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BRIEF COMMUNICATION

Electrostatic guarding of bookshelves for mould-free preservation of valuable library books

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Abstract Old books are highly susceptible to mould infection, and an effective method for avoiding moulding is needed to safely preserve valuable books in library stack rooms. Guarding a bookshelf with an electric field screen is a physical method that prevents airborne spores from entering the space used for book preservation. In this study, insulated conductor wires (ICWs) were used as electrodes to form electric fields. The ICWs were arrayed in parallel and linked to each other and to a direct current voltage generator. The electric field screen consisted of two layers of ICWs, which were negatively and positively charged with equal voltages to make dipoles, ICW(−) and ICW(+). Both ICWs generated an attractive force that captured airborne spores of *Penicillium digitatum* that were blown inside the screen. The attractive force was directly proportional to the applied voltage. At ≧0.9 kV, the screen exerted sufficient force to capture all airflow-carried spores, but a few spores that were once captured were repulsed out of the electric field when subsequent spores were attracted to positions proximal to them. This phenomenon was explained by creeping discharge between spores located close to each other on the ICW surface. This spore-repulsion problem was resolved by adding an additional ICW layer to the electric field screen, namely an electric field screen with an ICW(−) layer on both sides of an ICW(+) layer. The present study

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demonstrated that the three-layered electric field screen remained mould-free inside a screen-guarded bookshelf, irrespective of continuous spore exposure.

Keywords Electric field screen · *Penicillium digitatum* · Creeping discharge

1 Introduction

One of the most important precautions to safely preserve books in a library stack room is to keep the books from getting mouldy. Mould develops easily in poorly ventilated rooms, and thus improving the ventilation in the stack room is a basic measure for avoiding mould. However, large arrays of filled bookshelves are likely to be an obstacle to even airflow in the room. Moulding is most serious in older books because mould-proofing paper materials that inhibit colonisation by mould were not used. Anti-mould treatments have been used widely in recent books (Sequeira et al. 2012), and more than 55 % of our library-stocked books are mould-resistant. Our historically valuable books, however, are considerably old and are highly sensitive to mould infection. In fact, a thin film of mould has frequently grown over the entire surface of the books. To protect these books, we have been forced to conduct the costly and time-consuming fungicidal operations of periodically disinfecting the stack room with fumigants and routinely cleaning individual books by directly removing surface colonies with an alcohol-impregnated cotton wool. To solve this problem, it became essential to develop an alternative method to exclude airborne fungal spores from the space in which books were being preserved. For this purpose, we attempted to construct a bookshelf surrounded by an electrostatic device that generates an air-permeable shield that prevents spores from entering the bookshelf.

Developing an environmentally friendly method for protecting plants from pathogens during cultivation reflects our long-standing desire to replace conventional agrochemical technologies such as fungicides 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 was developed into a trap for aerial pathogens in glasshouses (Matsuda et al. 2006; Shimizu et al. 2007). The first electrostatic device 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 electric field. However, the screen required the impression of high voltages (10–30 kV) to create sufficient force to attract airflow-carried conidia that entered the electric field. Recently, we reported that two insulated electrodes that were oppositely charged with equal voltages could produce a strong force at a lower voltage range (5.0–5.8 kV; Matsuda et al. 2012). Nevertheless, this level of voltage impression still has the potential risk of arc (spark) discharge from the screen that could cause an electric-shock accident. To avoid this problem, it was essential to make a strong electric field in the application with much lower voltages. In the present study, the problem was solved by making duplicate electric field barriers in an electric field screen. The aim of the present study was to attain our target voltage (not exceeding 1 kV) for impression and to protect books from moulding by guarding a bookshelf with the improved electric field screens.

For a spore exclusion assay, we targeted cellulolytic fungi of genus *Penicillium* that are common causes of paper spoilage (da Silvia et al. 2006). In this study, we selected the species *P. digitatum* from our laboratory fungal stocks as a model of causal airborne fungi. These fungi were suitable for the preparation of abundant spores (conidia) because of their vigorous spore production (Kanetis et al. 2010). The present paper describes a successful application of the present electric field screen for physically excluding airflow-carried fungal spores from a bookshelf.

2 Materials and methods

2.1 Test fungi

Slant cultures of *P. digitatum* KPG-11 were transferred onto a potato dextrose agar medium in Petri dishes and cultured for 3 days in a growth chamber at 26.0 ± 2 °C. Young mycelia were excised from the colony edge and transferred to needle-injured sites of

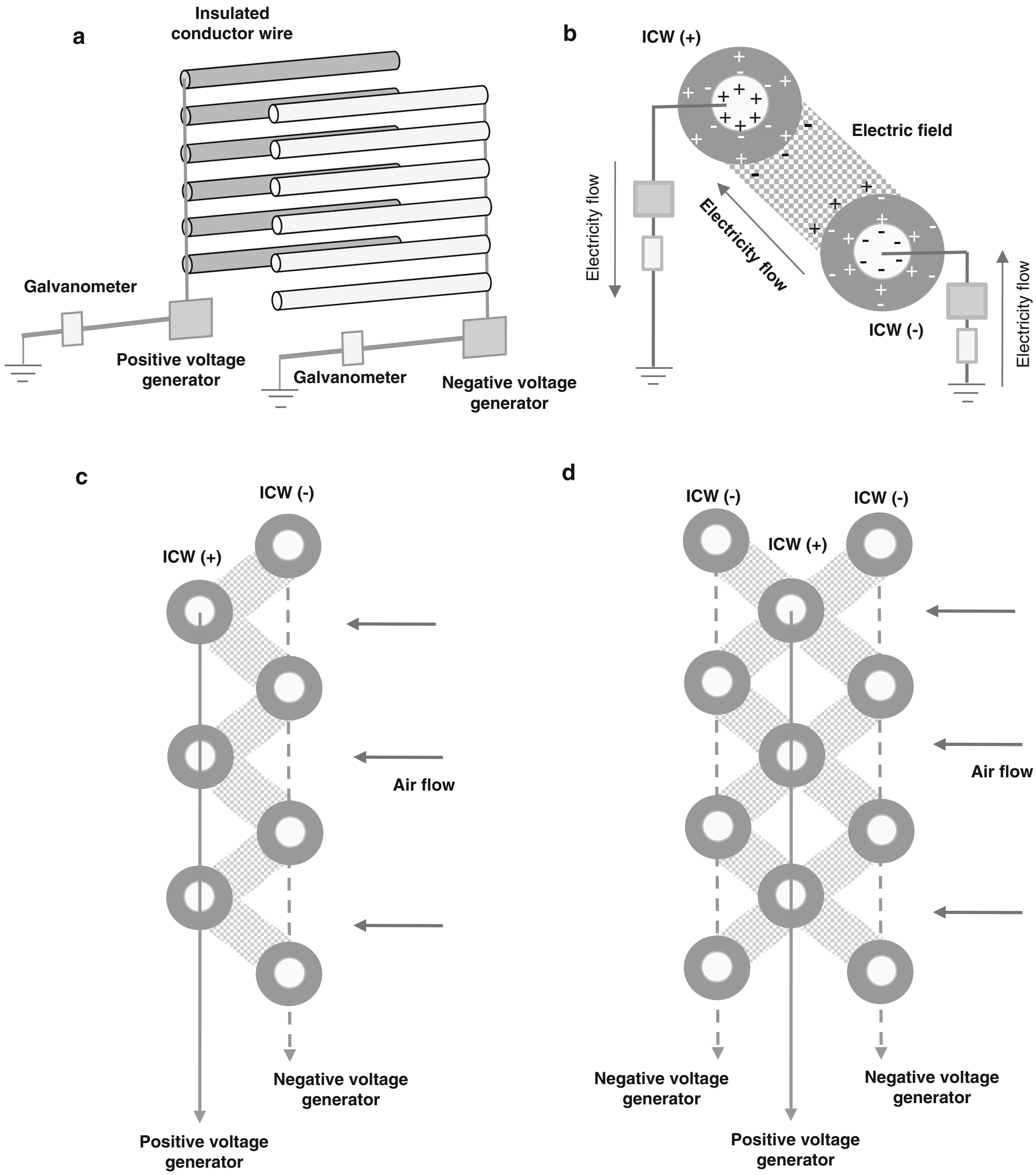

Fig. 1 Diagram of components (**a**) and cross-sectional views of insulated conductor wires (ICWs) (**b**–**d**) in the electric field screens. **a** Layers of ICWs arrayed in parallel and linked to each other and grounded DC voltage generators. **b** The electric field formed between ICW(−) and ICW(+). The *arrow* shows the direction of electricity flow by mechanical discharge between ICW(−) and ICW(+). **c**, **d** Arrangement of ICWs in the 2L screen (**c**) and the 3L screen (**d**)

market-purchased lemon fruits for inoculation. The inoculated fruits were placed in a moistened container and incubated 7–10 days for sporulation under the same culture condition mentioned above. Spores (conidia) formed on the fruits were collected and used for the following experiments.

2.2 Electric field screens

An iron conductor wire (2 mm diameter, 15–55 cm length) was insulated by passing it through a transparent insulator vinyl sleeve (1 mm thickness; bulk resistivity of $1 \times 10^9\ \Omega$) and used to construct an electric field screen. The screen had two components: two or three layers of insulated conductor iron wires (ICWs) in parallel arrays and two electrostatic direct current (DC) voltage generators (DMS-P and DMS-N; Max Electronics, Tokyo, Japan) that supplied negative and positive voltages to the ICWs (Fig. 1a), respectively. The ICWs of each layer were paralleled at a 5-mm interval and connected to each other and to a negative or positive voltage generator. The generators were linked to grounded lines and operated with 12-V storage batteries (power-supplied by a 150-watt solar panel) to supply equal negative and positive voltages to the ICWs (the negatively and positively charged ICWs are hereafter represented as ICW(−) and ICW(+), respectively). A galvanometer (PC7000; Sanwa Electric Instrument, Tokyo, Japan) was integrated into each grounded line of the voltage generators.

The ICWs of the electric field screen were oppositely charged with equal voltages. Cover sleeves were dielectrically polarised positively on the surface of the iron wire side and negatively on the outer surface of the insulator sleeve in ICW(−) and vice versa in ICW(+) (Fig. 1b; Matsuda et al. 2012). The opposite surface charges on the ICWs act as dipoles that form an electric field between them. Figures 1c, d show different arrangements of ICWs in two types of electric field screens: a two-layer screen consisting of one ICW(−) and one ICW(+) (2L screen; Fig. 1c) and a three-layer screen consisting of one ICW(+) layer with an ICW(−) layer on either side (3L screen; Fig. 1d). The layers were paralleled at a 2-mm interval, and the ICWs of the layers were offset to each other. Spore attraction was video recorded with a digital EOS camera (Canon, Tokyo, Japan) equipped with a high-fidelity digital microscope (KH-2700; Hirox, Tokyo, Japan) while voltages were applied.

2.3 Assay for spore capture

Fifteen wooden cubic boxes (side length, 15 cm) were used to prepare separate cells for comparison. Each box was furnished with an axial-flow fan (blade length, 8 cm) on one side and a 2L screen (15 × 15 cm) on the opposite side (Fig. 2a). All of the boxes were piled and subjected to spores blown by a blower (blade length, 40 cm; Fig. 2b). Conidia were dusted onto a parchment paper-covered tray by gently tapping the inoculated fruits to make a spore inoculum. Before blowing, we confirmed the fixed spore density (10^4–10^5 spores/cm^2/tray) by counting the number of spores at several areas of the tray selected at random, using a high-fidelity digital microscope according to the method of Matsuda et al. (2006). We confirmed that the spores were well separated from each other. The blower was placed 2 m from the boxes, and three parchment paper-covered trays (30 × 30 cm) onto which spores had been dusted were inserted into the airflow from the blower. The airflow rate of the blower was measured at the screen surfaces with an anemometer and adjusted to 1.0 m/s (corresponding to the airflow rate at most airy sites of our laboratory stack room). The rotation rate of each axial-flow fan was adjusted to this airflow rate. To collect conidia passing through a screen, an electrostatic spore attraction plate (Moriura et al. 2006a) was used; the spores were attracted to an ebonite plate (10 × 12 cm) electrified by a 15-kV-charged aluminium plate attached to the reverse side of the ebonite plate (Fig. 2c). A voltage generator (KMT-N; Max Electronics, Tokyo, Japan) was used to supply negative charge to the spore attraction plates. The spore attraction plates were placed vertically inside the boxes at a distance of 2 cm from the box edge on the screen-attached side. At the end of an experiment, each ebonite plate surface was scanned with a high-fidelity digital microscope to count the number of trapped conidia by the method mentioned earlier. In the first experiment, the screens of all the boxes were not charged and were exposed to airflow-carried spores for 30 min to check the even delivery of spores to all of the test boxes. The numbers of spores trapped by the electrostatic spore attraction plate in all test boxes were counted, and the data are given as means and standard deviations of five replicates. Significant differences between the test boxes were identified by Tukey's method. In the second experiment, the screens were tested for their capability to capture spores by charging them with different voltages (0.3, 0.6, 0.9 and 1.2 kV). Three boxes were used for each voltage, and three were used as a non-charged control. The number of spores trapped by the electrostatic spore attraction plate was counted, and the average of three boxes was calculated.

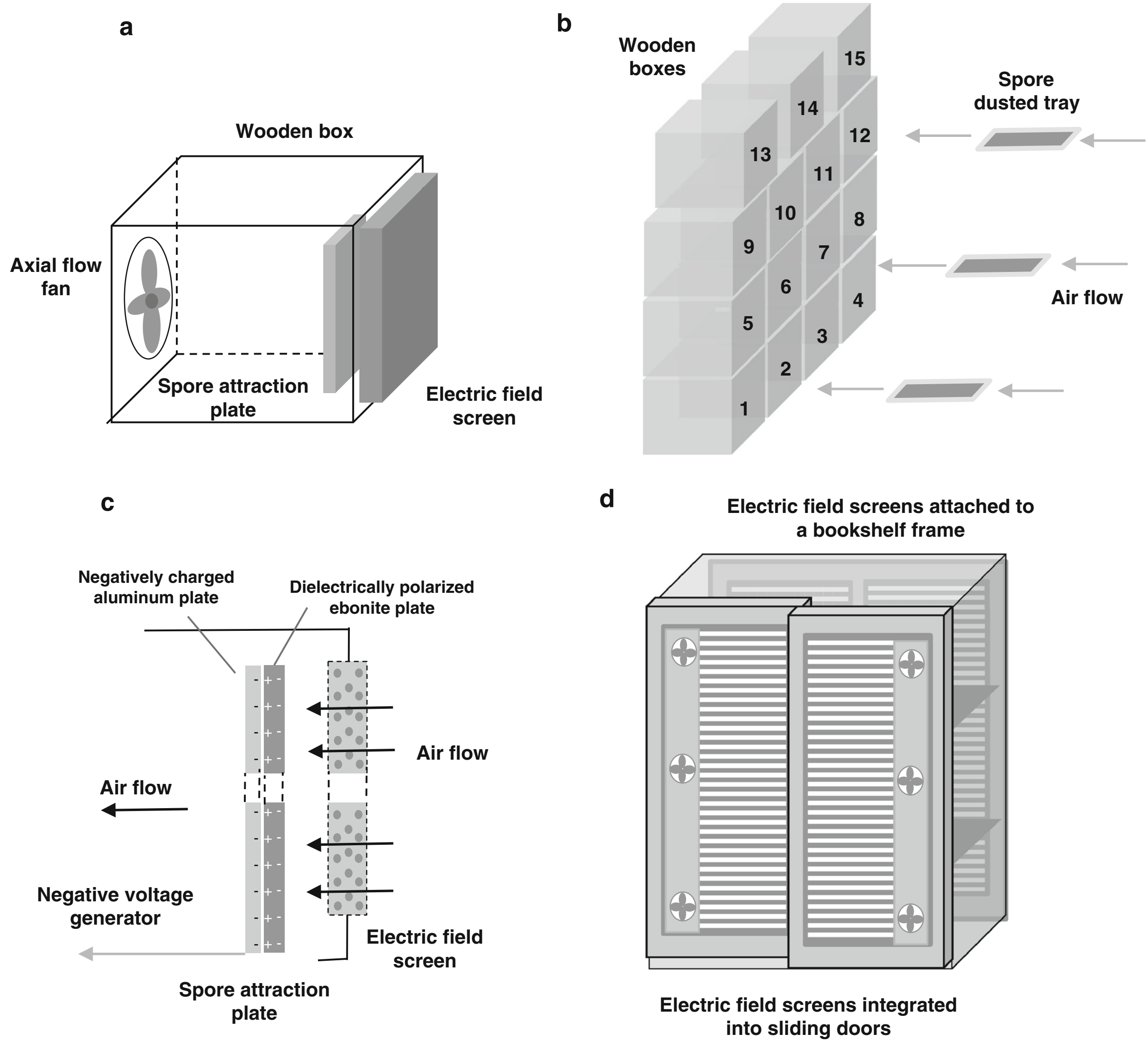

Fig. 2 Diagram of screen-installed boxes (**a**–**c**) and bookshelf (**d**). **a** A test box furnished with an electric field screen and an axial-flow fan on opposite sides. **b** Positions of test boxes and the blowing of spores from parchment paper-covered trays towards electric field screens attached to the boxes. **c** A spore attraction plate electrified with a negatively charged aluminium plate was placed inside a box along an electric field screen. **d** Electric field screens attached to fan (axial-flow fan)-installed sliding doors at the front and to the back side of a bookshelf

The number in the uncharged control was considered to be passage of 100 % of the spores through the screen, and the numbers in the charged screens were expressed as relative percentages of the uncharged control. The experiments were repeated five times, and the positions of the boxes were changed randomly in each experiment. Data are reported as means and standard deviations of five replicates and analysed statistically by Tukey's method. The same experiments were conducted again after the 2L screens had been replaced with 3L screens. All experiments were conducted at 25.0 ± 2 °C and at a relative humidity of 45–55 %.

2.4 Exclusion of airflow-carried conidia from a screen-guarded bookshelf

A steel bookshelf (180 × 120 × 40 cm) was screen-installed to examine whether an electric field screen (3L screen) could function normally during long-term continuous operation. Two 3L screens were attached to the bookshelf frame at the back of the bookshelf, and two additional screens were integrated into the fan-installed sliding doors at the front of the bookshelf (Fig. 2d). The screens of one bookshelf were oppositely charged at 0.9 kV, and the screens of another bookshelf were left uncharged as a control. Surface-cleaned books were arranged on both bookshelves and subjected to spores during the experimental period (1 month). Spores were blown three times a week during the experiment period using the method described earlier. At the end of the experiment, book surfaces were surveyed with a digital microscope to check for spores that may have reached the books. The experiment was repeated three times under the same conditions described above.

3 Results and discussion

The main point of the present work was to construct an electric field screen with gap-free multiple electric fields because successful spore capture depends on the formation of an electrostatic barrier with no spaces through which spores can pass. An essential step to form the electric fields was charging insulated electrodes. High voltages produced through a Cockcroft circuit (Wegner 2002) of two voltage generators were used to electrify both electrodes by adding electricity to ICW(−) and pushing electricity out of ICW(+). The flow of the accumulated electricity in ICW(−) depended on the voltage applied to the electrodes, the electrode separation distance, the insulation resistance of the ICW cover sleeve and the air conductivity between the two electrodes. The electric current from an insulated conductor was inversely proportional to increases in distance (Matsuda et al. 2012). Moreover, the current depended on the insulation resistance at a given voltage, which determined the level of insulator conductivity (Halliday et al. 2005). Air conductivity changes in response to changes in water-vapour concentration (relative humidity) of the air; the air conductivity becomes higher (i.e. higher amounts of electricity are transferred) under higher relative humidity (Jonassen 2002).

In this study, we set the distance and the relative humidity and then changed the voltage to examine the range of voltages that would cause a discharge from ICW(−) (mechanical discharge) because the absence of discharge was a necessity for safe use of the screen. From an electrical point of view, the present screen involved an electric circuit in which electricity moved from ground to ground (Fig. 1b). A constant flow of electricity (electric current) occurred at $\geqq 3.2$ kV and became larger as the applied voltage was increased (data not shown). From these results, we used the screen charged with <3.2 kV and determined the range of voltages that could provide sufficient force for the electrodes to capture all spores in a static electric field that caused no mechanical discharge.

Prior to an actual spore attraction assay, we tested whether spores could be delivered evenly to all of the piled boxes by the present method. Figure 3 shows the number of spores trapped by the spore attraction plate in each box. A statistical analysis indicated no significant differences in the number of trapped spores among the boxes for both the case of the 2L and 3L screens. These results suggest that the present method dispersed spores uniformly in the air and sent close densities of spores to the boxes. The axial-flow fans were also effective at constantly drawing outside air into the boxes through the screens.

Leach (1976) reported that many wind-dispersed fungal spores were violently ejected into the atmosphere and accumulated frictional electricity at their surface in response to changes in environmental factors, such as relative humidity, temperature, light and airflow. Also, in the present experiment, *P. digitatum* spores were dispersed by the airflow, but whether the spores accumulated surface charges during this process was not clear. If these surface charges become involved in the attraction, the spores with negative and positive surface charges would be attracted to ICW(+) and ICW(−), respectively, and non-charged spores would pass through the electric field. However, the present data clearly refuted this possibility. In fact, spores were attracted to both ICW(−) and ICW(+) at sufficient applied voltages to the electrodes. Obviously, an alternative mechanism was necessary to explain the present results.

Table 1 shows the number of spores trapped by the spore attraction plates of individual test boxes whose screens were charged with different voltages. The number of plate-trapped spores decreased as the applied voltage was increased. In the present electric field, spores were subjected to two forces (an electrostatic attractive force and an airflow force), and their direction was determined as the combined vector of these two forces. For both the 2L and 3L screens with

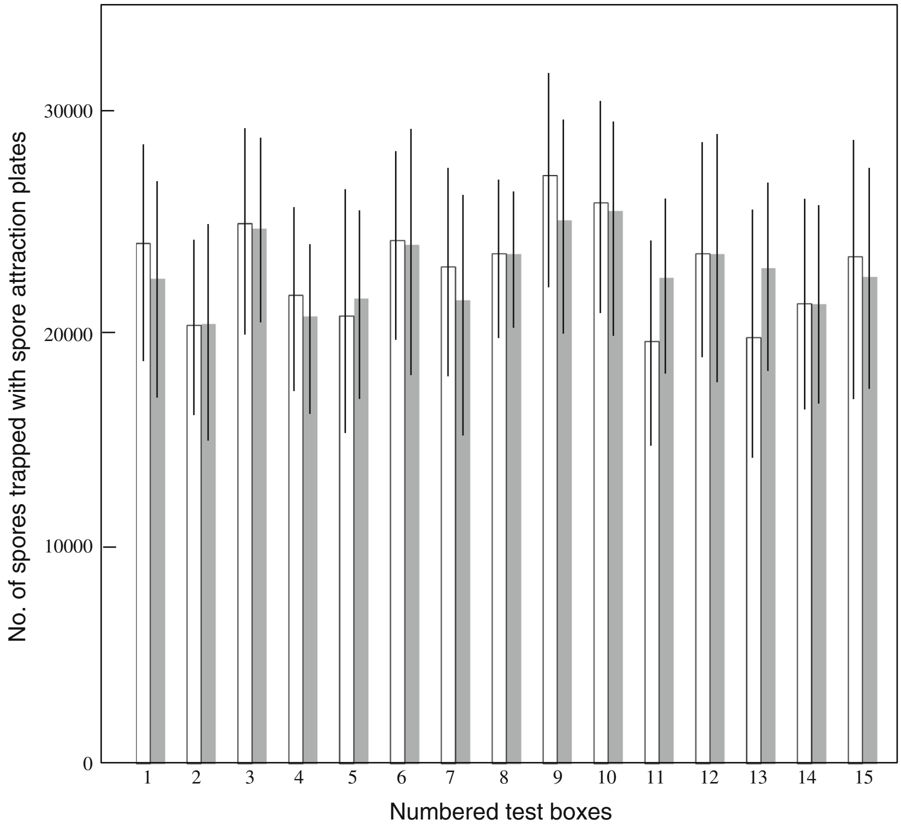

Fig. 3 Number of spores trapped by spore attraction plates in the electric field-attached test boxes. The open and *grey* columns represent 2L screen- and 3L screen-attached test boxes, respectively. Refer to Fig. 2**b** for positions of the numbered test boxes. No significant difference ($p < 0.05$) was noted between the text boxes (Tukey's method)

an applied voltage of $\geqq 0.9$ kV, the ICWs generated sufficient attractive forces to direct spores to the trap. Slightly oval spores of *P. digitatum* created various angular attachments to the ICW, reflecting their orientation in the airflow at the time of attachment. The spores rarely touched the ICW perpendicularly and immediately turned angular, which seemed to be the stable attachment orientation of the spores to the ICW.

Good airflow is a vital factor for efficient ventilation in most facilities. Effective air circulation was the primary reason for optimising the room conditions to enable preservation of old valuable books in the stack room of our university library. However, we should consider the downside risk of active air circulation; airflow is a possible medium through which airborne fungal spores can be transported throughout a room. Our primary concern was to eliminate airborne spores from the airflow passing through the electric field screen. However, elimination efficiency was markedly affected by the speed of the airflow carrying the spores. The present 3L screen was capable of completely trapping spores with application of 1.2 kV, even when the spores were transported by airflow of 3 m/sec (data not shown). In our preliminary survey, the internal airflow rate in well-ventilated facilities was 0.5–2 m/sec; thus, the screen was applicable to a broad range of facilities with ordinary airflow rates.

The mechanism of the spore attraction force is the main point of discussion. In an electric field, charged dipoles cause atmospheric ionisation so as to create a distinct distribution of positive ions around the negative pole and free electrons around the positive pole (Lamford 2002). For the present screen, we hypothesised that positive ions would gather around ICW(−) and that free electrons would gather around ICW(+) (Fig. 1b). This implies that ICW(−)

Table 1 Numbers of *P. digitatum* spores passing through the electric field screens with double or triple layers of oppositely charged ICWs

Electric field screens	Experiments	Voltages (kV) oppositely applied to ICWs				
		0	0.3	0.6	0.9	1.2
Double layers	1	24,959.5 (100)	10,892.1 (43.6)	1,790.0 (7.2)	227.2 (0.9)	221.6 (0.9)
	2	17,705.4 (100)	7,444.9 (42.0)	1,574.1 (8.9)	291.9 (1.6)	250.8 (1.4)
	3	25,908.6 (100)	10,411.8 (40.2)	2,019.3 (7.8)	330.8 (1.3)	291.4 (1.1)
	4	19,141.7 (100)	8,663.7 (45.3)	1,458.9 (7.6)	188.5 (1.0)	150.8 (0.8)
	5	21,498.2 (100)	8,512.9 (39.6)	1,601.8 (7.5)	201.4 (0.9)	176.5 (0.8)
	Average %	100 a	42.1 ± 2.4 b	7.8 ± 0.7 c	1.2 ± 0.3 d	1.0 ± 0.3 d
Triple layers	1	28,411.3 (100)	6,967.0 (24.5)	109.8 (0.4)	0 (0)	0 (0)
	2	18,849.4 (100)	4,671.1 (24.8)	96.5 (0.5)	0 (0)	0 (0)
	3	24,449.9 (100)	2,654.5 (10.9)	76.2 (0.3)	0 (0)	0 (0)
	4	28,212.2 (100)	5,254.2 (18.6)	108.1 (0.4)	0 (0)	0 (0)
	5	13,548.6 (100)	2,662.8 (19.7)	73.6 (0.5)	0 (0)	0 (0)
	Average %	100 a	19.7 ± 5.1 b	0.4 ± 0.1 c	0 d	0 d

Figures in parenthesis represent percentage of trapped spores relative to those of non-charged control. The different letters following the mean values in each horizontal row for 'average %' indicate a significant difference ($p < 0.05$) according to Tukey's method

generates a repulsive force to free electrons and an attractive force to positive ions and that the reverse circumstance occurs for ICW(+). Our previous work (Matsuda et al. 2012) revealed that ICW(−) pushed out free electrons from the surface cuticle layers (conductor) of insects released around ICW(−) to make the insects net positive, whereas insects around ICW(+) became net negative by the addition of free electrons to the cuticle layer. The negatively and positively electrified insects were attracted to opposite charges of the electrodes. The same mechanism is applicable to spores because the cell wall layer covering the conidial body is highly conductive (Mizuno and Washizu 1995) and can be a possible site for the movement of electricity. According to this mechanism, spores that came close to ICW(−) were deprived of free electrons from their cell wall, became net positive and were attracted to ICW(−), but spores approaching ICW(+) had free electrons added to the cell wall, became net negative and were attracted to ICW(+). Although this bidirectional attraction of spores was in agreement with the present data, we were unable to directly measure electricity transfer from/to the spores because the amount of electricity was undetectable. Thus, we present an alternative explanation of spore attraction in the electric field—dielectrophoretic movement of spores subjected to a non-uniform electric field. Dielectrophoresis is a phenomenon in which a force is exerted on a dielectric particle (oppositely polarised particle) in a non-uniform electric field (Cross 1987). This force does not require the particle to be charged, because all particles exhibit dielectrophoretic activity in the presence of a non-uniform electric field. Obviously, the round-shaped electrodes used here produced a non-uniform electric field, so the spores polarised dielectrically. According to the dielectrophoresis theory, the relative polarisability of the spores to the surrounding electric field changes along the gradient of the electric field strength. This changeable polarisation enables the spores to move towards the electrodes. Actually, the spores moved towards the nearest electrodes, that is, in the direction of an increasing electric field intensity produced by the electrodes. In the present study, the electrodes were oppositely charged with an equal voltage; therefore, both electrodes created the same gradient of field strength. These oppositely charged electrodes exerted a spore attraction force of identical strength to the electrodes. The field intensity gradient increased with the increase in the voltage applied to the electrodes; both electrodes eventually created a sufficiently strong force to capture the spores.

In an electric field with an appropriate field strength (in the case of charging the electrodes with >0.9 kV) (see lower column of Table 1), the electric field trapped all spores without escape. In contrast, the spores passed through the electric field screen when the electrodes were charged with insufficient voltage. Obviously, the reduction in trapping force was due to unsuccessful electrification or polarisation of the spores in the electric field. Under these conditions, the force appeared to be inferior to the airflow force. These results indicate that the reduction in the trapping force increased in response to the decrease in voltage applied.

The remaining question was why the 2L screens failed to capture all of the spores even when charged with sufficient voltages ($\geqq 0.9$ kV; Table 1). An additional video record (Video Supplement 1) indicated that the spores once captured became free when other spores reached proximal locations. This phenomenon was common to both ICW(−) and ICW(+) and can be explained by creeping discharge between the spores on an ICW surface. Creeping discharge is defined as a surface transfer of free electrons between two closely located conductors on an insulator (Kebbabi and Beroual 2006). Successful transmission depends on the distance between the two conductors, the surface resistivity of the insulator and the voltage applied to a conductor for insulator polarisation. In the present case, spores could be conductors for electron transfer, and creeping discharge occurred when two spores were within a close distance on an ICW. We measured this distance from the video pictures and obtained distances of <15.1 and <16.5 μm at 0.9 kV and <32.4 and <30.8 μm at 1.2 kV on ICW(−) and ICW(+), respectively. Obviously, the possible distance became larger as the applied voltage was increased. Judging from these results, we present the most suitable explanation of electron transfer accompanied by the simultaneous capturing and repulsing of two proximal spores by the ICWs. On ICW(−), previously captured spores were repulsed after receiving free electrons from newly attracted spores. Eventually, the electron-donor spores became net positive and were drawn to ICW(−), while the electron-recipient spores became net negative and were repulsed by the negative surface charge of ICW(−). On the other hand, spores on ICW(+) were repulsed after transferring their free electrons to subsequent spores. The electron-donor spores became net positive and were repulsed by ICW(+), while the electron-recipient spores became net negative and were captured by ICW(+). These spore repulsions could be a possible cause of spore escape from the 2L screens and occurred more frequently when more spores were attracted to the ICWs. From this viewpoint, the outside electric fields of the 3L screen were an effective auxiliary barrier for capturing the spores that escaped from the first electric field. Theoretically, spore repulsion could occur in this field, but the possibility of creeping discharge between two spores is negligible because of the highly limited number of spores reaching the field and the consequent unlikeliness of two spores coming within a distance of creeping discharge. In fact, scrutiny of the ICWs at the end of the experiment indicated that the average number of spores trapped by the outside ICWs was between 1 and 3 spores/cm^2 screen surface.

In addition to its ability to exclude spores, the low electric power consumption of the present screen system is important for practical use. As is generally known, major earthquakes have occurred in some years in our country. This situation implies that we are always confronted with the risk of major and frequent electric power failures that would bring spore capturing to a halt. In the electric field screen, the voltage generator is the only driving part requiring an electric power supply, and its electric power is 5W, equivalent to that of a small electric bulb. This characteristic enabled the use of a photovoltaic power generation method for supplying electric power to the voltage generators. Using this system, we continuously operated four 3L screens attached to a bookshelf for 1 month. During the experimental period, the power supply was stable and was not disturbed by changes in weather, so the screens constantly executed their spore-capturing function. All books in the screen-guarded bookshelf remained spore free, but books on the non-charged bookshelf were heavily attacked by spores, $1{,}214.5 \pm 832.5$ spores per book (mean of 50 randomly selected books). Thus, the present study has demonstrated that the 3L screen is a promising spore precipitator that can completely eliminate spores from the airflow passing through the screen. For visually demonstrating this conclusion, we finally present the additional video (Video Supplement 2) showing that the 3L screen can capture spores blown towards the screen. In the video, we can see the airflow-carried spores like a sprayed fine mist and can confirm that the electrostatic barrier completely prevent this mist by passing through the screen.

Many fungi can decay the materials used for historical art objects, including paintings, textile, paper, parchment, leather (Sterflinger 2010) and photographic materials (Lourenço and Sampaio 2009). Various measures, including climate control, regular cleaning and microbiological monitoring, have been used in museums and their storage rooms to prevent fungal contamination. The major contribution of our study was the development of a promising physical method of creating a spore-free space. An advantage of this physical technique is its possible application to a broad range of fungal deteriogens to preserve cultural heritage.

4 Conclusions

Old, mould-susceptible books in a stack room of a library were preserved using an electric field screen. The screen consisted of three layers of ICWs oppositely charged with 0.9 kV, and the electrodes formed an electric field complex that created a strong force for capturing spores blown inside the screen. The electric field screen is thus a promising physical method of producing a spore-free space to protect the cultural heritage from airborne fungal deteriogens.

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