

1 **The effect of indoor daylight spectrum and intensity on viability of indoor**  
2 **pathogens on different surface materials**

3 Running title: Indoor daylight effect on pathogens

4 Man In Lam<sup>1</sup>, Kinga Vojnits<sup>1</sup>, Michael Zhao<sup>1</sup>, Piers MacNaughton<sup>2\*</sup>, Sepideh Pakpour<sup>1\*</sup>

5 <sup>1</sup> Faculty of Applied Science, School of Engineering, University of British Columbia,  
6 Kelowna, BC, Canada

7 <sup>2</sup> Department of Environmental Health, Harvard T.H. Chan School of Public Health,  
8 Boston, MA, USA

9 Corresponding authors:

10 [sepideh.pakpour@ubc.ca](mailto:sepideh.pakpour@ubc.ca);

11 [piers.macnaughton@harvard.ca](mailto:piers.macnaughton@harvard.ca)

12 **ABSTRACT**

13 Built environments play a key role in the transmission of infectious diseases. Ventilation  
14 rates, air temperature and humidity affect airborne transmission while cleaning protocols,  
15 material properties and light exposure can influence viability of pathogens on surfaces.  
16 We investigated how indoor daylight intensity and spectrum through electrochromic (EC)  
17 windows can impact the growth rate and viability of indoor pathogens on different surface  
18 materials (polyvinyl chloride (PVC) fabric, polystyrene (PS), and glass) compared to  
19 traditional blinds. Our results showed that tinted EC windows let in higher energy, shorter  
20 wavelength daylight than those with clear window and blind. The growth rates of

21 pathogenic bacteria and fungi were significantly lower in spaces with EC windows  
22 compared to blinds: nearly 100% growth rate reduction was observed when EC windows  
23 were in their clear state followed by 41-100% reduction in bacterial growth rate and 26-  
24 42% reduction in fungal growth rate when EC windows were in their darkest tint. Moreover,  
25 bacterial viabilities were significantly lower on PVC fabric when they were exposed to  
26 indoor light at EC-tinted window. These findings are deemed fundamental to the design  
27 of healthy modern buildings, especially those that encompass sick and vulnerable  
28 individuals.

## 29 **PRACTICAL IMPLICATIONS**

- 30 • Light is an important factor that influences occupant health.
- 31 • Healthcare Associated Infections (HAI) bring substantial costs on the healthcare  
32 systems hence new disinfection methods are always needed to minimize fomites  
33 especially with the increasing antibiotic resistance.
- 34 • We found that indoor light modulated by the EC smart windows can significantly  
35 reduce the growth rate and viability of pathogenic bacteria and fungi, which is  
36 mainly due to the high energy blue light spectrum at wavelength of 400-500nm.
- 37 • Pathogenic fungi are found to be more affected by the indoor light intensity, while  
38 indoor bacteria on surfaces are more susceptible to the light spectrums.
- 39 • These results also demonstrate the promising potential of indoor daylight exposure  
40 as an alternative for fomite disinfection strategy and expand the benefits of EC  
41 window as part of healthy building design in the future.

## 42 **1 INTRODUCTION**

43 The built environment plays an important role in occupant health as people today spend  
44 the majority of their time indoors. Researchers and engineers have been cooperating  
45 together over the years to establish a more resource-efficient and healthier built  
46 environment for occupants<sup>1</sup>. However, assessing indoor environment quality is complex  
47 as buildings serve a variety of functions and many factors need to be taken into  
48 consideration. The Harvard T.H Chan School of Public Health established a Healthy  
49 Building framework which includes nine foundations: ventilation, air quality, thermal  
50 health, water quality, moisture, dust and pest, noise, safety, and lighting and views<sup>1</sup>.  
51 These factors act individually and interactively in shaping the indoor environment and  
52 affecting the physiological and psychological health of building occupants.

53 Among the nine foundations of healthy buildings, light is an important attribute affecting  
54 occupant's health and productivity. Namely, light catalyzes hormone secretions in human  
55 body, controls our circadian rhythms and thus regulates our sleep, mood, and work  
56 performance<sup>2,3</sup>. Therefore, daylight can not only affect thermal and visual comfort levels  
57 of the occupants but also influence their cognitive functions and mental health<sup>4</sup>.  
58 Inadequate daylight exposure have been frequently associated with poor sleep quality,  
59 decrease in productivity, and more workplace errors<sup>5-7</sup>. Windows, which modulate outdoor  
60 solar radiation transmission and indoor daylight spectrum, play a key role in determining  
61 the build environment quality. Modern buildings often designed to maximize glazing to  
62 increase the views, but in practice occupants lower the blinds to control for glare and  
63 thermal discomfort<sup>3</sup>. On average, 59% of window area is obstructed by blinds<sup>8</sup>. Moreover,  
64 traditional low emission (low-E) glass has a solar heat gain coefficient of 0.48, which

65 means approximately 48% of heat are transmitted into the building<sup>9,10</sup>. Building systems  
66 need to be sized to accommodate the hottest summer day, resulting in oversized systems  
67 to meet the peak load from solar heat gain in the building<sup>2,3,11</sup>. Studies have shown that  
68 up to 60% of energy is lost through the windows, and a range of 10-25% heat loss in the  
69 residential buildings are due to the windows<sup>2,12</sup>. Electrochromic (EC) windows have been  
70 developed to overcome these issues by embedding EC materials within the window layers  
71 and employing multiple-pane glazing<sup>11,12</sup>. When a low voltage electric current is applied  
72 to the EC materials, the consequential redox reaction changes the light transmission  
73 hence dynamically controlling the indoor light spectrum<sup>11</sup>. EC windows provide similar light  
74 transmission to low-E glass when the sun is not on the facade, while tinting to mitigate  
75 glare and solar heat gain when the sun is on the facade, which is more sustainable and  
76 provides a better occupant experience<sup>7,9,13,14</sup>.

77 In addition, indoor microbiota which consists of ever-changing combinations of bacteria,  
78 virus, and fungi have important relevance to the built environment quality<sup>24</sup>. Although  
79 exposure to beneficial microbes in indoor spaces can positively effect occupants' health,  
80 albeit still uncertain on its causality, exposure to indoor infectious agents, via aerosol  
81 droplets, direct contact with pathogens, or indirect contact with fomites<sup>25-28</sup>, are known to  
82 negatively impact occupants' health. Contaminated surfaces can serve as reservoirs for  
83 pathogens, particularly problematic in hospital settings, and facilitate disease  
84 transmissions<sup>30,31</sup>. Nosocomial infections, also known as the healthcare-associated  
85 infections (HAI), are diseases that do not present in patients during the time of admission  
86 but acquired during their hospital stays. Although all pathogens are problematic to  
87 hospitalized patients, HAIs are often related to only a few bacterial species, including

88 *Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter*  
89 *baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter faecium*, namely the ESKAPE  
90 pathogens<sup>32,33</sup>. Most of the ESKAPE species are on the list of the most problematic  
91 microbial species by World Health Organization (WHO) due to their multiple antibiotic  
92 resistances<sup>30,32</sup>. This could be accounted by the pathogens' biofilm-forming ability, which  
93 provides the mechanical and biochemical protections for microbes after attaching to  
94 inanimate surfaces and make hospital disinfection procedures more challenging<sup>30</sup>. The  
95 European Centre of Disease and Control (ECDC) estimated that an additional 900 million  
96 Euros hospital costs in European Union in 2007 was due to five of the ESKAPE pathogens,  
97 bringing significant financial burden to the healthcare system<sup>32</sup>. Extensive studies have  
98 investigated the inactivation methods of EKSPA E pathogens, though nosocomial  
99 infections are not only caused by these five bacterial species. Other biofilm-forming  
100 species such as *Escherichia coli* and *Staphylococcus epidermis* could also cause  
101 nosocomial infections and result in serious health outcomes such as sepsis when  
102 treatments are not received on time<sup>32,33</sup>. Fungi, viruses and parasites can also cause HAIs,  
103 with immunocompromised patients being the most vulnerable populations<sup>30</sup>. In fact, cases  
104 of fungal nosocomial infections have been noticeably increased over the past few decades  
105 due to aging populations in developed countries, with more immunocompromised patients  
106 being seen and more immunosuppressive agents being used in the hospitals<sup>34,35</sup>. The  
107 most common cause of fungal nosocomial infections are *Candida and Aspergillus species*,  
108 leading to candidemia and aspergillosis, respectively, both with high mortality rates<sup>34</sup>.  
109 Unfortunately, early diagnosis fungal nosocomial infections are often challenging due to  
110 lack of specific signs and late manifestation of symptoms which significantly render the  
111 efficiency of antifungal treatments<sup>35</sup>.

112 Considering these, although engineers and researchers are actively seeking for  
113 interventions that shape the indoor environment to be healthier for occupants, such efforts  
114 will not flourish until better undertesting is provided regarding interconnection between  
115 healthy building foundations. Among the nine foundations of healthy buildings, here we  
116 are particularly interested in the interaction of indoor light and indoor pathogens. Next to  
117 the psychological and physiological impact of daylight exposure on human body, light is  
118 an important environmental factor that shapes the microbial communities. As early as  
119 500BCR, Egyptians have used the sunlight to treat chronic ulcers successfully<sup>14</sup>. Sunlight  
120 therapy has been in practice among communities worldwide to treat various diseases  
121 before the discovery of ultraviolet radiation (UV), which provides the foundation of today's  
122 antimicrobial light therapy<sup>14</sup>. One of the breakthrough discoveries of photochemistry can  
123 be traced back to 1903 when Niels Ryberg won the Nobel Prize for using the Finsen lamp  
124 (>380nm) for treatments of skin tuberculosis<sup>15,16</sup>. The blue-light emitting lamp (400-500nm)  
125 effectively eradicates *Mycobacterium tuberculosis* and other pathogenic bacteria such as  
126 *P. aeruginosa*, *Methicillin-Resistance Staphylococcus aureus strains (MRSA)*, and *A.*  
127 *baumanni*, which saved many lives subjected to potentially lethal burn during that time<sup>15-</sup>  
128 <sup>19</sup>. Although other spectrums of the visible light have important biological relevance to  
129 human, majority of the antimicrobial light studies focused on the violet-blue light spectrum  
130 (400-500nm) as it emits the highest energy within the visible light range. Blue light therapy  
131 has shown to be effective against a wide range of microorganisms including bacteria, fungi,  
132 virus, and yeast without the need of additional photosensitizers, which could be a  
133 promising intervention for disease controls in the future<sup>14,19-23</sup>. However, to date, it is not  
134 systematically well understood whether changing indoor light intensity and bringing more  
135 blue light into spaces can impact the viability of indoor microbiota on different surfaces.

136 To partially fulfill these gaps, using a controlled living-lab set-up, we investigated the effect  
137 of indoor daylight, modulated by electrochromic (EC) window, on the growth rate and  
138 viability of four important surface borne pathogenic bacteria *MRSA*, *P. aeruginosa*, *K.*  
139 *pneumoniae* and *E. coli*, as well as three indoor pathogenic fungal species *Stachybotrys*  
140 *chartarum*, *Aspergillus fumigatus*, and *Aspergillus versicolor* on different surface materials.  
141 Indoor light exposed groups were compared with window and blind conditions to evaluate  
142 the indoor light effects.

## 143 **2 METHODS**

### 144 2.1 Experimental chamber setup

145 All experiments were performed inside a controlled mini-living lab set-up. EC smart  
146 windows glass were installed on the chamber panels (Figure 1A). All glasses contain  
147 electrochromic coating, allowing window tints to be manually controlled. A custom solar  
148 simulator (Sciencetech) consisting of a xenon arc lamp and a series of optical filters used  
149 to illuminate the inside of the chamber with simulated sunlight with the light spectrum of  
150 natural sunlight (Figure 1A). Indoor daylight levels were controlled by EC window tints,  
151 with EC window- Clear (60% light transmission) and EC window- Tinted (1% light  
152 transmission) tested in this study. EC window-Tinted showed excellent glare control and  
153 had similar light intensity as the Blinds condition. Temperature and relative humidity inside  
154 the chamber were maintained within a narrow range for testing, specifically  $24.7 \pm 1^\circ\text{C}$  and  
155  $42 \pm 3\%$ , respectively.

### 156 2.2 Strains and media preparation

157 Bacteria:

158 The selected bacteria and fungi strains were purchased from the American Type Culture  
159 Collection (ATCC) as follows: *Methicillin-resistant staphylococcus aureus* (MRSA; ATCC  
160 6538), *Pseudomonas aeruginosa* (strain Boston 41501; ATCC 27853), *Escherichia coli*  
161 (ATCC 11229), and *Klebsiella pneumoniae* (ATCC 1352).

162 MRSA and *P. aeruginosa* were seeded in sterile Tryptic Soy Broth (TSB, BD Diagnostic)  
163 and *K. pneumonias* and *E. coli* were seeded in sterile Difco™ Nutrient Broth (Fisher  
164 Scientific) and incubated at 37°C degree overnight prior to each experiment. Bacterial cell  
165 density was adjusted to approximately  $1 \times 10^5$  cells per ml based on the optical density  
166 reading at 600nm (OD<sub>600</sub>).

167 Fungi:

168 Fungal species tested in this study were *Aspergillus fumigatus* (ATCC 1022), *Aspergillus*  
169 *versicolor* (ATCC 11730) and *Stachybotrys chartarum* (ATCC 201867). All species were  
170 grown on Potato Dextrose Agar (PDA) (Difco™ Fisher) at 25°C. Spores were extracted  
171 from agar plates by flooding method with 10ml of autoclaved distilled water several times  
172 and stored at 4°C. Spore density for each fungal species were enumerated by an  
173 automated cell counter (Countness3, ThermoFisher) and aqueous fungal suspension with  
174 a concentration of  $1 \times 10^4$  spores per ml was prepared.

175 2.3 Indoor daylight effect on the growth rate of indoor bacteria and fungi using high  
176 nutrient agar plates

177 This part was designed to mimic conditions where pathogens have access to high amount  
178 of nutrients (here we used agar) and they could actively grow. For bacteria, agar plates  
179 (n=3 per bacterial species per light condition) were inoculated with known bacterial



180 concentration and placed inside the environmental chamber for indoor daylight exposure  
181 of 24 hours (T = 24.3°C, RH = 41%; Suppl Fig1A). Colonies forming units (CFU) on each  
182 plate were then counted. Negative controls (n=3 per bacterial species per light condition)  
183 were inoculated plates kept in the dark at 25°C (no indoor light exposure).

184 Similarly, PDA plates (n=3 for each fungal species) were inoculated with known  
185 concentration of fungal spores and exposed to the indoor daylight for 72 hours (T =  
186 25.2°C, RH = 42; Suppl Fig1A). Area of fungi mycelium growth on each plate was then  
187 measured to assess the light effects. Negative controls (n=3 per fungal species per light  
188 condition) were inoculated plates kept in dark at 25°C (no indoor light exposure).

189 Both bacteria CFU and area of mycelium growth on each plate were processed through  
190 semi-automated image analysis (NIH, ImageJ) for quantitative assessment. Workflow can  
191 be found in Suppl Fig 1A, Suppl Fig 2A. Bacterial and fungal growth rate (CFU per ml or  
192 area of mycelium) at EC window (both clear and tinted) were compared with Blinds  
193 individually. Percentage of growth rate reduction was calculated with Equation 1. Results  
194 were summarized in Table 1.

195 Equation 1 
$$\frac{\text{EC window (Clear or Tinted)} - \text{Blinds}}{\text{Blinds}} \times 100\%$$

196 2.4 Indoor daylight effect on the viability of indoor bacteria and fungi using low nutrient  
197 surface materials.

198 This part was designed to mimic conditions where pathogens do not access to high  
199 amount of nutrients, and they could not actively grow. Specifically, the indoor daylight  
200 effect on bacteria and fungi on inanimate surfaces were assessed by inoculation of known  
201 concentration of species on selected indoor surface materials: polystyrene (PS), polyvinyl  
202 chloride (PVC) fabric, and glass. All materials were autoclaved and performed with  
203 triplicates for each tested species.

204 For bacterial, 2ml of the bacterial suspension ( $10^5$  cell/ml) were placed onto the sterile  
205 tested surface material (PS, PVC fabric, Glass) and placed inside the chamber for indoor  
206 daylight exposure of 24 hours ( $T = 24.3^\circ\text{C}$ ,  $\text{RH} = 42$ ; Suppl Fig 1B). After exposure,  
207 bacteria from each sample were serially diluted and plated onto the agar plate (Tryptic  
208 Soy Agar for *MERS* and *P. aeruginosa*; Nutrient Agar for *E. coli* and *K. pneumoniae*). The  
209 plates were then incubated at  $37^\circ\text{C}$  overnight and the CFU were counted. Negative  
210 controls ( $n=3$  per fungal species per light condition) were inoculated plates kept in dark a  
211  $25^\circ\text{C}$  (no indoor light exposure). Positive controls were inoculated agar plates kept at  $37^\circ\text{C}$   
212 incubator.

213 For fungi, similar procedures were done with minor modifications: 3ml of aqueous fungal  
214 suspension with a concentration of  $1 \times 10^4$  spores/ml were placed on the three tested  
215 surface materials, placed inside the environmental chamber, and exposed to indoor  
216 daylight for 72 hours ( $T = 24.7^\circ\text{C}$ ,  $\text{RH} = 41\%$ ; Suppl Fig 1B). After exposure, samples were  
217 inoculated onto the PDA and incubated at  $25^\circ\text{C}$ .

218 After incubation, the bacteria CFU and area of fungal mycelium growth of each sample  
219 were quantified using ImageJ software. The workflow for nutrient poor experiment was  
220 included in the supplemental materials (Suppl Fig 1B, Suppl Fig 2A).

221 Bacteria and fungi viability reduction were also calculated for each material by comparing  
222 the EC window condition (Clear and Tinted) and Blinds. Percentage of reduction was  
223 calculated with Equation 1 and summarized in Table 2.

## 224 2.5 Statistical analysis

225 All statistical analysis were conducted using statistical software base R 4.0.5 and all tests  
226 were given 5% risk and visualization were carried out using GraphPad Prism version 7.0a  
227 (Graph Pad Software, Inc, USA). Normality of data sets were assessed using the Shapiro-  
228 Wilk test. Homogeneity of variance was assessed using either Bartlette's test or  
229 Levnene's test depending on the normality.

230 For analysis of indoor light effect on bacteria and fungi growth rate on high nutrient agar  
231 plates, One-Way ANOVA followed by Bonferroni post-hoc test were used to compare  
232 between Blinds and EC windows (Clear and Tinted) since all our data followed Gaussian  
233 distribution (Shapiro-Wilk:  $P>0.05$ ). Welch-corrected ANOVA was performed if equal  
234 variance assumption was not met (Bartlette's test  $P>0.05$ ), followed by Games Howell  
235 post-hoc test.

236 For analysis of indoor light effect on the viability of bacteria and fungi on low nutrient  
237 surfaces, Two-Way ANOVA was used to analyze the effect of light and material type if  
238 data was normally distributed (Shapiro-Wilk:  $P>0.05$ ), followed by TukeyHSD test to

239 compare Blinds with EC window condition. Kruskal Wallis test was used if data failed the  
240 normality test (Shapiro-Wilk:  $P>0.05$ ), followed by Bonferroni post-hoc test. Results with  
241  $P<0.05$  were considered statistically significant and shown in Figure2, Table 1 and Table  
242 2.

### 243 **3 RESULTS**

244 We developed a mini-living lab with electrochromic (EC) windows (Figure 1A); bacteria  
245 and fungi were placed on different surfaces and exposed to indoor daylight at different EC  
246 window tints inside the environmental chamber. For each experiment, the environmental  
247 chamber's temperature and relative humidity (RH) were kept between  $24.7^{\circ}\text{C} \pm 1^{\circ}\text{C}$  and  
248  $42\% \pm 3\%$ , respectively (Figure 1B).

249 Indoor daylight was controlled by different EC window tints, corresponding to 60% light  
250 transmission (EC Window-Clear) and 1% light transmission (EC Window-Tinted). Light  
251 conditions at each window tint were shown in Figure 1B. The reference condition was 1%  
252 openness blackout roller shades that fully cover the top chamber glass in its clear state.  
253 Focusing on indoor daylight intensity, results showed that EC window at its clear state  
254 have an average light intensity of  $29 \times 10^3$  (lx), which was much higher than tinted EC  
255 window and Blinds (880 and 526 (lx), Figure 1C). In additions, while the tinted EC windows  
256 and blind conditions both let in 1% of light, the tinted windows preferentially let in shorter  
257 wavelength, higher energy daylight (400 - 500 nm; Figure 1D) while conditions with blinds  
258 let in higher wavelength, shorter energy daylight (550 - 650 nm; Figure 1D).

259 3.1 Indoor daylight effect on bacterial and fungal growth rate on high nutrient agar plates

260 To investigate the effect of indoor daylight, with different intensity and spectrum in  
261 response to window settings, on bacterial and fungal growth rate, microorganisms were  
262 cultured on high nutrient agar plates and exposed to different daylight conditions for 24  
263 hours (bacteria) and 72 hours (fungi). Results showed that indoor daylight at EC window-  
264 Clear condition significantly reduced the viability and growth rate of all tested bacteria and  
265 fungi (One-way ANOVA; p-value < 0.05). Table 1 showed the percentage of reduction of  
266 bacteria CFU per ml and fungal area of mycelium by the two tested indoor daylight  
267 conditions compared to blinds. All tested bacteria viability were reduced more than 98%  
268 by indoor daylight in the EC Window – Clear condition and fungi mycelium growth were  
269 reduced more than 86% (Table 1) relative to blinds. The tinted condition significantly  
270 reduced the viability of *E. coli*, *K. pneumoniae* and *MRSA*, but not *P. aeruginosa*. The  
271 highest reduction was observed in *E. coli* and *MRSA*, in which the growth rate was  
272 reduced by 100% in both daylight conditions compared to blinds (Table1). Lowest  
273 reduction was observed in *P. aeruginosa*, which the growth rate was reduced by 41% at  
274 tinted condition.

275 For fungi, analysis showed significant reduction in fungal growth rate when exposed to  
276 high intensity of indoor light where windows were not tinted and blind was not present (EC  
277 Window-Clear). Under low indoor light intensity condition, results showed fungal growth  
278 rate reduction, but not statically significant when exposed to daylight through the tinted  
279 EC windows compared to blinds; 42.5% reduction for *S. chartarum*, 27% reduction for *A.*  
280 *fumigatus*, and 26% reduction for *A. versicolor* (Table 1, Figure 2B).

### 281 3.2 Indoor daylight effect on bacteria and fungi viability on low-nutrient surface materials

282 To examine the effect of daylight when bacteria and fungi were placed on different indoor  
283 surface materials, the tested microbes were placed on PS, PVC fabric, and glass for 24  
284 hours (bacteria) and 72 hours (fungi).

285 The results showed that majority of bacterial and fungal species were highly viable when  
286 windows had blinds; while lower viability was mostly detected when EC Window were  
287 present (Figure 3), either viability reduced in response to higher indoor intensity under EC  
288 Window - Clear condition or presence of blue light spectrum under EC Window - Tinted  
289 condition. However, the extent of indoor light effect also depends on type of surface  
290 materials as well as type of species applied (factors interaction). For example, focusing  
291 on bacteria, *E. coli*, as a gram-negative bacteria, its growth rate was significantly reduced  
292 under both EC Window - Clear and EC Window-Tinted condition on PVC fabric (Turkey  
293 HSD p-value = 0.015 and p-value = 0.037, respectively). However, on glass surfaces,  
294 significant growth rate reduction was only observed under EC Window-Tinted condition  
295 (Turkey HSD; p-value = 0.022). No significant reduction was observed when *E.coli* was  
296 on PS (Table 2A). In contrast, viability of *MRSA*, as a gram-positive bacteria, was higher  
297 under blind condition, especially when they were on glass materials (EC Window-Clear:  
298 100% reduction; Pairwise t-test with Bonferroni correction; p-value = 0.028, Table 2C).  
299 Interestingly, EC window conditions in its clear state reduced the viability of *MRSA* by  
300 95.5% and 100% on PS and glass, respectively, and tinted condition reduced *MRSA* by  
301 100% on PVC fabric (Table 2).

302 Viability of fungal pathogens was mostly reduced in response to higher indoor light  
303 intensity under EC - Clear condition, especially when they were on PS; 57 % reduction for

304 *A. fumigatus* and 55 % reduction for *A. versicolor*, (Turkey HSD; p-value = 0.005 and  
305 0.003 respectively (Figure 3 and Table 2A). EC Window– Tinted condition also reduced  
306 viability of *A. fumigatus* and *A. versicolor* on PS materials, but to a lesser degree (27% to  
307 23%, respectively). In contrast, EC window (both Clear and Tinted state) reduced the  
308 viability of *S. chartarum* on PVC materials but did not reach a statistical significance (Figure  
309 3 and Table 2B); EC Window – Clear achieved a 60% viability reduction and EC Window  
310 – Tinted achieved 39% reduction (Two-Way ANOVA; p – value = 0.056).

#### 311 **4 DISCUSSION**

312 Since indoor daylight and indoor microbiomes both have important relevance to occupant  
313 health, it is worth investigating their interactions. Our work indicates that indoor daylight  
314 modulated by the EC smart window can significantly reduce the viability and growth rate  
315 of pathogenic bacteria and fungi, especially when nutrients are available for active growth,  
316 mainly due to exposure to shorter wavelength and higher energy spectrum indoor light for  
317 bacterial pathogens. Interestingly, fungi mycelium growth and viability were more affected  
318 by light intensities rather than light spectrum, where light effect were mostly seen at EC-  
319 window-Clear condition when highest daylight intensities were transmitted.

320 Specifically, we found that the growth rate of all tested pathogenic bacteria on high nutrient  
321 condition were significantly reduced by daylight in both EC Window-Clear and EC  
322 Window-Tinted conditions. The results were expected since significant amount of high  
323 energy blue light (400-500nm) were transmitted through EC window tints relative to blinds,  
324 despite the tinted condition and blinds both having 1% overall light transmission. The  
325 bactericidal effect of blue light at 400-500nm have been extensively reported in many  
326 papers<sup>21,23,39–43</sup>. Bacteria employs different types of photosensitizers for blue light sensing,

327 with some commonly found examples being flavins, porphyrins and NADH<sup>21</sup>. The  
328 absorption efficiency of cytochromes directly determines the effectiveness of antimicrobial  
329 blue light, which varies between each species at the range of 400-500nm. Exposure of  
330 blue light at this range excites the cytochromes and induces a cascade of oxygen  
331 dependent photoexcitation reactions<sup>40,41</sup>. The generated Reactive Oxygen Species (ROS)  
332 can cause substantial oxidative damages, disrupt cellular functions and lead to cell death  
333 if accumulates in cells<sup>16,20,23,39,41</sup>.

334 Likewise, reduction of fungi mycelium growth by indoor daylight in the EC Window-Clear  
335 condition was also expected as fungi light response has long been understood<sup>44,45</sup>. Blue  
336 light response has been well-described in several *Aspergillus* species, which agreed with  
337 our finding that continuous white light and blue light exposure inhibits conidia germination  
338 and fungi mycelium growth<sup>22,46,47</sup>. However, daylight in the EC Window-Tinted condition  
339 did not significantly reduce the fungal mycelium growth. Unlike bacteria that uses  
340 cytochromes, blue light sensing in fungi involves the white-collar complex (WCC) which is  
341 not affected by its absorption efficiencies<sup>48</sup>. Secondly, fungi are known to produce  
342 pigments as first line of defense to photoinactivation<sup>49,50</sup>. Melanin is one of the  
343 photoprotective pigments that are found in many fungi species. The hydrophobic pigment  
344 serves as a scavenger for ROS and reactive nitrogen species (RNS) to protect the cells,  
345 which are important for UV and visible light protection in fungi<sup>49,51</sup>. 1,8-  
346 dihydroxynaphthalene (DHN) melanin are found in the conidia of *Aspergillus*, which is  
347 responsible for the gray-greenish color of the mycelium<sup>50</sup>. Multiple light defense  
348 mechanisms make fungi more resistant to indoor light compared to bacteria, thus higher  
349 doses of antimicrobial blue light (400-500nm) are needed for reducing fungal mycelium



350 growth. As daylight in the EC-Tinted condition shows much lower blue light intensity than  
351 the EC Window-Clear condition, it is not surprising that daylight in this condition (EC-  
352 Tinted) did not have a significantly potent effect on fungi growth. Studies have found that  
353 the impact of blue light is often at much higher light intensities<sup>22,46,52</sup>. Hatakeyama et.al  
354 (2017) exposed *Aspergillus oryzae* culture on high nutrient agar plates to continuous blue  
355 light at 430nm, and found that the fungal mycelium growth and number of fungal conidia  
356 were significantly decreased compared to those grew in the dark<sup>52</sup>. Note that the blue light  
357 intensity used in their study ( $94\mu\text{mol m}^{-2} \text{s}^{-2}$  for both) is much higher than our study ( $5\text{W/}$   
358  $\text{m}^{-2}$  for the EC Window- Tinted condition). Nevertheless, light still plays a critical role in  
359 regulating fungal biological activities, including conidial germination rate, sexual  
360 development and circadian rhythm, and thus should be taken into consideration for fungal  
361 disease transmission<sup>45,46,48,53</sup>.

362 We also investigated the effect of indoor daylight on the viability of bacteria and fungi  
363 under low nutrient condition using different surfaces materials: polystyrene (PS), polyvinyl  
364 chloride (PVC) fabric and glass. Our results showed that bacteria and fungi microbial  
365 viability were significantly lower on PVC fabric compared to glass and PS. This could be  
366 explained by the materials properties, as porous material (PVC fabric) entraps  
367 microorganisms within the matrix hence less viability bacteria were recovered compared  
368 to those on non-porous surfaces<sup>30,54</sup>. Another explanation of the low bacteria viability on  
369 PVC fabric could be the presence of chemical dye. Industrial textile often employed  
370 chemical agents and coatings that have known antimicrobial properties, which targets a  
371 wide range of microorganisms including bacteria, fungi and virus<sup>55</sup>. These type of fabrics  
372 are frequently used in high traffic built environments such as hotels and hospitals, where

373 materials such as towels, curtains, and carpets could all potentially serve as fomites that  
374 facilitate disease transmission<sup>55</sup>. However, we are not aware of any antibacterial agents  
375 on the PVC blind material tested in this study.

376 Our study also found that gram-positive bacteria (*MRSA*) were more susceptible to indoor  
377 daylight than gram-negative bacteria. As mentioned in the previous section, the type of  
378 porphyrins employed by the bacteria for blue-light sensing determine the photoinactivation  
379 efficiency, which varies at the strain levels<sup>23</sup>. The predominant porphyrin produced in *S.*  
380 *aureus* is coproporphyrin. In contrast, various types of porphyrins are found in gram-  
381 negative bacteria<sup>23</sup>. This could also explain the variability in blue light effectiveness  
382 between the bacterial species. Several studies have also reported the higher blue light  
383 susceptibility of gram-positive bacteria than gram-negative bacteria<sup>20,23</sup>, though  
384 contradictory findings were also reported: Guffey & Wilborn (2007) found that gram-  
385 positive bacteria (*S. aureus*) were more resistant to blue light inhibition than gram-  
386 negative bacteria (*P. aeruginosa*), which could be due to different experimental designs  
387 (starting concentration, exposure time, blue light intensity) and different bacterial strains  
388 used in the study<sup>56</sup>. Further investigations are needed to explain the contradictory findings  
389 between studies.

390 For fungi viability testing on different surface materials, significant fungal viability  
391 reductions were only observed on *A. fumigatus* on PS in both EC Window conditions. No  
392 light effects were found on glass for any of the three tested fungi species. Although fungi  
393 blue light studies are relatively sparse compared to bacteria, some assumptions can be  
394 made based on the characteristics of the fungi: Fungi in genus *Aspergillus* contains  
395 filamentous hyphae and conidia that are highly hydrophobic<sup>51,57</sup>. The shape and

396 properties of fungal spores various between species, and the chemistry and  
397 physiochemistry of surface materials also influence conidial binding ability hence affecting  
398 the indoor daylight effect<sup>58</sup>. We also did not detect any significant indoor daylight effects  
399 on *S. chartarum*, which is in line with previous findings that *S. chartarum* has high light-  
400 resistance. A study by Green et.al (2005) found that ultraviolet germicidal irradiation  
401 (UVGI) at 265nm (144mJ cm<sup>-2</sup> ) was not efficient to inactivate 90% of the *S. chartarum*  
402 spores<sup>59</sup>. It should note that UVGI emits the highest energy among the UV spectrum,  
403 which is much stronger than visible blue light<sup>59</sup>. Therefore, it is not surprising that indoor  
404 daylight used in this study was not efficient in reducing the viability of *S. chartarum*.  
405 Overall, this study provides important insights for fomite transmission and healthy building  
406 design for several reasons. Extensive studies have shown that pathogenic bacteria and  
407 fungi can persist on inanimate surfaces for prolonged period of time, leading to disease  
408 transmission<sup>30,60–62</sup>. Especially in healthcare settings, numerous healthcare-associated  
409 infections and outbreaks have been associated with patient's care items, ranging from  
410 personal items such as computer keyboard and tablets, to common high touch surfaces  
411 such as curtain, window, hand sanitizers dispensers, and medical devices such as,  
412 medical chart and thermometers<sup>33</sup>. The three tested materials (plastic for PS, PVC fabric  
413 for textile, and glass) in this study are frequently used in building materials, furnishings  
414 and devices, which could serve as a reservoir for indoor pathogen that causes nosocomial  
415 infections<sup>63</sup>. Moreover, the selected bacteria and fungi are all pathogenic species that are  
416 known to cause nosocomial infections, with the exception of *S. chartarum* which are  
417 known to produce various mycotoxins and often related to Sick Building Syndrome<sup>64</sup>.  
418 Additionally, among the tested bacteria pathogens, three (*MRSA*, *P. aeruginosa*, *K.*  
419 *pneumoniae*) of them belongs to EKSAPE pathogens which are biofilm-forming multidrug

420 resistant organisms. We tested more gram-negative bacteria as majority of the HAI  
421 outbreaks are associated with gram-negative rods bacteria such as the *P. aeruginosa*, *K.*  
422 *pneumoniae* and *E. coli*, which are what we tested in this study<sup>33</sup>. This highlights the  
423 importance of our results as disinfections of antibiotic resistant pathogens are becoming  
424 increasingly challenging, considering nearly every current antibiotics have been observed  
425 with microbial resistance<sup>35</sup>. In addition to the potential influence on HAIs, daylight and  
426 access to views can shorten hospital length of stay, reduce pain medication use and  
427 improve overall patient experience, resulting in higher patient satisfaction ratings<sup>65,66</sup>.  
428 Patients are 47% more likely to choose a hospital room that has EC Windows than one  
429 that has blinds.

430 However, it should note that hospitals are only one of the many types of built environments  
431 in the society. Fomite transmission and other indoor pathogens also presents in all indoor  
432 environments such as offices, schools, and homes where people spend significant  
433 amount of their time. Currently, many building elements are still far from optimized, with  
434 regular commercial windows being an example that transmits excessive glare and heats.  
435 EC-window technology shows promising potentials to replace blind as the predominant  
436 glare control strategy, which previous studies have shown to improve cognitive function  
437 and psychological health of the occupants<sup>4,7,13</sup>. This study further expands its potential in  
438 minimizing disease transmission, which could be implemented in various built  
439 environments for shaping healthy indoor microbiomes towards the occupants.

#### 440 **4.1 Strength & Limitations**

441 There are several notable strengths in our study design. First of all, this is the first study  
442 that investigated the interactions between indoor daylight and indoor microbiomes on  
443 different surfaces. Secondly, we utilized a highly controlled laboratory environment to  
444 simulate real indoor environments while still limiting the potential for confounding by  
445 temperature, humidity or ventilation. Current understandings of pathogenic persistence  
446 on inanimate surfaces is limited hence this study provides valuable insights on disease  
447 transmission. However, several limitations are also present. Fungi culture was only  
448 incubated for 72 hours (3 days), which may not be efficient for fungal mycelium to be fully  
449 developed. Longer exposure and incubation periods may be needed to see the indoor  
450 daylight effects. Furthermore, microbial contaminations are often caused by pathogens  
451 that dry on inanimate surfaces, where this study uses liquid bacterial and fungal spore  
452 culture for viability assessments due to the recovery limitations. It would also be valuable  
453 to test other surface materials such as stainless steel and textiles (clothes) to expand the  
454 understandings of indoor daylights effects on other type of high touch surface materials.  
455 Additionally, more gram-positive pathogenic bacteria can be tested as we only tested  
456 *MRSA* in this study. Finally, this study simulates a real world setting and does not  
457 necessarily reflect the germicidal effect that would be found in practice. The study focuses  
458 on the viability of bacteria and fungi rather than the risk of transmission or colonization.  
459 Research extending these findings to actual buildings or developing epidemiological  
460 models to estimate infection risk could extend the implications of these findings.  
461 Nevertheless, this study filled multiple knowledge gaps and provided important insights  
462 for future healthy building research.

## 463 5 CONCLUSION

464 In summary, we found that daylight passing through electrochromic (EC) windows, both  
465 in their clear state and tinted state, resulted in significant disinfection of bacteria on high  
466 nutrient surfaces relative to daylight passing through a clear window with blinds. This  
467 research shows that antimicrobial daylight in the 400-500nm range of the visible spectrum  
468 can limit the viability of bacteria and growth of fungi. Bacteria were highly sensitive to the  
469 light wavelength with significantly less viability when exposed to shorter wavelength light  
470 through a tinted window than the same intensity of light through a blind. Light intensity had  
471 stronger effects on fungi than light spectrum, which fungi mycelium growth and viability  
472 were only reduced at EC-Clear conditions. Indoor daylight effects various depends on the  
473 material types and microorganisms. Gram-positive bacteria (*MRSA*) were found to be  
474 more susceptible to indoor daylight compared to gram-negative bacteria, due to the  
475 different types of blue light photosensitizer employed by the species. Bacteria viabilities  
476 were significantly lower on porous material (PVC fabric) compared to non-porous  
477 materials (Glass & PS), which could be because of the material properties or chemical  
478 agents used in the textile. This study filled multiple knowledge gaps and showed the  
479 potential of EC window as an important technology to mitigate pathogen viability in office,  
480 residential, aviation and healthcare settings.

481

482 **REFERENCE**

- 483 1. Allen, J. G. & Macomber, J. D. Healthy Buildings. *Heal. Build.* (2020)  
484 doi:10.4159/9780674246102/HTML.
- 485 2. Cannavale, A., Ayr, U., Fiorito, F. & Martellotta, F. Smart Electrochromic Windows  
486 to Enhance Building Energy Efficiency and Visual Comfort. *Energies 2020, Vol.*  
487 *13, Page 1449* **13**, 1449 (2020).
- 488 3. Aries, M., Aarts, M. & Hoof, J. van. Daylight and health: A review of the evidence  
489 and consequences for the built environment:  
490 <http://dx.doi.org/10.1177/1477153513509258> **47**, 6–27 (2013).
- 491 4. MacNaughton, P. *et al.* The impact of working in a green certified building on  
492 cognitive function and health. *Build. Environ.* **114**, 178–186 (2017).
- 493 5. Boubekri, M., Cheung, I. N., Reid, K. J., Wang, C.-H. & Zee, P. C. Impact of  
494 Windows and Daylight Exposure on Overall Health and Sleep Quality of Office  
495 Workers: A Case-Control Pilot Study. *J. Clin. Sleep Med.* **10**, 603 (2014).
- 496 6. MacNaughton, P., Woo, M., Tinianov, B., Boubekri, M. & Satish, U. Economic  
497 implications of access to daylight and views in office buildings from improved  
498 productivity. *J. Appl. Soc. Psychol.* **51**, 1176–1183 (2021).
- 499 7. Nagare, R. *et al.* Access to Daylight at Home Improves Circadian Alignment,  
500 Sleep, and Mental Health in Healthy Adults: A Crossover Study. *Int. J. Environ.*  
501 *Res. Public Heal.* 2021, Vol. 18, Page 9980 **18**, 9980 (2021).
- 502 8. Seduced by the View | Urban Green Council.  
503 <https://www.urbangreencouncil.org/seduced-by-the-view>.
- 504 9. Tuchinda, C., Srivannaboon, S. & Lim, H. W. Photoprotection by window glass,  
505 automobile glass, and sunglasses. doi:10.1016/j.jaad.2005.11.1082.

- 506 10. Aguilar-Santana, J. L., Jarimi, H., Velasco-Carrasco, M. & Riffat, S. Review on  
507 window-glazing technologies and future prospects. *Int. J. Low-Carbon Technol.*  
508 **15**, 112–120 (2020).
- 509 11. Allen, K., Connelly, K., Rutherford, P. & Wu, Y. Smart windows—Dynamic control  
510 of building energy performance. *Energy Build.* **139**, 535–546 (2017).
- 511 12. Rezaei, S. D., Shannigrahi, S. & Ramakrishna, S. A review of conventional,  
512 advanced, and smart glazing technologies and materials for improving indoor  
513 environment. *Sol. Energy Mater. Sol. Cells* **159**, 26–51 (2017).
- 514 13. Boubekri, M. *et al.* The Impact of Optimized Daylight and Views on the Sleep  
515 Duration and Cognitive Performance of Office Workers. *Int. J. Environ. Res. Public*  
516 *Heal.* 2020, Vol. 17, Page 3219 **17**, 3219 (2020).
- 517 14. Hedge, A., Macnaughton, P., Woo, M., Guglielmetti, R. & Tinianov, B. Airport  
518 passenger experiences in concourses with either electrochromic or low-e glass  
519 windows. *Int. J. Aviat. Manag.* **5**, 1–16 (2021).
- 520 15. Enwemeka, C. S., Bumah, V. V. & Masson-Meyers, D. S. Light as a potential  
521 treatment for pandemic coronavirus infections: A perspective. *J. Photochem.*  
522 *Photobiol. B Biol.* **207**, 111891 (2020).
- 523 16. Gwynne, P. J. & Gallagher, M. P. Light as a Broad-Spectrum Antimicrobial. *Front.*  
524 *Microbiol.* **9**, (2018).
- 525 17. Møller, K. I., Kongshoj, B., Philipsen, P. A., Thomsen, V. O. & Wulf, H. C. How  
526 Finsen’s light cured lupus vulgaris. *Photodermatol. Photoimmunol. Photomed.* **21**,  
527 118–124 (2005).
- 528 18. Yang, P. *et al.* 460 nm visible light irradiation eradicates MRSA via inducing  
529 prophage activation. *J. Photochem. Photobiol. B Biol.* **166**, 311–322 (2017).



- 530 19. Christensen, T., Johnsen, B. J. & Bruzell, E. M. Violet-blue light exposure of the  
531 skin: is there need for protection? *Photochem. Photobiol. Sci.* 2021 205 **20**, 615–  
532 625 (2021).
- 533 20. Halstead, F. D. *et al.* Antibacterial activity of blue light against nosocomial wound  
534 pathogens growing planktonically and as mature biofilms. *Appl. Environ. Microbiol.*  
535 **82**, 4006–4016 (2016).
- 536 21. Tomb, R. M., Maclean, M., Coia, J. E., MacGregor, S. J. & Anderson, J. G.  
537 Assessment of the potential for resistance to antimicrobial violet-blue light in  
538 *Staphylococcus aureus*. *Antimicrob. Resist. Infect. Control* **6**, (2017).
- 539 22. Purschwitz, J. *et al.* Functional and Physical Interaction of Blue- and Red-Light  
540 Sensors in *Aspergillus nidulans*. *Curr. Biol.* **18**, 255–259 (2008).
- 541 23. Maclean, M., MacGregor, S. J., Anderson, J. G. & Woolsey, G. Inactivation of  
542 bacterial pathogens following exposure to light from a 405-nanometer light-  
543 emitting diode array. *Appl. Environ. Microbiol.* **75**, 1932–1937 (2009).
- 544 24. Abana, C. M. *et al.* Characterization of blue light irradiation effects on pathogenic  
545 and nonpathogenic *Escherichia coli*. *Microbiologyopen* **6**, (2017).
- 546 25. National Academies of Sciences, T. Microbiomes of the Built Environment: A  
547 Research Agenda for Indoor Microbiology, Human Health, and Buildings. (2017)  
548 doi:10.17226/23647.
- 549 26. Hu, J. *et al.* Impacts of indoor surface finishes on bacterial viability. *Indoor Air* **29**,  
550 551 (2019).
- 551 27. Li, S., Yang, Z., Hu, D., Cao, L. & He, Q. Understanding building-occupant-  
552 microbiome interactions toward healthy built environments: A review. *Frontiers of*  
553 *Environmental Science and Engineering* vol. 15 1–18 (2021).

- 554 28. Horve, P. F. *et al.* Building upon current knowledge and techniques of indoor  
555 microbiology to construct the next era of theory into microorganisms, health, and  
556 the built environment. *J. Expo. Sci. Environ. Epidemiol.* 2019 302 **30**, 219–235  
557 (2019).
- 558 29. Samet, J. M. & Spengler, J. D. Indoor Environments and Health: Moving Into the  
559 21st Century. *Am. J. Public Health* **93**, 1489 (2003).
- 560 30. Lopez, G. U. *et al.* Transfer Efficiency of Bacteria and Viruses from Porous and  
561 Nonporous Fomites to Fingers under Different Relative Humidity Conditions. *Appl.*  
562 *Environ. Microbiol.* **79**, 5728 (2013).
- 563 31. Kelley, S. T. & Gilbert, J. A. Studying the microbiology of the indoor environment.  
564 *Genome Biol.* 2013 142 **14**, 1–9 (2013).
- 565 32. Santajit, S. & Indrawattana, N. Mechanisms of Antimicrobial Resistance in  
566 ESKAPE Pathogens. *Biomed Res. Int.* **2016**, (2016).
- 567 33. Kanamori, H., Rutala, W. A. & Weber, D. J. The Role of Patient Care Items as a  
568 Fomite in Healthcare-Associated Outbreaks and Infection Prevention. *Clin. Infect.*  
569 *Dis.* **65**, 1412–1419 (2017).
- 570 34. Hoenes, K., Bauer, R., Meurle, T., Spellerberg, B. & Hessling, M. Inactivation  
571 Effect of Violet and Blue Light on ESKAPE Pathogens and Closely Related Non-  
572 pathogenic Bacterial Species – A Promising Tool Against Antibiotic-Sensitive and  
573 Antibiotic-Resistant Microorganisms. *Front. Microbiol.* **0**, 3429 (2021).
- 574 35. Greenhalgh, R., Dempsey-Hibbert, N. C. & Whitehead, K. A. Antimicrobial  
575 strategies to reduce polymer biomaterial infections and their economic  
576 implications and considerations. *Int. Biodeterior. Biodegradation* **136**, 1–14 (2019).
- 577 36. Perlroth, J., Choi, B. & Spellberg, B. Nosocomial fungal infections: epidemiology,

- 578 diagnosis, and treatment. *Med. Mycol.* **45**, 321–346 (2007).
- 579 37. Van Thiel, D. H., George, M. & Moore, C. M. Fungal Infections: Their Diagnosis  
580 and Treatment in Transplant Recipients. *Int. J. Hepatol.* **2012**, 1–19 (2012).
- 581 38. Gilbert, J. A. & Stephens, B. Microbiology of the built environment. *Nature*  
582 *Reviews Microbiology* vol. 16 661–670 (2018).
- 583 39. Lubart, R., Lipovski, A., Nitzan, Y. & Friedmann, H. A possible mechanism for the  
584 bactericidal effect of visible light. *Laser Ther.* **20**, 17 (2011).
- 585 40. Lipovsky, A., Nitzan, Y., Gedanken, A. & Lubart, R. Visible light-induced killing of  
586 bacteria as a function of wavelength: Implication for wound healing. *Lasers Surg.*  
587 *Med.* **42**, 467–472 (2010).
- 588 41. Maclean, M., McKenzie, K., Anderson, J. G., Gettinby, G. & MacGregor, S. J. 405  
589 nm light technology for the inactivation of pathogens and its potential role for  
590 environmental disinfection and infection control. *J. Hosp. Infect.* **88**, 1–11 (2014).
- 591 42. Enwemeka, C. S., Williams, D., Hollosi, S., Yens, D. & Enwemeka, S. K. Visible  
592 405 nm SLD light photo-destroys methicillin-resistant *Staphylococcus aureus*  
593 (MRSA) in vitro. *Lasers Surg. Med.* **40**, 734–737 (2008).
- 594 43. Halstead, F. D. *et al.* Antibacterial Activity of Blue Light against Nosocomial  
595 Wound Pathogens Growing Planktonically and as Mature Biofilms. (2016)  
596 doi:10.1128/AEM.00756-16.
- 597 44. Plavskii, V. Y. *et al.* Porphyrins and flavins as endogenous acceptors of optical  
598 radiation of blue spectral region determining photoinactivation of microbial cells. *J.*  
599 *Photochem. Photobiol. B Biol.* **183**, 172–183 (2018).
- 600 45. Purschwitz, J., Müller, S., Kastner, C. & Fischer, R. Seeing the rainbow: light  
601 sensing in fungi. *Curr. Opin. Microbiol.* **9**, 566–571 (2006).

- 602 46. Fuller, K. K., Ringelberg, C. S., Loros, J. J. & Dunlap, J. C. The Fungal Pathogen  
603 *Aspergillus fumigatus* Regulates Growth, Metabolism, and Stress Resistance in  
604 Response to Light. *MBio* **4**, (2013).
- 605 47. Bayram, Ö., Braus, G. H., Fischer, R. & Rodriguez-Romero, J. Spotlight on  
606 *Aspergillus nidulans* photosensory systems. *Fungal Genet. Biol.* **47**, 900–908  
607 (2010).
- 608 48. Tisch, D. & Schmoll, M. Light regulation of metabolic pathways in fungi. *Appl.*  
609 *Microbiol. Biotechnol.* **85**, 1259 (2010).
- 610 49. Lin, L. & Xu, J. Fungal Pigments and Their Roles Associated with Human Health.  
611 *J. Fungi* **6**, 1–37 (2020).
- 612 50. Wong, H. J., Mohamad-Fauzi, N., Rizman-Idid, M., Convey, P. & Alias, S. A.  
613 Protective mechanisms and responses of micro-fungi towards ultraviolet-induced  
614 cellular damage. *Polar Sci.* **20**, 19–34 (2019).
- 615 51. Mousavi, B., Hedayati, M., Hedayati, N., Ilkit, M. & Syedmousavi, S. *Aspergillus*  
616 species in indoor environments and their possible occupational and public health  
617 hazards. *Curr. Med. Mycol.* **2**, 36 (2016).
- 618 52. Hatakeyama, R., Nakahama, T., Higuchi, Y. & Kitamoto, K. Light represses  
619 conidiation in koji mold *Aspergillus oryzae*. *Biosci. Biotechnol. Biochem.* **71**, 1844–  
620 1849 (2007).
- 621 53. Fuller, K. K., Loros, J. J. & Dunlap, J. C. Fungal photobiology: visible light as a  
622 signal for stress, space and time. *Curr. Genet.* **61**, 275 (2015).
- 623 54. Bloomfield, S. *et al.* Lesser-known or hidden reservoirs of infection and  
624 implications for adequate prevention strategies: Where to look and what to look  
625 for. *GMS Hyg. Infect. Control* **10**, Doc04 (2015).

- 626 55. Gulati, R., Sharma, S. & Sharma, R. K. Antimicrobial textile: recent developments  
627 and functional perspective. *Polym. Bull. 2021* 1–25 (2021) doi:10.1007/S00289-  
628 021-03826-3.
- 629 56. Guffey, D. J. S. & Wilborn, J. In Vitro Bactericidal Effects of 405-nm and 470-nm  
630 Blue Light. <https://home.liebertpub.com/pho> **24**, 684–688 (2007).
- 631 57. Islam, M. R., Tudryn, G., Bucinell, R., Schadler, L. & Picu, R. C. Morphology and  
632 mechanics of fungal mycelium. *Sci. Reports 2017 71* **7**, 1–12 (2017).
- 633 58. Liauw, C. M. *et al.* The Effect of Surface Hydrophobicity on the Attachment of  
634 Fungal Conidia to Substrates of Polyvinyl Acetate and Polyvinyl Alcohol. *J. Polym.*  
635 *Environ.* **28**, 1450–1464 (2020).
- 636 59. Green, C. F., Davidson, C. S., Scarpino, P. V. & Gibbs, S. G. Ultraviolet germicidal  
637 irradiation disinfection of *Stachybotrys chartarum*. *Can. J. Microbiol.* **51**, 801–804  
638 (2005).
- 639 60. Kramer, A., Schwebke, I. & Kampf, G. How long do nosocomial pathogens persist  
640 on inanimate surfaces? A systematic review. *BMC Infect. Dis. 2006 61* **6**, 1–8  
641 (2006).
- 642 61. Wißmann, J. E. *et al.* microorganisms Persistence of Pathogens on Inanimate  
643 Surfaces: A Narrative Review. (2021) doi:10.3390/microorganisms9020343.
- 644 62. Katzenberger, R. H., Rösel, A. & Vonberg, R.-P. Bacterial survival on inanimate  
645 surfaces: a field study. *BMC Res. Notes 2021 141* **14**, 1–10 (2021).
- 646 63. Katzenberger, R. H., Rösel, A. & Vonberg, R.-P. Bacterial survival on inanimate  
647 surfaces: a field study. *BMC Res. Notes 2021 141* **14**, 1–10 (2021).
- 648 64. Bitnun, A. & Nosal, R. M. *Stachybotrys chartarum* (atra) contamination of the  
649 indoor environment: Health implications. *Paediatr. Child Health* **4**, 125 (1999).

- 650 65. Ulrich, R. S. View Through a Window May Influence Recovery from Surgery.  
 651 *Science (80-. ).* **224**, 420–421 (1984).  
 652 66. Mihandoust, S., Joseph, A., Kennedy, S., Macnaughton, P. & Woo, M. Exploring  
 653 the Relationship between Window View Quantity, Quality, and Ratings of Care in  
 654 the Hospital. *Int. J. Environ. Res. Public Health* **18**, 10677 (2021).

## 655 **ACKNOWLEDGEMENT**

656 This research was funded by MITACS grant IT21657. We acknowledge View Inc. for  
 657 providing the EC Window chamber used in the experiments.

658 **KEYWORDS:** HEALTHY BUILT ENVIRONMENT, INDOOR MICROBIOME, INDOOR DAYLIGHT, SMART  
 659 WINDOW, PATHOGENS ON SURFACES, PATHOGENS VIABILITY

## 660 **Tables**

661 **Table 1** Percentage of reduction of bacterial CFU per ml and fungi mycelium growth by indoor daylight at  
 662 EC Window – Clear and EC Window – Tinted on high nutrient agar plates.

	<b>EC Window – Clear condition vs Blinds condition</b>	<b>EC Window – Tinted condition vs Blinds condition</b>
<b>Bacteria</b>		
<i>E. coli</i>	100% ( $P < 0.001$ ) †	100% ( $P < 0.001$ ) †
<i>K. pneumoniae</i>	100% ( $P < 0.001$ ) †	75% ( $P < 0.001$ ) †
<i>P. aeruginosa</i>	98% ( $P = 0.024$ ) ‡	41%
<i>MRSA</i>	100% ( $P < 0.001$ ) †	100% ( $P < 0.001$ ) †
<b>Fungi</b>		
<i>S. chartarum</i>	99% ( $P = 0.001$ ) ‡	43%
<i>A. fumigatus</i>	86% ( $P = 0.035$ ) ‡	28%
<i>A. versicolor</i>	100% ( $P = 0.029$ ) ‡	26%

*P*-value of significant growth rate reduction comparing EC window and Blinds were reported, with the analysis test indicated as †: Bonferroni post-hoc Test, ‡: Games Howell Test

663  
 664 **Table 2** Percentage of reduction of bacterial CFU per ml and fungi mycelium growth by indoor daylight in  
 665 EC Window – Clear condition and EC Window – Tinted condition relative to Blinds condition on A)  
 666 Polystyrene B) PVC fabric and C) Glass.

667 **A) Polystyrene (PS)**

	<b>EC Window – Clear condition vs Blinds condition</b>	<b>EC Window – Tinted condition vs Blinds condition</b>
Bacteria		
<i>E. coli</i>	3%	44%
<i>K. pneumoniae</i>	59%	95%
<i>P. aeruginosa</i>	23%	0%
MRSA	96%	23%
Fungi		
<i>S. chartarum</i>	0%	2%
<i>A. fumigatus</i>	57% ( <i>P</i> = 0.005) ‡	27%
<i>A. versicolor</i>	55% ( <i>P</i> = 0.003) ‡	23% ( <i>P</i> = 0.018) ‡

668 **B) Polyvinyl chloride (PVC) Fabric**

	<b>EC Window – Clear condition vs Blinds condition</b>	<b>EC Window – Tinted condition vs Blinds condition</b>
Bacteria		
<i>E. coli</i>	90% ( <i>P</i> = 0.015) ‡	90% ( <i>P</i> = 0.037) ‡
<i>K. pneumoniae</i>	97%	94%
<i>P. aeruginosa</i>	85%	4%
MRSA	85%	100%

Fungi		
<i>S. chartarum</i>	60%	39%
<i>A. fumigatus</i>	52% ( $P = 0.023$ ) †	27%
<i>A. versicolor</i>	6%	0%

669 **C) Glass**

	EC Window – Clear condition vs Blinds condition	EC Window – Tinted condition vs Blinds condition
Bacteria		
<i>E. coli</i>	48%	89% ( $P = 0.022$ ) ‡
<i>K. pneumoniae</i>	63%	79%
<i>P. aeruginosa</i>	91% ( $P = 0.008$ ) ‡	1%
MRSA	100% ( $P = 0.028$ ) †	78%
Fungi		
<i>S. chartarum</i>	16%	17%
<i>A. fumigatus</i>	15%	27%
<i>A. versicolor</i>	6%	4%

$P$ -value of significant viability reduction comparing the EC window and Blinds were reported, with the analysis test indicated as †: Bonferroni Post-hoc Test ‡: Tukey HSD

670  
 671 **Figure Legends**  
 672 **Figure 1:** Experiment set up and conditions. **A)** Environmental chamber with EC Windows  
 673 from View Inc. and temperature and humidity control. Samples are placed inside the  
 674 chamber for indoor light exposure. **B)** Bar graph with standard deviation (SD) of  
 675 temperature (left) and humidity (right) for each light condition: Blinds (grey), Clear (light  
 676 blue), and Tinted (dark blue). **C)** Bar graph with standard deviation (SD) of light intensity  
 677 of each light condition: Blinds (grey), Clear (light blue), and Tinted (dark blue). **D)** Light



678 spectrum of three tested light conditions: Blind condition (grey line); EC Window - Clear  
679 (light blue line), and EC Window - Tinted (dark blue line). Violet-blue light (400 - 500nm)  
680 spectrum are highlighted with purple.

681 **Figure 2:** Bacteria and fungi viability on high nutrient agar plates after exposure of indoor  
682 light at different EC window conditions. **A)** Bacteria colonies forming units (CFU) per ml  
683 on high nutrient agar plates after 24 hours indoor daylight exposure. **B)** Fungi mycelium  
684 growth on high nutrient agar plates after 72 hours of indoor daylight exposure. Statistical  
685 analysis compared each condition relative to the Blind condition (grey) (\*,  $P<0.05$ ; \*\*,   
686  $P<0.01$ ).

687 **Figure 3** Effect of indoor daylight at different EC window conditions on bacteria and fungi  
688 variability on three different surface materials. **A)** Bacteria colonies forming (CFU) per ml  
689 on PS, PVC fabric and glass after 24 hours indoor daylight exposure. **B)** Fungi mycelium  
690 growth on PS, PVC fabric and glass after 72 hours indoor daylight exposure.

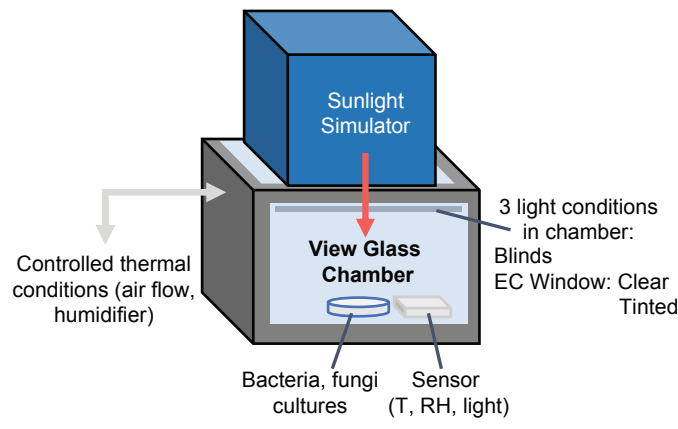
### 691 **Supplemental Materials**

692 **Supplemental Figure 1:** Experimental workflow of **A)** Indoor daylight effect on bacteria  
693 and fungi growth rate on high nutrient agar plates. **B)** Indoor daylight effect of bacteria and  
694 fungi viability on low nutrient surface materials experiment.

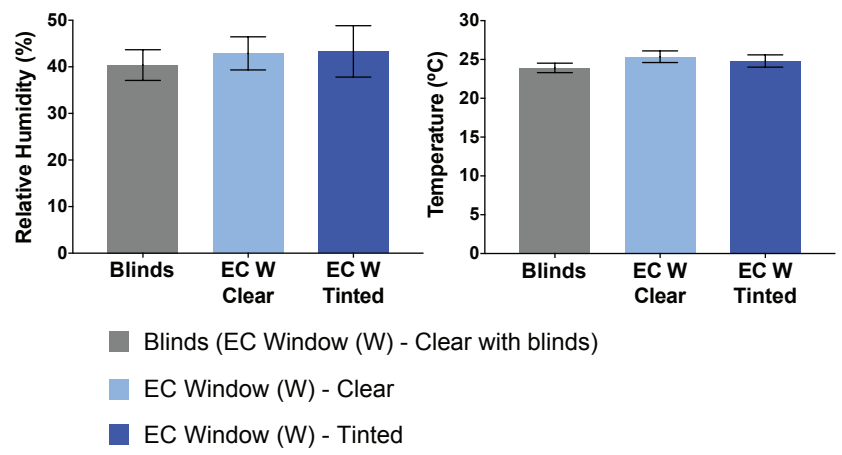
695 **Supplemental Figure 2:** Bacteria viability assessment **A)** Bacteria colonies forming unit  
696 counting using ImageJ software. **B)** Images of bacteria viability at different daylight  
697 conditions and control settings. From left to the right: bacteria growth at: 37°C in the dark  
698 incubator, 25°C in the dark incubator; environmental chamber at window with blind  
699 condition, environmental chamber at EC window-Clear condition at 25°C, environmental  
700 chamber EC window-Tinted at 25°C.

701 **Supplemental Figure 3** Images of fungal mycelium growth viability at different light  
702 condition and control settings. From left to the right: bacteria growth at: 37°C in the dark  
703 incubator, 25°C in the dark incubator; environmental chamber at window with blind  
704 condition, environmental chamber at EC window-Clear condition at 25°C, environmental  
705 chamber EC window-Tinted at 25°C.

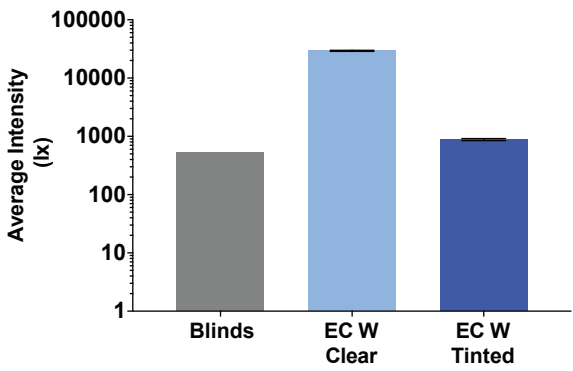
**A**



**B**



**C**



**D**

