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A Simple Window Screen to Create Electric Discharges for Repelling and Exterminating Stable Flies and Houseflies in Cattle Barns

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Abstract: The current study aimed to create an electrostatic window screen to keep stable flies and houseflies out of cattle barns. The screen comprised three identical framed metal nets arranged in parallel at specific intervals. The central net was connected to a negative-voltage generator to impart a negative charge, while the other two nets were grounded and placed on either side of the charged net. This configuration generated a corona-discharging electric field between the nets. The electric field produced negative ions and ozone around the negatively charged net, deterring houseflies from entering. Additionally, the screen emitted sparks via arc discharge to repel stable flies that did not exhibit avoidance behavior. The spark irradiation was intense enough to swiftly propel flies backward upon entering the electric field, ultimately leading to their demise. In summary, the device functioned as a corona-discharging screen to repel houseflies and as an arc-discharging screen to eliminate stable flies through spark irradiation. This study provides an experimental foundation for the development of an innovative device to manage undesirable flies in cattle barns.

Keywords: avoidance behavior; electric field; ionic wind; negative ion; ozone; pest control; spark irradiation

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1. Introduction

In the process of raising cattle, we have encountered significant public health challenges associated with two types of flies: stable flies (*Stomoxys calcitrans*) and houseflies (*Musca domestica*). Both fly species serve as vectors for human and bovine pathogens, respectively, with both originating from cow manure in barns.

Stable flies pose a significant hygiene challenge in cattle farming, as both male and female flies feed on blood. These flies are the primary carriers of the bovine leukemia virus (BLV), transmitting it through their blood-sucking behavior [1]. Bovine leukemia manifests as a lymphocytic cell tumor, leading to symptoms such as weight loss, reduced energy, lower milk yield, anorexia, diarrhea, constipation, and eventually, swollen lymph nodes and exophthalmos [2]. Even when stable flies do not transmit the virus, their blood-sucking activity causes various health issues in cattle. The prolonged blood-sucking process induces severe pain, disrupting the cows' sleep and reducing their feed intake. This results in decreased body weight gain, lower milk production, and the onset of mastitis [3]. Controlling stable flies is challenging due to their large numbers in cattle barns throughout the spring-to-autumn period [4]. Current measures include cleaning affected areas [5], installing insect nets to prevent barn invasion [6], insecticide spraying [7], using adhesive plates [8], and removing weeds in their habitats [9]. However, these methods have limitations such as the high cost and maintenance of nets, low effectiveness of insecticides, susceptibility of adhesive sheets to dust, and the labor-intensive nature of weed removal. Consequently, farmers are hesitant to adopt proactive measures against stable flies.

Houseflies pose a risk of transmitting pathogenic *Escherichia coli* O157, which can lead to food poisoning in humans who consume contaminated fresh food [10,11]. Although *E. coli* O157 is harmless in the intestines of cattle and sheep, it can enter the human food chain through feces from these animals [10–12]. Housefly larvae develop in animal feces, resulting in large populations in cattle farms and other agricultural facilities. *E. coli* O157 ingested by houseflies can remain viable in fly excreta, allowing houseflies to carry and spread the bacteria for several days [10]. Notably, this bacterial pathogen can also be transferred from cattle manure used as soil fertilizer [13], posing a serious threat to the food supply chain through contamination of cultivated and postharvest crops [14–16]. To address the emergence of houseflies from soil beds and their potential contact with crops in greenhouses, insecticide substitution becomes crucial. The traditional method involves covering the soil surface with a mulch film to control houseflies [17,18]. However, this approach is impractical for summer plant cultivation due to undesirable increases in soil temperature. To overcome this challenge, Kakutani et al. [19] developed an electric soil cover designed to zap houseflies emerging from the ground and entering the soil cover. Despite the progress of soil surface control of houseflies in greenhouse soil beds, the fundamental problem of controlling houseflies in cattle barns remains unresolved.

The objective of this study is to develop a novel device that serves the dual purpose of repelling and eliminating adult houseflies and stable flies in cattle barns. This device is envisioned to be attached to barn windows or entrances. Matsuda et al. [20] established a corona-discharging electric field by placing negatively charged metal needles in proximity to a metal net connected to the ground. This electric field generated a significant number of negative ions around the metal needles, transferred to the grounded metal net through airflow (ionic wind). In our preliminary experiments, we discovered that even when using the same metal net as the grounded electrode instead of metal needles, negative ions were generated at the convex sites of the charged net surface. Notably, flies perched on the outer surface of a grounded metal net avoided entering the electric field with corona discharge. This observation led us to propose a device capable of repelling flies by combining two identical metal nets at predetermined intervals—one linked to a negative-voltage generator and the other to a grounded wire. To achieve this, the study aimed to enhance a pair of negatively charged and grounded metal nets creating a corona discharge into a device, which was capable of (1) deterring target flies from entering a corona-discharging electric field formed between the metal nets and (2) killing the flies that entered the electric field using arc discharge-mediated sparks emitted from a negatively charged metal net.

In the corona-discharging electric field formed by the negatively charged and grounded metal nets, arc discharge of a negatively charged metal net does not occur because the distance to the grounded metal net that serves as the opposite electrode is too far or the applied voltage to the charged metal net is too low. However, when a conductor enters between these metal nets, this conductor serves as an intermediate electrode, allowing the charged metal net to generate arcing toward the intermediate electrode [21]. Specifically, a negative charge is passed from the charged metal net to the intermediate electrode through the arc discharge, and the charged intermediate electrode passes the charge to the grounded metal net through the second arc discharge. Since flies are biological conductors, when flies enter this electric field, they become intermediate electrodes and are exposed to arc discharges from charged conductors. In this case, since the convex sites on the surface of the charged metal net become the firing sites of the arc discharge, there is an advantage that the fly receives an arc discharge no matter which part of the electric field it enters. Since the arcing is accompanied by sparks, the fly will be irradiated with intense electric sparks made of high voltage. Taking advantage of these characteristics, we decided to create a new fly control screen. The solution involved utilizing a continuous-charging voltage generator with high output power, leading to the development of a three-layer corona- and arc-discharging screen (CADS). In this setup, a metal net is negatively charged using a continuous-charging voltage generator, and two identical metal nets connected to the ground are positioned on either side of the negatively charged metal net at regular intervals. An electric field is established between the central metal net and the ones on both sides. The grounded metal nets on each side serve as safety fences, mitigating the risk of electric shock in the case of contact with the central charged metal net. This design allows for the practical application of the device.

The aim of this study is to optimize the voltage applied to the metal net and the spacing between the negatively charged and grounded metal nets, referred to as the pole distance, in our current device. When a fly enters the device and forms a bridge between the negatively charged and grounded metal nets, the negative charge from the charged metal net passes through the fly's body, allowing current to flow directly without triggering an arc discharge toward other targets [22]. To prevent this issue, it is essential to establish a distance between the electrodes that cannot be bridged by flies. Our first objective is to set the pole distance based on the length of the houseflies and stable flies used and then determine the optimal voltage conditions for exterminating target flies through arc discharge-mediated spark irradiation, regardless of the fly species entering the device. The second goal is to investigate the device's ability to repel flies approaching its outer grounded net. Since insects tend to move upward [23], the device is positioned in the direction of their movement to observe whether flies enter it. Additionally, we measure negative ions and gaseous products, such as ozone [24], generated in the corona-discharging electric field and released outside the grounded metal net. This aims to determine if these products influence fly behavior and act as deterrents to prevent flies from entering the electric field. Finally, based on our findings, we discuss the effectiveness of using the present device for controlling houseflies and stable flies. This study provides an experimental foundation for developing a straightforward and unique electrostatic tool for fly control in cattle barns.

2. Materials and Methods

2.1. Fly Species

Adult houseflies, *Musca domestica* (Linnaeus) (Diptera: Muscidae) and stable flies, *Stomoxys calcitrans* (Linnaeus) (Diptera: Muscidae) were used in the present study. Adult houseflies were purchased from Sumika Technoservice (Hyogo, Japan) and reared on a certified diet (MF; Oriental Yeast Co., Ltd., Tokyo, Japan) [25] in a closed 30-mL transparent acrylic vessel. Insect rearing was conducted in a growth chamber (25 ± 0.5 °C, 12-h photoperiod, 4000 lux) from the egg to adult stages. Adult stable flies, gifted by Dr. Kazunori Matsuo, Faculty of Social and Cultural Studies, Kyushu University, Japan, were kept in a red net-covered cage within a growth chamber (24.0 ± 0.5 °C, 12-h photoperiod at 5000 lux). Adult flies were raised on cotton soaked with 5 mL of cow blood, which was regularly replaced with fresh cotton. The blood was supplied by Dr. Tamako Matsuhashi, Institute of Advanced Technology, Kindai University, Japan. The eggs obtained were transferred to a rearing medium, as described by Friesen et al. [26]. In addition to the two mentioned flies, we used adult greenbottle flies, *Lucilia sericata* (Meigen) (Diptera: Calliphoridae), for comparison. This fly was selected due to its comparable body length to the aforementioned flies. Greenbottle fly pupae were procured from Sumika Technoservice and reared using the method outlined earlier for houseflies. In all species, adult flies were randomly collected, irrespective of gender, and used in all experiments. The average body size of adult flies, measured as the mean length from the head to wing tip, was 8.55 ± 1.21 mm for houseflies, 6.88 ± 0.82 mm for stable flies, and 8.75 ± 1.38 mm for greenbottle flies. Adult flies were singly collected using an insect aspirator (Wildco, Yulee, FL, USA) and transferred to the space between the metal nets or inside the test box described below.

2.2. Anesthetizing Adult Flies Using Carbon Dioxide (CO_2)

To immobilize adult flies, we employed a previously described method involving exposure to carbon dioxide (CO_2) [27]. In summary, we placed vials containing an insect in a non-vacuum glass desiccator with a jar capacity of 5 L. CO_2 gas (Air Water West Japan Inc., Osaka, Japan) was continuously introduced into the desiccator at a pressure of 10 kg/cm^2 for 4–5 min while simultaneously removing air through the exhaust port of the desiccator lid. The introduction of CO_2 ceased once all insects were successfully anesthetized. Notably, in this CO_2 treatment, all anesthetized houseflies regained consciousness within 5 min.

2.3. Construction of the CADS

An expanded aluminum net (18 × 18 cm^2) (Okutani Wire Netting, Kobe, Japan) (Figure 1A) was fitted into a polypropylene frame to create a metal net unit (MN unit) (Figure 1B,C). The CADS was constructed using three identical MN units. One MN unit was connected to a negative-voltage generator (maximum electric current, 10 mA) (Logy Electric Co., Ltd., Tokyo, Japan) to give it a negative charge, while the other MN units were linked to a grounded wire and positioned on either side of the negatively charged net (Figure 1D). A negative-voltage generator is a booster to enhance the initial voltage (12 V) to desired voltages (1–10 kV). This enhanced voltage caused the voltage generator to draw a negative charge from the ground and supply it to the metal net connected to the generator. The accumulation of negative charge on this metal net pushed free electrons out of the grounded metal nets, positively charging them through electrostatic induction [28]. The opposite charges on the negatively charged and grounded metal nets created an electric field between them (Figure 1E).

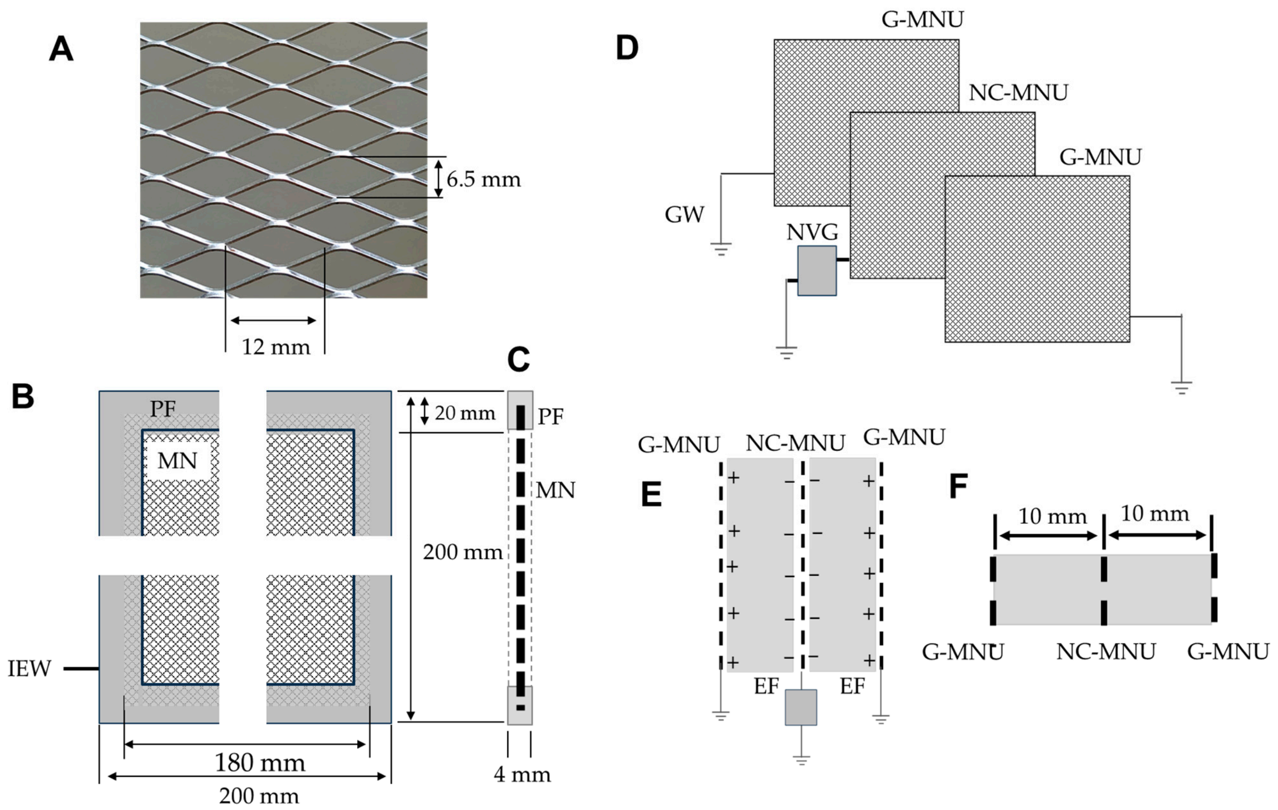

Figure 1. (**A–C**) Construction of a metal net unit. (**A**) An expanded aluminum net with diamond-shaped mesh (strand width, 2 mm). (**B**) A metal net (MN) fitted to a polypropylene frame (PF) and connected to a negative-voltage generator or grounded wire with an insulated electric wire (IEW). (**C**) A cross-sectional view of a metal net unit. (**D–F**) Construction of a corona- and arc-discharging screen (CADS). (**D**) The CADS consisting of three identical metal net units. One metal net unit was

connected to a negative-voltage generator (NVG), and two metal nets were linked to a grounded wire (GW). Grounded metal net units (G-MNUs) were placed on each side of the negatively charged metal net (NC-MNU). (**E**) Electric fields (EFs) formed between the NC-MNU and two G-MNUs) (cross-sectional view). (**F**) Spacing (10 mm) between the metal nets to prevent flies from forming a bridge between the nets.

To identify the ideal gap where flies do not create bridges between metal nets, considering the average body length of flies (approximately 6.9–8.8 mm), the CADS was constructed with charged and grounded metal nets set at a distance of 10 mm (Figure 1F). Spacers, consisting of polypropylene plates, each 1 mm thick, were used to maintain the specified space between the nets. This CADS was used for subsequent experiments.

2.4. Determination of Optimal Voltages for Repelling and Spark-Exposing Flies Using a Closed-Box System

In the first experiment, we assessed the effectiveness of the CADS by observing the upward movement behavior of flies using a closed-box system (Figure 2). The closed-box system comprised the CADS positioned between two identical transparent acrylic boxes measuring 20 cm on each side. The central metal net unit of the CADS was connected to a negative-voltage generator, while the other two metal net units were connected to a grounded wire. The CADS was situated on the upper open surface of the bottom box, and the second box was placed on top of the CADS, with its open face directed downward. Test flies were released into the lower box to observe whether flies passed through the CADS and entered the upper box. The CADS was negatively charged with different voltages (1–9.8 kV). The non-charged CADS was used as a control. In cases where flies remained on the walls and bottom of the box, the tip of the fly manipulator, which was inserted into the box through the wall, was brought closer to encourage them to fly upward (Figure 2). Experiments were conducted at 26 °C, allowing all flies to move actively. In this experiment, we recorded the proportion of

1. flies that avoided entering the electric field of the CADS;
2. flies that entered the electric field and were irradiated with sparks;
3. flies that were bounced back to the bottom of the lower box and examined the survival of these flies.

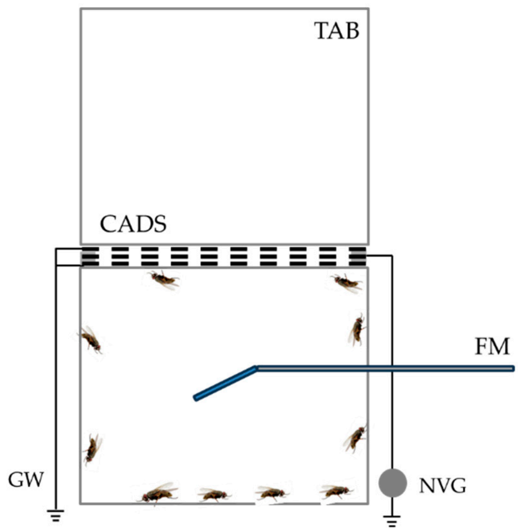

Figure 2. A closed-box system comprising a corona- and arc-discharging screen (CADS) positioned between two identical transparent acrylic boxes (TABs). The central metal net of the CADS was connected to a negative-voltage generator (NVG), while the other two metal nets were connected to a grounded wire (GW). The CADS was situated on the upper open surface of the bottom box, and the

second box was placed on top of the CADS, with its open face directed downward. Test flies were released into the lower box to observe the proportion of flies that passed through the CADS and entered the upper box. This was carried out both with and without voltage applied to the CADS. In the cases where flies remained on the walls and bottom of the box, the tip of the fly manipulator (FM) was brought closer to encourage them to fly upward.

Twenty flies of each species were used for each voltage, and the experiment was repeated five times for statistical analysis.

2.5. Measurement of Electric Current in Anesthetized Flies Exposed to Sparks

To assess the electric current flow in flies exposed to sparks, we immobilized (anesthetized) individuals from three species. Each fly was placed individually on a plastic spatula and inserted through a mesh into an electric field created between the negatively charged and grounded metal net units of the CADS (Figure 3), which was negatively charged within the 1–6 kV range. The space between the NC-MNU and G-MNU was divided into five zones to determine the fly's position when the spark was generated at each voltage. The magnitude and flow pattern of the electric current were recorded using a galvanometer (Sanwa, Tokyo, Japan) integrated into the grounded line of the G-MNU (Figure 3). As the spark exposure ceased autonomously, we examined the duration of spark exposure. For each voltage, 20 flies of each species were used, and the experiment was repeated five times for statistical analysis.

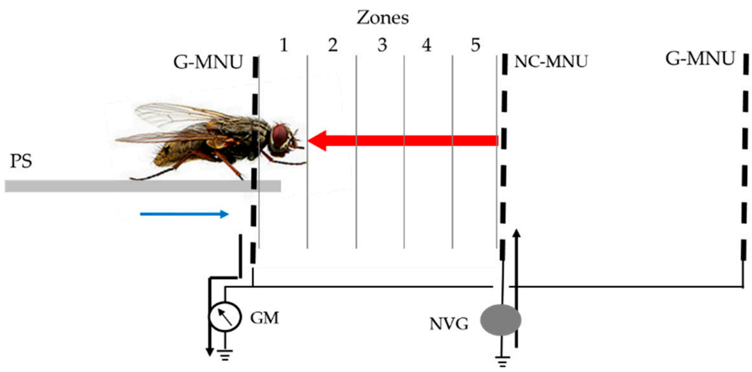

Figure 3. Illustration of the insertion of an anesthetized fly into the electric field of a corona- and arc-discharging screen (CADS). The CADS consisted of three identical metal net units, with the central unit connected to a negative-voltage generator (NVG), and the other two units connected to a grounded wire. A galvanometer (GM) was integrated into a grounded wire to measure the current flow generated through an arc discharge. The space between the negatively charged metal net unit (NC-MNU) and the grounded metal net unit (G-MNU) was divided into five zones (Zones 1–5) at 2-mm intervals. A fly is placed on a plastic spatula (PS) and inserted through the mesh of the G-MNU into the electric field between the nets of the CADS. The blue arrow indicates the direction of insect insertion, while the black arrow represents the direction of the movement of negative charge through an arc discharge-mediated spark (red arrow) in a ground-to-ground circuit.

2.6. Measurement of Ionic Wind, Negative Ion, and Ozone Generation in a Corona-Discharging Electric Field

Within the present voltage range, causing no arc discharge, a negatively charged metal net induces a corona discharge at the convex sites on its surface [23]. The intensity of this corona discharge is directly proportional to the applied voltage. In the electric field with corona discharge, numerous negative ions are produced around the charged net, generating an airflow known as the ionic wind from the negatively charged metal net to the grounded metal net [20]. In our second experiment, we investigated corona discharge occurrence using the CADS negatively charged with the same voltages mentioned above. In this experiment, we measured the speed of the ionic wind and estimated the number of negative ions involved in the airflow on the outside surface of the grounded metal net using a high-sensitivity anemometer (Climomaster 6533; Kanomax, Tokyo, Japan) and a Gerdien atmospheric ion counter (NKMH-103; Hokuto Electronic, Hyogo, Japan), respectively. The volumetric flow rate (m^3/min) of the ionic window was calculated using the equation Q (m^3/min) = V (m^2) × A (m/s) × 60 (s). Since ozone is known to be produced in the corona-discharging electric field [24], we determined ozone productivity (μg/min) of the CADS to which the above voltage is applied. Specifically, the air in the vicinity of the outside metal net of the CADS was aspirated and transferred to a flow cell of an ozone monitor EG-700E3 (Ebara Jitsugyo, Tokyo, Japan), and the UV absorption at 254 nm was measured by a standard method [29] for ozone estimation.

2.7. Evaluation of Feasibility for CADS Installed on a Greenhouse Window

We developed the CADS units with dimensions of 60 cm by 30 cm for a greenhouse trial. In this experiment, we utilized a small film house (Figure 4A) within a glass greenhouse maintained at a controlled temperature of 27 ± 1 °C to encourage active movement of the flies. Four CDASs were installed into the window frame on the lateral face of a film house (Figure 4A). A cuboid plastic frame was covered with a conventional insect net (mesh size, 1.5 mm) to ensure air permeability and affixed to each side of the CADS (Figure 4B,C). Among the CADS units, three were negatively charged at 1, 5, and 7 kV, respectively, while the fourth CADS remained uncharged to serve as a control. A total of 40 adult houseflies and stable flies (20 adults for each species) were simultaneously released into the exterior compartments of each CADS. The experiment spanned 24 h, after which we recorded the count of surviving and deceased flies within the boxes and inside the CADS. The experiments were repeated five times for statistical significance. Experiments were carried out between April and July for two consecutive years (2023–2024).

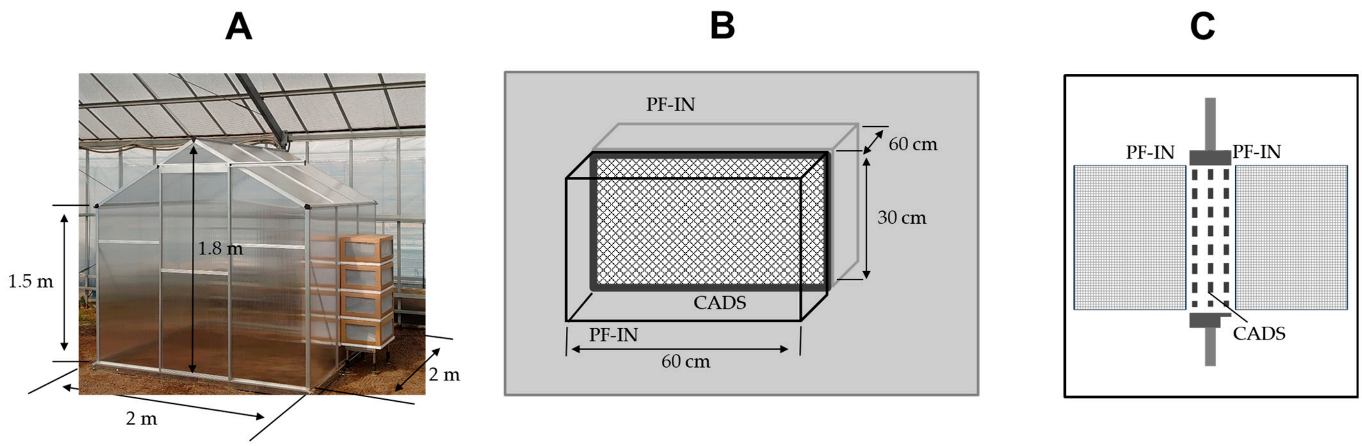

Figure 4. Photograph (**A**) and illustration (**B**,**C**) of a corona- and arc-discharging screen (CADS) used for a greenhouse assay. (**A**): Four CADSs installed on a lateral window of a film house within a glass house. Three CADSs were negatively charged at 1, 5, and 7 kV, respectively, while the fourth CADS remained uncharged to serve as a control. (**B**): A rectangular plastic frame covered with an insect net (PF-IN) was attached to each side of the CADS. (**C**): A cross-sectional view of (**B**). Test insects were released into the net box on the front side to evaluate the CADS's ability to prevent flies from entering.

2.8. Statistical Analysis

All experiments were repeated five times, and all data are presented as mean and standard deviation. Tukey's test was performed using EZR software (ver. 1.54; Jichi Medical University, Saitama, Japan) [30] to detect differences among the various conditions. A *p*-value < 0.05 was considered significant.

3. Results

3.1. Evaluation of Fly Avoidance Behavior in Response to an Electric Field Using a CADS-Equipped Enclosure

The CADS plays a crucial role in repelling flies that approach the device. The effectiveness of this repellent function is gauged by observing whether flies hesitate to enter the device. To achieve this, we capitalized on the typical behavior of flies. Fortunately, many insects, including flies, tend to move upward [23]. Therefore, we positioned the CADS in alignment with the fly's upward movement and created an environment for the flies to traverse. In the experiment, flies were released into the lower box of two boxes, one placed on top and the other at the bottom of the CADS, to evaluate the fly-repelling function at each voltage level. The results, presented in Table 1, categorized houseflies, stable flies, and greenbottle flies into four groups:

1. those successfully passing through the CADS and moving to the upper box;
2. those avoiding the electric field of the CADS by remaining on the outer metal net surface or the wall and bottom of the lower box;
3. those perishing after spark irradiation within the electric field;
4. those being bounced back to the bottom of the lower box before entering the electric field.

Table 1. Percentage of houseflies (HF), greenbottle flies (GF), and stable flies (SF) categorized into four groups in a closed box partitioned with a corona- and arc-discharging screen (CADS) negatively charged with different voltages.

Category [1]	Flies	Voltage (kV) Applied										
		0	1	2	3	4	5	6	7	8	9	9.8
A	HF	100	0	0	0	0	0	0	0	0	0	0
	GF	100	0	0	0	0	0	0	0	0	0	0
	SF	100	0	0	0	0	0	0	0	0	0	0
B	HF	0	86.7 ± 2.8 a	87.8 ± 1.6 a	98.6 ± 0.5 a	99.3 ± 0.3 a	100 a	100 a	100 a	100 a	100 a	100 a
	GF	0	87.1 ± 1.7 a	88.6 ± 1.1 a	98.9 ± 0.3 a	99.6 ± 0.2 a	100 a	100 a	100 a	100 a	100 a	100 a
	SF	0	2.5 ± 1.3 b	3.5 ± 0.8 b	5.5 ± 0.9 b	5.1 ± 1.8 b	0 b	0 b	0 b	0 b	0 b	0 b
C	HF	0	13.3 ± 2.7 a	12.2 ± 1.7 a	1.4 ± 0.6 a	0.7 ± 0.09 a	0 a	0 a	0	0	0	0
	GF	0	13.8 ± 1.8 a	11.4 ± 1.2 a	1.2 ± 0.4 a	0.4 ± 0.09 a	0 a	0 a	0	0	0	0
	SF	0	97.5 ± 1.2 b	96.5 ± 0.8 b	94.5 ± 0.9 b	95.9 ± 1.8 b	62.5 ± 2.5 b	23.1 ± 1.5 b	0	0	0	0
D	HF	0	0	0	0	0	0	0	0 a	0 a	0 a	0 a
	GF	0	0	0	0	0	0	0	0 a	0 a	0 a	0 a
	SF	0	0	0	0	0	37.5 ± 2.6 a	76.9 ± 1.5 a	100 b	100 b	100 b	100 b

[1] A, flies that passed through the CADS and moved to the upper box; B, flies that avoided entering the electric field of the CADS; C, flies that perished after spark irradiation inside the electric field; D, flies that were bounced back to the bottom of the lower box. Twenty flies were used for each voltage and each fly species. The means and standard deviations were calculated from five repetitions of the experiments. The letters (a, b) on the means in each vertical column of each category indicate significant differences ($p < 0.05$) according to Tukey's method.

As a control, we used the non-charged CADS to assess whether flies could pass through the device and move upward. Surprisingly, in the case of three fly species, over 90% of the released flies successfully traversed the CADS within a 5-minute experimental period. Notably, flies residing on the wall of the lower box also ascended when the tip of the fly manipulator was brought close to them (Category A in Table 1). Based on these findings, we concluded that our chosen methodology effectively examined whether flies avoided entering the electric field of the CADS, particularly under voltage-applied conditions. The key finding in Category A of Table 1 was that, at all applied voltages, no flies from any species entered the upper box through the CADS. This suggests that the device effectively prevents fly entry when a voltage is applied, irrespective of its level. The mechanisms behind fly prevention can be understood by examining Categories B–D.

Category B illustrates the percentage of flies staying in the lower box at different CADS voltages (Table 1). Based on these findings, we further categorized flies into two groups: those avoiding the electric field, like houseflies and greenbottle flies, and those entering the field without hesitation, such as stable flies (experiencing spark irradiation, as shown in Categories C and D in Table 1). The avoidance behavior of houseflies and greenbottle flies varied depending on the applied voltage. At lower voltages (1–4 kV), flies released into the lower box initially flew up toward the outer surface of the metal net of the CADS. However, they subsequently moved to the wall of the box without entering the inside of the CADS. Video S1 illustrates houseflies exhibiting hesitation in response to the electric field of the CADS. In Video S1A, as a control without applied voltage, flies passed through the metal net and entered the CADS. Conversely, in Video S1B, with 4 kV applied, flies briefly stopped on the metal net but then flew back without entering the CADS. Flies that moved to the box wall from the metal net remained stationary. When chased away with a fly manipulator, they flew up and landed on the metal net again but quickly relocated. At higher voltages (5–9.8 kV), all flies released into the lower box stopped on the wall surface, avoiding the metal net of the CADS entirely. Even when chased away by a fly manipulator, these flies only moved to other parts of the box and never approached the CADS. In summary, houseflies and greenbottle flies seem capable of detecting something in the electric field of the CADS, exhibiting hesitation at lower voltages and actively avoiding it at higher voltages. It is likely that substances inducing repellency in the electric field of the CADS increase proportionally with the applied voltage.

3.2. Generation of Negative Ions, Ozone, and Ionic Wind by the CADS

The production of negative ions and ozone can be attributed to the corona-discharging electric field [20,24]. This study confirmed that the CADS generated negative ions and ozone, as shown in Figure 5A,B. Higher voltages applied to the CADS resulted in increased production of negative ions and ozone. The ionic wind generated by the apparatus (Figure 5C) facilitated the transportation of these products to the designated location, which, in this case, is the outer surface of the grounded metal net where flies may land. Unfortunately, this study provides no evidence that these products contribute to the reluctance of houseflies and greenbottle flies to enter the electric field. Additionally, it cannot be ruled out that unidentified substances produced by the CADS may deter flies from entering the electric field. Further analysis is required to address these points. It is worth noting that even after continuous operation of the CADS, with the highest applied voltage, for two days in a closed box, both species of flies in the box survived. This suggests that the CADS does not produce any lethal substances.

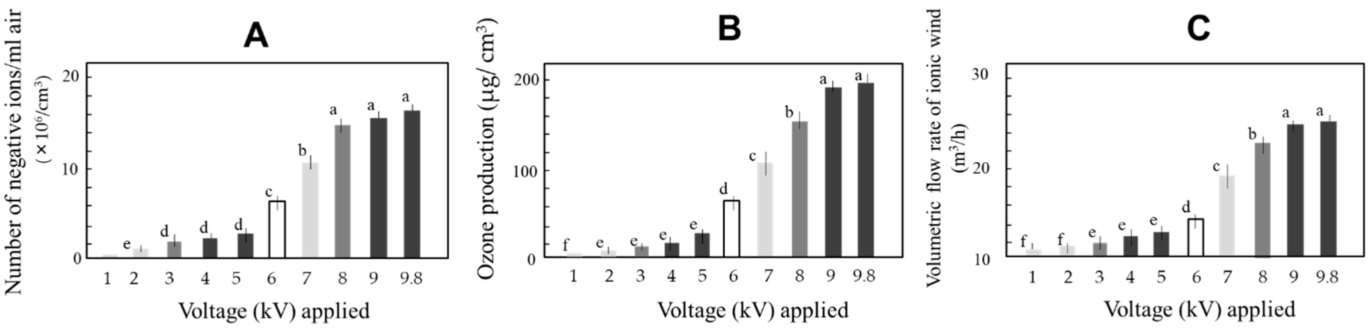

Figure 5. Generation of negative ions (**A**), ozone (**B**) and ionic wind (**C**) by a corona- and arc-discharging screen (CADS) negatively charged with different voltages. The mean and standard deviation were calculated from five replicates. The different letters (a–f) on the column indicate significant difference ($p < 0.05$) according to Tukey's method.

3.3. Extermination of Flies Entering the CADS through Arc Discharge-Mediated Sparks

In this study, the CADS serves the purpose of irradiating flies entering the device with arc discharge-mediated sparks. To prevent invading flies from forming a bridge between the metal nets, which allows current to flow on the fly body without causing arcing, it was crucial to set the spacing appropriately. Considering the body length of three fly species, the distance between the metal nets of the CADS was fixed at 10 mm. Preliminary tests confirmed that at this interval, no bridges between the metal nets were formed by flies. Using this CADS, we initially determined the voltage suitable for spark irradiation. The voltage generator in this study can use voltages from 1 to 10 kV (at 100 V intervals). However, applying a voltage above a certain threshold (9.9 kV) broke down the insulation resistance of the air between the negatively charged and grounded metal nets, leading to arcing between them [31]. On the other hand, within the voltage range below that threshold (1.0–9.8 kV), the negatively charged metal net caused corona discharge. The arcing process occurs when a grounded conductor enters the corona-discharging electric field generated by charged and grounded metal nets [23]. As the body of a fly is a biological conductor [23], it can also act as a grounded conductor when it perches on the grounded metal net and pushes its body into the electric field. The objective of the experiment was to investigate the effectiveness of subjecting flies to arc discharge-mediated sparks, regardless of their varying body sizes.

In the experiment involving a two-layer box and stable flies, it was observed that flies reaching the bottom layer of the metal nets in the CADS entered the interior without regard for the electric field formed between the metal nets. Categories C and D in Table 1 represent the proportion of stable flies that received spark irradiation at various voltages. The results revealed two distinct patterns of spark irradiation based on voltage differences. Category C describes instances where flies experienced continuous sparks by placing their entire bodies or most of their bodies in the electric field of the CADS (Video S2A). This was observed at lower voltages (1–4 kV), as shown in Table 1. Conversely, Category D refers to cases where flies were repelled by instantaneous double or triple sparks at higher voltages (5–9.8 kV) when they introduced a part of their body into the electric field (Video S2B). It is noteworthy that in both categories, all flies were confirmed to perish after spark irradiation.

However, it was still unclear why the spark irradiation pattern changed with varying applied voltage. To address this, we conducted experiments by placing an anesthetized fly in a specific position within the electric field to observe where spark irradiation occurs at different voltages. In Figure 6, we illustrate the electric field zone of the CADS where a fly, positioned at various distances from the charged metal net, experienced spark irradiation corresponding to different voltage levels. It was evident that for successful spark irradiation, the fly needed to be closer to the charged metal net, especially at lower voltages. In the voltage range of 7–9.8 kV, where flies were repelled, a fly entering Zone 1 (within 2 mm inside from the outer metal net) was immediately irradiated with sparks (Figure 6). However, since only part of the fly's body was in the electric field, it was bounced back. Conversely, in the voltage range of 1–4 kV, where flies consistently received spark irradiation, they experienced it upon entering Zone 3 (or deeper zones) (Figure 6). Here, most of the body was inside the electric field, and the weaker impact during spark irradiation allowed the fly to stay within the electric field and continue receiving sparks. At 5 and 6 kV, flies were irradiated with sparks in Zones 1–3, and both of the above situations were observed (Figure 6). These results indicate that higher voltages applied to the metal net can break down a thicker air layer, enabling spark irradiation even for flies at greater distances.

Kusakari and Toyoda [23] observed that flies subjected to continuous exposure to arc discharge-mediated sparks autonomously ceased spark exposure due to a decrease in the fly's body conductivity. This reduction resulted from the evaporation of body water, facilitated by Joule heating from the electric current flowing through the fly. Similarly, stable flies in Category C also autonomously halted continuous spark exposure, allowing for the measurement of spark irradiation duration. Figure 7 illustrates the duration of electric current and the highest current magnitude in stable flies exposed to continuous spark irradiation ranging from 1 to 6 kV. The results indicate that higher voltages led to shorter durations of spark irradiation (Figure 7A) and higher maximum magnitudes of electric current (Figure 7B).

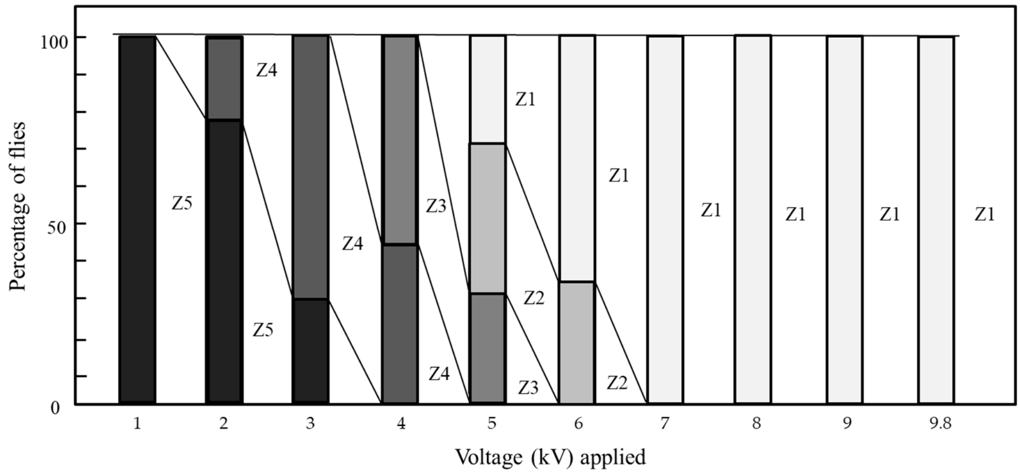

Figure 6. Proportion of stable flies irradiated with arc discharge-mediated sparks in the zones established in an electric field between negatively charged and grounded metal nets of a corona- and arc-discharging screen (CADS) negatively charged with different voltages. The electric field was segmented into five zones at 2-mm intervals. To identify the zone where spark irradiation occurred for each voltage, adult stable flies under CO_2 anesthesia were positioned on a plastic spatula and inserted through the metal net into the electric field. For each voltage, 20 flies were used, and the average percentage of flies experiencing spark irradiation in Zones 1–5 (Z1–Z5) were represented in the figure columns.

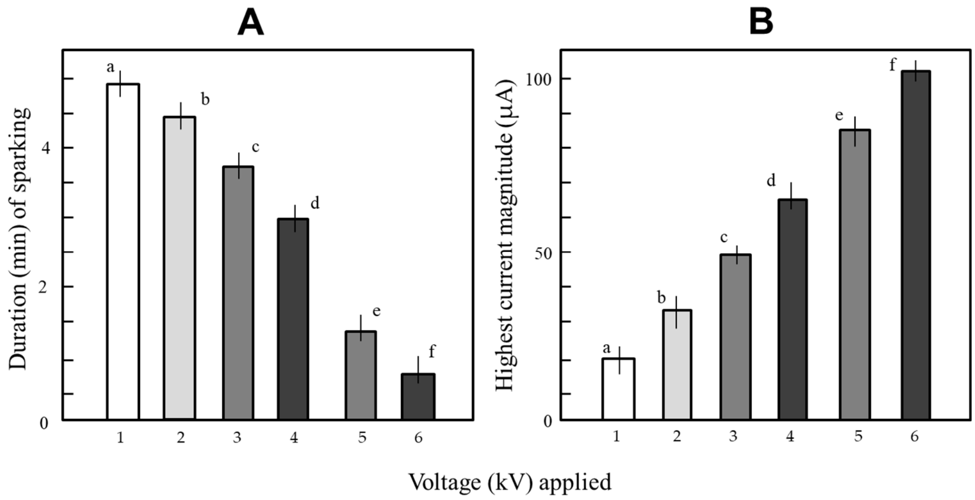

Figure 7. Assessment of the duration of spark exposure (**A**) and the highest electric current (**B**) in CO_2-anesthetized stable flies placed within the electric field of a negatively charged corona- and arc-discharging screen (CADS) ranging from 1 to 6 kV. The flies underwent continuous exposure to arc discharge-mediated sparks. Twenty flies were included for each voltage, and the mean and standard deviation were computed from five replicates. Different letters (a–f) on the columns indicate a significant difference ($p < 0.05$) based on Tukey's method.

3.4. Practical Tasks Assigned to the CADS for Fly Control

In our final experiment, we implemented a unique fly control strategy using the CADS, evaluating its effectiveness within a dual-box system. The scenario simulated the attachment of the CADS to a building window for fly elimination and repellence. Our laboratory experiments indicated that all voltages (1–9.8 kV) applied allowed the CADS to prevent the entry of flies. However, it was crucial to determine the most suitable voltage for the practical use of the CADS. In this experiment, we selected 1, 5, and 7 kV for negatively charging the CADS installed on the greenhouse window and released both flies into the same outside box to test the CADS's ability to repel houseflies and kill stable flies by emitting sparks. To achieve our goal, we needed to confirm that flies could efficiently move from the outside to the inside box when the CADS was not charged. Table 2 shows that almost all flies from both species successfully crossed the non-charged CADS and entered the inside box. This indicated that the current method was suitable for the experiment's requirements.

Table 2. Percentage of adult houseflies and stable flies categorized into four groups in a dual-box system of a corona- and arc-discharging screen (CADS) negatively charged with different voltages.

Voltage (kV) Applied	Categories [1]			
	A	B	C1	C2
0	96.6 ± 1.8 a	0 a	1.2 ± 0.3 a	2.2 ± 0.5 a
1	24.8 ± 1.2 b	69.2 ± 0.8 b	1.4 ± 0.6 a	5.2 ± 0.7 a
5	2.1 ± 0.7 c	40.6 ± 1.2 c	1.2 ± 0.2 a	57.2 ± 4.5 b
7	0 d	0 a	31.2 ± 0.8 b	69.2 ± 7.8 b

[1] A, flies that passed through the CADS and moved to the inside from the outside box, where flies had been released, to the inside box; B, flies that perished after spark irradiation inside the electric field; C1 and C2, Living and dead flies that stayed in the outside box, respectively. Twenty flies were used for each voltage and each fly species. The means and standard deviations were calculated from five repetitions of the experiments. The letters (a–d) on the means in each vertical column of each category indicate significant differences ($p < 0.05$) according to Tukey's method.

In this experiment, we were concerned that continuous arcing in one part of the charged metal net causes the loss of the charge in other parts, compromising the CADS's function during the period of arcing. At this time, even if other flies enter the CADS, the flies are not irradiated by the spark so that they can pass through the CADS. In fact, we frequently observed that other flies passed through the CADS while the flies were receiving continuous irradiation of sparks in the CADS, to which 1 kV was applied (Table 2). With the CADS applied at 5 kV, the duration of continuous irradiation was shortened, and the number of other flies passing through the CADS decreased significantly (Table 2). However, even in the case of 5 kV, if the fly population used is enlarged, the number of flies entering at the same time is expected to increase, so even if it is raised to 5 kV, it is still not a solution to this problem.

Charging the CADS at 7 kV was successful, allowing it to repel houseflies and emit sparks to repel stable flies. Flies were prevented from entering the CADS (Table 2), eliminating the risk of other flies entering during irradiation. These findings highlight the CADS's effectiveness in completely preventing fly passage. Based on our results, we conclude that the current CADS system holds promise as a device for controlling undesirable flies in a cowshed.

4. Discussion

The CADS introduced in this paper was designed as a continuous producer of negative ions in the absence of flies within the electric field. The negative ions generated in this field are particularly noteworthy for their potential to precipitate both biological and non-biological airborne nuisances, which pose public health concerns. These nuisances encompassed infectious particles such as viruses [32–35], bacteria [34,36,37], fungal spores [36,37], certain allergens [34], and passive inhalation of tobacco smoke particles [20]. This study focused on the use of CADS for controlling houseflies and stable flies, but its applicability extends beyond these targets. The potential of CADS for a diverse range of applications makes it a promising subject for further research.

The major discovery in this study revealed that houseflies and greenbottle flies are deterred by a corona-discharging electric field, whereas stable flies are unaffected by it. Kusakari and Toyoda [23] introduced a distinctive electrostatic device designed to repel insects. This device consisted of a negatively charged insulated metal conductor (comprising metal wires and nets) and a grounded non-insulated metal net, creating a static electric field without inducing a discharge phenomenon. Many insects, upon reaching the grounded metal net, refrained from entering the electric field due to an attractive force acting on their antennae or legs that extended into the field [23,38]. However, when exposed to the electric field generated by the CADS, houseflies and greenbottle flies exhibited a complete avoidance of the grounded metal net outside the device. It became apparent that these flies detected certain materials produced by the CDAS's electric field, which were emitted to the surroundings. Consequently, this study suggests a novel type of pest-repelling device for effective pest control. By unraveling the mechanism of electric field repellency and identifying the specific pests that can be repelled, the application of CADS is expected to broaden significantly.

The core function of the CADS was the ability to irradiate flies with arc discharge-mediated sparks when flies put all or part of their bodies into the corona-discharging electric field. The intense burst of energy produced by an arc discharge is so potent that it can swiftly eliminate a fly by forcefully propelling it to the ground in a single discharge [23]. Even when multiple flies simultaneously enter the electric field, the spark occurs rapidly, sequentially knocking down the flies. In fact, in the present study, we verified that five flies introduced simultaneously were successively knocked down by several quick spark emissions. Nevertheless, in typical control scenarios, it is uncommon for multiple flies to enter at the same time. Therefore, it may not be necessary to address this issue more than required. The prominent feature of the CADS was that it was able to irradiate sparks regardless of the types of insects that entered the device. In fact, this technique has also been applied to spark irradiation-based elimination of mosquitoes [23] and rice weevils [21], as well as to control weed seedlings emerging from the soil [23]. However, this approach is not universally effective against all pests. For instance, when dealing with smaller flies like fruit flies and leaf miner flies, the intervals in the metal nets designed for houseflies and stable flies are too wide to expose these flies to sparks [22]. To address the control of these small-sized flying pests, it is advisable to use a trapping device equipped with a pair of insulated conductors charged positively and negatively [23].

In the present devices, the charging electrode and the grounded electrode both consist of identical metal nets. Essentially, any metal net products can be utilized for these devices. The key aspect is that the metal net has numerous protruding parts on its surface, which serve as the points where an arc discharge is generated [23]. In practice, regardless of where a fly enters the electric field between the nets, the closest protrusion to the fly arcs and emits a spark. The occurrence of arcing at a specific point on the metal net surface suggests that enlarging the net does not pose an issue for spark generation [23]. Matsuda et al. [21] found that as the size of the electrically charged metal net increases, there is a proportional increase in the amount of negative charge accumulated on the net's surface. Consequently, the electric energy of a spark generated by a single arc discharge also increases, leading to more significant damage to the target insect.

The CADS, composed of three layers of metal nets, is highly practical due to its large mesh size. This design ensures outstanding air permeability and reduces the likelihood of issues such as mesh clogging, a widespread problem with traditional insect-repellent nets used in cowshed windows. As a result, there is a significant reduction in the need for frequent cleaning of the insect-repellent net, leading to labor savings.

The voltage generator is the only electrical component that needs to be purchased. There are two types of voltage generators: variable voltage and fixed voltage. While a variable-voltage generator was necessary in this study to determine optimal voltage conditions, a fixed-voltage generator is more economical for practical fly control, as its price is much lower than that of the variable type [23].

In the present study, we proposed the CADS designed for installation on a window of a cowshed. In this device, establishing a ground-to-ground circuit for a negative charge is crucial for inducing an arc discharge in the circuit. To achieve this, two grounded wires connected to a voltage generator and a metal net are essential. One wire is responsible for picking up a negative charge from the ground, while the other wire facilitates the return of this charge to the ground. The electric wires are grounded by connecting them to a metal rod driven deep into the ground. While this setup is suitable for stationary devices installed on a window, it poses challenges for mobile devices like the CADS stand placed on a floor, which frequently changes its placement. To address this issue, we have introduced a non-grounded circuit that directly connects two grounded wires [23]. In this circuit, the voltage generator extracts free electrons from the metal net and transfers them to another net. Consequently, the metal net that provides free electrons becomes positively charged, while the net receiving free electrons becomes negatively charged. Adopting this circuit eliminates the need for a grounded wire, allowing for greater flexibility in equipment placement. Moreover, as the voltage generator operates using a 12 V lithium storage battery [19,23], there is no requirement for wiring to the generator, simplifying the mobility of the device.

In this study, we introduced a unique corona- and arc-discharging device characterized by its simple structure. The device's simplicity allows ordinary readers without special technical skills to inexpensively construct it using common materials or modify it to suit their preferences. In fact, one only needs to place predetermined spacers between multiple metal nets, secure all the parts, and connect some of the metal nets to a voltage generator or grounded wire. In this article, we provided basic information and explanations about an electric field-generating device for ordinary workers 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 pest control methods.

5. Conclusions

The CADS is a device used to control flies by generating corona and arc discharges. These discharges create an electric current between the charged and grounded metal nets. The strength of this current depends on the output of the voltage generator used to charge the metal nets. As the area of the charged metal net increases, the current from the corona discharge also increases. This means that the size and number of metal nets that can be charged by a single voltage generator are limited by its current output. Higher current output requires a more expensive voltage generator, which could be a significant cost factor for livestock farmers using this system. Therefore, it is important to compare the costs of using this system with those of traditional fly control methods.

This research highlights key issues for the practical use of the CADS over long periods. The first issue is understanding how environmental factors affect the device's performance. Specifically, the relative humidity (RH) of the air is a major factor influencing the effectiveness of the electric discharge. Higher RH increases the air's conductivity, leading to stronger discharges. It is important to investigate how daily changes in RH impact the device's performance. Another concern is the device's longevity. The CADS features three metal nets attached to a polypropylene frame. While this design simplifies dust cleaning and the aluminum nets resist rust, it is necessary to determine if dust and rust on the metal surfaces affect the discharge generation. Lastly, ozone production is a concern. We need to examine how the ozone produced by the CADS impacts the surrounding air. Specifically, we should investigate the amount of ozone produced, how long it remains in the barn, and how far it spreads, considering both its potential benefits (such as disinfecting airborne microbes) and drawbacks (such as air pollution).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14091435/s1, Video S1: Reluctance of houseflies to enter an electric field of a corona- and arc-discharging screen (CADS) negatively charged; Video S2: Irradiation of adult stable flies with arc discharge-mediated sparks from a negatively charged metal net of a corona- and arc-discharging screen (CADS).

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