



Characterization and decontamination of deposited dust: a management regime at a museum

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Abstract Deposited dust represents a nutritional niche for microflora. Inhibiting microflora-associated deposited dust is a critical approach to manage cultural heritage buildings. Knowledge on the effectiveness of commercial disinfection on microflora in a real field environment is limited. The present study aims to: (1) characterize deposited dust composition, and (2) assess the effectiveness of several commercial biocides/and an air ionizer on microflora-associated floor surface and air before and after treatment. Deposited dust was collected using a dust collector and microbial air sampling was conducted via a volumetric impactor sampler. Susceptibility of microorganisms to biocide/ionizer was performed in a naturally ventilated unoccupied room with a floor area of 18 m². One-treatment protocol, a daily disinfection mode, was applied to each biocide/ionizer. The surface floor was adjacently sprayed by a biocide, and the ionizer was turned on for 30 min. Indoor deposited dust rates varied between 0.75 and 8.7 mg/m²/day with indoor/outdoor ratio of ~1:100. Ion concentrations of NH₄⁺, Cl⁻, SO₄²⁻ and NO₃⁻ were higher indoor than outdoor. The concentration of microorganisms-associated deposited dust averaged 10⁶ CFU/g; 10⁵ CFU/g and 10⁴ CFU/g for bacteria,

fungi and actinomycetes, respectively. A total of 23 fungal taxa were identified, with *Aspergillus flavus*, *Asp. fumigatus* and *Asp. niger* were the predominant taxa. Biocides quickly reduced floor surface and airborne microbial loads. The biocidal effect was time limited, as microflora loads increased again after ~4 days of the treatment protocol. Benzalkonium chloride (BAC) out-performed other biocides, showed a relatively permanent microbial inhibiting effect. The air ionizer reduced airborne microorganisms and increased surface floor ones. Characterizing of deposited dust (rate and composition) and choice an appropriate biocide may effectively reduce biodegradation. Further real field treatment trials under various microenvironmental conditions are needed to determine the effectiveness of disinfection treatment.

Keywords Museum · Deposited dust · Biocontamination · Floor surface · Ion profile · Biocide · Ionizer

1 Introduction

The study of the effect of environmental parameters on cultural heritage has increased in the last decades. Air pollution represents a critical risk factor for cultural heritage objects in cultural heritage buildings (Karbowska-Berent et al., 2011). Dust is one of the atmospheric aerosol components which affect air quality, climate and settle on surfaces

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(Fuzzi et al., 2006). Dust particles originate from a variety of natural and anthropogenic sources according to source region and emission mechanism (Chen et al., 2018). The composition (biological and chemical fractions), concentration and size of dust particles differ depending on geographical location, long-range transport of pollutants and meteorological conditions (Adams et al., 2015; Rintala et al., 2012). Dust is introduced into indoor buildings from outdoor environment, human activities and internal materials (Godish, 1989). Accumulation of a variety of dust particles in indoor environments may create conditions required for microbial growth (Nevalainen & Morawaska, 2009; Saiz-Jimenez, 1995). Microorganisms can settle, colonize and deteriorate cultural heritage items (Gadd & Dyer, 2017; Mesquita et al., 2022). Deposited dust and its components can cause physical damage, chemical alteration and microbial deterioration of cultural heritage items (Cappitelli et al., 2020; Scheerer et al., 2009).

The degree of dust's damage depends on its composition (Borrego & Molina, 2020; Mallo et al., 2017). Metals, sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), sea salt, mineral dust, organic compounds and black carbon are the predominant chemical components of dust particles (Raes et al., 2000). The components of SO_4^{2-} , NO_3^- and NH_4^+ are formed as secondary aerosols. Microclimatic conditions and chemical variables are critical for formation of secondary aerosols and microbial proliferation (Camuffo, 2013; De Nuntiis & Palla, 2017), which negatively influence artworks (Rahmawati et al., 2018) by excreting pigments, metabolic products and acids (Anaf et al., 2013; Fomina et al., 2010).

Sulfuric and nitric acid gases nucleate, in the presence of water vapor, to form sulfuric acid and nitric acid droplets, and neutralize by ammonia to form ammonium sulfate and ammonium nitrate, respectively (Watson et al., 1994). Acidic air pollutants lead to hydrolytic degradation of artworks (Vallero, 2008). The deposited dust may react chemically with surfaces, producing irreversible degradation. Sulfur-rich materials can cause discoloration of paintings, and ammonium sulfate induces bloom on varnish (Maricq, 2007). Diesel particles are hygroscopic (Popovicheva et al., 2011), accelerating hydrophilic and oxidative process, leading to fading and degradation of papers and textiles (Gysels et al., 2002).

Conservation and decontamination of the cultural heritage items in museums depend on the control of environmental conditions (pollution, ventilation and microclimatic conditions) (Proietti et al., 2015). Biocides (oxidizing and non-oxidizing agents), mechanical removal and physical treatment (UV, laser, microwaves and purifiers) are also techniques adopted to reduce biodegradation in cultural heritage buildings (Cappitelli et al., 2020). Biocides display different killing modes of action, stability and reactivity with materials (Denyer, 1995). Biocides are widely used to control microbial contamination, in spite of their drawbacks (Fiorillo et al., 2020). The ability of biocides to inhibit microorganisms residing on surfaces is limited and varied (Li et al., 2020). Biocides may change the original microbial community (Mulec & Kosi, 2009) or develop new generation of resistant microbes (Cole & Foarde, 1999). Application of water-based biocides increases moisture in indoor environment, promoting growth of biofilms (Liu et al., 2018). Biocides may promote microbial growth through non-active ingredient in their formulations, nitrogen and organic carbon (Kakakhel et al., 2019). Some biocides can oxidize metal ions leading to corrosion and rusting of minerals, as well as chlorine-containing biocides interact with stone materials (Pinna, 2017), altering their composition. Quaternary ammonium compounds contribute to the degradation of lime mortars and hardened Portland cement (Tudor et al., 1990). Biocides or chemical cleaning solutions can introduce materials and form soluble salts (Griffin et al., 1991).

Air purification technique is commonly used to reduce microbial aerosols contamination (Grinshpun et al., 2007). A wide range of air purifiers generate ozone, negative ions and UV irradiation (EPA, 2023; Pham & Lee, 2015), which effectively improve indoor air quality. Air purifiers with filters are used to trap and eliminate microbial particles; however, light catalyzer and UV lamp are used to kill microorganisms (Zacarias et al., 2012).

The Prince Mohamed Ali palace is preserved as a historical museum. It is characterized by its architectural Maghreb style and contains many of unique artworks. The palace is located on the western bank of the River Nile, in the Al Manial district; it is a highly crowded and polluted region. The palace is surrounded by complex, variable and changeable urban atmosphere, characterized by high traffic

congestion intensity, diverse commercial activities, parking, workshops, hospitals and educational settings. The palace contents may be vulnerable to chemical and biological pollution that may alter their composition and color.

Air sampling alone does not always indicate the presence of microbial pollution. Multi-approaches should be used to characterize microbial pollution in cultural heritage buildings including (1) consider contamination rate, density and settling velocity, (2) consider material and microbial type and (3) reduce deposited dust and evaluate its composition (Awad et al., 2020). The present study aims to develop a prevention strategy to reduce microbial and chemical harms on surfaces. This will be achieved through (1) characterizing microbial and chemical composition of deposited dust, (2) assessing the effectiveness of some commercial biocides belonging to different chemical groups (chlorine bleach, ethyl alcohol, Dettol, Savlon and BAC)/and an air ionizer (unipolar-ion emitter) on microflora-associated surface floor and air state in the real field environment.

2 Materials and methods

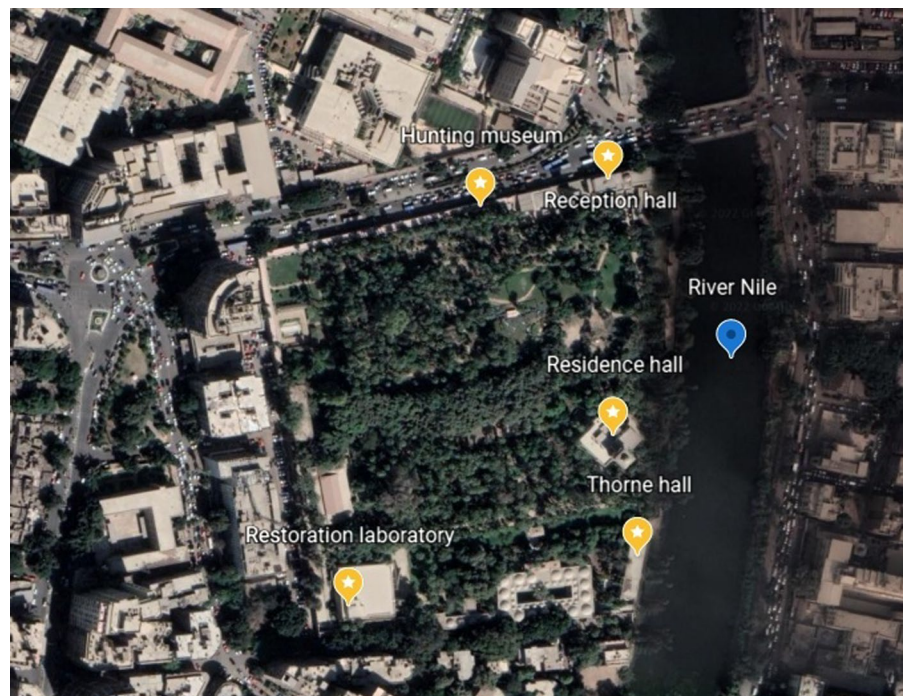
2.1 Description of the museum

In brief, the Prince Mohamed Ali palace is composed of five separate and distinctive buildings. A sampling campaign was performed for a period of 3 years at the museum's buildings namely "reception hall, residence hall, Thorne hall, hunting museum and restoration laboratory" (Fig. 1). The characteristics of the museum's buildings are previously described by Awad and his coauthors (2020).

2.2 Sampling of deposited dust

Deposited dust was passively collected using a dust collector. The collector consists of a cylindrical glass beaker with 170 mm height and 80 mm diameter, positioned at ~2 m above the floor surface indoor and at ~6 m outdoor. The dust collectors were frequently replaced every 3 months. The deposited dust was carefully transferred to a dry sterilized-pre-weighted beaker, and the dust rate was calculated and reported as milligram per square meter per day ($\text{mg}/\text{m}^2/\text{day}$).

Fig. 1 Image of Prince Mohamed Ali museum, showing location and adjacent buildings. Map data ©Google, 2022 Terra Metrics



2.3 Ion profile

The deposited dust samples were homogenized dried in a non-vacuum desiccator (Duran, Fisher scientific, USA) no more than 24 h before analysis. A portion of the deposited dust (100 mg) was dissolved in 10 ml double-sterilized distilled water and shaken in a shaking incubator (HYSC, Korea) at 150 rpm for 30 min. A portion of aliquot (5 ml) was analyzed for water-soluble ions “Cl⁻, SO₄²⁻ and NO₃ and NH₄⁺” using ion chromatography (Dionex-ICS-11000, USA). An Ion Pac ASRS-4 suppressor and an Ion Pac AS11-HC×250 mm analytical column were used for the detection of anions, whereas an Ion Pac CSRS-4 suppressor and an Ion Pac CS12A×250 mm analytical column were used for cations detection. The eluents of 10 mmol/L Na₂CO₃ and 10 mmol/L CH₄O₃S were used for anions and cations analysis, respectively. A 10 µL loop was used for the sample’s injection. The ion chromatography was calibrated using the prepared standard solutions. The ion concentration was reported as microgram per gram of dust (µg/g).

2.4 Microorganisms-associated deposited dust

Aliquots (500 µl) of the original sample were spread-plated, in triplicate, onto the surface of 2% Malt extract agar, nutrient agar and starch casein agar media (Hi-media laboratories, Mumbai, India) to count fungi, bacteria and actinomycetes, respectively. Bacterial and actinomycete Petri plates were incubated at 28 °C±2 °C for 2 and 7–14 days, respectively. However, fungal Petri plates were incubated at 25 °C for 3 days and checked daily. The resultant colonies were counted and reported as colony forming unit per gram of dust (CFU/gm).

2.5 Identification of fungi and bacteria

Fungal isolates were identified by direct observation of micro- and macro-morphological features, reverse and surface coloration of colonies on Sabouraud’s dextrose agar, Czapek dox agar; Potato dextrose agar (Difco, Detroit, MI) and Malt extract agar media (Hi-media laboratories, Mumbai, India) using various literatures (Barnett & Hunter, 1999; Ellis, 1971; Pitt &

Hocking, 2009; Raper & Fennell, 1977; Singh et al., 1991).

The relative frequency (RF) of fungal taxa-associated deposited dust was calculated using Eq. (1) (Esquivel et al., 2003).

$$RF = \frac{\text{Times a taxa is detected}}{\text{Total number of sampling realized}} \times 100 \quad (1)$$

Moreover, the agreement ratio (*R*) was calculated to reflect the number of identical fungal species isolated from both of two environments (shared species) in relative to the total number of species identified in both samples (sum of all species) (Eq. 2). The agreement ratios ≥0.8 are considered very high (Macher, 1999).

$$R = \frac{2W}{A + B} \quad (2)$$

where *W*=number of species both samples have in common, *A*=total number of species in environment *A* and *B*=total number of species in environment *B*.

Moreover, the bacterial isolates were identified using Biolog 21124 system (Cabot Blvd, Hayward, CA 94545). The Biolog’s microbial identification system software (OmniLog ® Data Collection) was used to identify the bacterium from its phenotypic pattern in the GEN III Micro-Plate.

2.6 Susceptibility of microorganisms to biocide/air ionizer

The properties of five commercial biocides/ and an air ionizer are shown in Table 1. The susceptibility of the environmental microorganisms to a biocide/or an air ionizer was conducted in the real field, inside naturally ventilated office room (*L*×*W*×*H*=3 m×6 m×4.85 m), connected to the residence hall, during the period between 2017 and 2020.

One-treatment protocol, a daily disinfection mode, was applied to each biocide test, and ~6 months between each experimental treatment. The experimental office room was never cleaned during the period of experimental tests. The disinfection test was only limited to the floor surface. The biocide (40 ml/m²) was adjacently sprayed to the floor surface using a Kingjet hand sprayer (Co Ban Kiat Hardware, Philippines). The air ionizer (Air Clinic, Malsutek®, China) was operated at a flow rate of 4.7 m³/min for

Table 1 Properties of the biocides and the air ionizer

Biocide/air ionizer	Active principle	Concentration applied on surface/ or flow rate	Target region	Remark
Ethanol	Ethyl alcohol-C ₂ H ₆ O	70% 70 ml:30 ml H ₂ O	Cell wall and cytoplasmic membrane	PIOCHEM- CoMr 46.01 g/mol
Dettol	4-Chloro-3,5-dimethyl-phenol	2.43% 2.5 ml:100 ml H ₂ O	Cell wall	Chloroxylenol, PCMX(Royal-Cosmetic CO,UK)
Savlon	Chlorhexidine gluconate–cetrimide	2.5% 2.5 ml:97.5 ml H ₂ O	Cytoplasmic membrane and cell wall	EMACO, UK
Clorox	Sodium hypochlorite-NaOCl	4.76% 5 ml:100 H ₂ O	Cell wall	Chlorine bleach liquid
Benzalkonium chloride	Alkyldimethylbenzylammonium chloride	4% 2 ml:48 H ₂ O	Cytoplasmic membrane, phospholipid bilayer	LOBA, Chemic, India
Air clinic	A multistage filtering system consisted of micro-activated charcoal filters and electrostatic ionizer	Flow rate was 4.7 m ³ /min, operated for 30 min	Physical removal by diffusion sedimentation and filtration	– ve ions emitter

30 min. The experimental room was wet swept and dried after each experimental treatment. On each experimental treatment, surface swabs/and air samples were taken according to the following time lines:

T₀:Samples were taken before applying a biocide/ or turn on the purifier device (background).

T₁:Samples were taken 60 min after applying a biocide/or turn on the purifier device to demonstrate immediate effect.

T₂:Samples were taken 4 days after applying a biocide/or turn on purifier device to demonstrate the expected level of permanent prevention and end point of disinfection.

Surface swabs were randomly collected, in triplicate, using a template (10 cm × 10 cm) during each sampling time line. The swab was eluted in 5 ml sterilized saline solution (0.8% NaCl). Aliquots (500 µl) of the original sample were spread-plated, in triplicate onto the surfaces of agar media as previously mentioned. The resultant colonies were counted and expressed as colony forming units per square centimeter of the surface area (CFU/cm²).

Air sampling was taken ~1 m height above the surface floor, at the center of the room, in duplicate, using Andersen 2 stage viable impactor (TE-10-160-Tish Environmental Cleves, Oh, USA), operating at

28.3 l/min for 5 min and using the previously mentioned agar media (NIOSH, 1998). Positive-hole correction was applied (Andersen, 1958), and the resultant colonies were reported as colony forming unit per cubic meter of air (CFU/m³).

The effectiveness of the biocide/air ionizer on microbial load (removal efficiency) was calculated using Eq. (3).

$$N = \frac{C_1 - C_2}{C_1} \times 100 \quad (3)$$

where N = is the microbial removal efficiency (%); C_1 = is the initial microbial value (before applying biocide/or turn on the air purifier); and C_2 = is the microbial value measured at n time line (after applying biocide/or turn off the air purifier).

2.7 Microclimatic conditions

Measurements of temperature and relative humidity were carried out using a portable weather instrument (SATO, PC-5000 TRH-II sampler), at each sampling event. Temperature measurements varied between 11–29 °C indoors and 14–34 °C outdoors. Relative humidity measurements varied within 24–64% indoors and 32–52% outdoors. The 75th percentile showed that 25% of temperature records exceeded

26 °C in the reception hall, and the relative humidity records exceeded 56% in the reception hall, Thorne hall and hunting museum.

2.8 Statistical analysis

Statistical analysis was conducted using Mann–Whitney (two samples Wilcoxon) and Pearson correlation coefficient with a significant level of $P=0.05$.

3 Results

3.1 Dust deposition and its chemical and microbial fractions

The deposited dust rate and its chemical composition indoor and outdoor of the museum's buildings are shown in Table 2. The deposited dust rates varied within 0.75–8.1 mg/m²/day indoor and 117.5–607.5 mg/m²/day outdoor. Indoor deposited dust rate represented ~0.6% to 1.8% of the outdoor deposited dust rate. The highest mean deposited dust (6.83 mg/m²/day) was found in the reception hall. In spite of low deposited dust rate indoors, its ion concentrations were higher indoors than outdoors. The highest mean ion concentration of NH₄⁺ (7.9 mg/g) was found in the restoration laboratory. Moreover, the highest concentrations of Cl⁻ (63.4 mg/g) and SO₄²⁻ (68.7 mg/g) were detected in the reception hall. NO₃⁻ (3.23 mg/g)

was found in the highest concentration in the residence hall (Table 2). In general, SO₄²⁻ constituted the highest ion concentration and NO₃⁻ the lowest one. Significant correlations were found between NH₄⁺ with both SO₄²⁻ and Cl⁻ ($P\leq 0.01$). However, nonsignificant correlation was found between NH₄⁺ and NO₃⁻.

The concentrations of microorganisms-associated deposited dust are shown in Table 3. Generally, the concentrations of microorganisms-associated deposited dust reached ~10⁴ CFU/g outdoor and 10⁶ CFU/g indoor. Concentrations of bacteria, fungi and actinomycetes associated deposited dust ranged between 2.7×10⁴–8.02×10⁶ CFU/g, 8.76×10³–2.1×10⁵ CFU/g and 2.9×10²–4.3×10⁴ CFU/g, respectively (Table 3). The profile of microbial concentrations was in the order of restoration > hunting > Thorne > residence > reception > outdoor for bacteria, as well as restoration > hunting > residence > reception > Thorne > outdoor for fungi and restoration > hunting > Thorne > residence > reception > outdoor for actinomycetes. The highest microbial concentrations were found in the restoration laboratory and the lowest in the outdoor environment.

Nonsignificant correlations ($P\geq 0.05$) were found between deposited dust rate and its microbial load. In addition, significant correlations ($P\leq 0.05$) were found between the concentrations of NH₄⁺ and Cl⁻ with bacterial and actinomycete loads. On the other hand, nonsignificant correlations were found

Table 2 Mean annual deposited dust rate and its chemical composition of the museum's buildings

Location	Dust rate (mg/m ² /day)	Ion concentration (mg/g)			
		NH ₄ ⁺	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻
Outdoor	(117.5–607.5) [380±189.6]	(0.45–6.4) [2.28±2.39]	(5.9–52.2) [20.88±18.3]	(8.70–93) [38.24±32.40]	(0.0–8.38) [2.15±3.6]
Reception hall	(5.9–7.7) [6.8±0.73]	(1.07–16.06) [6.05±5.9]	(18.5–153) [63.40±52.88]	(30.20–148.9) [68.7±84.2]	(0.0–5.55) [2.25±2.27]
Residence hall	(4.1–8.1) [5.5±1.58]	(1.45–2.4) [2.03±0.36]	(12.8–27.03) [18.60±5.51]	(19.10–37.69) [30.36±7]	(1.05–6.97) [3.23±2.63]
Thorne hall	(5.8–7) [6.3±0.52]	(1.13–10.73) [4.8±3.6]	(5.42–13.98) [10.23±3.33]	(11.02–74.89) [34.4±24.3]	(0.0–0.483) [0.14±0.2]
Hunting museum	(3.1–4.8) [4.0±0.71]	(0.38–11.56) [5.85±5.4]	(2.39–30.8) [16.97±12.6]	(2.57–44.76) [21.77±17.45]	(0.0–8.7) [2.83±3.47]
Restoration lab	(0.75–2.9) [2.12±0.83]	(0.23–18.75) [7.9±7.98]	(1.96–61.1) [27.5±25.9]	(1.37–57.6) [23.2±22.9]	(0.0–3.39) [1.52±1.233]

(Range), [mean ± standard deviation]

Table 3 Mean and range annual concentrations of microorganisms-associated deposited dust of the museum's buildings

Location	CFU/g × 10 ³		
	Bacteria	Fungi	Actinomycetes
Outdoor	(1.3–57) [27 ± 21]	(1.53–5.6) [3.8 ± 1.5]	(0.7–1.74) [1.1 ± 0.41]
Reception hall	(38.7–152.8) [87 ± 41.5]	(9.6–37) [18.4 ± 11]	(0.29–3.8) [1.8 ± 1.3]
Residence hall	(26.8–243.8) [123 ± 96]	(8.76–50.5) [22.3 ± 16.9]	(0.66–2.8) [1.82 ± 0.83]
Thorne hall	(43–339) [143 ± 115]	(11–13.6) [12 ± 0.934]	(5–8.9) [6.4 ± 1.5]
Hunting museum	(169–589) [242 ± 174]	(17–70.7) [55.8 ± 33.9]	(22–32) [18 ± 10.8]
Restoration lab	(322–8017) [2781 ± 3134]	(89.8–205) [134.7 ± 42.8]	(2–43) [31 ± 15.5]

(Range), [mean ± Standard deviation]

between fungal concentrations and chemical ion composition.

3.2 Identification of bacteria and fungi

A total of 12 bacterial taxa were identified in the deposited dust. Gram-positive bacteria constituted 100% of the identified bacterial isolates. Firmicutes (*Bacillus*, *Staphylococcus* and *Micrococcus*) and Actinobacteria (*Micrococcus* and *Rothia*) were commonly found. *B. atropheus*, *B. pumilus* and *B. subtilis* were the most predominant *Bacillus* species associated deposited dust.

A total of 23 fungal taxa were identified in deposited dust and differed within the museum's buildings (Table 4). The isolated fungal taxa mainly belonged to ascomycota and zygomycota phyla. *Asp. flavus*, *Asp. niger* and *Asp. fumigatus* were the dominant fungal taxa (RF=100–80%). *Aspergillus*, *Rhizopus*, yeast and sterile hyphae (mainly ascomycetes) were commonly detected (RF=79–60%). Some of the identified fungal taxa are included in the risk group-2: *Asp. fumigatus* and *Penicillium* (Directive, 2000/54/EC), and many of the isolated taxa can cause allergic reactions. Moreover, primary (*Aspergillus*, *Penicillium* and *Eurotium*), secondary (*Alternaria*, *Cladosporium*, *Asp. flavus*, *Phoma* and *Ulocladium*) and tertiary (*Aureobasidium*, *Chaetomium*, *Stachybotrys* and *Trichoderma*) fungal colonizers were detected in deposited dust samples (Table 4).

The highest fungal diversity (16 taxa) was found in the restoration laboratory and the lowest (11 taxa) in the Thorne hall. Very high agreement ratios (>0.8) were found between fungal taxa in the residence hall with reception hall, Thorne hall and restoration laboratory. A relative high fungal similarity (0.69–0.78)

was found between indoor and outdoor environments, indicating that the outdoor environment was a main contributor of indoor fungal particles. However, a relative unsimilarity was found between fungal taxa in the hunting museum with Thorne hall (0.52) and the residence hall (0.59), indicating that each of these building environments had their own fungal sources, and the contribution of outdoor environment was thus limited.

3.3 Biocide/air ionizer (purifier) efficacy

The effectiveness of disinfectants on microorganisms laden floor surface and airborne is illustrated in Fig. 2. The effectiveness of disinfectants remarkably varied in respect to type of the biocide and microorganism. Biocides quickly (T_1) reduced both microflora laden floor surface and in the air state. The removal efficiency ranged between 38.8–100% and 13–76% for microflora laden floor and in the air, respectively. Between the time lines T_1 and T_2 , the effectiveness of biocides decreased, i.e., the microbial counts, started to increase again. Ethyl alcohol had good removal efficiency of microflora-associated floor surface at time line T_1 , reaching ~81.3%, 64% and 58% for bacteria, fungi and actinomycetes, respectively (Fig. 2a–c). The removal efficiency of Savlon was lower than others for airborne fungi and actinomycetes. BAC achieved the highest removal efficiency (71.4%) for bacteria and actinomycetes (100%) associated floor surface at the time line T_2 (Fig. 2a–c).

Air ionizer achieved the highest removal efficiency of airborne microorganisms. Although airborne microbial load immediately decreased (Fig. 2d–f), microbial load associated floor surface increased

Table 4 Mean annual concentrations of fungal taxa-associated dust and their relative abundance of the museum's buildings

Taxa	CFU/g						*RF (%)
	Outdoor	Reception hall	Residence hall	Thorne hall	Hunting museum	Restoration laboratory	
<i>Absidia</i>	–	73	–	–	543.5	–	8.3
<i>Alternaria</i>	451	870	–	–	4742	10,044	33.3
<i>Asp. flavus</i>	656	8690	8348	4186	10,180	14,234	95.8
<i>Asp. fumigatus</i>	1620	2583	2815	305.4	16,562	22,973	91.8
<i>Asp. niger</i>	590	5193	8954	437	10,543	45,224	100
<i>Asp. ochraceus</i>	7	218	67	–	–	86	16.6
<i>Asp. terreus</i>	47	104	454.8	19	–	324	33.3
Other <i>Aspergillus</i> sp.	18	689	381	175	5162	16,741	62.5
<i>Aureobasidium</i>	–	–	–	–	–	6696	8.3
<i>Cladosporium</i>	543	198	63	72	–	235	29
<i>Chaetomium</i>	30	–	–	10	–	–	12.5
<i>Drechslera</i>	–	–	314	–	–	1116	8.3
<i>Emericella</i>	–	18.6	67	–	629	192	16.6
<i>Eurotium</i>	–	19	54	–	17	43	25
<i>Fusarium</i>	–	–	–	–	182	–	12.5
<i>Penicillium</i>	29	–	–	–	2959	12,600	25
<i>Phoma</i>	–	–	–	7	–	–	4.2
<i>Rhizopus</i>	31	204	323.8	243	528	1242	79.2
<i>Stachybotrys chartarum</i>	–	–	–	–	694	–	4.2
Sterile hyphae	143	238	560	260	1388	–	62.5
<i>Trichoderma</i>	–	10	17	71	–	1644	16.6
<i>Ulocladium</i>	15	–	–	–	–	–	4.2
Yeast	285	–	–	–	694	1116	12.5
Total identified taxa	14	14	13	11	14	16	

*RF: The relative frequency: Abundant = 100–80%, Common = <80–60%, Frequent = <60–40%, Occasional = <40–20%, Rare = <20%, –: not detected

(Fig. 2a–c). The air ionizer reduced airborne microbial levels by ~64%, 36% and 19% at T_1 and reached ~58.4%, 11.9% and –9% at T_2 (Fig. 2d–f) for bacteria, fungi and actinomycetes, respectively. Actually, the effectiveness of the biocide/or air ionizer on microflora was limited (temporally) and varied. Ethyl alcohol, Dettol and Clorox had the highest removal efficiencies of microflora laden floor surface at T_1 . However, BAC demonstrated a relatively permanent prevention (T_2) to microflora than other biocides.

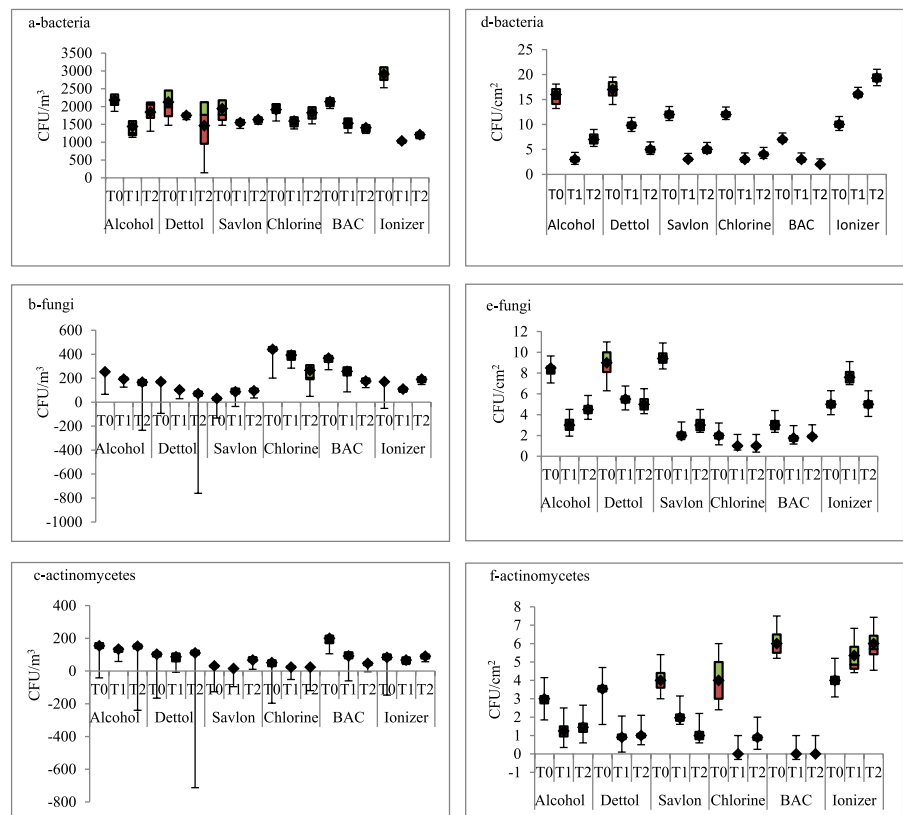
The effectiveness of biocides/air ionizer on fungal taxa-associated floor surface and airborne before and after treatment at each time lines are shown in Table 5. The biocides treatment reduced both count and diversity of almost fungi-associated floor surface and airborne. However, airborne fungi had no clear

pattern of reduction in respect to count and diversity. The air ionizer reduced and increased fungal counts and diversity of airborne state and surface floor, respectively. Fungal taxa with different water activities were detected such as *Alternaria*, *Aspergillus*, *Eurotium*, *Trichoderma*, *Aureobasidium* and *Stachybotrys*, confirming the presence of variable micro-environmental conditions for fungal growth in the museum's buildings.

4 Discussion

Mohamed Ali palace is vulnerable to bioaerosols/aerosols emission. Dust particles play an important role in degradation and biodegradation of substrates. The

Fig. 2 Susceptibility of microflora-associated floor surface (a–c) and in the air state (d–f) to the biocides and air ionizer. The top of the box plot represents the 75th quartile and the bottom the 25th quartile, the median is the horizontal band, the inside rhombus represents the mean and the lower whisker represents the minimum with the upper whisker represents the maximum. T₀: samples were taken before applying a biocide/ or turn on the ionizer; T₁: samples were taken 60 min after applying a biocide/ or turn on the ionizer; T₂: samples were taken 4 days after applying a biocide/ or turn on ionizer



aggressiveness of deposited dust depends on its composition, size and solubility. Surface deposition serves as an important sink for particulate matter rich in organic and inorganic matters which represent a nourishment source for proliferation of microorganisms. The concentration and composition of deposited dust may be high enough to damage cultural heritage items inside Mohamed Ali palace. The museum's collections are subjected to dust accumulation and degradation when available conditions (microclimatic conditions, porosity and substrate type) are met. Therefore, characterization of accumulated dust (deposition rate and composition) is an important approach to reducing degradation of cultural heritage buildings.

In the present study, indoor deposited dust existed at a lower rate ($\sim 1\%$) compared to outdoors, and the highest indoor deposited dust rate was found in the reception hall. This is because the reception hall is directly affected by the high dust load generated outdoor by traffic, visitor activity and uncontrolled access conditions. Generally, low indoor deposited dust rate is attributed to indoor particulate matter mainly having smaller particle sizes and tending to linger in the

air for longer time. Indoor deposited dust is mainly related to infiltration of outdoor dust particles, topography and human activity (Patel et al., 2020). Dust particles may enter indoors through inlets, openings and with visitors (Zhu et al., 2005). Moreover, air exchange rate, removal of particles by deposition to surfaces and human behavior critically affect infiltration mechanisms (Stephens, 2015), varying in respect to location and properties of the building.

Ion concentrations of the deposited dust were higher indoors than outdoors. This indicated that the indoor built environment of the museum affected dust chemistry, as indoor materials could be a source of air pollutants/precursors, and humid environment increases reactivity of gaseous pollutants. The evaluated ions were mainly secondary except for Cl^- , which represented the major water-soluble components of dust (Srimuruganandam & Shiva-Nagendra, 2011). Secondary ions are produced in the atmosphere from precursor gases/or nucleation of new particles (Ervens et al., 2011). Secondary aerosols have sizes $\sim \leq 1 \mu\text{m}$ and a longer lifetime in the airborne state, and easily infiltrate the indoor environment.

Table 5 Fungal taxa identified before and after applying biocide/ or turn on air ionizer

Taxa	Biocide/ionizer															
	E ₀		E ₁		E ₂		D ₀		D ₁		D ₂		Sa ₀		Sa ₁	
	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A
<i>Absidia</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Asp. flavus</i>	+	+	-	+	+	+	+	+	+	+	-	+	-	-	-	-
<i>Asp. fumigatus</i>	-	-	-	-	+	-	-	-	+	-	+	+	-	+	-	+
<i>Asp. niger</i>	+	+	+	+	+	+	+	+	-	+	-	+	+	+	+	+
<i>Asp. ochraceus</i>	-	-	-	+	-	-	-	+	-	-	-	-	-	-	-	-
<i>Asp. terreus</i>	-	+	-	-	-	+	-	+	-	+	-	-	-	-	-	-
<i>Other Aspergillus sp.</i>	+	+	-	+	-	+	+	+	-	+	+	+	+	+	-	+
<i>Alternaria</i>	-	-	+	-	-	-	-	-	-	+	-	-	-	-	-	-
<i>Aureobasidium</i>	-	+	-	+	-	+	-	-	-	-	-	-	-	-	-	-
<i>Eurotium</i>	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Chaetomium</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Cladosporium</i>	-	-	-	-	-	+	+	+	-	-	+	-	-	-	-	-
<i>Curvularia</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Trichoderma</i>	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Drechslera</i>	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	+
<i>Emericella</i>	+	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
<i>Penicillium</i>	+	+	-	+	+	+	+	+	-	+	-	+	+	+	-	+
<i>Rhizopus</i>	+	-	-	-	+	-	-	-	-	-	+	-	-	-	-	-
<i>Stachybotrys</i>	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-
<i>Sterile hyphae</i>	-	+	-	+	+	+	-	+	+	+	-	-	+	+	+	+
Yeast	-	-	-	-	+	-	-	-	-	-	-	+	+	-	+	-
Total taxa	9	8	3	7	8	8	6	8	3	7	4	6	4	5	3	6

Taxa	Biocide/ionizer																				
	Sa ₂		Ch ₀		Ch ₁		Ch ₂		BAC ₀		BAC ₁		BAC ₂		AP ₀		AP ₁		AP ₂		
	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	
<i>Absidia</i>	-	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Asp. flavus</i>	-	+	-	+	-	-	-	-	+	+	-	+	+	+	-	+	+	+	+	+	+
<i>Asp. fumigatus</i>	-	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+	+
<i>Asp. niger</i>	+	+	+	-	-	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+
<i>Asp. ochraceus</i>	-	-	-	-	-	+	-	+	-	+	-	+	-	-	-	-	-	-	-	-	+
<i>Asp. terreus</i>	-	-	-	-	-	-	-	-	-	+	-	+	-	-	-	+	-	-	-	-	-
<i>Other Aspergillus sp.</i>	-	+	-	+	-	+	-	+	+	+	-	+	-	+	-	+	-	+	-	+	+
<i>Alternaria</i>	-	-	+	-	-	+	-	+	+	-	-	+	-	+	-	+	-	-	-	-	+
<i>Aureobasidium</i>	+	-	-	-	-	-	-	-	-	+	-	+	-	+	-	-	-	-	-	-	+
<i>Eurotium</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	+	-	-
<i>Chaetomium</i>	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-
<i>Cladosporium</i>	-	-	-	+	-	+	-	+	-	-	-	-	-	-	-	-	-	-	-	-	+
<i>Curvularia</i>	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	+	-	-	-	-	-
<i>Trichoderma</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Drechslera</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+
<i>Emericella</i>	-	-	+	+	-	-	-	-	+	-	-	-	-	-	-	+	-	-	-	-	+
<i>Penicillium</i>	-	+	-	+	+	+	+	+	-	-	-	-	-	-	-	+	+	-	+	+	+

Table 5 (continued)

Taxa	Biocide/ionizer																				
	Sa ₂		Ch ₀		Ch ₁		Ch ₂		BAC ₀		BAC ₁		BAC ₂		AP ₀		AP ₁		AP ₂		
	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	S	A	
<i>Rhizopus</i>	-	-	-	-	-	-	-	+	-	-	-	-	-	+	-	-	-	-	-	-	-
<i>Stachybotrys</i>	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
<i>Sterile hyphae</i>	-	+	+	+	+	+	+	+	+	+	-	+	-	-	-	-	-	+	-	-	+
Yeast	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-
Total taxa	2	7	5	7	3	8	3	9	6	10	2	9	3	7	2	9	5	6	5	12	

E: ethanol; D: Dettol; Sa: Savlon; Ch: Clorox; BAC: benzalkonium chloride; AP: air purifier; S: surface, A: air; -: not detected; +: detected; 0:T₀; 1: T₁; 2: T₂

Sulfur and sulfate aerosols are a proxy of infiltration for particulate matter (Wallace & Williams, 2005). Oxidants in the indoor environments can react with organic components to produce oxidized organic and inorganic products, condensing to form secondary aerosols (Avery et al., 2019). NO₃⁻ mainly exists in coarse particles (Hayami & Carmichael, 1998), confirming low infiltration of coarse particles indoor and consequently low NO₃⁻ concentration (Table 2). Ammonium sulfate and nitrate are formed in the presence of ammonia gas. Volatilization of semi-volatile species (e.g., ammonium nitrate) depends on changes on temperature, relative humidity and pH of the particles (Galindo et al., 2011; Guo et al., 2018).

In the present study, nonsignificant correlations ($P \geq 0.05$) were found between the deposited dust rates and their microbial loads. The highest microbial concentration was found in the restoration laboratory and the lowest outdoor. This confirmed that dust composition, microclimatic conditions and building environment critically influenced microflora contents, regardless of the rate of the deposited dust. The composition of deposited dust may inhibit microflora growth depending on ion nature and its concentration. However, ions may be utilized by microflora as micronutrient at a low concentration. Therefore, the toxicity/ or nutritional value of dust components is not limited to their nature but to their concentrations as well. The restoration laboratory contains various mediums and materials (wood, papers and resins) in addition to a high amount of dirt that may be rich/and appropriate for microbial growth. Microorganisms-associated dust reflects microbial load accumulated; suitability of microenvironmental conditions; and interference of outdoor environment. In general, the

deposited particles may constitute an important step in the process of degradation/biodegradation of surfaces and artworks. Microorganisms-associated dust reached ~10⁶ CFU/gm and differed regarding each museum's building. Biodegradation is a result of complex interaction between microbial community and its substrate (surface), depending on microclimatic conditions and surface topology (Proietti et al., 2015). Deposited particulate matter and its composition may trigger damage of cultural heritage by promoting microbial growth, actively penetrating surfaces lead to change type and concentrations of ions, pH and excrete chemical reactions (pigments and organic acids) (Lazaridis et al., 2015).

The present study is mainly focused on fungi-associated deposited dust. This is because fungi are important microbial type in indoor environment, easy to sample and identify and related to the deterioration of materials (Meng et al., 2017; Nevalainen et al., 2014). The primary fungal types, *Asp. niger*, *Asp. fumigatus* and *Asp. flavus*, were the predominant species associated deposited dust. This is attributed to *Aspergillus* species can be present as aggregates of biological cells (Górny et al., 1999), and thus deposit on the ground more quickly as a result of their larger effective particle size. However, high water activity fungi ($aw \geq 0.9$) including *Aureobasidium*, *Chaetomium*, *Phoma*, *Stachybotrys* and *Trichoderma* were also detected. The detection of high water activity fungi indicates diverse and variable local microenvironmental conditions, with high water availability, nutrient-rich niches and poor ventilation. *Aspergillus*, *Penicillium*, *Alternaria* and *Cladosporium* are predominantly found in all geographical locations (Govi, 1993). Slow growing ascomycetes (sterile

hyphae) and xerophilic fungi (e.g., *Aspergillus*, *Paecilomyces*, *Penicillium* and *Cladosporium*) can colonize documents made of paper (Pinzari & Montanari, 2011). *Trichoderma* and *Penicillium* are cellulolytic fungi whereas *Fusarium* and *Aspergillus* species are lignocellulolytic fungi, constituting a matter of concern. Bacteria display proteolytic activity, deteriorating artworks. *Bacillus*, *Staphylococcus*, *Pseudomonas* and *Micromonospora* species have been isolated from deteriorated parchments (Kráková et al., 2012). Actinobacteria species have been connected with a typical damage phenomenon (e.g., discoloration of parchments) (Pinzari et al., 2012). Thus identification of microorganisms involved in biodeterioration is an important step to propose prevention strategy.

Biocides have been used for a long time to inactivate microbial growth and consequent deleterious effects. Commercial biocides may be dangerous to human health, environment and materials, depending on a biocide type (Fidanza & Caneva, 2019). Therefore, evaluation of the efficacy and limitation of biocides has become necessary in recent decades (Li et al., 2020). Biocides should be effective against microorganisms and compatible with the environment, not causing alternation or interference to the substrate where it applied (Pinna, 2022). In the present study, the effectiveness of biocides was assessed on microflora laden floor surface not on artwork surfaces. This is due to: (1) Knowledge on suitability and compatibility of biocides with historic materials are limited, (2) field-based experiment and choice of an appropriate biocide treatment of valuable surfaces are limited (Price, 1996) and (3) the museum's security instruction.

In the present study, biocides quickly reduced microflora laden floor surface (varied with biocide and microbial type) and microflora loads increased again after ~4 days of the treatment protocol. BAC out-performed other biocides; however, the air ionizer reduced airborne microbial concentrations and increased microbial concentrations on surface floor. The variation of the biocides efficacy may be attributed to (1) the biocidal effect is time limited, (2) the presence of indoor microbial source continuing to replenish the microflora, (3) recovery of biocide-stressed microbial community, (4) presence of a mixed microbial community with different susceptibility level toward a biocide and (5) the experimental tests were conducted in different microenvironmental

conditions, season and human behavior. In addition airborne microbial types showed no clear pattern of reduction/inactivation. This is logical due to: (1) no direct contact between biocide spray and airborne microorganism, and (2) the killing effect depends on evaporation and condensation of biocide on a microbe.

Biocides have different killing mechanisms, dictating specific target in response to morphology and physiology of the cell (Denyer, 1995). Biocides have more than one potential target, and chemical structure of a biocide determines its affinity to specific targets (Speranza et al., 2012). Biocides have microbiostatic (reversible)/or microbicidal effects (irreversible). A wide range of biocide products, based on organic and inorganic compounds, alcohols, aldehydes, phenols, quaternary ammonium compounds, activated halogen compounds and oxidizing agents have been used; however, the number of compounds suitable for cultural heritage is limited. The choice of an appropriate biocide is limited by the European Union's Biocidal Products Directive (BPD) (<http://ec.europa.eu/environment/biocides/index.htm>). The stability of the applied biocides is varied over time. Quaternary ammonium compounds (Diaz-Herrera et al., 2013) and formaldehyde (Piñar et al., 2009) are frequently used in restoration of artworks. Ethanol has a good fungitoxic effect if the contact time is at least 2–3 min (Nittérus, 2000).

Air ionizer reduced/and increased airborne and surface microbial loads, respectively. Higher air ions concentration reduces suspended particles load in indoor environment. The behavior of suspended particles depends on physicochemical properties "sedimentation, agglomeration, shape and surface charge" (Oberdörster et al., 2005). Air ions can have biological impacts (Krueger & Reed, 1976). Air ions transfer biological particles from the air to walls, ceiling and floor, removing ~97% of particles $\leq 1 \mu\text{m}$ by diffusion and gravitational deposition (Lee et al., 2004a, 2004b) and ~80% of infectious pathogens (Grinshpun et al., 2007). Air ions increase physical decay rate of aerosols through increased electrostatically agglomeration (Krueger, 1969). Microbial particles deposited on surfaces might be grown and re-emitted again, representing a side effect. In addition, deposited microbial aggregates may have better survivability, leading to increased microflora loads on surface and in air state with time line after biocide treatment.

Actually, the removal efficiencies of biocides on surfaces (~38–100%) were lower than those recommended by the international agencies (~99%). From our point of view, this is contributed to a complex microbial community from time to time, uncontrolled microclimatic conditions in the real field environment and a large area space of the experimental room.

Nonsignificant shift was found between the fungal community composition (richness and diversity) associated floor surface/or air before and after applying biocide (Table 5). This may be attributed to much fungal materials potentially being released from the nearby natural sources/or to changes in macro- and microenvironmental conditions between the buildings. House dust, furniture items and building materials are potential sources of indoor fungal spores (Maunsell, 1952), and fungi-associated dust are related to that of airborne samples as well (Schaffer et al., 1953).

5 Conclusion

Dust rate and its composition determine its toxicity or nutritional value. Secondary air pollutants were higher in the indoor environment of the museum, indicating the presence of precursors and multiple gas phase reactions that may be related to ventilation and deposition rate over time indoor. The concentrations of deposited dust and its components may be high enough to damage cultural heritage items. Microorganisms-associated deposited dust concentrations ranged between $\sim 10^4$ and 10^6 CFU/g, considered a matter of concern. The presence of *Aspergillus*, *Penicillium*, *Fusarium*, *Trichoderma*, *Eurotium* and *Stachybotrys* indicated that diverse and variable microclimatic conditions in the museum might be suitable for fungal growth on surfaces. Microorganisms showed different levels of susceptibility toward biocides, depending on type of microbe and biocide. The removal efficiency of the biocides differed over time. The biocides immediately reduced microorganisms, but this effect was limited. BAC showed a longer term killing effect compared to other biocides. In spite of air ionizer improving microbial air quality, it worsened surface microbial quality. Air ionizer therefore was not recommended for use inside museums. Disinfection treatment should be applied only in extreme circumstances. Surface sampling in

conjunction with air sampling could enhance detection of microbial contamination in cultural heritage buildings.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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