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Editorial

Electrostatic Techniques for Physically Managing Pathogens, Insect Pests, and Weeds in Field and Greenhouse Cropping Systems

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1. Introduction

The primary focus in pest management across all pest classes, including pathogens, insect pests, and weeds, is on shifting towards methods that do not rely on pesticides. This shift is driven by the emergence of pesticide-resistant pests due to the extensive use of chemicals [1–4] and increasing public demand for reduced or pesticide-free agriculture. In alignment with this research direction, this editorial introduces a new wave of electrostatics-based physical pest control methods.

A thorough understanding of electrostatics has laid the foundation for the development of innovative tools to combat plant pathogens, insect pests, and weeds in both field and greenhouse settings. These tools encompass devices that create an electric field [5], defined as the region surrounding an electric charge where it can exert a noticeable force on another electric charge [6]. The core component of these devices is an insulated conductor charged negatively using a voltage generator [5]. The insulation of the charged conductor is crucial to establish a non-discharging electric field around it. These electric field-based devices are known as electric field screens and are of three types: single-charged monopolar, single-charged dipolar, and double-charged dipolar [5]. The force generated by these electric field screens has been harnessed to capture airborne spores [7], plant pollen [8], and flying insect pests [9,10]. In contrast, a different type of device, constructed with a non-insulated charged conductor, generates an arc (spark) discharge aimed at targets [11]. This device is referred to as an arc-exposing electric field screen and is employed to manage insects and weed seedlings emerging from the ground [9]. Hence, these devices can be customized to suit the specific electrostatic characteristics based on the nature of the targets.

The most notable feature of these electric field-based devices is their straightforward design, which allows ordinary workers to construct them inexpensively using readily available materials or modifying them as required. Electrostatic traps have demonstrated practicality in preventing wind-borne pathogen spores and flying insect pests from infiltrating greenhouses [12] and in monitoring their spatial and temporal patterns to design safe crop production areas [13]. Safe arcing devices can also serve as practical tools for simultaneously eliminating weeds and insect pests emerging from crop fields [14].

In this editorial, the author provides basic information and explanations about electric field screens for ordinary crop growers who may not be familiar with the technical aspects. The aim is to encourage their active participation in new research endeavors related to pest control. Ongoing research in this area offers fresh insights for developing reliable plant protection methods and ensuring sustainable crop production that can effectively adapt to various changes in different cropping systems.

2. Charging of an Insulated Conductor

A conductor can be charged either negatively or positively by connecting it to a grounded voltage generator. This voltage generator increases the initial voltage to the desired level [15]. When using a negative voltage, the generator takes free electrons (negative charge) from the ground and transfers them to the conductor, resulting in negatively charging the conductor. Conversely, when using a positive voltage, the generator pushes free electrons out of the conductor into the ground, causing it to acquire a positive charge. To prevent the discharge of the conductor, it is coated with an insulating material like soft polyvinyl chloride, which has a recommended volume resistivity of 10^9 Ωcm [5].

3. Construction of Electric Field Screens

Figure S1 illustrates the components (Figure S1A–E) and units (Figure S1F–H) needed to build electric field screens. These components consist of a negative or positive voltage generator (Figure S1A), a grounded line (Figure S1B), a layer of insulated metal wires (Figure S1C) arranged horizontally at specific intervals and interconnected, a metal net (Figure S1D), and a polypropylene frame (insulator) (Figure S1E) [5]. A voltage generator is connected to both a grounded line and a layer of insulated metal wires or a metal net. A layer of insulated metal wires is secured within a frame and serves as a metal-wire unit for screen construction (Figure S1F). The framed metal net is connected to a negative voltage generator to function as a charged metal-net unit (Figure S1G) or connected to a grounded line to serve as a grounded metal-net unit (Figure S1H).

4. Single-Charged Monopolar Electric Field Screen for Trapping Airborne Spores

Figure S2A depicts a single-charged monopolar electric field screen (SM-screen), which consists of a layer of insulated metal wires (metal-wire unit) connected to either a negative [16] or positive voltage generator [17]. The SM-screen was originally designed to capture airborne conidia of the powdery mildew pathogen [16]. Each insulated charged metal wire (conductor) creates an electrostatic field (a monopolar electric field that does not produce electric discharge) concentrically in the surrounding space, and an electric field barrier is created when multiple insulated charged conductors are arranged in parallel at specific intervals. Within this electric field barrier, small particles such as fungal spores are attracted to the charged conductor due to their dielectrophoretic movement [18]. Specifically, airborne spores become polarized positively on the side facing the charged conductor and negatively on the opposite side. An attractive force is generated between the positive charge on the spore and the negative charge on the conductor, causing the spore to be drawn towards the charged conductor [16]. In the case of a positively charged insulated conductor, the spore is oriented in the opposite direction due to dielectrophoresis. When the applied voltage is the same in both conductors, an attractive force of equal strength is generated between the spore and the charged conductor [17].

In practical spore trapping scenarios, the target is typically wind-borne spores. The movement of these spores within an electrostatic field is influenced by the wind velocity vector and dielectrophoretic attractive force. To capture the spores effectively, an attractive force greater than the force associated with the wind velocity is required. Increasing the voltage applied to the conductor results in a stronger attractive force. However, it is important to note that the SM-screen was not very effective at trapping small flying insect pests, even when the highest achievable force was applied.

5. Single- and Double-Charged Dipolar Electric Field Screens for Trapping Flying Insect Pests

A single-charged dipolar electric field screen (SD-screen) (Figure S2B) was designed to capture small flying insect pests that could pass through a typical insect-proof net with a mesh size of around 1.5 mm on a greenhouse window [19]. In the SD-screen, an electric field was created in the space between oppositely charged poles. This involved a layer of negatively charged insulated metal wires (the metal-wire unit, serving as the negative pole) and a grounded non-insulated metal net (the metal-net unit, functioning as the positive pole) positioned within the electrostatic field formed by the metal-wire unit [20]. In this setup, a negative voltage generator collected negative charge from the ground and transferred it to the insulated metal wires. An insulating cover (made of a soft polyvinyl chloride tube) prevented the dissipation of surface charge from the charged metal wires. Simultaneously, it became dielectrically polarized due to the negative charge on the metal wire. This polarization resulted in a negative charge on the outer surface and a positive charge on the conductorfacing surface of the insulator cover due to dielectric polarization [21]. The negative charge on the insulator surface induced a positive charge on the grounded metal net via electrostatic induction [22]. Essentially, the opposite charges on the insulated metal wires and the grounded metal net established an electric field between them [20].

A crucial factor for the dipolar electric field was the volume resistivity (Ωcm) of the insulator used to cover the charged conductor. While the insulating cover could prevent discharge from the charged conductor, if the voltage applied to the conductor exceeded a certain threshold, a negative charge could pass through the insulator cover and move to the ground through the electric field and the metal net (continuous corona discharge) [23]. In the SD-screen, a metal wire was coated with a soft polyvinyl chloride tube (10^9 Ωcm) with a voltage limit of 8 kV, causing no discharge below this voltage. In other words, at voltages below 8 kV, the SD-screen formed a static electric field (a dipolar electric field with no discharge) between the charged metal wires and the grounded metal net [20].

A significant characteristic of the static electric field was that the negative charge on the insulated charged conductor exerted a repulsive force on another negative charge within the electric field. Consequently, when an insect entered this field, its free electrons were pushed out of its body, making it positively charged (discharge-mediated positive electrification of an insect). Eventually, these positively charged insects were attracted to the negatively charged insulated conductor. This force was strong enough to prevent insects from escaping, and based on this electrostatic principle, an electrostatic insect sweeper was developed to eliminate insect pests that infest host plants [24].

A double-charged dipolar electric field screen (DD-screen) was also created to trap flying insect pests in a greenhouse [25,26]. The DD-screen was constructed by pairing metal-wire units connected to negative and positive voltage generators (Figure S2C). A static electric field was established in the space between these two units. When an insect enters this electric field, it can be captured in two ways [27]. The first scenario involves the insect entering the vicinity of the negatively charged insulated metal wire. The insect loses its free electrons, becoming positively charged, and is attracted to the negative pole [27]. This is essentially the same phenomenon observed in a single-charged dipolar electric field. In the second scenario, the insect enters the region near the positively charged pole. In this case, the insect acquires electrons from the surrounding space, becoming negatively charged and being attracted to the positive pole [27].

The explanations above apply to a static electric field. When the applied voltage surpasses the insulating limit and results in a silent discharge between the opposite poles, the static electric field is converted into a dynamic electric field. However, the generation of electric current does not affect the capture of insects. In fact, the insects are securely trapped, even when an electric current is generated in the dynamic electric field.

6. SD-Screen for Repelling Insect Pests

The SD-screen is composed of negatively charged insulated metal wires placed at specific intervals and a grounded metal net (Figure S2B). Insects that entered the electric field were strongly drawn towards the charged conductor wire due to the discharge-mediated positive electrification of their bodies [28,29]. Conversely, insects that landed on the outer surface of the net exhibited a completely different behavior. These insects, upon reaching the net, stopped and extended their antennae into the static electric field, displaying a 'searching' behavior inside the field [30]. This behavior deterred them from fully entering the static electric field, and they ultimately flew away without going inside. This avoidance behavior was observed in a wide range of insects, including 17 orders, 42 families, 45 genera, and 82 species [31]. These findings strongly suggest that all insects are deterred by a static electric field, making the devices utilizing this electric field a promising tool for repelling insect pests.

Some studies [32,33] reported that cockroaches are capable of detecting electric fields with their antennae. Cockroaches, when subjected to an electric field, deflect their antennae in response to the attraction forces, moving their antennae towards the electrode [32]. The force arose from the uneven charge distribution on the cockroach, with negative charges being attracted to the oppositely charged electrode [32]. Recently, Matsuda et al. [34] used cockroaches to analyze how insects avoid this electric field and concluded that cockroaches perceive an attractive force acting on their antennae when introduced into a static electric field due to the removal of electrons from the antennae. In other words, when an antenna is inserted into a static electric field, it becomes positively charged due to discharge-mediated positive electrification and is attracted to the oppositely charged insulated metal wire. The insect then instinctively retracts its antennae and moves backward. Positively polarized antennae attract free electrons from the air, neutralizing the charge when pulled back out of the electric field [35]. Gordon et al. [36] reported that mosquitoes are capable of recognizing and avoiding entry into a static electric field generated by non-insulated charged and grounded metal plates.

7. Arc Discharge-Generating Electric Field Screen for Eliminating Insect Pests and Weed Seedlings

A discharge-generating electric field screen (DG-screen) was created by connecting two metal-net units: one linked to a negative voltage generator and the other to a grounded line (Figure S2D). This setup generated a dynamic electric field in the space between the two units. Two types of DG-screens were established by adjusting the applied voltage: corona discharge and arc discharge.

The arc discharge-generating type was initially developed to exterminate rice weevils infesting dried rice grains after harvesting [37] and was later applied to pigsty windows to eliminate mosquitoes [38]. The occurrence of an arc discharge (spark) depended on the applied voltage and the distance between the two units, with higher voltages and shorter distances generating stronger arc discharges in the electric field [37]. In the arc discharge-generating DG-screen, the two units were set at a distance where no arc discharge occurred. When insects entered the space between the units, regardless of their location, they effectively became intermediate poles. Consequently, these insects experienced an arc discharge from the negatively charged metal net due to their conductive cuticle outer layer. As a result, the negative charge was transferred to the insect and then to the grounded metal net via a two-step arc discharge process [11]. This electrocution method effectively eliminated the insects. Despite its simple structure, this screen demonstrated excellent functionality.

An electric weeding method based on an arc discharge exposure was originally proposed by Wilson and Anderson [39] and subsequently adopted by others [40–45]. The arc discharge-generating devices were operated using a continuous-charging type of voltage generator. This type had a high output power for charging but carried the risk of electric shock from the charged metal net. In contrast, a pulse-charging type of voltage generator was safer and commonly used with electric fences to deter wild animals [46]. In cases of unintentional human contact with electric fences, it resulted in only temporary discomfort [46]. For safe usage, the pulse-charging type of voltage generator was employed to operate screens for eliminating invasive kudzu vines climbing on a fence [47], weed seedlings emerging in crop fields [48], and adult houseflies emerging from underground pupae [49]. Recently, Matsuda et al. [50] integrated a continuous-charging type of voltage generator into an unattended electric weeder and effectively controlled ground weeds in a greenhouse orchard while ensuring safety.

8. Conclusions

Electric field-based devices for pest control have been categorized based on whether the conductor is insulated for charging purposes. Insulating the charged conductor is crucial for creating insect-capturing and repelling devices. In laboratory-scale experiments, an insulated conductor wire is created by passing a metal wire through a soft polyvinyl chloride tube. The volume resistivity of polyvinyl chloride is typically 10^{15} Ωcm, but it can be reduced to the range of 10^{14} to 10^{8} Ωcm by adding plasticizers or ultraviolet absorbents to enhance weather resistance. Various polyvinyl chloride materials mixed with different substances are available in the market as soft polyvinyl chloride, each with distinct properties and varying volume resistivities. Previous devices were effectively operated using a conductor covered with a soft polyvinyl chloride tube with a resistivity of 10^{9} Ωcm. In future studies, it is crucial to investigate the relationship between the volume resistivities of insulating materials and their functionalities.

The DG-screen could be constructed more easily because it did not require conductor insulation; in fact, it was simply created by pairing two non-insulated metal nets. A metal net was suitable for this purpose because numerous convex portions on the net surface served as sites for discharge generation. Depending on the applied voltage, the type of discharge at these convex sites could be adjusted from corona to arc discharges. Specifically, two types of DG-screens could be constructed by varying the applied voltage. While this editorial mainly focused on the arc discharge-generating types to present the current state of arc-based pest control methods, the use of corona discharge-generating types may provide opportunities to develop new devices for managing a wide range of targets.

In a corona discharge-generating electric field, numerous negative ions were generated at the convex sites of the negatively charged metal net and transferred to the positively charged grounded metal net. Previous studies have shown that these negative ions were attached to small particles, such as tobacco smoke [51] or small droplets containing viral pathogens [52], which were present within the electric field. This ionization process negatively charged these particles, ultimately leading to their capture by the oppositely charged grounded metal net. Therefore, these successful applications may provide insights into the development of discharge-based electric field screen technologies for pest control in the next stage.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13122855/s1, Figure S1: Components (A–E) and units (F–H) for constructing electric field screens; Figure S2: Different types of electric field screens constructed using combinations of metal wire units and/or metal-net units.

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