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Review

Electrostatic Insect Repulsion, Capture, and Arc-Discharge Techniques for Physical Pest Management in Greenhouses

Shin-ichi Kusakari [1], Yoshinori Matsuda [2,*] and Hideyoshi Toyoda [1]

[1] Research Association of Electric Field Screen Supporters, Nara 631-8505, Japan
[2] Laboratory of Phytoprotection Science and Technology, Faculty of Agriculture, Kindai University, Nara 631-8505, Japan
* Correspondence: ymatsuda@nara.kindai.ac.jp

Abstract: This article reviews the development of electrostatic apparatuses for controlling insect pests in greenhouses. The apparatuses control insects by repelling them, capturing them, and killing them by producing an arc discharge. The single-charged dipolar electric field screen (SD screen) repels insects due to insects' inherent avoidance behavior toward entering the electric field produced. As this behavior is common to many insect pests, the SD screen effectively prevents many pests from entering a greenhouse. The double-charged dipolar electric field screen (DD screen) has a strong attractive force that captures insects entering its electric field. The DD screen is useful for capturing small insects that pass through a conventional insect net, and unique derivatives of this screen have been invented to trap various insect pests on-site in a greenhouse. An arc-discharge exposer was used as a soil cover to kill adult houseflies that emerged from underground pupae transferred along with cattle manure used for soil fertilization. The houseflies were subjected to arc discharge when they appeared at the soil surface. These apparatuses have the common characteristic of a simple structure, so ordinary workers can be encouraged to fabricate or modify them based on their own needs. This review provides an experimental basis for designing efficient physical measures for controlling insect pests in greenhouses.

Keywords: aphid; attractive force; electrostatic field; electrostatic soil cover; housefly; shore fly; static electric field; thrips; tomato leaf miner; whitefly

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1. Introduction

The primary strategy for physical pest control in greenhouses is the prevention of their entry [1]. Netting greenhouse windows has been a basic approach for this purpose [2,3]. However, mesh sizes of conventional woven insect-proof nets are ordinarily between 1 and 1.5 mm, so some small pests can pass through. In our tomato greenhouses, whiteflies, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae); tomato leaf miners (syn. vegetable leaf miner), *Liriomyza sativae* Blanchard (Diptera: Agromyzidae); western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae); winged green peach aphids, *Myzus persicae* (Sulzer) (Hemiptera: Aphididae); and shore flies, *Scatella stagnalis* (Fallén) (Diptera: Ephydridae) frequently enter by passing through such nets. The biggest problem has been that whiteflies, thrips, and aphids transmit viral pathogens: tomato yellow leaf curl virus [4,5], tomato spotted wilt tospovirus [6,7], and cucumber mosaic virus [8], respectively, and shore flies transfer rhizosphere fungal pathogens (*Verticillium dahliae* and *Fusarium oxysporum* f. sp. *radicis-lycopersici*) [9,10]. Tomato plants are vulnerable to direct attacks by these pests, as well as the serious infections caused by viral, bacterial, and fungal pathogens carried by them. Most seriously, a viral disease caused by the tomato yellow leaf curl virus has been a major cause of loss of tomato crops grown in greenhouses nationwide [11].

Insect-excluding woven nets with a fine mesh size have been extensively employed to minimize whitefly entry into greenhouses, but the netting has the disadvantage of reducing ventilation, which causes overheating and an increase in relative humidity [2]. Electrostatic techniques have been used to solve this problem. Matsuda et al. [12] created an electrified insect net (electric field screen), consisting of a layer of multiple insulated conductor (iron or copper) wires arrayed in parallel at a definite interval and two identical insect nets woven with stainless strands of the same thickness as a conventional net and linked to a grounded line. The nets were placed on each side of the insulated conductor wire layer, and negative charging of the insulated conductor wires formed an electric field between the charged insulated conductor wire and the grounded metal net. In tests, insects that reached the grounded metal net of the electric field screen appeared to sense the electric field inside the screen and were deterred from entering [12,13]. This peculiar reaction, which was considered a result of inherent hesitant behavior, was ultimately detected in 13 orders, 45 families, and 62 genera of arthropods [14]. Based on the results of such studies, the insect-repelling function of the electric field screen was widely acknowledged [15] and it came to be known as the single-charged dipolar electric field screen (SD screen) and was put into practical use [16].

Initially, the concept of the screen was presented as an air-shielding barrier to precipitate wind-carried spores of powdery mildew pathogens [17,18]. The electrostatic principles implemented for this purpose were that the negative charge supplied to a conductor wire accumulates on its surface and polarizes the insulating coating of the conductor dielectrically, negatively on the outer surface and positively on the inner surface of the coating [19]; the surface charge on the insulating coating produces an electrostatic field in the air [20]. In the proposed devices, cylindrical insulated conductor wires negatively charged to produce an electrostatic field concentrically surrounding the wires were arrayed in parallel to combine the electrostatic fields [17]. Spores that reached the air-shielding barrier (combined electrostatic fields) were drawn to the charged insulated conductor wires by their dielectrophoretic movement in the electrostatic field [18,21]. This device was named the single-charged monopolar electric field screen (SM screen) and positioned as a prototype for subsequent types of electric field screens [22].

Another tactic is the use of colored sticky traps for phototactic insect pests that may enter a greenhouse. Due to the strong photoselective behavior of these insects, colored sticky traps have been widely used to explore the population fluctuations of such flying insects. Yellow and blue sticky traps effectively attract many insect species. In particular, the yellow sticky trap has been used to monitor populations of western cherry fruit fly (*Rhagoletis indifferens*) [23], sweet pepper whitefly (*Trialeurodes vaporariorum*) [24], sweet potato whitefly (*B. tabaci*) [25], western flower thrips (*F. occidentalis*) [26], and chrysanthemum leaf miner (*Liriomyza trifolii*) [27]. Similarly, the blue sticky trap has been used to monitor populations of melon thrips (*Thrips palmi*) [28] and bean flower thrips (*Megalurothrips usitatus*) [29]. Therefore, because the yellow sticky trap has a strong insect-attracting ability, many growers who cultivate plants organically in large greenhouses have used the traps as an insecticide-independent method to reduce populations of phototactic insects. The traps are often hung from crossbeams and lateral pillars near greenhouse windows. However, the stickiness of the trap surface gradually deteriorates with the increasing number of trapped insects, so traps must be exchanged for fresh ones frequently during the peak pest season. Another weak point is the sticky surface of the trap, which limits trap placement in the vicinity of cultivated plants. Thus, greenhouse operators have requested a less expensive and reusable trap with a non-sticky surface that could attract and capture targeted insect pests. This demand has encouraged the development of a new type of electric field screen.

The double-charged dipolar electric field screen (DD screen) was constructed by pairing two oppositely charged SM screens [30]. The insulated conductor wires of the SM screen are negatively and positively charged by linking them to a grounded negative and positive voltage generator, respectively. The opposite charges on the insulated conductor wires of the paired SM screens form a dipolar electric field in the space between the oppositely charged conductor wires. Insects that enter this electric field are subjected to a strong force drawing them toward the nearest charged insulated conductor. This makes it unnecessary to make the surface of the trap sticky. The insulated conductor wire is prepared by passing a metal wire through an acrylic cylinder or soft polyvinyl chloride tube for insulation, and it is washable for reuse. Importantly, a change in conductor material from metal wire to water enabled the construction of a yellow-colored DD screen [31,32]. Because water conducts electricity, a transparent polyvinyl chloride tube filled with charged water (with watercolors) could be electrified to form an electric field for capturing insects. The colored DD screen can be placed at any location within a greenhouse, and it attracts and captures insects distant from the apparatus. This screen has led to the development of other insect-trapping apparatuses [33–36].

A third application of electrostatic principles is the production of an arc discharge-generating device for electrocuting insects that enter the electric field [37–40]. This technique was originally devised to kill rice weevils *Sitophilus oryzae* (Linnaeus) (Coleoptera: Curculionidae) nesting in dried rice [37,40]. The arc-discharge exposer is simple, fabricated by pairing two identical metal nets in parallel at a definite interval; one net is linked to a negative voltage generator and the other is connected to a grounded line. Negative charge accumulates on the charged metal net and polarizes the grounded metal net positively by electrostatic induction [41]. Eventually, an electric field forms in the space between the oppositely electrified nets. Negative charge on the metal net surface is released as an arc discharge toward an insect that enters the electric field [37], and the insect is killed instantly. This apparatus has been most effective for killing *Musca domestica* (Linnaeus) (Diptera: Muscidae) houseflies emerging from underground pupae at the soil surface, which are possible vectors of pathogenic *Escherichia coli* O-157 and can be introduced with manure used as soil fertilizer [42].

For the remainder of this article, we describe the development of electric field screen research, focusing on the desirable functions that should be conferred to each type of screen. From the perspective of effective pest management, we categorize the major electrostatic techniques based on three functions (repelling, capturing, and electrocuting insect pests), as mentioned above. These works are unique challenges to developing new physical methods for pest control, and the newly devised apparatuses possess a simple structure, allowing ordinary greenhouse workers to fabricate or improve them for their own requirements and exert prominent control functions to target insect pests. While providing a detailed explanation of the electrostatic principles used for constructing electric field screens and the structural characteristics of the screens, we discuss the current state and future potential of electric field screen research.

2. Construction of the SM-Screen

A conductor (metal wire and net) can be charged by linking it to a negative or positive voltage generator. A voltage generator is an amplifier used to increase the initial voltage (12 V) to the desired voltage (1–30 kV) using a transformer and Cockcroft circuit integrated into the voltage generator [43]. A negative voltage generator using an enhanced voltage draws negative charge (free electrons) from the ground and supplies it to a conductor linked to the voltage generator. The negative charge accumulates on the surface of a conductor and produces an electric field in the surrounding space. In the case of an insulated conductor, negative charge on the conductor surface dielectrically polarizes an insulating coating, negatively on its outer surface and positively on its inner surface (dielectric polarization of an insulator) [19]. Eventually, the negative charge on the insulator coating surface generates an electric field in the surrounding space.

Electric fields can be classified into three types: electrostatic, static, and dynamic electric fields. An electrostatic field is the electric field produced by a single-charged conductor (monopole), where the discharge of the charged conductor does not occur (i.e., no electric current). The SM screen was constructed based on this electrostatic field. In the first example of the SM screen, a negatively charged conductor (iron wire) was passed through an acrylic cylinder (volume resistivity of 10^{12} Ωcm) for insulation [17]. The negative charge on the conductor wire polarized the acrylic cylinder dielectrically.

Eventually, an electrostatic field formed concentrically in the air surrounding the cylinder (Figure 1A). The screen was constructed by arraying negatively electrified cylinders in parallel at a definite interval to combine the electrostatic fields (Figure 1B).

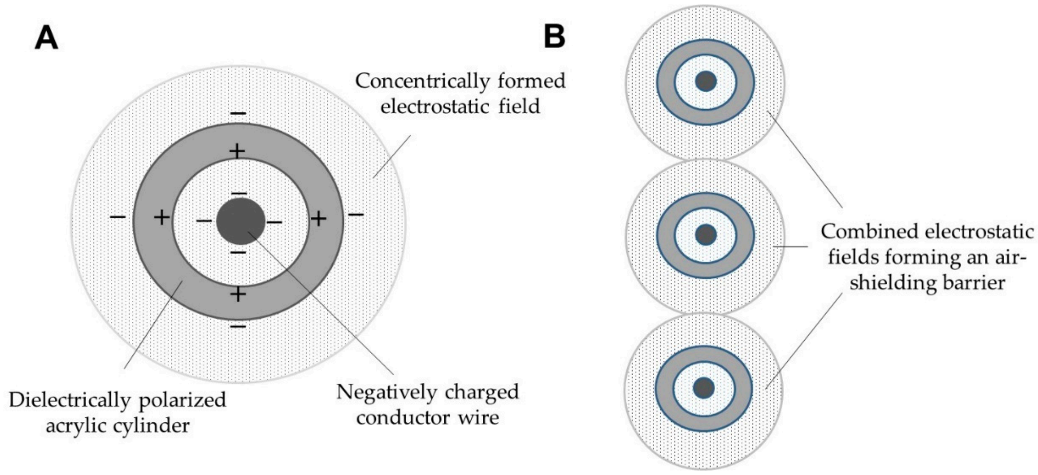

Figure 1. Schematic representation of the electrostatic field produced by a negatively electrified insulator (acrylic cylinder) covering a negatively charged conductor (iron wire) (**A**) and insulated conductor wires in a vertical array forming an air-shielding barrier of combined electrostatic fields (cross-sectional view) (**B**).

Acrylic resin is an outstanding insulator, so a high voltage can be applied to a conductor insulated with this resin. However, it is difficult to process. This problem was an obstacle, particularly in the development of new types of electric field screens. To solve this problem, developers turned to polyvinyl chloride resin, which had frequently been used to insulate metal materials. However, because of a lack of equipment to coat metal materials with this resin, commercially available soft polyvinyl chloride tubes had to be substituted. The most substantial disadvantage of using soft polyvinyl chloride tubes is their lower volume resistivity, which was a limiting factor in charging the material. However, this limitation served as a motivating force to develop a new method to create the necessary capabilities with lower voltage applications. The invention of the SD screen was the first such instance.

In subsequent experiments, an insulated conductor was fabricated by passing a metal wire (copper or iron) through a soft polyvinyl chloride tube (volume resistivity of 10^9 Ωcm). The insulated wires were arranged in a parallel configuration, with a constant separation interval of 5 mm, as a common skeletal structure for subsequent electric field screen designs.

3. Dual Functions of the SD Screen: Insect Capture and Repulsion

3.1. Construction of the SD-Screen

Theoretically, the dipolar electric field formed between oppositely charged poles causes an electric discharge if the applied voltage exceeds a certain limit, regardless of whether or not the conductor is insulated. The type of electric field is determined by the existence or nonexistence of discharge. Hereafter, the non-discharging and discharge-generating electric fields are referred to as static and dynamic electric fields, respectively. During electric field screen research, a new method by which a dipolar static electric field could be generated via single charging was devised. The electric field screen integrating this field exhibited revolutionary power for capturing insects.

As described earlier, a negatively charged insulated conductor wire causes dielectric polarization within the insulating coating, thus creating a negatively charged insulator surface. The charged surface of the insulator produces an electrostatic field in the surrounding space. The difference in the design of the SD screen is that a grounded metal net is placed inside the electrostatic field produced by the insulated conducting wire (Figure 2).

Eventually, the grounded metal net was positively electrified as a result of electrostatic induction [41]. The opposite charges of the insulated conductor wire (negatively charged) and the grounded metal net (positively charged) create a dipole, forming an electric field in the space between them. Thus, we can create a positive pole (grounded metal net) without using a positive voltage generator. This is our single-charged dipolar electrification system.

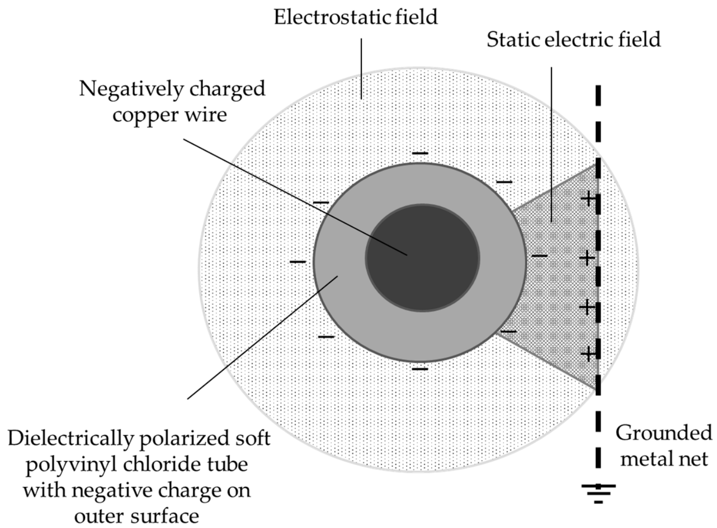

Figure 2. Formation of a static electric field inside the electrostatic field formed by a single-charged monopolar electric field screen (SM screen) (cross-sectional view).

As shown in Figure 2, a static electric field is formed inside the electrostatic field. The static electric field is formed in a bilaterally symmetrical manner by placing another grounded net on the opposite side of the insulated conductor wires (Figure 3A). Accordingly, a new electrostatic barrier of static electric fields is constructed by arranging the insulated conductor wires such that the upper and lower ends of the two static electric fields contact each other (Figure 3A) [12].

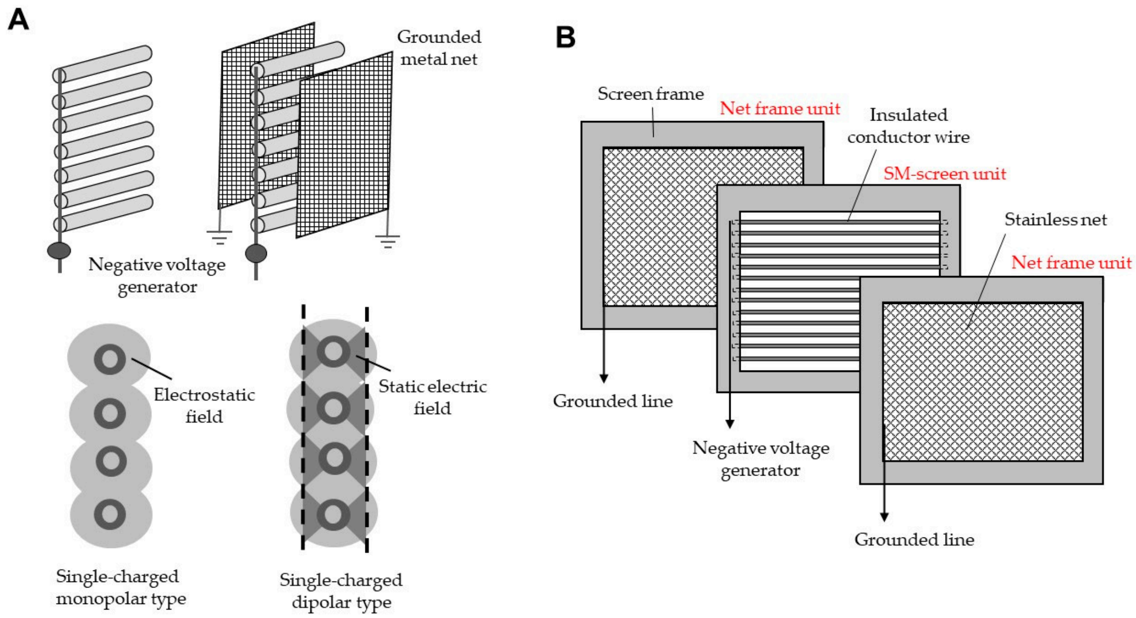

Figure 3. (**A**) Comparative representation of single-charged monopolar and dipolar electric field screens forming an electrostatic field and static electric field, respectively. (**B**) Schematic representation of a single-charged dipolar electric field screen (SD screen) consisting of three units. Two net frame units are placed on each side of the SM screen unit.

We produced the unit-type SD screen (Figure 3B), which consists of three units: the insulated conductor wires held with a polypropylene screen frame (SM screen unit), which is linked to a negative voltage generator, and two framed stainless net units (mesh size of 1.5 mm, which is equivalent to a conventional insect-proof net), which are linked to a grounded line. For completion, three frame units are combined simply by placing the two net units on either side of the SM screen unit (Figure 3B).

3.2. Comparison of Insect-Capturing Ability of Single-Charged Monopolar and Dipolar Types

The SD screen is formed by placing two grounded metal nets inside the electrostatic fields produced by the SM screen (Figure 3A). However, there is a remarkable difference in insect-capturing capability between the SM and SD screens. In the SM screen, the insect is attracted to the charged insulated conductor wire by dielectrophoresis. However, the force generated is not sufficiently strong for insect capture. Indeed, the captured insect struggles strenuously to free itself from the attractive force of the insulated conductor wire and ultimately escapes. By contrast, the SD screen exerts a strong attractive force so that the insect cannot escape, despite its struggle.

The static electric field is specialized by the negative charge on the surface of the insulated conductor wire. The negative charge has a strong repulsive force on other negative charges (electrons) in the electric field; eventually, the free electrons are pushed toward the ground via the metal net (Figure S1(A1)). According to this mechanism, any conductor in the static electric field is deprived of its free electrons and becomes positively charged. This phenomenon is called discharge-mediated positive electrification of a conductor [44,45]. In this section, we focus on an insect that enters the static electric field. Most insects possess a solid protective layer (cuticle layer) that covers the body. This layer is highly conductive [46–50]; thus, an insect that enters the static electric field is deprived of its free electrons in the cuticle layer and becomes positively electrified. This implies that discharge-mediated positive electrification can be induced in the insect [44,45]. The positively electrified insects are attracted to the insulated conductor wire (Figure S1(A2)), and this force is strong enough that the captured insect cannot escape the trap. This capturing mechanism is applicable to almost all insects that have a cuticle [44].

3.3. Insect Avoidance of the Static Electric Field: The SD Screen as an Insect-Repellant Type of Screen

Matsuda et al. [12] devised the SD screen and reported that vinegar fly *Drosophila melanogaster* Meigen (Diptera: Drosophilidae) and cigarette beetle *Lasioderma serricorne*; (Fabricius) (Coleoptera: Anobiidae) avoided entering the electric field of the screen. Video S1 shows the remarkable avoidance behavior of the cigarette beetle. In addition, we have frequently observed insects reaching the grounded metal net of the SD screen installed to a greenhouse window and flying away without entering the screen [13]. Video S2A shows that the insects were deterred from entering the static electric field. Video S2B shows that the insects were captured by the strong force of the electric field when they were forcibly pushed inside the electric field. This observation suggests that the screen actually repels the pests.

Matsuda et al. [14] further examined the insect avoidance behavior to the static electric field of the SD screen by placing transparent acrylic cylinders on and beneath the screen and putting test insects at the bottom of the lower cylinder. All of the insects tested, covering 17 orders, 42 families, 45 genera, and 82 species, exhibited avoidance behavior with respect to the static electric field [14]. These results strongly suggest that all insects are deterred by the static electric field of the SD screen.

To capture most of the insects that were forcibly pushed inside, 4.2 kV charging was required [51,52]. Thus, the SD screen is practical as an insect-repelling type of screen because the screen is fully functional with 1.2 kV of charging; in fact, it is capable of repelling all insects with this voltage [15].

4. DD Screens for Insect Capture

4.1. Construction of DD Screens and Their Insect-Capturing Ability

Based on the arrangement of insulated conductor wires, DD screens are classified into three types: the single-layered type, possessing oppositely charged insulated conductor wires arranged alternately (Figure 4A); two-layered type; and three-layered type, possessing oppositely charged insulated conductor wires arranged in an offset configuration (Figure 4B,C). The two- and three-layered types have a shorter distance between insulated conductor wires than the single-layered type (Figure 4) and therefore create a stronger force when the same voltage is applied due to the higher potential difference.

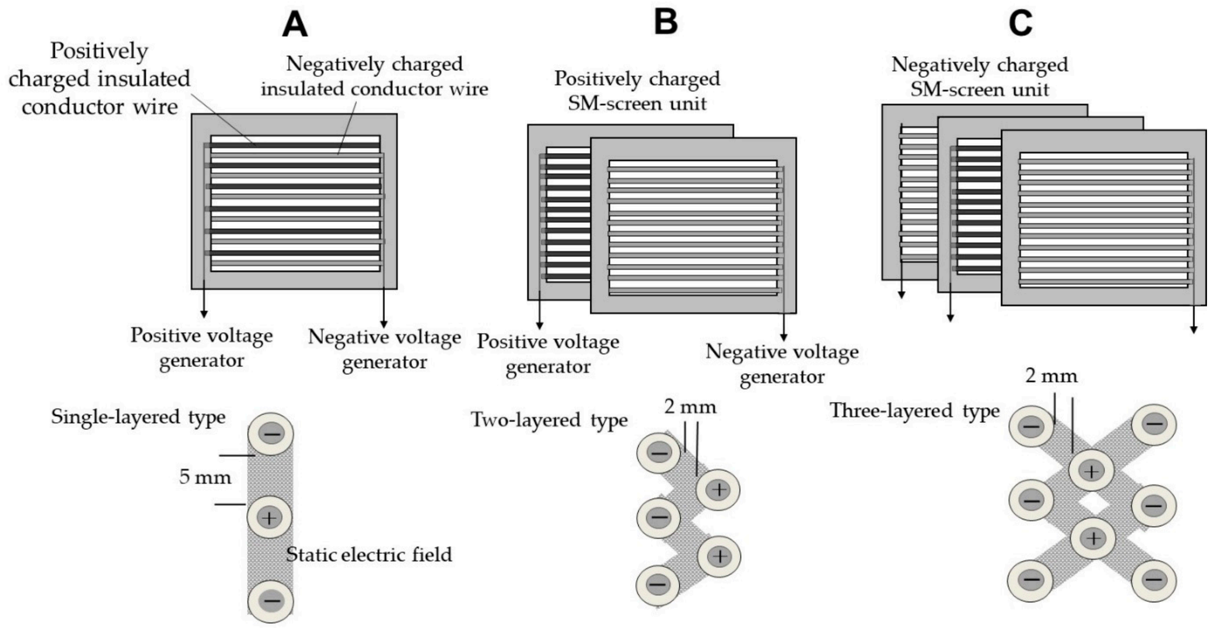

Figure 4. Three types of DD screens for capturing insect pests and the static electric fields formed by the DD screens. (**A**) A unit of the single-layered DD screen, where oppositely charged insulated conductor wires are arrayed alternately. (**B**,**C**) Two- and three-layered DD screens. Two or three oppositely charged SM screen units were combined in an offset arrangement with the oppositely charged insulated conductor wires.

Toyoda et al. [52] discussed the insect-capturing ability of DD screens, in which they determined the appropriate voltage setting for capturing all insect pests tested. The assay was conducted by blowing the insects toward the screen. Table S1 shows that the voltage should be enhanced in response to the wind velocity and size of the test insects. A 2.0 kV charging was sufficient to capture all of the test insects at the highest wind speed and by all screens [52]. Incidentally, the screen was charged with the same magnitude of negative and positive voltage. Therefore, the actual potential difference was twice the difference between the voltages listed in the table. Video S3 shows the successful capture of whiteflies by the single-layered DD screen. At insufficient voltage (−0.6 kV), some whiteflies escaped from the trap (Video S3A) but at 1.2 k they were not able to escape (Video S3B).

Figure S1B shows the insect-capturing mechanism in the static electric field of the DD screen [53]. In this field, free electrons in the air are drawn to the positively charged insulated conductor wire (positive pole) (Figure S1(B1)). When an insect enters this field, there are two ways that it can be captured. The first is that the insect invades the space near the negatively charged insulated conductor wire (negative pole) (Figure S1(B2)). Here, the insect is deprived of free electrons, electrified, and thus attracted to the negative pole. This is the same phenomenon that occurs in the static electric field (discharge-mediated positive electrification) of the SD screen. The second is the case in which the insect enters the space of the positive pole (Figure S1(B3)). In this case, the insect receives electrons and is electrified negatively for attraction to the pole (charge-mediated negative electrification).

4.2. Practical Application of DD Screens

4.2.1. Grounded and Ungrounded Circuits for Charging

In the usual electric circuit (grounded circuit) configuration for voltage charging of the DD screen, a negative voltage generator pumps negative charge from the ground and supplies it to the insulated conductor wires while a positive voltage generator pushes free electrons from the linked insulated conductor wires to the ground to generate positively charged insulated conductor wires (Figure S2A). From the viewpoint of electricity movement, the same amount of electricity can be returned to the ground from the conductors.

In the ungrounded circuit, the free electrons of the insulated conductor wires are supplied directly to the other insulated conductor wires by the voltage produced by the two generators (Figure S2B). Therefore, an electric field screen with this circuit has no need for a grounded line. For this reason, the placement of the electric field screen is freely selectable, allowing portability of the electric field screen.

4.2.2. Diversification of DD Screens

The bamboo blind-type electric field screen (Figure S3A) is a single-layered type of screen that was devised to reduce construction costs, particularly for practical applications involving a plastic hoop greenhouse [36]. This screen can be hung easily anywhere and can be positioned at the openings of lateral-side plastic film roll-ups. Although it is not possible to prevent the entry of pests completely, this approach is useful for greatly diminishing the interior pest population.

An electrostatic flying insect catcher (electrostatic racket) is a two-layered apparatus used to capture flying pests directly (Figure S3B) [30]. This apparatus is carried by the greenhouse attendant during ordinary plant care checks and is used to capture flying insects quickly (as they appear). It is possible to reduce the pest population significantly with the continued diligent use of this device. The apparatus can be used in various facilities, such as food-processing factories, warehouses, and facilities that provide meals, in which the use of insecticides is strictly regulated or prohibited.

An electrostatic cabinet (two-layered type) (Figure S3C) system was designed for use inside facilities, including greenhouses [35]. The entire structure has a simple design. The frame is furnished with two electric field screens, which are installed on opposite faces of the frame for better ventilation. The door of the cabinet and the remaining faces are covered with reinforced plastic film. The electrostatic cabinet can be set up affordably compared to more involved greenhouse screen installations. The cabinet can also be used as a cultivation facility for specific plants that should be protected from pests or as a pest-free laboratory and workroom.

An electrostatic nursery shelter (three-layered type) (Figure S3D) is an apparatus used to raise healthy plant seedlings [34]. The shelter is designed so that it can be installed in a greenhouse that is not furnished with electric field screens. The reason for using the three-layered type screen is to prevent the entry of pests as well as pathogen spores [54]. Because the structure is simple, its size can be easily modified to the scale needed for seedling cultivation. To obtain better ventilation, the screens can be installed on opposite faces of the shelter, along with a small axis fan.

4.2.3. Yellow-Coloring of DD Screen for Attracting Phototactic Insect Pests

Many insects are attracted to a particular type of light (or color). We utilized this characteristic in our capture method. The following experiments were conducted to examine whether this behavior could be applied to enhance the capture capability of the DD screen. Although the DD screen was able to capture insects entering the static electric field of the screen, it did not attract distant insects.

Nonomura et al. [33] used a single-layered DD screen backed with a yellow board, gray board, or gray net to examine the effects of better light reflection for bringing out insect photoselectivity (Figure S4A). As insects attracted by the color plate were captured by the insulated conductor wires of the screen, the feasibility of this method was evaluated by counting the number of insects trapped. As a control, DD screens with a gray-colored board and gray net were also used. These three screens were placed in a greenhouse where numerous whiteflies were present. The results showed, as expected, that whiteflies were preferentially trapped by the screen with the yellow-colored board [33].

Takikawa et al. [31,32] used a yellow-colored insulated conductor to fabricate a colored DD screen. For this purpose, the conductor metal wire in the insulator coating was changed to water. Because water conducts electricity, the transparent polyvinyl chloride tube filled with charged water was similarly electrified and produced an electric field in the space surrounding the tube. Two-layered, yellow-colored DD screens were constructed by pairing two identical yellow-colored SM screen units (Figure S4B). In this screen, the yellow-colored tubes of the two units were arranged in an off configuration (Figure S4C). The yellow-colored DD screen was highly effective at attracting and trapping whiteflies, thrips, and leaf miners distant from the apparatus in the greenhouse [31]. The wide selection of commercially available watercolors is useful for constructing devices with the coloration most suitable for attracting phototactic insect pests.

5. Soil-Surface Control of Insect Pests Emerging from Underground Pupae

In our greenhouses, houseflies and tomato leaf miner flies (Figure 5A,B) are problematic insect pests to control using various electrostatic methods because both flies emerge from underground pupae in the soil bed of a greenhouse. Houseflies introduced in cattle manure used for soil fertilization present a risk for transmitting pathogenic bacteria (*Escherichia coli* O-157) [55–57]. Contamination of cultivated and postharvest crops with this pathogen is a serious problem that can endanger the food supply chain [58,59]. On the other hand, adult leaf miners deposit eggs in leaves. The larvae hatched from the eggs form extensive mines within the leaves and then crawl out and fall to the ground. The larvae then enter the ground and pupate, and adult flies emerge from the underground pupae and oviposit eggs on host plants [60]. Thus, tomato leaf miner flies can cause a persistent infestation of greenhouse tomato plants throughout their life cycle [61]. Because of the great body size differences between these two flies (Figure 5), it was impossible to control them simultaneously using a single method. The following sections describe two effective control-measure methods for each fly.

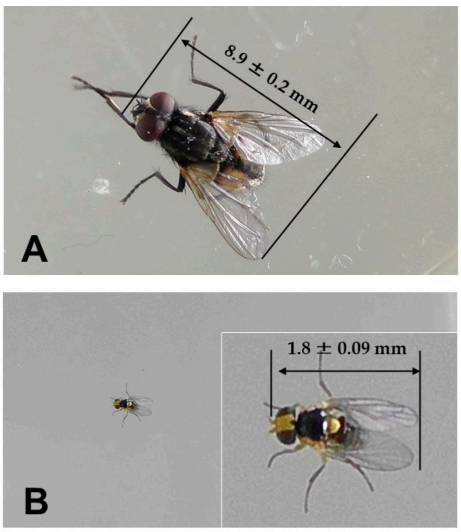

Figure 5. Comparative demonstration with test flies of different body sizes: housefly (**A**) and tomato leaf miner (**B**). The inserted photograph in (**B**) is an enlarged image of the fly.

Figure 6A shows the structure of an arcing-type soil cover method, an arc discharge exposer designed to kill insect pests that emerge from a soil bed instantaneously [42]. The apparatus consisted of two identical expanded metal nets, a square polypropylene frame (height of 6 mm), and a plastic grating (height of 54 mm). One metal net was linked to a negative voltage generator, and the other was connected to a grounded line. The frame was placed between the two nets to create a separation interval of 6 mm. The grating was placed beneath the grounded metal net and on the soil bed. The arc-discharge exposure method was originally devised to eradicate warehouse pests, such as the rice weevil, nesting in dried post-harvest products [37,40]. In addition, Kakutani et al. [38] applied it to a pigsty window to kill mosquitoes that transmit Japanese encephalitis viruses between pigs and humans. In this study, the system was used to kill adult houseflies that emerged from underground pupae.

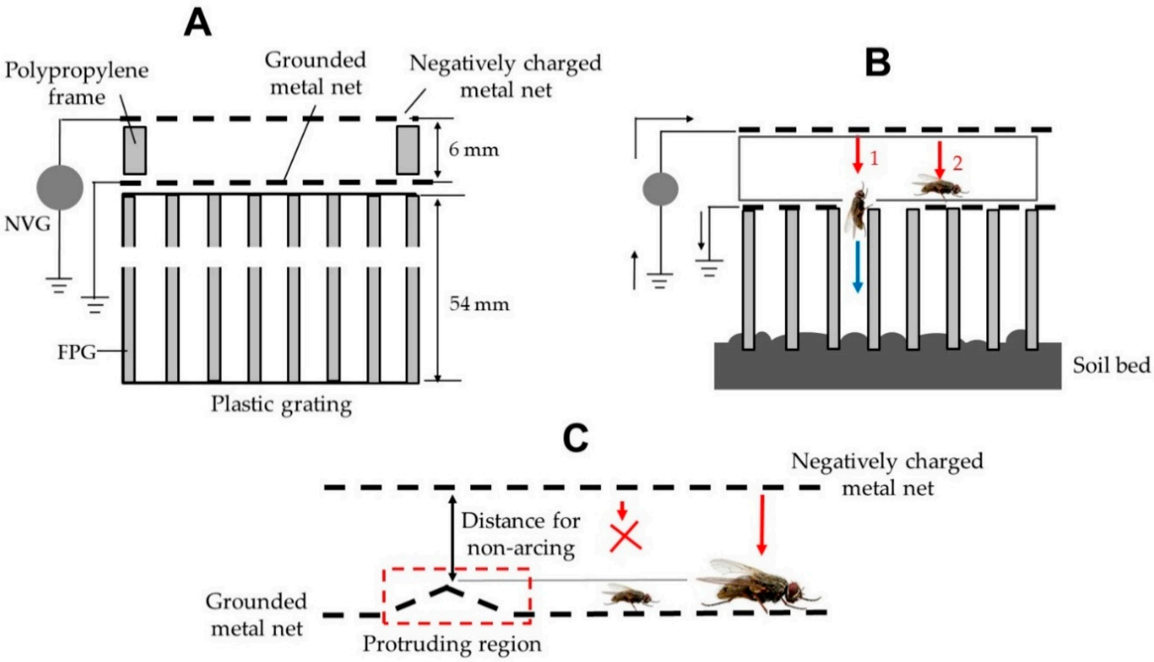

Figure 6. (**A**) Schematic representation of an arc-type soil cover system developed to kill insect pests that emerge from a soil bed. (**B**) Two-step arcing from the charged metal net to a fly that climbed along the wall of the grating and reached the electric field (red arrow 1) and a fly that clambered over the grounded metal net (red arrow 2) (cross-sectional view). The black arrow represents the direction of current flow, and the red arrow shows the electricity movement caused by arc discharge. The blue arrow represents the fall of an insect to the bottom of the grating after arc discharge exposure. (**C**) Successful and unsuccessful arcing to target flies based on their body size difference.

The essential goals were to examine the relationship between the pole distance (the separation distance between the negatively charged and grounded metal nets) and the occurrence of arcing and establish the optimal operating condition, where arcing occurs only when the insect enters the electric field between the two nets and is directed toward the insect. As mentioned earlier, insects are conductive and so become an intermediate pole between the two nets. In this situation, two-step arcing occurs. A first arcing occurs between the charged metal net and the insect, and a second occurs between the insect and the grounded metal net. In the present soil cover system, the insect was subjected to arc discharge from the charged metal net when the adult housefly extended a portion of its body over the grounded net (Figure 6B, red arrow 1) (Video S4). The arcing occurs specifically at any location of the target in the electric field. The insect is then pushed to the bottom by the strong impact caused by arc discharge [42]. In addition, the device produces a second arc discharge toward any housefly that evades the first arc and clambers over the grounded metal net (Figure 6B, red arrow 2). This two-step arc system was highly effective at controlling houseflies emerging from underground pupae at the soil bed surface.

Nevertheless, it is unsuitable for smaller flies, such as tomato leaf miner flies (Figure 5B). The problem is the low uniformity of the metal nets used for the construction of the apparatus. The separation interval of the two nets is formed by the 6 mm high square frame placed between the two nets. However, any protruding region on the net surface can be a site ejecting or receiving discharge because arcing occurs at the short distance between the nets; moreover, other non-protruding (lower) regions on the net become safety zones for small insects (Figure 6C). In the case of adult tomato leaf miner flies, a small protrusion with a height of less than 1 mm can invalidate the arc discharge exposure treatment. On the other hand, adult houseflies are large enough that a small protrusion from the net surface can be ignored (Figure 6C).

Figure 7A shows the structure of a capturing-type soil cover system [61]. Adult tomato leaf miner flies were effectively trapped by the system when they emerged from pupae and flew upward (Figure 7B) (Video S5). This device consists of two sets of iron rods welded to an iron frame. The iron rods and frame of one set were coated with a soft polyvinyl chloride resin (10^9 Ωcm) and linked to a negative voltage generator. The iron rods of the other set were not insulated and linked to a grounded line. The iron rods of both sets were arranged in an offset configuration to produce static electric fields between the oppositely charged iron rods (a modified SD screen) (Figure 7B). Adult houseflies emerged from pupae, climbed to the soil surface, and then flew into the static electric field of the soil cover (Figure 7B). The charged insulated conductor wire had a strong force and captured the flies.

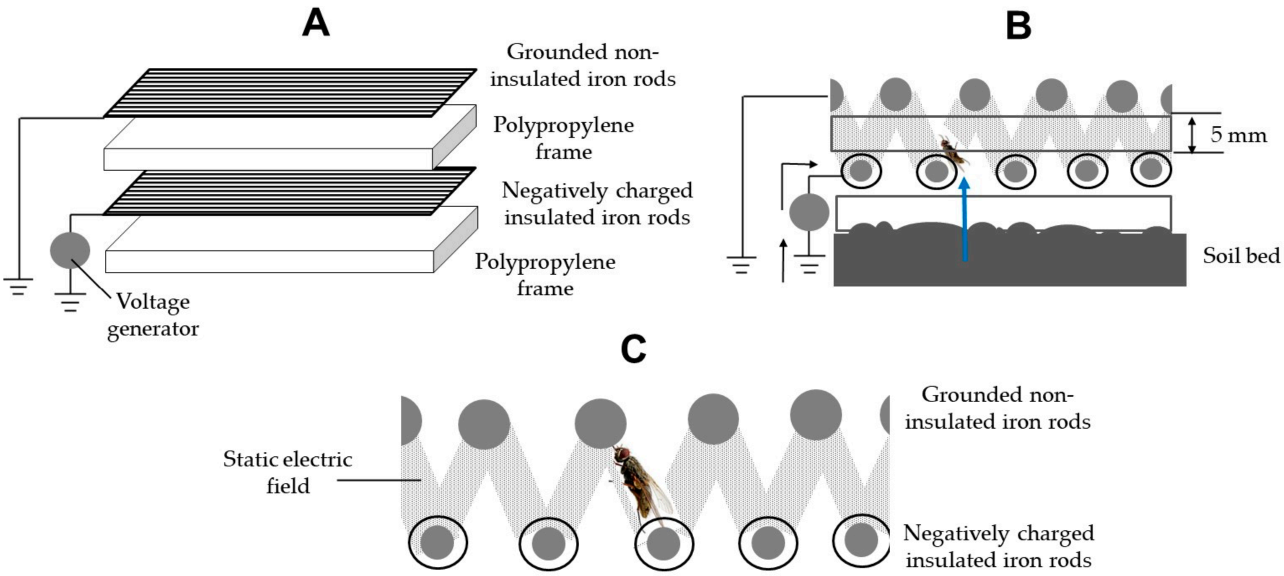

Figure 7. (**A**) Schematic representation of a capturing-type soil cover system developed to trap adult tomato leaf miner flies emerging from underground pupae. (**B**) Capture of a fly entering the static electric field of the negatively charged insulated conductor wire (cross-sectional view). The blue line represents the path of adult houseflies emerging from underground pupae. (**C**) Bridge formation by a fly caught between the opposite poles (negatively charged insulated and grounded non-insulated conductor wires). Larger flies reach both poles and form a direct route for electric current flow between the opposite poles.

This capture-type system, negatively charged at 4 kV, generated a force strong enough to capture the leaf miner flies that flew up toward the charged insulated conductor wire. However, this voltage was insufficient to capture larger insects such as adult houseflies. In fact, −7.5 kV charging is necessary for the successful capture of this fly due to its larger body size [62]. However, if that charge is applied, the charged conductor causes a continuous corona discharge (silent discharge) or spark (arc) discharge between the poles [63]. Furthermore, a bridge between the opposite poles may be established by an insect's body because the adult housefly is large enough to touch both poles (Figure 7C). In this case, electric current flow occurs easily and eventually causes the insulating coating to break down. Thus, this system was used only for small flies.

6. Current Condition and Future Perspectives of Electrostatic Pest Management Research

This review article provides a summary of the electrostatic approach for greenhouse pest management. The approach consists of techniques for constructing unique apparatuses for generating electric fields. The basic components are conductor materials, insulating coatings for conductors, and negative and/or positive voltage generator(s). A common characteristic of the systems is a simple structure that enables ordinary greenhouse workers to fabricate and implement their own versions cheaply using common materials. In this article, we describe various examples of electric field-generating apparatuses to provide useful guidelines for this purpose. Conversely, the arc discharge-generating devices are even simpler, eliminating the need for any guidance toward designing them.

A voltage generator is an electrical appliance involved in all of the pest management instruments. The difference between a negative and a positive voltage generator is that the Cockcroft circuit is set oppositely. Two configurations are commercially available for both generators: a fixed voltage and an adjustable voltage. In our approaches, the adjustable voltage model was used to examine the relationship between applied voltage and the occurrence of electrostatic phenomena. However, after an optimal voltage is determined, the fixed voltage model is more suitable for practical use because of its lower cost.

In our electrostatic research, two problems remain unresolved. One is theoretical, and the other is practical. The first problem is the volume resistivity of the insulating coatings. This problem is critical, particularly when producing the static electric field of the SD and DD screens. The data obtained indicate that the resistivity range of 10^8–10^9 Ωcm is ideal for producing a static electric field that can exhibit the desired functions of repelling or capturing insects entering the field. The resistivity of the insulating coating limits the range of the applicable voltage. We used the voltage range causing no arc discharge between opposite dipoles. Nevertheless, in this voltage range, we detected the occurrence of silent discharge (continuous corona discharge) between the poles, which is accompanied by a very small amount of electric current (approximately equal to or less than 0.01 μA, beyond the detection limit of our current detector). This trace current has no effect on the repelling or capturing function of the electric field screens. In our preliminary analysis, these functions were not detected in either the case of an acrylic resin with higher resistivity (10^{12} Ωcm), which produces a stronger electric field intensity by the higher voltage applied without causing any silent discharge, or a soft polyvinyl chloride tube possessing lower resistivity (10^4 Ωcm), which produces a larger electric current by silent discharge with weaker field intensity. In future work, it is essential to clarify the complicated relationships among volume resistivity, applied voltage, and field intensity in terms of the insect repelling and capturing functions.

The second remaining problem is the improvement of the weatherability of the insulating coating. The insulation of the conducting material is a vital point in electric field screen construction. Conductor wire is typically insulated by passing it through a soft polyvinyl chloride tube. This is easy to prepare, and there is no problem with functionality. However, the insulated conductor wire is susceptible to serious deterioration, such as deformation, discoloration, hardening, and cracking, due to changes in ultraviolet (UV) irradiation, temperature, and humidity in the outdoor environment. Fundamentally, adding a conductive substance to an insulator reduces the insulator's resistivity. For example, adding a plasticizer or UV absorbent material (to improve weatherability) lowers the volume resistivity (10^{15} Ωcm) of polyvinyl chloride resin to the level of 10^{14} to 10^8 Ωcm. In fact, polyvinyl chloride materials mixed with various substances are commercially available as various soft polyvinyl chloride tubes, and these materials have distinct qualities with different volume resistivities and weather resistance levels. From a practical point of view, an exploration of suitable insulating materials is a vital step in the quality testing of the electric field screen.

7. Conclusions

Various instruments for pest management were introduced based on related electrostatic principles. The wide variety of devices and their structural simplicity enable ordinary greenhouse workers to fabricate a particular tool that is most suited to their demands cheaply and using common materials. Three alternative pest-control functions, repulsion, capture, and arc exposure, were discussed to assess the feasibility of each choice. The repelling function of the SD screen is applicable to a variety of insect pests, irrespective of pest size. The DD screen is applied most effectively to capture small insect pests that pass through a conventional insect-proof net. At present, the use of the arc discharge method is restricted to larger flies that emerge from underground pupae. Thus, this review article provides an experimental basis for developing efficient physical methods to control insect pests in greenhouses.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13010023/s1. Figure S1: (A) Schematic representation of insect capture by discharge-mediated positive electrification of the insect in the static electric field of a single-charged dipolar electric field screen (SD screen). (B) Schematic representation of the insect capture mechanism in the static electric field of the double-charged dipolar electric field screen (DD screen); Figure S2: Schematic representations of (A) grounded and (B) ungrounded circuits integrated into a DD screen; Figure S3: Photograph and schematic representation of a bamboo blind-type electric field screen (A), an electrostatic flying insect catcher (B), an electrostatic cabinet (C), and an electrostatic nursery shelter (D); Figure S4: (A) Three types of single-layered DD screen examined during a greenhouse assay. (B) Schematic representation of a DD screen consisting of two identical SM screen units with an insulating coating (transparent soft polyvinyl chloride tube) filled with yellow-colored water. (C) Transparent tubes with yellow-colored water arranged in an offset configuration; Table S1: Capture of insect pests blown toward insulated conductor wires of different types of double-charged dipolar electric field screens (DD screens); Video S1: Demonstration of avoidance of the static electric field of the SD screen by cigarette beetles; Video S2: (A) Avoidance of static electric field of the SD screen (negatively charged with 1.5 kV) by adult whiteflies under the no-blow condition. (B) Capture of whiteflies that were forcibly pushed into the electric field under the blowing condition of 5 m/s; Video S3: Capture of whiteflies by insulated conductor wire of the single-layered DD screen negatively charged with 0.6 kV (A) and 1.2 kV (B); Video S4: Arc-discharge exposure of an adult housefly by the negatively charged metal net of the arc-type soil cover system; Video S5: Emergence of an adult tomato leaf miner from a pupa and capture of the fly with an insulated iron rod of the horizontally placed electrostatic cover (−4 kV charge).

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