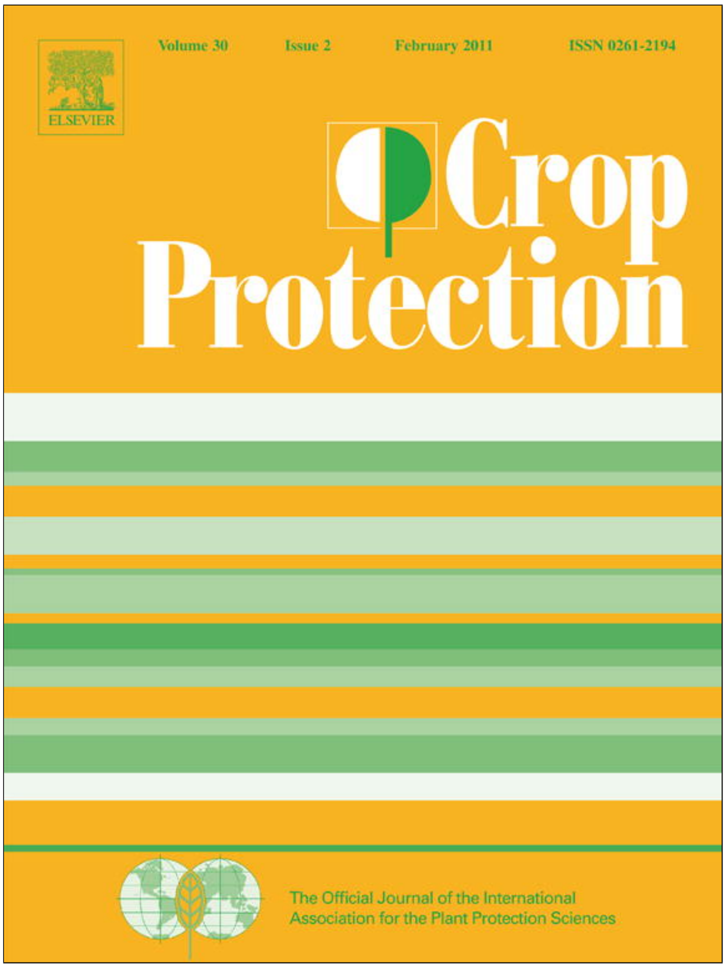
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Crop Protection 30 (2011) 155–162

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

A newly devised electric field screen for avoidance and capture of cigarette beetles and vinegar flies

Yoshinori Matsuda [a], Teruo Nonomura [a], Koji Kakutani [b], Yoshihiro Takikawa [c], Junji Kimbara [d], Yoshihiro Kasaishi [e], Kazumi Osamura [f], Shin-ichi Kusakari [g], Hideyoshi Toyoda [a,*]

[a] Laboratory of Plant Protection and Biotechnology, Faculty of Agriculture, Kinki University, Nara 631-8505, Japan
[b] Pharmaceutical Research and Technology Institute, Kinki University, 3-4-1 Kowakae, Higashi-Osaka, Osaka 577-8502, Japan
[c] Plant Center, Institute of Advanced Technology, Kinki University, Wakayama 644-0025, Japan
[d] Research Institute, Kagome Company, Tochigi 329-2762, Japan
[e] Leaf Tobacco Research Center, Japan Tobacco Inc., Tochigi 323-0808, Japan
[f] Research and Development Division, Navec Inc., Aichi 486-8624, Japan
[g] Agricultural, Food and Environmental Sciences Research Center of Osaka Prefecture, Osaka 583-0862, Japan

A R T I C L E I N F O

Article history:
Received 17 March 2010
Received in revised form 30 August 2010
Accepted 3 September 2010

Keywords:
Electric field screen
Cigarette beetles
Vinegar flies
Pest management

A B S T R A C T

A bifunctional electric field screen was proposed to physically exclude insect pests from warehouses. The screen consists of insulated iron wires (ICW) arranged in parallel and two earthed conductor nets placed on both sides of the ICW. A negative charge (0.1–8.0 kV) was applied to the insulated wires with a voltage generator to polarize an insulator sleeve used to cover the wire, negatively on the outer surface and positively on the inner conductor wire surface of the sleeve. The negative surface charge of the ICW caused an electrostatic induction in the earthed nets and an opposite charge on the net surfaces facing the ICW. An electric field formed in a space between the ICW and the earthed net, and the field strength increased in direct proportion to increasing voltages applied to the ICW. Adults of the test insects (cigarette beetle (*Lasioderma serricorne*) and vinegar fly (*Drosophila melanogaster*)) reaching the outer surface of the earthed net were deterred from entering the inside of the charged screen, whereas all insects immediately passed through the screen when the ICW was not charged. This avoidance was directly proportional to the increase in the voltage. In addition, the capability of the screen to capture insects that enter inside the screen was proven by introducing insects into the space between the ICW and the earthed net. Strong capture was observed when the ICW was negatively charged with more than 4.1 kV, under which conditions a short-term electric current (peaking at 0.3–0.6 μA, for 3 min) occurred transiently. This electric current was due to the release of electricity from the insects, giving a net overall positive charge to the insects, which therefore were attracted more strongly to the negatively charged ICW. A test using an attractant-set chamber showed that the insects were completely prevented from passing through the charged screen, in contrast to a rapid transfer of all insects when the screen was not charged. Thus, the present results show that the described screen is a promising physical tool for controlling insect pests in warehouses.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Developing an environmental friendly method for protecting plants from pathogens and pests during cultivation is our long-standing desire, to replace conventional agrochemical technologies such as fungicides and insecticides in crop production and protection. We therefore tested the use of electrostatic force as an environmentally safe tool. This method was first devised to electrostatically collect airborne conidia of powdery mildews (Moriura et al., 2006a,b; Nonomura et al., 2009) and has been developed into a trap for aerial pathogens and flying pest insects in greenhouses. The device was successfully used to capture airborne conidia of tomato powdery mildew (Matsuda et al., 2006; Shimizu et al., 2007) and flying adult whiteflies (Tanaka et al., 2008), with the aims of excluding pathogens and pests from greenhouses.

In the area of postharvest crop protection, two storage insects, cigarette beetles (*Lasioderma serricorne*) and vinegar flies (*Drosophila melanogaster*), have been targeted as the most serious pests to be expelled. Adults of the cigarette beetle damage a wide range of stored

* Corresponding author.
E-mail address: toyoda@nara.kindai.ac.jp (H. Toyoda).

0261-2194/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cropro.2010.09.001

Author's personal copy

agricultural products, including cocoa, beans, cereals, cereal products, oilseeds, pulses, spices, dried fruits, cured tobacco leaves, and some animal products (Hill, 1990). In addition, some small flies, such as the Mediterranean fruit fly (Cayol et al., 1994; Sela et al., 2005) and vinegar fly (Janisiewicz et al., 1999), have been reported to transfer human-pathogenic bacteria to postharvest wounded fruits. In our attempts to physically trap storage pests with an electrostatic device, we found that insects strongly avoid the electric field of our electrostatic device. This finding pushed us to develop an electric field-forming screen that both repels insects that come close to the electric field and also captures insects that casually enter the electric field.

The first electrostatic spore precipitator that we reported was a screen that created a non-uniform electric field around insulated copper conductor wires arranged in parallel (Matsuda et al., 2006). The electric field generated an electrostatic force that could be harnessed to attract fungal conidia entering the field. Unfortunately, the spore precipitator was ineffective in trapping major insects that fly into greenhouses. The second device used to solve this problem was a dielectric screen in which paired insulator cylinders were arranged in parallel and oppositely charged with equal magnitude using two separate electrostatic voltage generators (Tanaka et al., 2008). This type of screen utilized electric lines of force that move a positively charged particle from the positive to the negative pole (Griffith, 2004; Halliday et al., 2005). The force was strong enough to capture adult whiteflies, and therefore is potentially applicable to other flying insect pests of similar body length (0.8–1.3 mm), such as thrips, aphids, and leaf miners. However, the screen was ineffective in capturing much larger insects such as cigarette beetles and vinegar flies (body lengths of 2–4 mm), as larger insects are stronger and therefore more able to escape from the screen trap. Therefore, it was essential to create a screen with a much stronger force to capture larger insects. In our incremental attempts to improve the electrostatic device, a new three-layered version of the electric field screen, in which the earthed metal meshes were placed on both sides of the original spore precipitator to make dielectric poles, was found to be able to strongly capture insects that were blown into the inner space of the screen. Interestingly, because the outer surface of the nets was electrically inactive, insects could walk on it. This structural characteristic was very useful to examine the avoidance actions of insects reaching the net surface of the screen. The present study proposes a newly devised bifunctional electric field screen as an ecologically safe method for excluding insect pests from warehouses by both repelling and capturing them.

2. Materials and methods

2.1. Pest insects

Adults of the cigarette beetle *L. serricorne* (Fabricicus) (Coleoptera: Anobiidae) were obtained from stock cultures that have been maintained for several years in the laboratory of the Leaf Tobacco Research Center (Hori, 2005). The cigarette beetles were reared on oatmeal powder in plastic containers (20 cm in diameter, 10 cm high) at 25 ± 2 °C and 60 ± 5% relative humidity (RH) in the laboratory of Kinki University. Five- to seven-day-old adults were collected using an insect aspirator (Wildlife Supply, NY, USA).

Adults of the vinegar fly *D. melanogaster* (Drosophilidae) were purchased from Sumika Technoservice (Hyogo, Japan) and reared on blue medium (Wako Pure Chemical, Osaka, Japan) under the above conditions, and adults (1–10 days old) were collected with an insect aspirator.

2.2. Electric field screen

The electric field screen consists of 50 insulated iron conductor wires and two stainless nets with 1.5-mm mesh (0.3 mm thick mesh strands) (Fig. 1A). An iron wire (2-mm diameter, 90-cm length) is passed through a transparent insulator vinyl chloride sleeve (1-mm thickness) to make an insulated conductor wire as described previously (Tanaka et al., 2008). Insulated conductor wires (ICW) are arrayed in parallel at intervals of 5 mm and linked to one another and to a connector terminal of an electrostatic voltage generator (Kansai Denshi, Tokyo, Japan). Stainless nets are earthed and placed 3 mm from and on both sides of the ICW.

The ICW is negatively charged to dielectrically polarize the insulator sleeve of the ICW: negatively on the outer surface and positively on the inner conductor wire surface (Fig. 1B). The negative surface charge of the ICW causes an electrostatic induction in the earthed nets (conductor), creating the opposite surface charge on the ICW side of the nets. These opposite charges act as dielectric poles to form an electric field between the ICW and the earthed nets. In the present study, the ICW was negatively charged with voltages between 0.1 and 8.0 kV to create different field strengths,

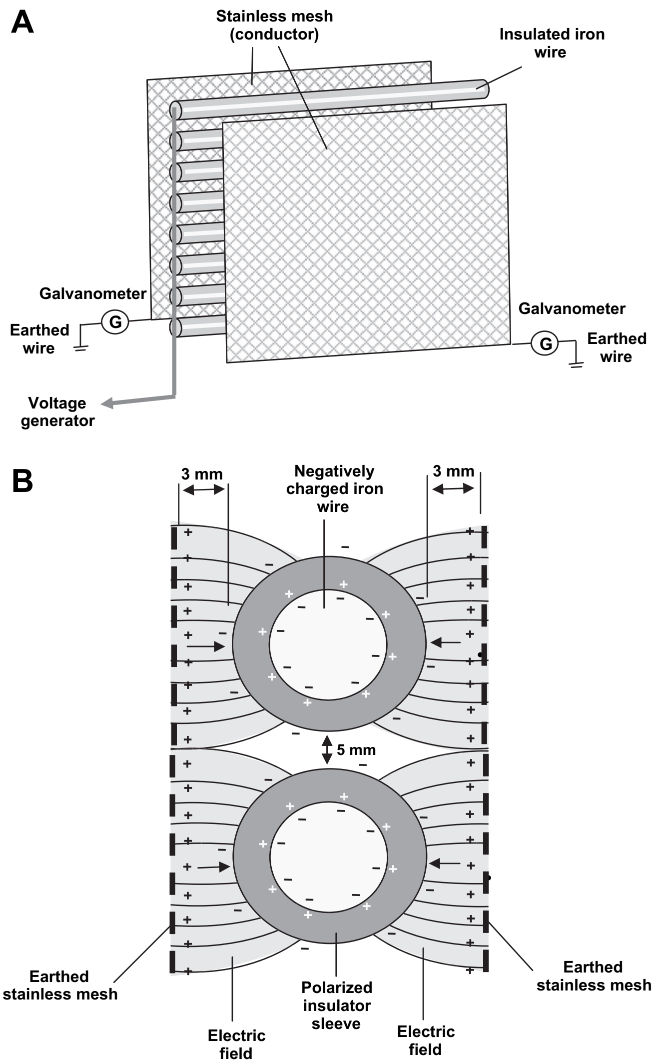


Fig. 1. Structure of the electric field screen (A) and electric field formed inside the screen (B). The screen consists of insulated iron wires (ICW) arrayed in parallel and two stainless nets placed on both sides of the ICW. The ICW was negatively charged with various voltages. A negative charge of the conductor wires dielectrically polarized the cover insulator, and the surface charge of the insulator cover caused the electrostatic induction in the earthed nets to generate the opposite surface charge. Electric fields formed in the space between the ICW and the earthed nets, and lines of electric force were generated from the meshes to the ICW. The electric current was measured using a galvanometer set in the earth lines.

Author's personal copy

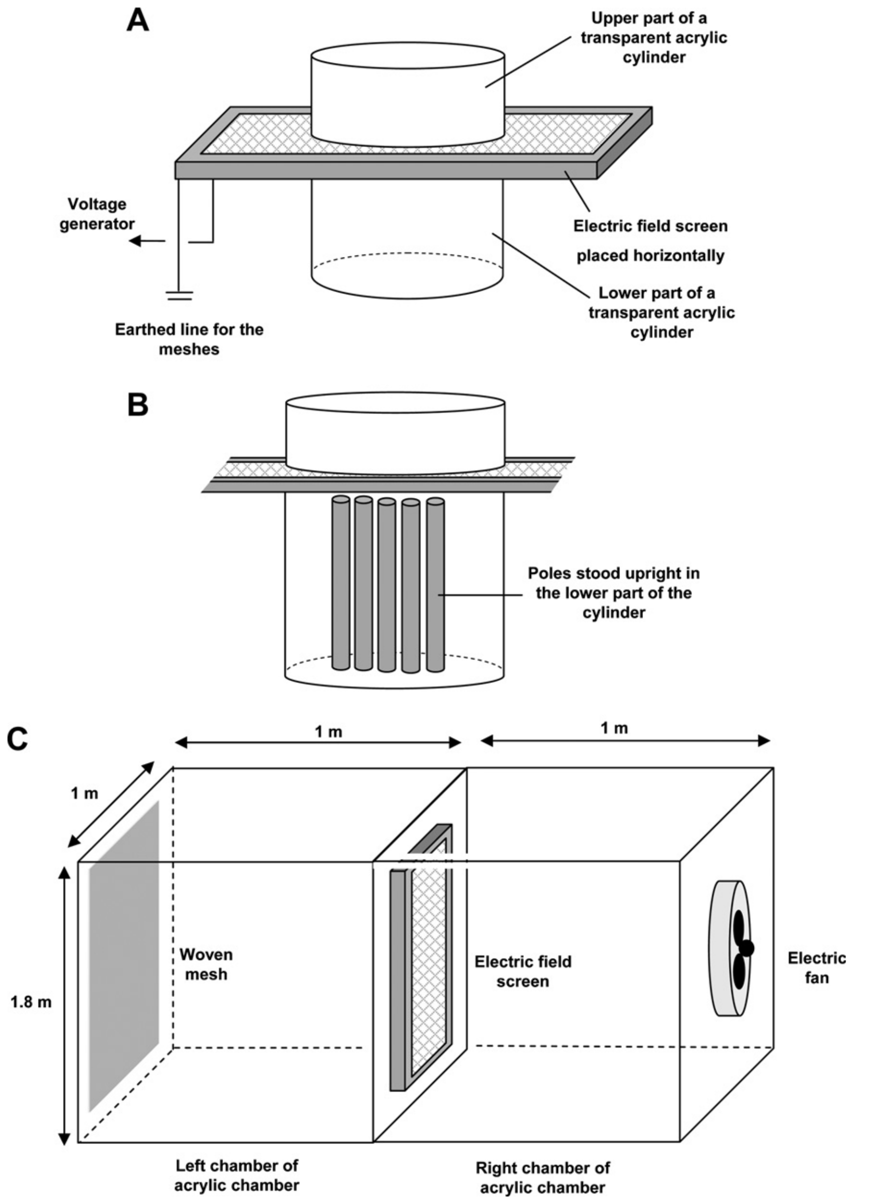


Fig. 2. Structures of the screen cylinder (A and B) and screen chamber (C) used in the present study. Poles were placed upright in the lower part of the screen cylinder to use a climbing assay of cigarette beetle adults released at the bottom.

and the electric current generated during the discharge of the ICW was measured using a galvanometer (Kenis, Osaka, Japan) linked to the earth line of the metal nets (Fig. 1A).

2.3. Assay for capturing insects with the screen

To test whether the ICW could capture insects that enter the screen, we collected adult cigarette beetles or vinegar flies with an insect aspirator and blew them into the space between the ICW and the earthed net. In this experiment, the screen was held with clamps and negatively charged with different voltages. Twenty insects were used per voltage tested, and the numbers of tightly and weakly captured or not captured insects were recorded. Tightly-captured insects could not move, whereas weakly captured insects fluttered their legs, turning their bodies to escape the site of attraction.

In the second experiment, we tested whether tightly-captured insects could be released from the ICW by directly blowing the captured insects with a portable blower (wind speed, 5 m/s). The wind velocity was gauged at the surface of the screen using an anemometer (Kenis, Osaka, Japan). Twenty adults of the test insects were used per experiment, and each experiment was repeated five times. Additionally, we examined the screen for its ability to capture insects carried with air blown from an electric fan. The fan was placed 30 cm from the screen, and air was blown toward the screen at 7 m/s at the screen surface. We dropped adults of both insects into the current at a position 5 cm from the screen and checked for the tight capture of insects that entered the screen. Fifty adults of each insect were used per experiment, and the experiment was performed five times.

2.4. Assay for repelling insects with the electric field screen

To test whether the insects avoid the electrified screen, we constructed a transparent acrylic cylinder (30-cm diameter, 40-cm length) partitioned into two parts with a screen (screen cylinder)

Author's personal copy

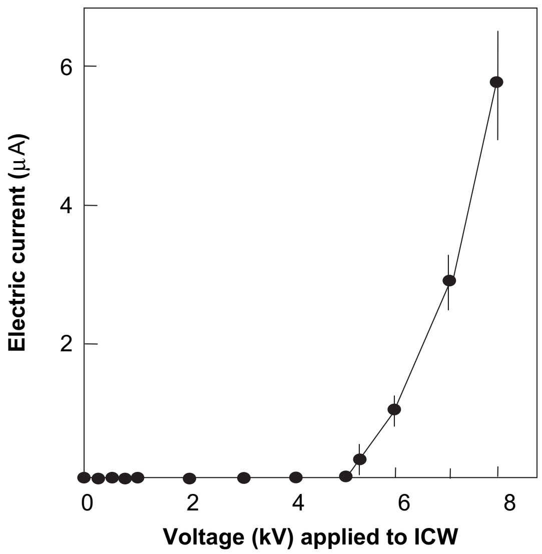


Fig. 3. Relationship between voltages applied to the ICW and the electric current flowing from the ICW to the earthed nets.

(Fig. 2A). The screen cylinder was placed horizontally, and the ICW was negatively charged with different voltages (0.1–8.0 kV). In the first experiment, adults of the vinegar fly were released at the bottom of the screen cylinder in order to observe their actions when they flew up to the earthed net of the screen. In the second experiment, adults of the cigarette beetle were tested for their behavior using a screen cylinder in which five straw poles (5-mm diameter, 19.5-cm length) were placed upright in the bottom part (Fig. 2B). Adults were released near the base of the poles, as cigarette beetles tend to climb up poles. In both experiments, we examined how long the insects stayed on the net (time until the insects entered the screen or avoided the screen without entering). Twenty insects were used per voltage tested, and the experiments were performed five times.

2.5. *Exclusion of insects from a storage chamber with the screen*

We constructed a transparent acrylic rectangular box ($2 \times 1.8 \times 1$ m^3) partitioned with the screen at the center to create two linked chambers (screen chamber) (Fig. 2C). An opening was made on the lateral side of each chamber, and an electric fan (producing a current of 2.0 m/s for cigarette beetles and 1.0 m/s for vinegar flies at the site of the screen net) and an insect-proof woven net (mesh size 0.4 mm, completely preventing adults of both species from passing through) were installed at the openings of the right and left rooms of the screen chamber, respectively. The screen chamber was placed in a temperature-controlled room (25 °C), and the ICW was negatively charged with 4.1 kV. The screen was continuously operated for 1 month. In this experiment, pieces of peeled mango fruits were used as attractants for vinegar flies (Zhu et al., 2003), and commercial attractant-containing pheromone and food attractants (New Serrico) (Kokusai Eisei, Tokyo, Japan) were used for cigarette beetles. The attractant was placed in the left chamber, and 1000 adults per species were released in the right chamber twice during the continuous operation period (immediately and 28 days after the screen was electrified). We counted the number of insects several times during the 48 h after each insect release. The resulting data are expressed as the number of the insects that moved into the left chamber, remained in the original right chamber, escaped out of the box through the opening of the ventilating fan, or were captured with the ICW of the screen. The experiments were performed five times per species.

3. Results

First, we clarified the voltage range that caused an electric current from the ICW to the earthed nets at a distance of 3 mm (Fig. 3). The current was initially established when the ICW was negatively charged with 5.2 kV, and was enhanced with increasing voltages applied to the ICW. Therefore, the voltage range was divided into two parts, one of a lower voltage range causing no electric current, and the other of a higher voltage range causing a current.

In the subsequent experiment, we tested whether the screen could capture insects that were blown inside the screen. Table 1 shows the ratio of non-captured, weakly captured, and tightly-captured insects at each voltage. Between 0.1 and 0.8 kV, all insects quickly entered and passed through the screen. Between 1.0 and 4.0 kV, in addition to non-captured insects, insects were weakly captured with the ICW. The number of weakly captured insects increased with increasing voltage. These insects struggled, escaped the ICW, and then exited the screen. At voltages between 4.1 and 5.1 kV, a transient electric current occurred when the insects were blown inside the screen. Fig. 4A shows the durations and patterns of the transient electric current detected at the time of insect attraction. The current instantaneously rose, with a peak of

Table 1
Capture of adults of cigarette beetle and vinegar fly blown inside the electric field screen whose ICW was negatively charged with different voltages.

Voltage (kV) applied to ICW	Electric current		Percentage of insects					
	Constant	Transient[a]	Cigarette beetle			Vinegar fly		
			Non-captured	Weakly-captured	Tightly-captured	Non-captured	Weakly-captured	Tightly-captured
0	No	No	100	0	0	100	0	0
0.1	No	No	100	0	0	100	0	0
0.2	No	No	100	0	0	100	0	0
0.4	No	No	100	0	0	100	0	0
0.6	No	No	100	0	0	100	0	0
0.8	No	No	100	0	0	100	0	0
1	No	No	71.6 ± 4.2	28.2 ± 4.3	0	81.6 ± 5.2	18.4 ± 5.2	0
2	No	No	58.8 ± 5.8	41.2 ± 5.8	0	59.4 ± 5.0	40.6 ± 5.0	0
3	No	No	13.2 ± 1.9	86.8 ± 1.9	0	28.8 ± 3.1	71.2 ± 3.1	0
4	No	No	1.2 ± 0.4	98.8 ± 0.4	0	1.0 ± 0.7	99.0 ± 0.7	0
4.5	No	Yes	0	0	100	0	0	100
5	Yes	Yes	0	0	100	0	0	100
6	Yes	Yes	0	0	100	0	0	100
8	Yes	Yes	0	0	100	0	0	100

One hundred adults were used at each voltage application, and data were given as means and standard deviation of 5 replications.
[a] Electric current transiently generated only when the insects were blown into the space between ICW and earthed nets.

Author's personal copy

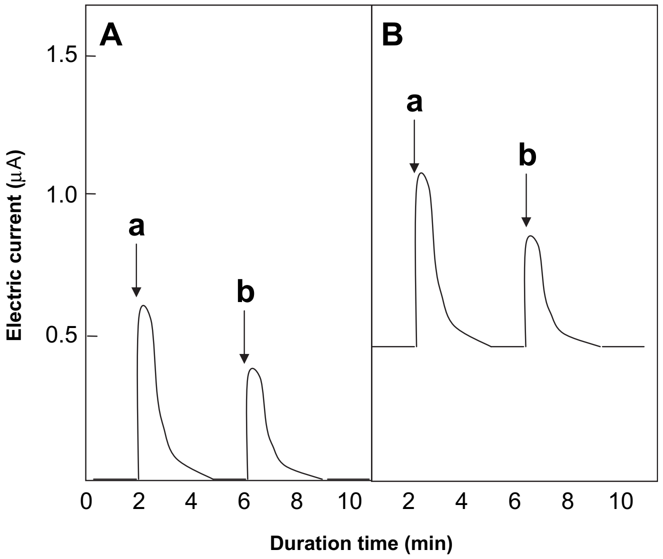


Fig. 4. Electric current generated at the time of insect-capture with the ICW at the lower voltage range (4.1-kV charge) (A) or at the higher voltage range (5.2-kV charge) (B). The arrows 'a' and 'b' represent the timing of blowing an adult vinegar fly or cigarette beetle, respectively, into the screen.

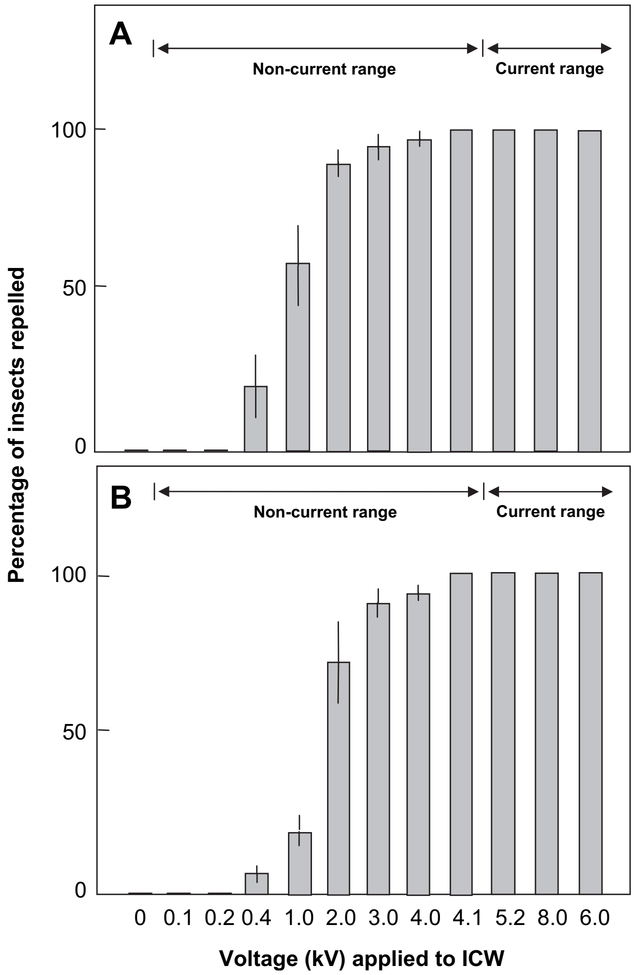


Fig. 5. Repellence of cigarette beetle (A) and vinegar fly adults (B) by the electric field screen placed in the middle of a transparent acrylic cylinder. After reaching the net of the screen, the insects passed through the screen (non-repelled) or removed themselves from the screen without entering (repelled). The data were given as means and standard deviation of five replications.

0.3–0.6 μA when single insects were brought into the screen, and then gradually decreased and disappeared within 3 min. Under these voltage applications, all insects were tightly captured with the ICW such that they could not escape the ICW, even though they struggled to get free from the screen. The present study showed that this attraction force was so strong that the captured insects were not released from the ICW even when directly blown with an air current of 5 m/s for 30 min. In the highest voltage range (greater than 5.2 kV), the electric currents were continuous and varied with different voltages (Fig. 3). Also in this voltage range, a transient electric current occurred when an insect was blown into the screen (Fig. 4B). The force was much stronger, and all insects were captured such that they were not able to move their legs. In an additional experiment, using a screen negatively charged with 4.1 kV, the screen captured adults of the cigarette beetle and vinegar fly carried with an air current of 7 m/s. In this experiment, a small number of insects (average 2.3 ± 0.5% of cigarette beetles, 23.1 ± 1.6% of vinegar flies) successfully entered the space between the ICW and the net, although many wind-carried insects struck the net and were projected back from it. The ICW caught every intruding insect.

With the screen cylinder, we tested the behaviors of the cigarette beetle (Fig. 5A) and vinegar fly (Fig. 5B) against the electric field. Of insects passing through the screen (passing-insects) and insects removing themselves from the screen without entering inside (removing-insects), the data are shown as the ratio of the removing-insects (as the insects repelled) at each voltage. In addition, Table 2 shows the times that passing-insects and removing-insects stayed on the net of the screen. On a non-charged screen or a screen charged with lower voltages (less than 0.2 kV), both cigarette beetles and vinegar flies passed freely through the screen, with times on the net between 1 and 2 s. On a screen charged with voltages between 0.3 and 5.1 kV, both species took avoidance actions, sticking their antennae inside the screen and immediately pulling in their heads. After taking this particular action several times, some insects entered the screen, and others did not. Within this range, the ratio of removing-insects increased, and their stay on the net became shorter with increasing voltage. Considerable differences were observed in the on-net time of insects between the non-charged and charged screens and among the screens charged with different voltages (Table 2). The data indicate that the passing-insects also hesitated rather than entering the electric field. Also, at voltages of greater than 5.2 kV, the insects tried to stick their antennae inside, but all immediately avoided the screen with no repeat of the action mentioned above. In Fig. 6, we schematize the voltage ranges applied to the screen in terms of their electric current generation, insect-capture capability, and induction of avoidance responses of the insects.

Finally, we tested the effectiveness of the electric field screen in excluding the released insects from the test chamber (Table 3). In the non-charged screen, almost all adults of both species moved to the neighboring attractant-set chamber within 24 h after the release of the insects in the right room of the screen chamber. In contrast, the charged screen completely prevented adults of both the cigarette beetle and vinegar fly from moving to the left room of the screen chamber. The cigarette beetles walked along the wall toward the screen and tried to get on the screen several times in the first 6–12 h. Less than 1% of the insects were tightly captured with the ICW until the end of the experiment, but the remaining insects removed themselves from the screen and then stayed motionless at the corner of the original room of the screen chamber throughout the rest of the experiment. A few insects escaped the room through the vent opening. Similarly, adult vinegar flies sat on the screen net and immediately flew away from the screen.

Author's personal copy

Table 2
Time length of insects' staying on the net of the electrostatic field screen.

Insects	Voltage (kV) applied to ICW	Time length (s) on the net	
		Passing-insects	Removing-insects
Cigarette beetle	0	1.2 ± 0.4 a	n.d.[a]
	0.1	1.3 ± 0.5 a	n.d.
	0.2	1.3 ± 0.8 a	n.d.
	0.4	5.6 ± 1.9 b	7.5 ± 1.1 a
	1	7.5 ± 1.3 b	4.5 ± 0.9 b
	2	15.2 ± 3.0 c	1.1 ± 0.3 c
	3	22.2 ± 5.8 d	<1
	4	23.2 ± 4.4 d	<1
	4.1	n.d.	<1
	5.2	n.d.	0
	6	n.d.	0
	8	n.d.	0
Vinegar fly	0	1.2 ± 0.3 a	n.d.[a]
	0.1	1.2 ± 0.5 a	n.d.
	0.2	1.3 ± 0.6 a	n.d.
	0.4	5.1 ± 1.1 b	10.2 ± 4.9 a
	1	6.8 ± 1.3 b	5.7 ± 0.8 b
	2	16.5 ± 3.6 c	1.1 ± 0.1 c
	3	25.3 ± 7.2 d	<1
	4	26.2 ± 3.1 d	<1
	4.1	n.d.	<1
	5.2	n.d.	0
	6	n.d.	0
	8	n.d.	0

Adults of cigarette beetle or vinegar fly reaching the net of the screen-cylinder were grouped into two on the basis of their actions: one was the group of insects passing through the screen (passing-insects) and the other the insects removing from the screen without entering the inside (removing-insects). Time length these insects stayed on the net before entering or removing was measured. Data were given as means and standard deviation of five replications. Different letters on mean values indicate a significant difference ($p < 0.05$) according to Tukey's method.

[a] Not detected.

Between 5 and 10% of the adults was captured, and the remaining insects stayed on the ceiling of the right room of the screen chamber. In the same type of experiment conducted at 28 days after the screen was switched on, similar results were obtained for both insects (Table 3), indicating the functioning of the screen throughout its continuous operation.

4. Discussion

The electric field is a physical factor that affects insects, causing attraction or avoidance (Tanaka et al., 2008; Chaoui and Keener, 2008; Newland et al., 2008). Chaoui and Keener (2008) reported the repelling of earthworms in soil by flowing an electric current across the earthworms (electric shock) when they entered the electric field formed by non-insulated opposite dielectric poles inserted into the soil, and Newland et al. (2008) reported that cockroaches detected static electric fields formed by single mono-electric-charged poles with no flow of electricity from the charged pole. In the present work, we found that adult cigarette beetles and vinegar flies sense electric fields produced by dielectric poles, subsequently avoiding entering the electric field produced inside the electric field screen. With the present screen, two types of electrification were used to make the electric field: dielectric polarization in the insulator cover of the charged conductor wire, and electrostatic induction in the earthed net.

The surface charge of the polarized insulator can cause an electrostatic induction in the earthed conductor (Griffith, 2004). A non-insulated charged conductor also induces electrostatic induction in the earthed conductor, but at the same time, it causes a spark discharge when the earthed conductor is brought close (Kaiser, 2006). The use of insulated conductor wires completely suppressed the spark discharge, at least within the voltage range used. The surface charge of the insulated wires is in direct proportion to the voltage applied to the conductor wires (Tanaka et al., 2008), and a higher surface charge of the charged conductor wires induces a higher opposite charge of the same magnitude in the earthed conductor (Griffith, 2004; Giancoli, 2005). In our system, the ICW (with a negative surface charge) and the earthed nets (with a positive charge) gave rise to an electric field in the space between them; the field strength was controllable by altering the voltage applied to the conductor wires. Importantly, the electric field formed inside the earthed meshes, but not on the outer surface of the screen nets. This lack of surface charge on the outer surface of the nets was favorable for the insects to stay there and recognize the inside electric field.

The screen provided two distinct voltage ranges: a lower voltage range without an electric current and a higher voltage range with a minute current. Adults of both the cigarette beetle and vinegar fly were very sensitive to changes in the electric field even when no electric current was present. In order to judge their sensitivities, the present assays (the climbing-up assay for the cigarette beetle and the flying-up assay for the vinegar fly) were very useful, because both insects showed a steady habit of going upward. Because all insects released into the screen cylinder went up toward the screen, we could follow the behaviors of the insects reaching the net. Insects on the charged screen were hesitant to enter the net, in contrast to insects on the non-charged screen, which immediately passed

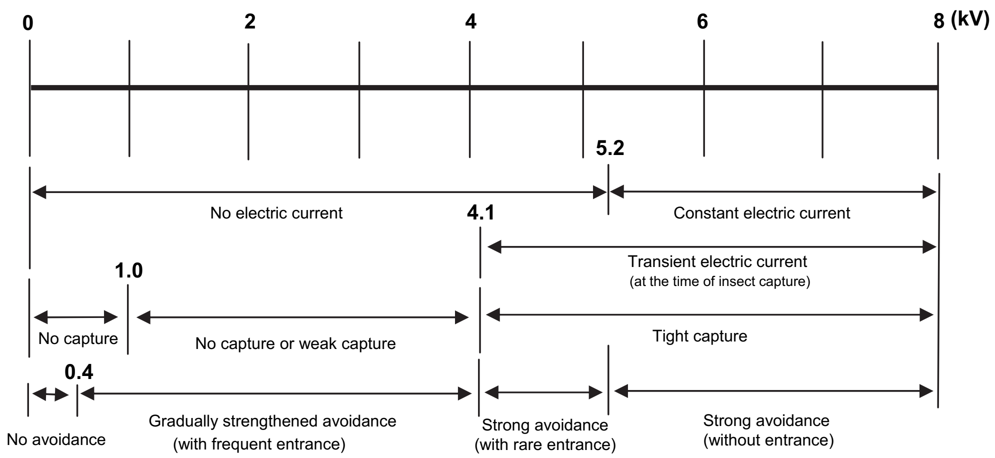


Fig. 6. Schematic expression of voltage ranges applied to the screen in terms of electric current generation, insect-capture capability, and induction of avoidance responses of adult cigarette beetles and vinegar flies.

Author's personal copy

Table 3
Test of the effectiveness of the electric field screen for its capability to exclude insects from the test chamber.

Insects	Electric filed screen	Time duration (h)	Percentage of adults[a]					
			Immediately			28 days		
			Remaining	Captured	Passing	Remaining	Captured	Passing
Cigarette beetle	Non-charged (control)	6	84.9 ± 5.6	0	15.1 ± 5.6	77.3 ± 6.4	0	22.7 ± 6.3
		12	10.7 ± 5.1	0	89.3 ± 5.1	9.9 ± 1.3	0	90.1 ± 1.3
		24	7.6 ± 2.4	0	92.4 ± 2.4	5.7 ± 1.6	0	94.3 ± 1.6
		48	3.9 ± 1.2	0	96.1 ± 1.2	4.4 ± 1.0	0	95.6 ± 9.8
	Charged	6	100	0	0	100	0	0
		12	100	0	0	100	0	0
		24	95.3 ± 3.2	0.7 ± 0.2	0	95.8 ± 1.2	0.5 ± 0.4	0
		48	94.9 ± 2.5	0.8 ± 0.3	0	94.9 ± 1.9	0.8 ± 0.5	0
Vinegar fly	Non-charged (control)	6	78.4 ± 4.3	0	21.6 ± 4.3	79.7 ± 1.1	0	20.3 ± 1.1
		12	7.9 ± 2.2	0	92.1 ± 2.2	11.8 ± 1.8	0	88.2 ± 1.8
		24	5.2 ± 1.3	0	94.8 ± 1.3	5.5 ± 1.4	0	94.5 ± 1.4
		48	3.8 ± 1.2	0	95.2 ± 1.2	3.8 ± 0.9	0	96.2 ± 1.0
	Charged	6	100	0	0	100	0	0
		12	100	0	0	100	0	0
		24	92.6 ± 3.9	5.3 ± 2.8	0	92.6 ± 2.9	6.6 ± 3.9	0
		48	89.4 ± 5.9	9.7 ± 6.5	0	88.9 ± 5.7	8.8 ± 6.7	0

[a] One thousand adults of each insect were used in each experiment. The insects were released immediately and 28 days after the screen was switched on. The experiment was conducted at the wind of 2.0 m/s for cigarette beetles and 1.0 m/s for vinegar flies, because vinegar flies hung on the wall without flying at the higher wind speed. Data were given as means and standard deviation of 5 separate experiments. Insects escaping from the vent of the chamber were not shown in the table.

through the net. In the lower voltage range, the insects fell into two groups (screen-passing and non-passing insects) at each voltage application, and their long response times (time for the insects to decide to pass through the screen or remove themselves from the screen) reflected the deterrence of the insects from entering the electric field. Interestingly, the 5.2 kV-charged screen immediately repelled insects that thrust their antennae inside the electric field.

Another remarkable characteristic of the screen is its ability to tightly capture the insects that enter the inner space of the screen. In the present screen, the site of insect-capture was the negative pole (ICW), and in fact, all insects that were purposely thrust into the inner space of the screen were attracted to the nearest insulated wire. This suggests that the insects were transferred according to the electrostatic lines of force that were directed from the positive pole (earthed mesh) to the negative pole (ICW) (Tanaka et al., 2008). In the lower voltage range (between 1.0 and 4.0 kV), however, this type of electrostatic force was generally insufficient to hold the insects tightly. Interestingly, insects were captured tightly with a transient generation of electric current from the insect to the earthed net at higher voltage range (more than 4.1 kV). To our understanding, this release of electricity makes the insect positively charged, leading to a more effective attraction to the negative pole. In the electric field, the highly charged pole ionizes the air to create positive and negative ions, and only positive ions remain in the electric field as a result of the movement of negative ions to the earthed positive pole (Jonassen, 2002). This negative ion movement is detectable as an electric current. Also in the present study, an electric current was constantly measurable in the higher voltage range, strongly suggesting that positive ions exist in the electric field of the screen. It is well known that objects entering high-voltage electric fields receive these positive ions, becoming positively charged (Mill and Milligan, 2002). The insects likely received positive ions in the electric field. In the present higher voltage range, both the transient discharges of the insect and the atmospheric ionization were additive to tightly attract the positively charged insects toward the negative pole. As a result, this attraction force was sufficient to resist the air current (5 m/s) blown from an electric fan.

The present screen chamber assay was a simulation of the practical application of the screen in a warehouse. The major aim of the test was to confirm the normal functioning of the screen during continuous operation. For this purpose, we designed a short-term test (a 2-day observation) at both ends of a 1-month-long period of operation. The 2-day observation was sufficient to discern the behaviors of the insects because all insects passed through the screen to move to the neighboring attractant-containing chamber within the period when the screen was not charged. At the same time, all adults starved to death in the original chamber within this period (vinegar flies) or remained motionless at locations distant from the screen in the original chamber (cigarette beetles), when the screen was charged with 4.1 kV. Moreover, the two times of observation at both ends were sufficient to discern that the functioning of the screen was sustained during continuous operation.

In order to effectively exclude insects from warehouses, it is essential to close all gaps or openings through which the insects enter (Hill, 1990). In many cigarette factories, adult cigarette beetles inhabiting airways and vents are the major source of infestation, in addition to external invasion (Hill, 1990; Carvalho et al., 2006). The major openings of our warehouse are external windows, vents, and airways. These openings are often subjected to natural and artificial air currents, which we found affect the insect-repellent or insect-capture functioning of the screen. In our facilities, the wind speed varied among the openings; the vents were subjected to air currents of 0.1–1.0 m/s depending on the speed of the air produced by the air conditioner. These wind speeds, however, were too weak to always push the insects on the mesh inside the screen, and in fact, only the avoidance reaction by the insects was detectable at this range of wind speed (data not shown). In contrast, the wind speed at the window is mostly between 0.1 and 3.5 m/s, and rarely 4–5 m/s, depending on the outside weather. The present screen prevented insects from passing through the screen, even when natural wind of 7 m/s blew toward the screen.

Another factor in the practical use of the screen is electricity consumption during the operation of the screen. In our screen system, the driving part requiring an electric power supply is the electrostatic voltage generator. The voltage generator is a booster to raise the initial voltage (100 V) to the desired levels (between 0.1 and 8.0 kV). Our trial calculations suggest that the electric power consumption by the generator is low (between 10 and 20 W), corresponding to the consumption of a single standard fluorescent lamp (20 W). The practical voltage is 4.1 kV for the operation of the

Author's personal copy

screen, generating a short-term electric current (between 0.3 and 0.6 μA) in the rare cases of the insect entrance into the screen. However, this current was negligible in measurements with a watt-hour meter.

Electric field screens comprise a variety of insect-proof screens that have been utilized to impede the entrance of the insects into greenhouses (Teitel et al., 1999). The disadvantage of screening is a reduction in ventilation that causes overheating and increased relative humidity (Weintraub and Berlinger, 2004). However, our screen can result in better air penetration for ventilation because of the use of airy side nets. The mesh size of the net (1.5-mm mesh) is considerably larger than those (0.4–0.5-mm mesh) of our conventional woven screens, with better prevention of insects from passing through the screen. Thus, the present screen is safe, economical and eco-friendly, providing a promising new tool for physically controlling product pests in warehouses.

References

Carvalho, M.O., de Carvalho, J.P., Torres, L.M., Mexia, A., 2006. Developing sequential sampling plans for classifying *Lasioderma serricorne* (F.) (Coleoptera, Anobiidae) status in a cigarette factory. J. Stored Prod. Res. 42, 42–50.

Cayol, J.P., Causse, R., Louis, C., Barthes, J., 1994. Medfly *Ceratitis capitata* Wiedemann (Dipt., Trypetidae) as a rot vector in laboratory conditions. J. Appl. Entomol. 117, 338–343.

Chaoui, H., Keener, H.M., 2008. Separating earthworms from organic media using an electric field. Biosystems Eng. 100, 409–421.

Giancoli, D.C., 2005. Electric charge and electric field. In: Challice, J. (Ed.), Physics, Principles with Applications. Pearson Education International, London, pp. 439–469.

Griffith, W.T., 2004. Electrostatic phenomena. In: Bruflodt, D., Loehr, B.S. (Eds.), The Physics of Everyday Phenomena, a Conceptual Introduction to Physics. McGraw-Hill, New York, pp. 232–252.

Halliday, D., Resnick, R., Walker, J., 2005. Electric fields. In: Johnson, S., Ford, E. (Eds.), Fundamentals of Physics. John Wiley & Sons, New York, pp. 580–604.

Hill, D.S., 1990. Pests of Stored Products and Their Control. Belhaven Press, London, pp. 1–274.

Hori, M., 2005. Development of repellent strips for controlling the cigarette beetle, *Lasioderma serricorne* (Fabricius) (Coleoptera: Anobiidae). Appl. Entomol. Zool. 40, 373–377.

Janisiewicz, W.J., Conway, W.S., Brown, M.W., Sapers, G.M., Fratamico, P., Buchanan, R.L., 1999. Fate of *Escherichia coli* O157:H7 on fresh-cut apple tissue and its potential for transmission by fruit flies. Appl. Environ. Microbiol. 65, 1–5.

Jonassen, N., 2002. Abatement of static electricity. In: Electrostatics. Kluwer Academic Publishers, Massachusetts, pp. 101–120.

Kaiser, K.L., 2006. Air breakdown. In: Electrostatic Discharge. Taylor & Francis, New York, pp. 1–102.

Matsuda, Y., Ikeda, H., Moriura, N., Tanaka, N., Shimizu, K., Oichi, W., Nonomura, T., Kakutani, K., Kusakari, S., Higashi, K., Toyoda, H., 2006. A new spore precipitator with polarized dielectric insulators for physical control of tomato powdery mildew. Phytopathology 96, 967–974.

Mill, G.S., Milligan, W.O., 2002. Electrostatic precipitator. In: Geller, E., Moore, K. (Eds.), McGraw-Hill Encyclopedia of Science & Technology, pp. 413–415. New York.

Moriura, N., Matsuda, Y., Oichi, W., Nakashima, S., Hirai, T., Sameshima, T., Nonomura, T., Kakutani, K., Kusakari, S., Higashi, K., Toyoda, H., 2006a. Consecutive monitoring of lifelong production of conidia by individual conidiophores of *Blumeria graminis* f. sp. *hordei* on barley leaves by digital microscopic techniques with electrostatic micromanipulation. Mycol. Res. 110, 18–27.

Moriura, N., Matsuda, Y., Oichi, W., Nakashima, S., Hirai, T., Nonomura, T., Kakutani, K., Kusakari, S., Higashi, K., Toyoda, H., 2006b. An apparatus for collecting total conidia of *Blumeria graminis* f. sp. *hordei* from leaf colonies using electrostatic attraction. Plant Pathol. 55, 367–374.

Newland, P.L., Hunt, E., Sharkh, S.M., Hama, N., Takahata, M., Jackson, C.W., 2008. Static electric field detection and behavioural avoidance in cockroaches. J. Exp. Biol. 211, 3682–3690.

Nonomura, T., Matsuda, Y., Xu, L., Kakutani, K., Takikawa, Y., Toyoda, H., 2009. Collection of highly germinative pseudochain conidia of *Oidium neolycopersici* from conidiophores by electrostatic attraction. Mycol. Res. 113, 364–372.

Sela, S., Nestel, D., Pinto, R., Nemny-Lavy, E., Bar-Joseph, M., 2005. Mediterranean fruit fly as a potential vector of bacterial pathogens. Appl. Environ. Microbiol. 71, 4052–4056.

Shimizu, K., Matsuda, Y., Nonomura, T., Ikeda, H., Tamura, N., Kusakari, S., Kimbara, J., Toyoda, H., 2007. Dual protection of hydroponic tomatoes from rhizosphere pathogens *Ralstonia solanacearum* and *Fusarium oxysporum* f. sp. *radicis-lycopersici* and airborne conidia of *Oidium neolycopersici* with an ozone-generative electrostatic spore precipitator. Plant Pathol. 56, 987–997.

Tanaka, N., Matsuda, Y., Kato, E., Kokabe, K., Furukawa, T., Nonomura, T., Honda, K., Kusakari, S., Imura, T., Kimbara, J., Toyoda, H., 2008. An electric dipolar screen with oppositely polarized insulators for excluding whiteflies from greenhouses. Crop Prot. 27, 215–221.

Teitel, M., Barak, M., Berlinger, M.J., Lebiush-Mordechai, S., 1999. Insect-proof screens in greenhouses: their effect on roof ventilation and insect penetration. Acta Hortic. 507, 25–34.

Weintraub, P.G., Berlinger, M.J., 2004. Physical control in greenhouses and field crops. In: Horowitz, A.R., Ishaaya, I. (Eds.), Insect Pest Management. Springer-Verlag, Berlin, pp. 301–318.

Zhu, J., Park, K.-C., Baker, T.C., 2003. Identification of odors from overripe mango that attract vinegar flies, *Drosophila melanogaster*. J. Chem. Ecol. 29, 899–909.