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*Review*

# A Promising Physical Pest-Control System Demonstrated in a Greenhouse Equipped with Simple Electrostatic Devices that Excluded all Insect Pests

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**Abstract:** Applied electrostatic engineering can be used to construct greenhouses that prevent entry of insect pests. Two types of electric field screen were used to exclude pests from the greenhouse: single- and double-charged dipolar electric field screens (S- and D-screen, respectively). The S-screen consisted of iron insulated conductor wires (ICWs) arrayed in parallel (ICW-layer), a grounded metal net on either side of the ICW-layer, and a direct current voltage generator. S-screens were attached to the side windows of the greenhouse to repel whiteflies (*Bemisia tabaci*) that approached the nets. The D-screen was installed in a small anteroom at the greenhouse entrance to capture whiteflies entering through it. The ICW-layers of the D-screen were oppositely charged with equal voltages and arrayed alternately, and an insulator board or grounded metal net was placed on one side of the ICW-layer. The ICW-layers captured whiteflies entering the electric field of the double-charged dipolar electric field. Three screens equipped with yellow or gray boards or a grounded metal net were installed in the anteroom based on the airflow inside the room, as most whiteflies were brought in by air when the door was opened. Two D-screens with boards were useful for directing the airflow toward the wall with the netted D-screen. This screen eliminated the insects and the pest-free air was circulated inside the greenhouse. The D-screen with the yellow board attracted the whiteflies and was effective for trapping them when there was no wind. Our method kept the greenhouse pest-free throughout the entire period of tomato (*Solanum lycopersicum*) cultivation.

**Keywords:** electric field screen; pest management; photo-selective nets; whiteflies

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## 1. Introduction

The protection of crop plants from infection or attack by pathogens and pests using safe, environmentally benign methods has been a long-standing goal. Much effort has focused on developing biological and chemical methods to achieve this, including the production of resistant crop plants using conventional and new biotechnological techniques, biocontrol of pathogens and pests using antibacterial, antifungal, and entomopathogenic microorganisms, and the screening of biologically synthesized compounds that inhibit pathogen growth [1, 2]. Despite much interesting work, there has been little practical progress because the protective effects are easily overcome, and because of problems with agent preparation, limited targets for application, and high costs [1]. The principal barrier to practical implementation lies in the application of individual methods for pathogen and pest control at scales larger than in test experiments, and variable environmental conditions. Trials have shown that the aforementioned techniques are, in essence, supplementary measures suitable for a limited range of targets under specific conditions. The lack of reliable basic methods that can be combined to constitute a suitable approach must be addressed.

Once a realistic research objective is set, steady progress can be made via the creation and refutation of working hypotheses formulated from reproducible experimental results, eventually leading to new applications for electric field screens [3]. An electric field screen is an air-shielding apparatus based on the principles of applied electrostatic engineering, and was introduced in 2006 as a physical tool to trap airborne conidia of tomato powdery mildew (*Oidium neolycopersici*) [4]. Powdery mildews are fungal pathogens in the order Erysiphales that affect many plant species. Powdery mildews grow well in environments with high humidity and moderate temperatures; greenhouses provide an ideal moist and temperate environment for spreading these diseases. We focused on *O. neolycopersici* on greenhouse tomatoes (*Solanum lycopersicum*), which infects not only all commercial tomato cultivars tested [5], but also cultivars bred for resistance against a European isolate of the tomato powdery mildew pathogen [6]. In a preliminary survey, we found fungicide-tolerant isolates of *O. neolycopersici* on naturally infected tomato leaves, indicating the need for alternative measures to control the pathogen. Although breeding pathogen-resistant traits is the conventional method used to protect crop plants from disease [7-9], we need to remain alert to outbreaks of new pathogenic strains of the pathogen on resistant tomatoes [10-12]. Therefore, we developed new physical electrostatics-based control measures to prevent the spread of the disease [4, 13-15].

Initially, the test apparatus was conceived as a new device for capturing airborne spores of phytopathogenic fungi during crop cultivation in greenhouses [16]. Physical methods, especially those exploiting electrostatic phenomena, can generate physical forces sufficiently strong to catch airborne fungal spores [17] or small flying insects that may pass through the conventional insect netting used to protect greenhouse crops [14, 15, 18-22]. If an effective force could be generated, an electrostatic approach would be an extremely promising tool to provide a spore-free, pest-free space for crop plants in greenhouse environments (**Figure 1A**).

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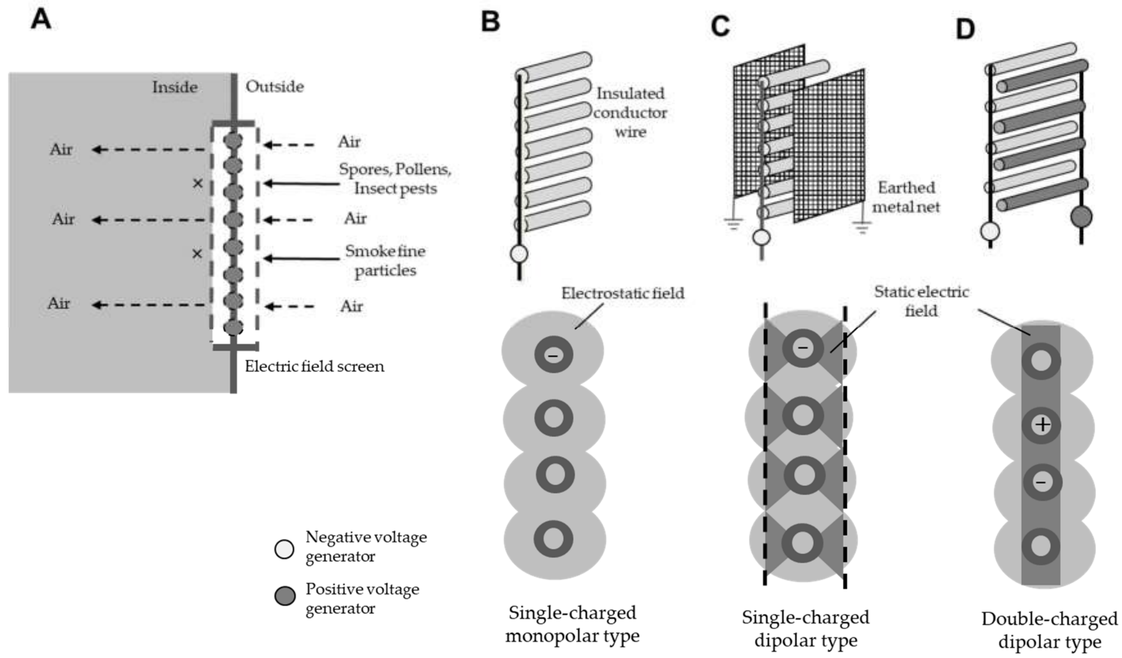


**Figure 1**. Conceptual diagram of the roles of the electric field screen (A), schematic representations of single-charged monopolar (B), single-charged dipolar (C), and double-charged dipolar electric field screens (D) and a cross-sectional view of the insulated conductor wires (ICWs) with an electrostatic field or static electric field in each screen.

As the research progressed, the structure of the electric field screen was optimized so that it could capture not only fungal spores and flying insect pests, but also pollen grains [23] that cause pollinosis [24, 25], and fine particles [26, 27] in tobacco smoke that can cause disease, disability, and death [28-30]. Advances in electric field screen technology have allowed broader application of the device, from agricultural fields, *e.g.*, crop production, processing, and storage, to environmental and public health. Indeed, electric field screens can be used in houses, hospitals, schools, greenhouses (for crop production), warehouses, plants (for processing harvested crops), and animal husbandry facilities [3]. A wide variety of electric field screen structures can be customized to prevent the entry of biotic and abiotic environmental nuisances [25]. **Figure 1B–D** shows the electric field screen types used herein. The terms 'single-charged' and 'double-charged' in the figure refer to how the voltage is applied, i.e., using either a single negative or positive voltage generator, or both types of voltage generator, to produce monopolar and dipolar electric fields, respectively [31-34]. The rod-shaped structures in the figures represent metal (iron or copper) wire with an insulating coating, *i.e.*, an insulated conducting wire; the different colors indicate the application of a positive or negative voltage. The net-like structure is a grounded metal net made of stainless steel or iron. All of the screens have a simple, common structure; therefore, the cost of production is relatively low. Using these devices, we describe the development of two types of electric field screen, with unique structures and electrostatic mechanisms, to construct an ideal greenhouse that can completely prevent the entry of greenhouse pests.

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## 2. Structure and function of a double-charged dipolar electric field screen (D-screen)

### *2.1. Basic structure*

There are various types of electric field screen, all of which include a screen body and an electric driver, *i.e.*, an electric power source and direct current (DC) voltage generator. While the same electric driver is used for all electric field screen types, the screen body may vary depending on the application, and all types involve insulated conductor wires (ICWs) that are arranged vertically to make a barrier of static electric fields (**Figure 1C and D**). An insulated conductor is produced by passing a copper or iron wire through a soft polyvinyl chloride (PVC) tube (1-mm thickness, $1 \times 10^9$ Ω·m) [18].

The voltage generator can be operated by a 12-volt storage battery, and used to boost the initial voltage (12 V) to the designated voltage (1–30 kV) using a transformer and Cockcroft circuit [35] integrated into an electric circuit in the voltage generator (**Supplementary Figure 1A and B**). The difference between the negative and positive voltage generators is that the Cockcroft circuit is set in reverse, such that the negative charge (or free electrons) moves in the reverse direction. A negative voltage generator draws negative free electrons from the ground, which serves as an infinite source or sink of electrons (a source in this case) and supplies electrons to the conducting wire [36]. A negative charge accumulates on the surface of the wire conductor and is induced on the outer surface of the insulated coating of the wire, thereby negatively electrifying the insulator via dielectric polarization [31, 32] (**Supplementary Figure 1A**). A positive voltage generator pushes free electrons to the ground (an infinite sink of electrons) to positively charge the conductor wire (positive electrification) [36], and a positive charge is induced on the outer surface of the insulating coating surrounding the conducting wire (positive electrification) due to electrostatic induction [32]. The positive electrification of the insulated conducting wire causes the insulating coating to become positively charged as a result of dielectric polarization (**Supplementary Figure 1B**).

The most advantageous characteristic of the voltage generator used in this study is the ability to operate the generator using a 12-V DC source. The electric power consumption is small (5 W), effectively equivalent to that of a small lightbulb, so the screen can operate for long periods using a standard storage battery. This feature is useful for the practical implementation of electric field screens. Here, two types of electric field screen are used for this purpose: a single-charged dipolar electric field screen (S-screen; with grounded metal nets) (**Figure 1C**) and a D-screen (single layer type) (**Figure 1D**).

### *2.2. A non-grounded electric circuit is essential for practical implementation*

In the standard electric circuit configuration for negative voltage charging of the electric field screen, electrons are pumped from the ground and supplied to the ICW using a voltage generator. The grounded metal net eventually becomes electrified by electrostatic induction [32]. In terms of current movement, the same amount of electricity can be supplied by the ground to create a static electric field (**Supplementary Figure 1C**). In a non-grounded circuit, the free electrons in the metal net are supplied directly to the ICW using the voltage produced by the generator (**Supplementary Figure 1D**). Therefore, the electric field screen with this circuit does not need to be grounded. By this principle, the electric field screen can be placed freely, allowing portable electric field screens [37, 38].

The principle is exactly the same in the double-charged type, which uses both negative and positive voltage generators; namely, the free electrons in the metal net are supplied to the ICW (**Supplementary Figure 1E**) [39]. In this case, however, the potential difference between the opposite poles (oppositely charged ICWs) doubles, and the force generated is strengthened [25].

*2.3. Insect-capturing function of a double-charged dipolar electric field screen*

The whitefly (*Bemisia tabaci* Gennadius) is a major pest in tomato cultivation capable of passing through conventional insect-proof nets (approximately 1.5 mm mesh) [40]. The greatest economic threat in tomato cultivation is the transmission of damaging plant viruses, primarily Geminiviruses [41, 42]. The whitefly is difficult to control with insecticides because it feeds and oviposits mainly on the abaxial leaf surfaces [43], and because it has developed resistance to most classes of insecticides used for its control [44-47]. Physical methods could provide an alternative means of managing this pest, since they would be compatible with other components of integrated pest management, have little impact on the environment, and reduce pesticide use, thus slowing the development of insecticide resistance [48]. In Japan, *B. tabaci* carries Tomato yellow leaf curl virus (TYLCV), which is a major cause of loss of tomato crops grown in greenhouses [49]. To solve this problem, we used an electrostatic spore precipitator that had been developed to control tomato powdery mildew [4]. This device is so effective at attracting air-borne conidia that tomato plants guarded by the spore precipitator remain uninfected [4]. Despite the success of an electric field in pathogen control, a preliminary attempt to utilize this device for pest control was unsuccessful, because the electrostatic force of the spore precipitator was insufficient to retain trapped adult whiteflies. Successful application of the electric field screen enabled the management of whiteflies and other greenhouse pests [14, 15, 19, 20].

A double-charged dipolar-type screen is easily constructed by linking the ICWs alternately to negative and positive voltage generators [21, 50], forming an electric field between the oppositely charged conductor wires. We know that some electrons are present in air. In this field, the force always works to push electrons (negative electricity) toward the ground [50]. In this field, however, the electrons accumulate around the positive pole because it is insulated (**Figure 2A**). When an insect enters this field, it can be captured in two ways [50]. First, an insect enters the space near the negatively charged ICW (negative pole) (**Figure 2B**). Here, the insect is deprived of its free electrons and is electrified positively and attracted to the negative pole (discharge-mediated positive electrification). Alternatively, an insect enters the space near the positively charged pole (**Figure 2C**), receives electrons and is negatively electrified and attracted to the pole (charge-mediated negative electrification). Video data demonstrated the successful attraction of insects to the ICW (**Video Supplement 1**); the force was strong enough to capture the insects despite a 7 m/s wind. Four kinds of greenhouse pests were included in the tests: whitefly (*B. tabaci*), western flower thrip (*Frankliniella occidentalis* Pergande), green peach aphid (*Myzus persicae* Sulzer), and tomato leaf-minor fly (*Liriomyza sativae* Blanchard). All of these pests can pass through conventional insect-proof nets (mesh size, ~ 1.5 mm) [48]. In farms, small insect pests pose a serious threat to crops. Three of the pests listed above cause particularly severe viral diseases, in addition to damage by pest attack. Whitefly, western flower thrips, and green peach aphid also carry the TYLCV, tomato spotted wilt tospovirus (TSWV), and cucumber mosaic virus (CMV), respectively. All of these pests have already acquired resistance

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against the major available insecticides [47]. **Supplementary Table 1** shows that it is necessary to enhance the voltage in response to the wind velocity and size of the test insects; charging at 2.0 kV was sufficient to capture all of the test insects at the highest wind speed with all screens. Because each screen was charged with the same magnitude of negative and positive voltages, the actual potential difference was twice that of the voltages listed in the table [32]. These results indicated that the screen could deal with all of the major pest insects tested under real-world conditions in a greenhouse.

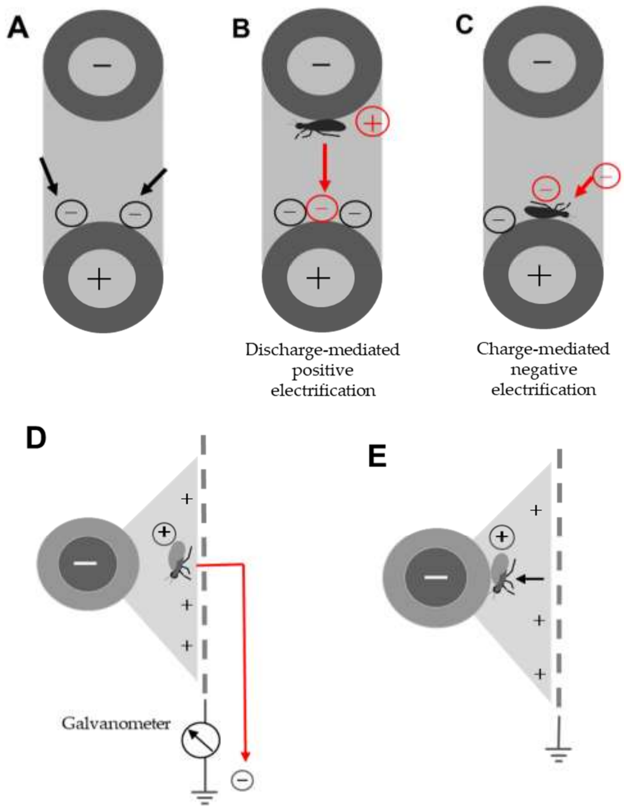


**Figure 2**. Schematic representation of the insect-capturing mechanism of the electric field of double-charged (A–C) and single-charged (D, E) dipolar electric field screens.

*2.4. Insect-repelling function of a single-charged dipolar electric field screen*

During our research, we devised a new method to generate a dipolar static electric field via single charging (**Figure 1C**). The electric field screen creating this field exhibited a revolutionary function for repelling insect pests [19, 51, 52]. An ICW charged with a negative voltage causes dielectric polarization within the insulating coating, creating a negatively charged insulator surface. The charged surface of the insulator produces an electrostatic field in the surrounding space [32, 33] (**Figure 1B**). The difference from the S-screen design is that we placed a grounded metal net inside the electrostatic field produced by the insulated conducting wire (**Figure 1C**) [51]. The grounded metal net facing the charged insulated conductor becomes positively charged as a result of electrostatic induction [32]. Therefore, given that the ground is an electron source or sink, the free electrons in the metal net are pushed to ground by the negative insulator surface, because like charges

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repel. The electron deficiency in the metal net leaves the net with a positive charge. The opposite negative charge of the ICW and positively charged grounded net create a dipole, forming an electric field in the space between them. Therefore, we can create a positive pole (grounded metal net) without using a positive voltage generator. This is our single-charged dipolar electrification system. As shown in the figure, a static electric field is formed inside the electrostatic field. If we place another grounded net on the opposite side of the ICW, a static electric field forms in a manner consistent with bilateral symmetry. Accordingly, if we arrange the ICWs such that the upper and lower ends of the two static electric fields contact each other, a new electrostatic barrier consisting of static electric fields is formed (**Figure 1C**) [51].

In an experiment to examine the entry of insect pests, using partitions a greenhouse was divided into three rooms equipped with S-screens installed in the windows of both end rooms. The numbers of pests that entered each room were determined by counting the pests trapped on the yellow and blue adhesive plates hung therein. In this experiment, many whiteflies and tomato leaf-minor flies were trapped by the yellow plates. The results clearly show that the electric field screen excluded pests from the greenhouse. Over the 2-week experiment, an average of 1,000 pests entered the unguarded center room. In comparison, no pests were observed on the adhesive plates in screen-installed, door-locked rooms. In the side room that allowed the entry/exit of workers during the experiment, a few pests entered via the door. Nevertheless, the rate of pest exclusion exceeded 92%, indicating that the electric field screens successfully prevented pest entry through the windows. Because numerous pests invaded the central room, it is reasonable to assume that similar numbers of pests attempted to invade both side rooms of the same greenhouse. Therefore, we initially expected to find that the electric field screens of these side rooms had trapped the same number of pests as were trapped in the central room. In fact, fewer insects were trapped, suggesting that the electric field screens actually repel the pests.

To prove this, an acrylic cylinder with an axial fan was constructed to examine the behavior of pests placed therein (**Video Supplement 2**) [19]. The cylinder was placed in contact with the grounded metal net of the screen to observe the insects reaching the net. Moreover, insects were blown forward when they reached the net. With no airflow, all of the pests that reached the net stopped and placed their antennae or legs inside the static electric field of the screen, similar to a 'searching' behavior. These pests were deterred from entering the static electric field of the screen (**Video Supplement 2A**). In comparison, when the pests were blown forward, almost all of them clung to the net and assumed a posture to avoid the wind. However, some of the pests lost their grip and were forcibly pushed inside the screen. These pests were captured by the strong force of the electric field (**Video Supplement 2B**). These results are important as they confirm that all pests reaching the grounded net of the electric field screen attempted to avoid the field (*i.e.*, they were repelled by the screen), and had to be forcibly pushed inside it by air. This is in good agreement with the experimental results described in the previous section. The results of the insect avoidance assay indicated that all insects tested exhibited avoidance behavior with respect to the static electric field. The insects tested covered 17 orders, 42 families, 45 genera, and 82 species (**Supplementary Table 2**) [52]. From these results, we concluded that all insects are deterred by the static electric field of the electric field screen.

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### 2.5. Insect-capturing function of the single-charged dipolar electric field screen

**Video Supplement 2B** shows that the ICW of the S-screen can capture insects blown inside the electric field. This screen uses a strong force to capture various insect pests, including greenhouse pests [whitefly, green peach aphid, western flower thrip, tomato leaf-minor fly, green rice leaf hopper (*Nephotettix cincticeps* Uhler), and shore fly (*Scatella stagnalis* Fallen)] [53, 54], warehouse and food processing factory pests [cigarette beetle (*Lasioderma serricorne* F.), rice weevil (*Sitophilus oryzae* L.), red flour beetle (*Tribolium castaneum* Herbst), Adzuki bean weevil (*Callosobruchus chinensis* L.), and vinegar fly (*Drosophila melanogaster* Meigen)], museum pests [book louse (*Liposcelis bostrychophila*)], and domestic pests [common clothes moth (*Tineola bisselliella* Humm.), bathroom fly (*Clogmia albipunctata*), German cockroach (*Blattella germanica* L.), Oriental termite (*Nasutitermes matangensis*), and Asian tiger mosquito (*Aedes albopictus*)] [55, 56], indicating that our method is applicable to a wide range of pest control problems.

The major characteristic of the static electric field is the negative charge of the ICW, which creates a strong repulsive force for other negative charges in the electric field, pushing them toward the ground via the metal net. In this way, any conductor that enters the field is deprived of its free electrons and becomes positively charged. This phenomenon is called discharge-mediated positive electrification (of the conductor), and can be used to the insect itself and how it responds to the static electric field upon entering. Most insects possess a solid cuticle layer, which is the outer protective layer that covers the body. This layer is conductive [57-61]. Consequently, an insect that enters a static electric field is deprived of free electrons in the cuticle layer and becomes positively charged (**Figure 2D**) [62-64]. Discharge-mediated positive electrification can be induced in actual insects, as the free electrons of the cuticle layer move to ground. A galvanometer for detecting electric current can be integrated into the ground circuit to detect this type of electron movement. Positively electrified insects are attracted to the central ICW (**Figure 2E**). The force is so strong that the captured insect cannot escape. This capturing mechanism is applicable to almost all insects, as they tend to possess conductive cuticle layers. **Supplementary Table 1** shows the results of the insect-capturing assay. The results are summarized below. Larger voltages are required to capture larger pests. In all pests, higher voltages produce stronger forces for capture. Charging at 4.2 kV was sufficient for capturing all of the pests tested in this study. The captured insects were held tightly and were not blown away with airflow at 7 m/s. Therefore, the electric field screens installed in the greenhouse were charged at 4.2 kV for field experiments.

## 3. Configuration of a model greenhouse completely preventing the pest entry

### 3.1. Installment of electric field screens on the side windows of a greenhouse

The electric field screen first put to practical use was the single-charged dipolar type produced by our laboratory (Faculty of Agriculture, Kindai University) (**Figure 3A**) [65], and units were developed to install the screens on the side windows of the experimental greenhouse. The electric power consumed by the voltage generator was minimal, and could be provided by a standard lithium storage battery; normal alternating current (AC) domestic power sources could also be used. The screens were negatively charged at 4.2 kV, as described above. The ventilating fan was also covered with an electric field screen box to prevent pests from invading via the opening for the fan, especially

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when the fan was stopped (**Figure 3A**). The grounded metal net of the electric field screen was a stainless steel net with the same mesh size (~1.5 mm) as a conventional woven insect net. Larger pests that cannot pass through this mesh were not tested, as they were prevented from entering by the net, without the need for an electric field screen.

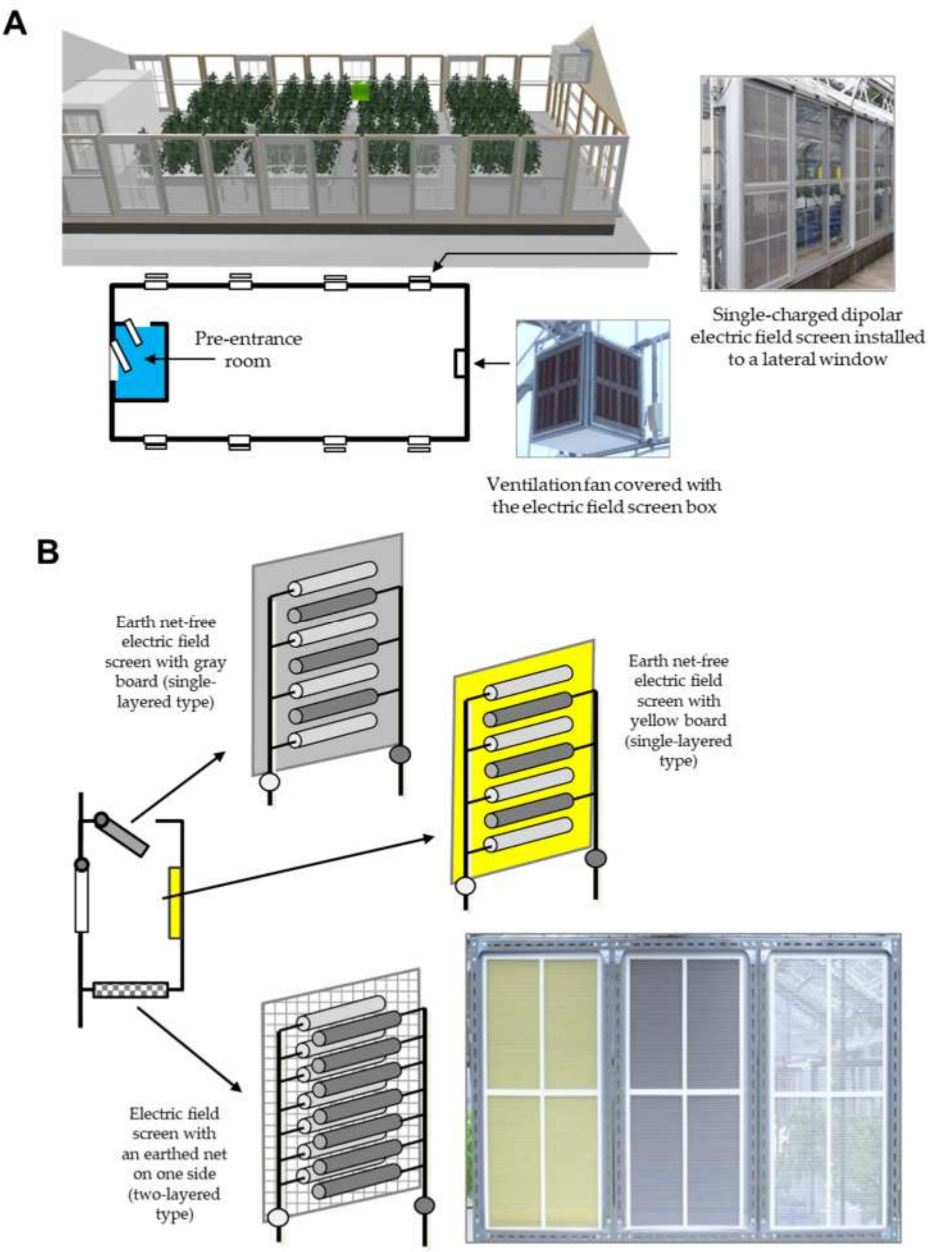


**Figure 3**. An ideal greenhouse that completely excludes pests (A) and the three types of electric field screens installed in the anteroom (B).

In the S-screen, all parts are integrated into the main body (**Supplementary Figure 2A**). This screen requires no special modifications or ground installation. The first S-screen produced by our laboratory consists of three units: ICWs held by a frame that integrates a negative voltage generator,

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two stainless net frames containing contact plugs and electric lines to the voltage generator, and a lithium battery. The lithium battery is installed on the surface of one of the net frames. The three unit frames are combined by simply placing the two net frames on either side of the ICW frame.

In laboratory-scale experiments, the ICW, which is the heart of the electric field screen, was made by passing a metal wire through a soft PVC tube. The electric field screen is easy to construct and there are no functional problems. In outdoor experiments with longer exposure periods, however, installed electric field screens are susceptible to discoloration, deformation, and cracking due to changes in temperature, humidity, and ultraviolet irradiation. These issues limit the practical implementation of electric field screens. In commercial electric field screens (single-charged dipolar type), the conductors are coated with PVC resin to prolong screen operation in outdoor environments with minimal deterioration [65]. Such screens are built and sold by Sonoda Seisakusho (Osaka, Japan), a joint-stock company that designs, installs, inspects, and maintains electric field screens. A commercial electric field screen produced by Sonoda Seisakusho was installed in a greenhouse in Osaka Prefectural Research Institute of the Environment, Agriculture, and Fisheries (**Supplementary Figure 2B**). It was constructed by welding multiple iron wires to an iron frame, coating it with PVC resin, and placing grounded metal nets on either side of the frame. Another marketable electric field screen is manufactured by Nabec (Panasonic Environment Engineering, Nagoya, Japan) and the ICW is produced by coating iron-expanded metal with PVC resin (**Supplementary Figure 2C**). Grounded stainless steel nets with a diamond-shaped mesh were placed on each side [65]. This electric field screen is also weatherproof, and can be used outside for long periods without performance deterioration.

### *3.2. Construction of an air-oriented anteroom with an electric field screen*

In a greenhouse in which the side windows were equipped with S-screens, the problem of pest entry through the greenhouse door remains. To solve this problem, an anteroom was created to eliminate pests (**Figure 3B**) [21]. Ground net-free D-screens were installed in the anteroom in an attempt to create an ideal greenhouse that excluded all pests. Three types of electric field screen were installed in this anteroom: 1) a ground net-free, single-layer type with a yellow board on the wall opposite the entrance to the anteroom; 2) a ground net-free, single-layer type with a gray board at the entrance to the greenhouse, and 3) a single-layer type with a grounded metal net on one side on the wall opposite the greenhouse entrance (**Figure 3B**). A preliminary study indicated that whiteflies were preferentially trapped by the screen with the yellow board due to their photoselectivity.

The concept of an anteroom for eliminating pests combines the functions of electric field screens with regulation of the airflow in the room (**Figure 4**). This room was designed to generate airflow mechanically when the doors were opened, and to direct the airflow through the electric field screen [21]. To evaluate the effectiveness of this system, we blew air into the anteroom when the door was opened and simultaneously released whiteflies to examine the direction of the airflow and the capture of insects by the electric field screens (**Figure 4A**). More than 90% of the insects released were directed by the airflow and captured by the screen with the yellow board installed on the front wall. When there was no blowing air, although more time was needed, this screen attracted and trapped almost all of the insects. Next, air was automatically blown inside the anteroom when the greenhouse entrance was opened (**Figure 4B**). The airflow passed through the electric field screen to the opposite

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wall. The screen trapped the insects and pest-free air was directed into the greenhouse. This screen was furnished with a grounded metal net on one side to repel useful insects, such as pollinators, from inside the greenhouse.

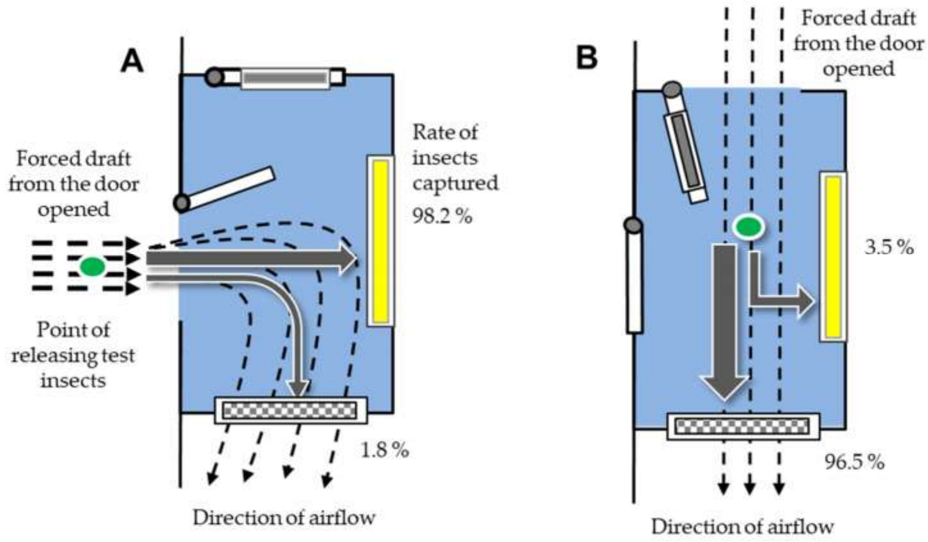


**Figure 4**. Schematic representation of pest elimination in an airflow-oriented anteroom with electric field screens.

### *3.3. Supplementary electrostatic devices*

In a greenhouse in which the side windows and anteroom are furnished with electric field screens, the entry of pests through the windows is prevented. Nevertheless, there was a risk of invasion by insect pests that avoid the electric field screens installed in the greenhouse. The rate of pest invasion through the entrance is low; however, such entry cannot be neglected as secondary propagation of invading pests can lead to serious insect damage to cultivated plants. An electrostatic insect sweeper and electrostatic flying insect catcher are useful for eliminating these pests in the initial stage of invasion.

The second apparatus put into practical use was an electrostatic insect sweeper (**Supplementary Figure 3A**) [37]. In this apparatus, a S-screen is wound around a cylindrical PVC pipe (**Supplementary Figure 3B**). The non-grounded circuit was integrated such that no ground line was necessary. This apparatus is easy to operate in greenhouses (**Supplementary Figure 3C, D**). The electrostatic insect sweeper is useful for trapping insect pests that frequently rest on leaf surfaces, such as whiteflies and aphids [37]. This apparatus was developed as a supplementary device for use in greenhouses guarded by electric field screens. The pest population can be reduced considerably by incorporating a sweeper as part of the routine care of cultivated plants. The electrostatic insect sweeper is also produced by Sonoda Seisakusho [65]. The electrostatic insect sweeper has a non-grounded circuit that produces a static electric field in the space between the ICW and the non-grounded metal net. Insect pests are captured in this field. The size of the pests trapped varies with

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the charging voltage. Whiteflies and western flower thrips were captured with a 0.8 kV charge, whereas green peach aphids, tomato leaf-miner flies, and shore flies required 1 kV [37]. Insects are trapped easily after gently brushing the leaves they are resting on with the sweeper (**Supplementary Figure 3B**). This approach is especially effective for trapping whiteflies, as they tend to stay on leaf surfaces for long periods (**Supplementary Figure 3E**).

An electrostatic flying insect catcher (electrostatic racket) (**Supplementary Figure 4**) [38] is a device used to capture flying pests. It is carried by a greenhouse attendant during routine plant-care checks and is used to capture flying insects quickly, as they appear. It is possible to reduce the pest population significantly with continual, diligent use of the device. The catcher was developed to supplement the electric field screens, but is also useful in unprotected greenhouses. The area of the racket surface is easily modified so that 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. Sonoda Seisakusho also makes a commercial electrostatic flying insect catcher [65].

## 4. Evaluation of the effectiveness of pest exclusion from a greenhouse by electrostatic guarding

In an actual greenhouse experiment, the greenhouse was separated into two rooms by a partition. In one of the rooms, the anteroom was furnished with D-screens, and all of the side windows were equipped with S-screens (negatively charged at 4.2 and 2 kV, respectively). The ventilating fan was also covered with an electric field screen box to prevent pests from invading via the opening for the fan, especially when the fan was stopped. The second room had no anteroom; no screens were installed on the side windows and it served as a control. We examined the entry of insect pests into both rooms. Each experiment lasted 2 weeks, and six experiments were conducted in total. In the greenhouse, blue and yellow adhesive plates were hung at constant intervals to trap any pests that invaded from the outside. Whiteflies, tomato leaf-minor flies, and green peach aphids are attracted to the color yellow, while the western flower thrip prefers blue. The number of pests trapped by the adhesive plates was counted to determine the number of pests in the greenhouse. In this experiment, we also carefully surveyed individual tomato plants cultured in the screen-furnished room to check for insects that may have hidden under plant leaves.

Over the course of the experiment, no green peach aphids or western flower thrips were found, while moderate to severe whitefly and tomato leaf-minor fly invasions were evident. As shown in **Supplementary Table 3**, both types of pests were completely prevented from entering the screen-installed room in all experiments. These experiments clearly demonstrated the practicality of the electric field screens. The severity of the pest invasion was clear from the number of pests trapped by the yellow adhesive plates hung inside the control room, and the experimental room would have been invaded similarly without the preventive measures. These results again demonstrate the effectiveness of electric field screens for pest control.

In this greenhouse study, the installed electric field screens effectively excluded the pests, and no supplementary devices (i.e., the electrostatic insect sweeper and electrostatic flying insect catcher) were required. Nevertheless, supplementary devices are an emergency measure when pests evade other means of trapping.

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## 5. Conclusions and future perspectives

Applied electrostatic engineering has successfully managed pathogens and insect pests affecting agricultural crops at various stages of crop production and preservation. Electrostatic principles have been applied in diverse ways, including for capturing spores and insects by exploiting the attractive force generated in a static electric field (without electric discharge) [4, 20, 21, 50, 51, 66-69], repelling insects via their aversion to electric fields [19, 51, 52], disinfecting bacterial and fungal pathogens using ozone produced through streamer discharge [16], instantaneously dislodging fungal pathogens from plants through exposure to a plasma stream produced via a corona discharge in the electric field [13], instantaneously pulverizing insects nesting in dried rice grains [70], electrocuting virus-carrying mosquitoes in the screen by insect-mediated arch discharge [71], and negatively ionizing smoke particles in the ionic wind produced during corona discharge [27]. In this work, we used electrostatic devices to repel and capture insect pests, creating a pest-free space in a greenhouse with open windows. Based on these successful applications, we could realize a non-insecticidal pest control system for crop plants.

The electrostatic devices described here are patented inventions. The patent holders are Kindai University (Osaka, Japan), Kagome (Tokyo, Japan), Panasonic (Tokyo, Japan), and Osaka Prefecture (Osaka, Japan). Kindai University is in charge of managing the patent licenses and has prepared contracts for patent use. Contractors (including farmers) are allowed to make electric field screens (single-charged dipolar type) and related apparatuses (electrostatic insect sweeper, electrostatic flying insect catcher, electrostatic cabinet [20], and electrostatic seedling shelter [15]) for personal use or to produce and sell under specific agreements. Research that has a real impact on society has been our dream from the beginning. Therefore, the concepts and technologies originating from our university laboratory are made readily available to the public, in an effort to fulfill our mission of contributing to society by helping to solve real-world problems and move science forward. Our role will not change with greater recognition of this technology, and we will continue to research diligently and promote reliable techniques to improve the lives of others.

**Supplementary Materials**: Video Supplements 1 and 2: Test insect pests (whiteflies, western flower thrips, green peach aphids, and tomato leaf minor flies) captured with the insulated conductor wires (ICWs) of D-screens (1) and whiteflies captured and repelled with a S-screen (2). Supplementary Figures 1–4: Structure and function of voltage generators (1) and the marketable electrostatic devices developed (2–4). Supplementary Tables 1–3: List of voltages applied to the single- and double-charged dipolar electric field screens (S-screens and D-screens, respectively) to capture all test insects blown toward the insulated conductor wires at different wind speeds (1); list of insects examined in terms of their avoidance of the electric field of the S-screen (2); and the results of a pest exclusion assay in a greenhouse, in which the side windows and anteroom were furnished with S- and D-screens, respectively (3).

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