Schematic representation of the inner EIS structure. (**D**) EIS capturing whiteflies on leaves. (**E**) Schematic representation of insect capture on a leaf (plan view). Red and green arrows indicate the directions of insect attraction and leaf-surface sweeping with the EIS, respectively. (**F**) Whiteflies trapped by the EIS insulated conductor wire. SC, sealing cap; SN, stainless net; SP, spacer; ICW, insulated conductor wire; PVC-P, polyvinylchloride pipe; N-VG, negative voltage generator; SB, storage battery; GR, grip; SDEF, single-charged dipolar electric field; WF, whitefly; LS, leaf surface. [7].

4. Double-Charged Dipolar Electric Field Screen (DD Screen)

4.1. Mechanism and Design of the DD Screen

The DD screen is fabricated by pairing two oppositely charged, insulated conductor wires (OC-ICWs) [5]. Single-layered (1L) DD screens have alternating OC-ICWs, whereas two- (2L) and three-layered (3L) DD screens have offset layers of OC-ICWs (Figure 14). Both 2L and 3L DD screens have shorter distances between the insulated conductor wires, and therefore create a stronger force for the same applied voltage due to higher potential difference (Figure 14).

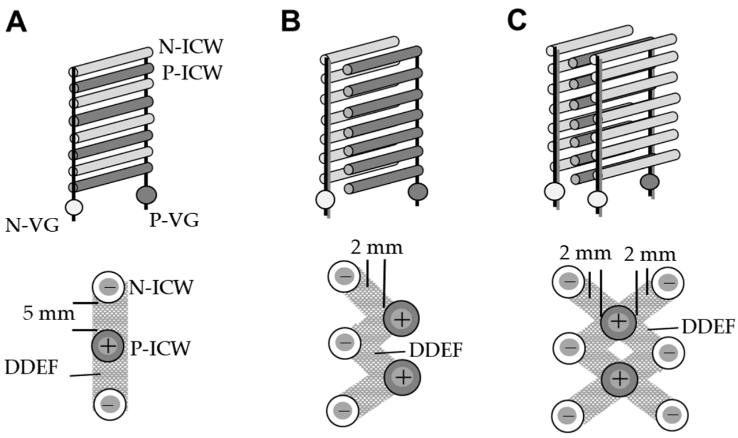

Figure 14. Single- (1L) (**A**), two- (2L) (**B**) and three-layered (3L) (**C**) DD screens (upper) and double-charged dipolar EFs (DDEFs) produced by oppositely charged insulated iron wires in each DD screen (lower). N-VG, negative voltage generator; P-VG, positive voltage generator; N-ICW, negatively charged insulated conductor wire; P-ICW, positively charged insulated conductor wire; DDEF, double-charged dipolar electric field.

The DDEF differs from the SDEF in that the EF is formed by double charging, thereby doubling the potential difference compared to the SDEF, producing a much stronger force for capturing insects. In the SDEF, the electrical force always pushes electrons (negative electricity) toward the ground, whereas in the DDEF, electrons accumulate around the positive pole because it is insulated (Figure 15A).

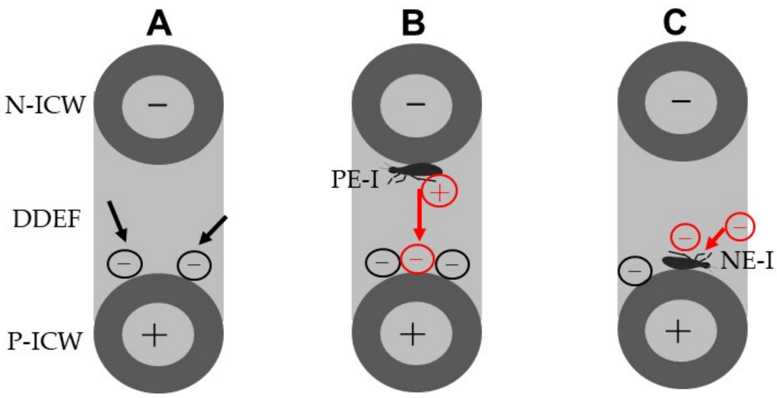

Figure 15. Schematic representation of the insect capture mechanism of the DD screen. (**A**) DDEF produced by two oppositely charged insulated conductor wires. Free electrons in the air are attracted to the positive pole. (**B**) Insect capture by the negative pole. The insect was positively electrified by discharge-mediated positive electrification and then attracted to the negative pole. Free electrons (red arrow) in the insect were released and attracted to the positive pole. (**C**) Insect capture by the positive pole. The insect was negatively electrified by free electrons around the positive pole and then attracted to the positive pole (charge-mediated negative electrification). N-ICW, negatively charged insulated conductor wire; P-ICW, positively charged insulated conductor wire; DDEF, double-charged dipolar electric field; PE-I, positively electrified insect; NE-I, negatively electrified insect [39].

When an insect enters the DDEF, it can be captured in one of two ways, either by losing free electrons to become positively electrified in the space near the NC-IC (negative pole) and being attracted to the negative pole, as in an SDEF device (Figure 15B), or by receiving electrons accumulated around the positively charged pole and being negatively electrified (Figure 15C) [39].

4.2. Practical Application of 1L, 2L, and 3L DD Screens

In our experiments, all screens were charged by using positive and negative voltage generators with non-grounded circuits, in which free electrons migrated among the iron wires [40]. Because the DD screen does not require a ground, it can effectively function as a portable EF screen. In an assay to determine the optimum voltages for a range of target pests, insects were blown toward the screen by using compressed air at varying wind speeds, measured at the screen surface. Examples of successful insect capture by the device as they are blown toward the OC-ICWs are shown in Video S4. As the wind speed and insect size increase, the voltage must also increase to maintain a high capture rate; a voltage of 2.3 kV was sufficient to capture all test insects at the highest wind speed (3 m/s) in all screens (Table 2). We selected a maximum wind speed of 3 m/s, because our observations of insects subjected to artificial wind showed that they clung to plant leaves or stems and covered their body with their wings to prevent being blown away at higher wind speeds; thus, insects are unlikely to attempt greenhouse infiltration at wind speeds < 3 m/s.

Table 2. Capture of insect pests blown toward the insulated conductor wires by different types of double-charged dipolar electric field screens (DD-screens) [8,41,42].

Insect Pests Tested	Voltage Required to Completely Capture Insects (-kV)								
	Single-Layered Type			Two-Layered Type			Three-Layered Type		
	1	2	3	1	2	3	1	2	3 [a]
Whiteflies	0.8	1	1.2	0.8	0.8	0.8	0.8	0.8	0.8
Green peach aphids	1	1	1.2	0.8	1	1	0.8	1	1
Western flower thrips	1.5	2	2	0.8	1	1	0.8	1	1
Tomato leaf miner flies	1.2	1.5	1.5	1	1	1.2	1	1	1.2
Shore flies	1.5	2.1	2.3	1	1.2	1.2	1	1	1.2

[a] Wind speed (m/s).

Examples of practical application of the 1L, 2L, and 3L DD screens are shown in Figure 16. The 1L DD screen was shaped as a bamboo blind for inexpensive fabrication and installed in a plastic hoop greenhouse (Figure 16A) [8]. This screen is easily hung anywhere, with no additional construction required; for example, in a plastic hoop greenhouse, it is typically secured at the rolled-up side openings. Pest entry cannot be completely prevented by using the 1L DD screen; however, it greatly reduces pest populations within the greenhouse, and remaining pests can be removed by using portable devices such as the EIS or the electrostatic flying insect catcher (EFIC; Sonoda Seisakusho Co., Ltd., Osaka, Japan) (Figure 16B), which is a racket-shaped 2L device used to directly capture flying pests [41]. The EFIC can be applied as needed during ordinary plant care in greenhouses with or without SD screens. The area of the racket surface can be changed to suit the facility where it is being used, such as food-processing factories, warehouses, and catering facilities where insecticide use is strictly regulated. The electrostatic seedling shelter (ESS; Sonoda Seisakusho Co., Ltd. Osaka, Japan) (Figure 16C) is a 3L DD screen apparatus for raising healthy plant seedlings by excluding insect pests and pathogen spores [42]; it can be custom designed for seedling cultivation at any scale. For better air permeation, the screens are installed on opposite faces of the greenhouse, with a small axis fan.

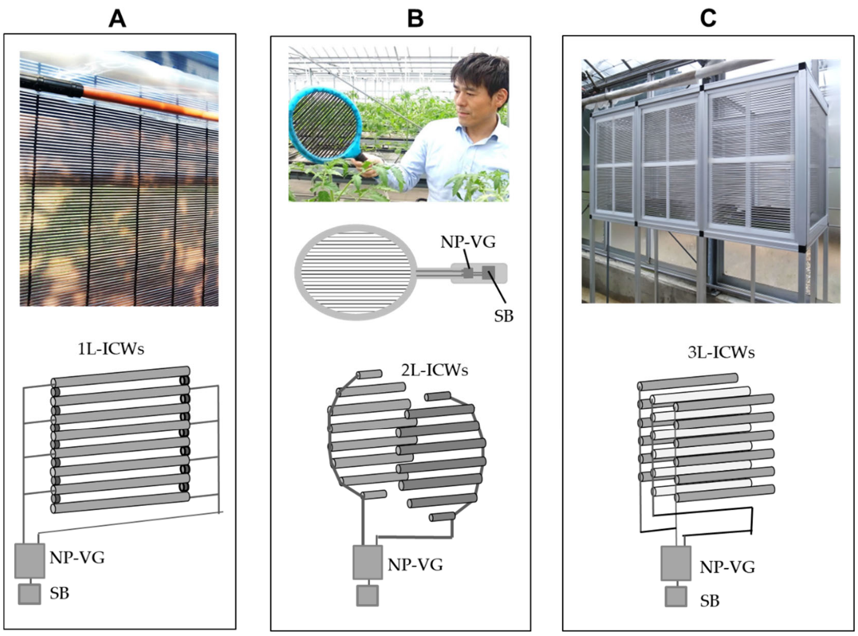

Figure 16. Photographs and schematic representation of a bamboo blind-shaped 1L DD screen (**A**) [8], an electrostatic flying insect catcher (2L DD screen) (**B**) [41], and an electrostatic seedling shelter (3L DD screen) (**C**) [42]. NP-VG, negative and positive voltage generators in one box; SB, storage battery.

4.3. Construction of a Colored 1L DD Ccreen to Capture Phototactic Insects

4.3.1. Combination of a 1L DD Screen and a Yellow Plate

Many insects are attracted by specific light wavelengths or color [43]. The 1L DD screen described in this section incorporates a yellow plate to trap insects such as whiteflies, aphids, and leaf miners, which are attracted to yellow objects, whereas thrips are attracted to blue objects.

To test the efficacy of the device, we constructed 1L DD screens with a yellow board, a gray board, or a gray net at the back of the screen and evaluated their whitefly capture rates (Figure 17A) [9]. The three screens were placed in a greenhouse inhabited by numerous whiteflies; as predicted, the whiteflies were preferentially trapped by the screen backed with the yellow board (Figure 17B).

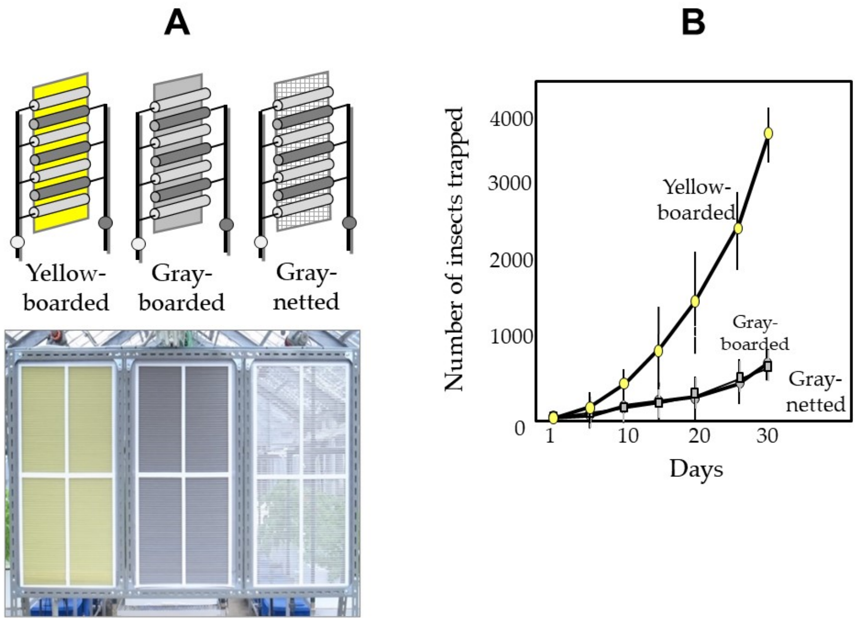

Figure 17. (**A**) Three types of 1L DD screen examined in a greenhouse assay. Three 1L DD screens backed with a yellow board, gray board, or gray net (left to right) were fixed with a metal frame and placed in a greenhouse, where 50 tomato plants were heavily infested with numerous whiteflies, for 1 month. (**B**) Whitefly capture by the three DD screens [9].

4.3.2. Combination of a 2L DD Screen and Oppositely Charged Yellow Water

The DD screen captures all insects entering the EF, but it lacks the ability to attract insects to the apparatus. Therefore, to control phototactic pests such as whiteflies and tomato leaf miners, we enhanced the DD screen by adding an attractive color to lure insects distant from the apparatus. The DD screen was constructed by using a PVC tube through which a metal wire was passed for insulation [9]. As water may be used as a conductor in DD screens [10], we used charged water to dielectrically polarize the insulator tube. Watercolor paint was added to the water to construct a colored DD screen.

The apparatus was insulated by a soft PVC tube; both ends of the tube were connected by using a T-shaped pipe fitting and a channel-switching cock; the open ends of the fitting on one side were linked to a water tank and an injector syringe with the needle removed, respectively (Figure S2A). Water within the tank was pumped into the soft PVC tube and syringe by using a peristaltic pump. The end of the iron wire outside the syringe was connected to a negative and a positive voltage generator. Two identical tube layers were coupled to form the DD screen (Figure S2B). The tubes of each layer were offset, such that the DDEF formed between all tubes (Figure S2C). Colored water was introduced into the transparent PVC tubes (Figure S2D–F). The Munsell hue/value/chroma indices of the watercolors corresponded to the colors of commercially available yellow and blue sticky traps (Figure S2G,H) and a commercial red insect-proof net (Figure S2I). The concentration of the watercolor paint was adjusted to ensure that the color reflected by the PVC tube matched those of the yellow and blue sticky plates, or that of the red net. Next, these apparatuses were used for insect attraction assays.

In the first experiment, the four 2L DD screens were placed in a transparent acrylic box (Figure S3A), which was illuminated for 12 h by a white fluorescent lamp positioned at 30 cm above the roof of the box. In the second experiment, two yellow DD screens and yellow sticky traps were placed along the opposite faces of the box (Figure S3B). In the third experiment, a potted tomato seedling and an insect vial were placed along the opposite faces, and a yellow DD screen was placed in front of the potted plant (Figure S3C). In all experiments, at 24 h after the insects were released, we counted the number of test insects that had been captured by the DD screens and sticky trap plates, or had reached the plant, or had remained in the vial or on the box.

In the first experiment, we found that whiteflies and tomato leaf miners were preferentially attracted to the yellow DD screen, whereas western flower thrips were equally preferentially attracted to yellow and blue DD screens (Figure S3D). These findings are consistent with those previously reported for these phototactic insects [44], indicating that these colored DD screens were effective for attracting phototactic insects. By contrast, few test insects of any type were captured by the red DD screen, which showed capture rates that did not differ significantly from those of the uncolored DD screen or other sampled locations. Shimoda [43] noted that many insects are unable to see red light (600–700 nm). We attribute the insect capture rates of the red DD screen to accidental contact of the insect with the apparatus, rather than to attraction to the apparatus. In subsequent experiments, the yellow DD screen was used because yellow attracts all of the test insect species used in this study. We detected no significant difference in the number of insects captured by the yellow DD screen and yellow sticky trap (Figure S3E), indicating that the yellow DD screen was functionally equal to the commercial yellow sticky trap. We detected a significant difference in the numbers of insects trapped by the yellow DD screen and found on plants placed behind the DD screen (Figure S3F), which indicates that the yellow DD screen positioned in front of the plants preferentially attracted test insects, thereby effectively minimizing the number of insects visiting host plants.

Thus, the wide selection of commercially available watercolors allowed us to fabricate an apparatus that could incorporate a yellow or blue DD screen to attract phototactic insects distant from the apparatus. Such colored DD screens are useful traps for both pest control and the analysis of photoselective behavior in various insect species.

5. Conclusions

Electrostatic techniques that generate an EF are useful approaches for constructing devices to control various insect pests through physical, rather than chemical, means. In this study, we explored the application of various SDEF and DDEF devices to capture or repel small flying insect pests that can pass through conventional insect-proof nets in a greenhouse. The performance of devices that capture insects through a physical force generated in the EF is not susceptible to biological or environmental influences, whereas insect-repelling devices function through the EF-avoiding behavior of the insects. Our EF-based pest management approach was applied to design various innovative apparatuses for chemical-free control of insect pests of greenhouse tomatoes.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/horticulturae8060543/s1. Figure S1, (A, C) Schematic representation of negative (A) and positive (C) voltage generators used for negative and positive charging of an insulated conductor (iron wire), respectively. (B, D) Schematic representation of dielectric polarization of an insulated conductor charged negatively (B) or positively (D); Figure S2, Structure of colored DD screens consisting of paired PVC tubes filled with colored water and oppositely charged; Figure S3, Experiment to evaluate the ability of colored and uncolored DD screens to attract test insects (adult whiteflies, western flower thrips, and vegetable leaf miners (D–F) Comparative assay of insect photoselective responses to colored DD screens; Video S1, Capture of a whitefly (A), green peach aphid (B), western flower thrips

(C), and tomato leaf miner fly (D) by using a single-charged dipolar electric field screen (SD screen) negatively charged with a voltage of −1.2 kV; Video S2, Emergence of an adult tomato leaf miner from a pupa and capture of the fly by the insulated iron rod of the horizontally placed electrostatic soil cover (ESC) at a voltage of −4 kV; Video S3, (A) Avoidance behaviors by adult female (upper) and male (lower) Turkestan cockroaches released in a square surrounded by four SDEFs charged at a voltage of −6 kV. (B) Non-avoidance of the SDEF by a cockroach when the ground line of a galvanometer was removed to impede the flow of the insect-mediated transient electric current to the ground; Video S4, Photographs (upper) and video images (lower) of a whitefly (A), western flower thrips (B), green peach aphid (C), and tomato leaf miner fly (D).

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