



Article

Study on the Effectiveness of a Copper Electrostatic Filtration System “Aerok 1.0” for Air Disinfection

Roberto Albertini ^{1,2}, Maria Eugenia Colucci ¹, Isabella Viani ¹, Emanuela Capobianco ¹, Michele Serpentino ¹, Alessia Coluccia ¹, Mostafa Mohieldin Mahgoub Ibrahim ¹, Roberta Zoni ¹, Paola Affanni ¹, Licia Veronesi ¹ and Cesira Pasquarella ^{1,*}

¹ Department of Medicine and Surgery, University of Parma, Via Gramsci 14, 43126 Parma, Italy; roberto.albertini@unipr.it (R.A.); mariaeugenia.colucci@unipr.it (M.E.C.); isabella.viani@unipr.it (I.V.); michele.serpentino@studenti.unipr.it (M.S.); roberta.zoni@unipr.it (R.Z.); paola.affanni@unipr.it (P.A.); licia.veronesi@unipr.it (L.V.)

² Geriatric-Rehabilitation Department, University Hospital-Azienda Ospedaliero-Universitaria di Parma, Via Gramsci 14, 43126 Parma, Italy

* Correspondence: cesiraisabellamaria.pasquarella@unipr.it

Abstract: Background: Bioaerosols can represent a danger to health. During SARS-CoV-2 pandemic, portable devices were used in different environments and considered a valuable prevention tool. This study has evaluated the effectiveness of the air treatment device “AEROK 1.0[®]” in reducing microbial, particulate, and pollen airborne contamination indoors, during normal activity. Methods: In an administrative room, airborne microbial contamination was measured using active (DUOSAS 360 and MD8) and passive sampling; a particle counter was used to evaluate particle concentrations; a Hirst-type pollen trap was used to assess airborne pollen and *Alternaria* spores. Statistical analysis was performed using SPSS 26.0; *p* values < 0.05 were considered statistically significant. Results: The airborne bacterial contamination assessed by the two different samplers decreased by 56% and 69%, respectively. The airborne bacterial contamination assessed by passive sampling decreased by 44%. For fungi, the reduction was 39% by active sampling. Airborne particles (diameters ≥ 1.0, 2.0 μm) and the ratio of indoor/outdoor concentrations of total pollen and *Alternaria* spp. spores significantly decreased. Conclusions: The results highlight the effectiveness of AEROK 1.0[®] in reducing airborne contamination. The approach carried out represents a contribution to the definition of a standardized model for evaluating the effectiveness of devices to be used for air disinfection.

Keywords: air contamination; microorganisms; pollen; particles; sampling; air disinfection



Citation: Albertini, R.; Colucci, M.E.; Viani, I.; Capobianco, E.; Serpentino, M.; Coluccia, A.; Mohieldin Mahgoub Ibrahim, M.; Zoni, R.; Affanni, P.; Veronesi, L.; et al. Study on the Effectiveness of a Copper Electrostatic Filtration System “Aerok 1.0” for Air Disinfection. *Int. J. Environ. Res. Public Health* **2024**, *21*, 1200. <https://doi.org/10.3390/ijerph21091200>

Received: 5 August 2024

Revised: 2 September 2024

Accepted: 3 September 2024

Published: 10 September 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

A part of aerosol consists of particles of biological origin (bioaerosol). Airborne particulate is a topic of great interest in many areas of human activity, as it represents a danger to human health and the integrity of materials [1–11]. In indoor environments, the concentrations of particulate may be higher than outdoor depending on the activity taking place there, the number of occupants, construction characteristics, materials and furnishings characteristics, and the possible presence of air treatment systems. Indoor air quality plays an important role in human health if we consider that we spend up to 90% of our time indoors (domestic, work, leisure, transport, etc.) [12–14].

World Health Organization has described a combination of symptoms associated with staying in a building, without specific causes, named sick building syndrome (SBS) [15]. It is a disease with multifactorial etiology, with non-specific symptoms, such as headache, drowsiness, difficulty concentrating, memory issues, asthenia, nausea, eye irritation, nose, throat, asthmatic respiratory problems, skin rashes, dryness and irritation of the throat and gastrointestinal manifestations. The presence of particulate matter, especially of fungal

origin, together with unfavorable microclimatic parameters is often considered one of the causes of the symptoms [16–19]. Indoor air quality also can affect mental well-being [20].

To achieve high-quality indoor air, various air treatment systems, with different mechanisms of action, have been used, including HVAC (heating, ventilation, and air conditioning) systems equipped with HEPA (high-efficiency particulate air) filters, UV-C treatment, electrostatic filtration, chemical treatment, ozone treatment, plasma treatment, or a combination of some of the different methods [21–47].

Ventilation and air disinfection were a valuable prevention tool during the SARS-CoV-2 pandemic, and portable air purification devices have also been used [48–52] in different kinds of environments. In this regard, it is of particular importance that air purifying devices are also assessed based on their effectiveness against different kinds of bioaerosols [53] and could be useful to emphasize that the use of air purifiers does not replace natural ventilation and air exchange outdoors/indoors.

This study aimed to evaluate the effectiveness of the air treatment device “AEROK 1.0[®]” (AERSAFE s.r.l., Trento, Italy), hereinafter AEROK, in reducing microbial, particle, and pollen airborne contamination in working environments.

2. Methods

2.1. Features of the Device AEROK

AEROK treats 1250 m³/h of air. Air disinfection is carried out by a copper electrofilter. The filter undergoes periodic self-washing with distilled water, which removes solid particles present on the accumulation plates, restoring the initial filtration capacity. The water is constantly disinfected by UV radiation. The noise level is lower than 40 dB.

2.2. Study Site

AEROK was installed in a room used for administrative purposes at the Laboratory of Hygiene and Public Health, of the Department of Medicine and Surgery of the University of Parma. The room had the following dimensions: 4.50 m height, 5.25 m length, 3.50 m width of 18.25 m² surface area, and 82.68 m³ volume. The room was occupied by 2–3 people.

2.3. Microbial Sampling

The airborne concentration of microorganisms (cfu/m³, colony forming units per cubic meter of air) was measured by active sampling, and the sedimentation rate of microorganisms on surfaces (cfu/plate/time) was measured by passive sampling [54–61].

2.3.1. Active Sampling

Two PBI (VWR)—DUOSAS 360 samplers with 55 mm diameter RODAC plates (Replicate Organism Detection and Agar Counting) for bacterial and fungal evaluation were used. A Sartorius MD8 Airport Portable Air Sampler, with gelatine filter membranes, for bacterial evaluation was used; after sampling the gelatine membranes were put on Petri dishes of 9 cm diameter. The results were expressed as cfu/m³.

2.3.2. Passive Sampling

Petri dishes of 9 cm in diameter were exposed at a height of 1 m for 1 h to determine the Index of Microbial Air (IMA) for bacterial and fungal evaluation.

2.3.3. Cultural Conditions

TSA medium (tryptic soy agar) and SDA medium (Sabouraud dextrose agar) were used, to determine bacterial and fungal contamination, respectively. TSA plates were incubated for 48 h at 36 ± 1 °C and SDA plates were incubated for 120 h at 25 ± 1 °C.

2.3.4. Microbial Monitoring Plan

Microbial monitoring was carried out for five working days, with samplers and plates positioned according to the scheme shown in Figures 1 and 2. The study involved two hours

of sampling with AEROK turned off; then AEROK ran for one hour, without sampling. The sampling started again at the 2nd hour of the AEROK running over the next two hours. The sampling took place during regular working activity, and the number of door openings in the room was recorded during the sampling time to assess the working traffic.

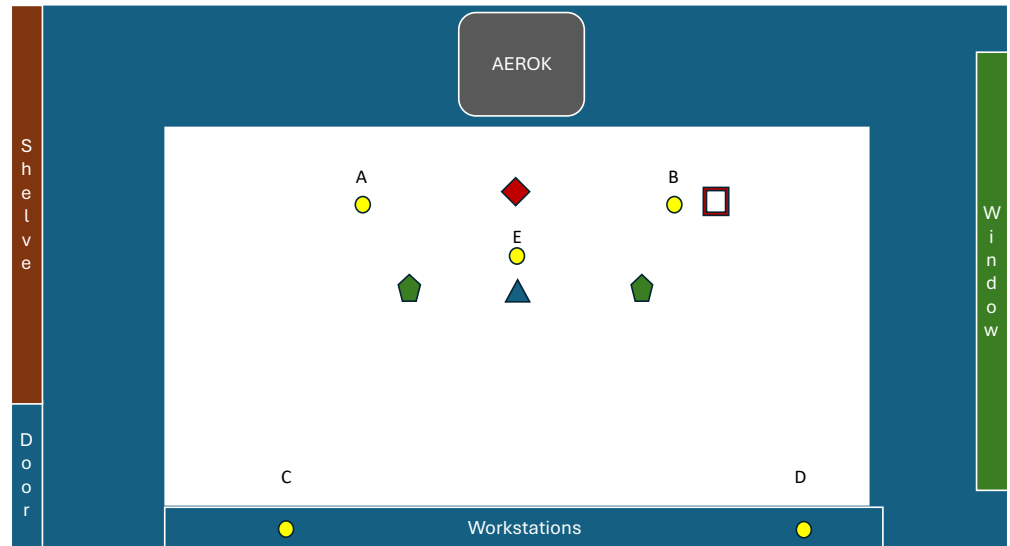


Figure 1. Positioning points of air samplers (active sampling with DUOSAS, MD8), Petri dishes (passive sampling), particle counter (), pollen trap (), and “AEROK” in the studied room. Particle sampler and pollen trap were used at different times than active and passive microbial sampling.

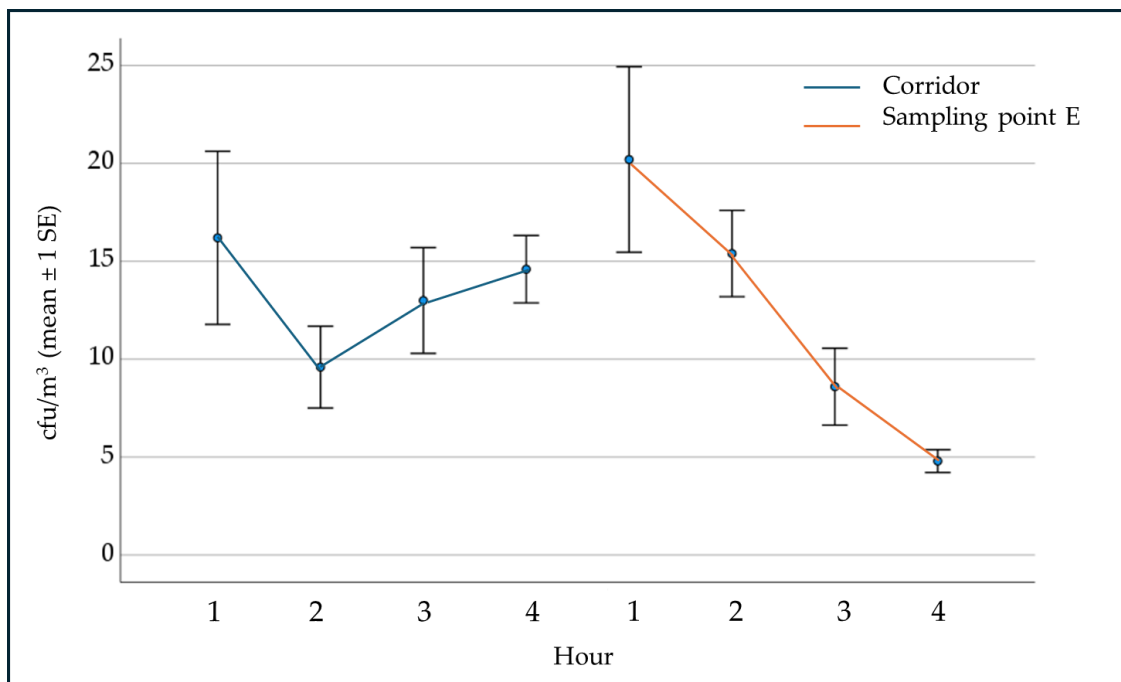


Figure 2. Bacterial air contamination (IMA) at point E and at corridor.

For one-hour sampling, serial active microbiological sampling with the suction of 125 L of air four times was performed (every 20 min, at 0, 20, 40, and 60 min), and settle plates were exposed in the studied room. Furthermore, an additional passive sampling point was placed in the corridor adjacent to the room, where air treatment was absent.

2.4. Particle Sampling

The particle concentration measurements were carried out in the center of the room by using a particle counter LASAIR III 5100 (Particle Measuring System) according to ISO 14644-1 and 14644-2 [61,62] (Figure 1).

Particles Sampling Plan

Two hundred measures each were taken (one per minute) by continuously sampling 100 L of air, with AEROK off and then with AEROK on, in the absence of people.

The particle counter LASAIR III 5100, with a flow rate of 100 L/minute and channels for sampling particles ≥ 0.5 ; 1.0; 2.0; 5.0; 10.0; 25.0 μm , was certified and validated according to ISO 21501-4:2018 [63].

2.5. Aerobiological Sampling of Pollen and Fungal Spores

The sampling of airborne pollen and fungal spores was carried out using a volumetric Hirst-type pollen trap (7-day Burkard spore trap) [64,65]. The sampler worked continuously for two weeks with the change in the sampling tape on the seventh day. After sampling, the tape, previously treated with silicone, was mounted with gelatine on slides, one for each day of sampling, stained with fuchsin, and observed under a microscope for the recognition and counting of total pollen and fungal spores of *Alternaria* spp. The values obtained were expressed as spores per m^3 .

The concentration of indoor (I) total pollen and fungal spores of *Alternaria* spp. were compared to those outdoor (O) (kindly provided by the Regional Agency for Prevention, Environment and Energy of Emilia-Romagna, ARPAE). The indoor-to-outdoor concentration ratio (I/O) result was used as a reference value to compare the results obtained with AEROK off and with AEROK on.

2.5.1. Sampling Points

Inside the room, the sampling of total pollen and fungal spores of *Alternaria* spp. was performed according to the scheme shown in Figure 1.

2.5.2. Pollen and Fungal Spores Sampling Plan

The sampling of total pollen and *Alternaria* spores was carried out simultaneously, keeping the windows constantly open to allow the aerospora entry from outside, for 7 days, with AEROK off, and for 7 days with AEROK on in the absence of people.

2.6. Measurement of Temperature, Relative Humidity and CO_2 Concentration

The microclimatic parameters were measured, during microbial monitoring, by Kimo AMI 310 STD device equipped with multifunction probes for temperature, relative humidity, and CO_2 . The measurements of temperature, relative humidity, and CO_2 were performed within the same time frame as the microbial monitoring inside the room.

2.7. Instruments Calibration

All the samplers used were calibrated and certified by the manufacturers; in the case of the particle counter according to ISO 21501-4:2018 [63]. The pollen trap was regularly calibrated weekly with the flowmeter provided by the manufacturer according to ISO 16868:2019 [65].

2.8. Statistical Analysis

Statistical analysis was performed using the SPSS 26.0 package. Mean, standard deviation, minimum value, maximum value, and confidence intervals were calculated. For the comparison of bacterial and fungal contamination detected with AEROK off and with AEROK on, Student's *t*-test was performed for paired data. In particular, the results of the 2nd hour were compared with the ones obtained in the 3rd hour and with the mean of the results of 3rd and 4th hour. Student's *t*-test for independent data was used

to assess the difference in particle concentration. Chi-square test was used to assess the difference between the concentration ratio I/O of pollen and fungal spore concentrations of *Alternaria* spp. with AEROK off and with AEROK on. *p* values < 0.05 were considered statistically significant.

3. Results

3.1. Microbial Air Sampling

3.1.1. Bacteria

Table 1 shows the mean, standard deviation, and confidence interval of cfu/m³ for active sampling carried out by the DUOSAS sampler (mean values from the two DUOSAS samplers) over the 5 working days. The decrease in airborne bacterial contamination between the 2nd hour of sampling (AEROK off) and the 3rd hour (AEROK on) was 69%; between the 2nd hour and the mean between the values of the 3rd and 4th hour (AEROK on) was 70%.

Table 1. Bacterial air contamination (cfu/m³) assessed by DUOSAS samplers.

| Hour | Mean | Standard Deviation | 95% Confidence Interval | |
|------|--------|--------------------|-------------------------|--------|
| | | | Upper | Lower |
| 1 | 243.50 | 88.51 | 102.66 | 384.34 |
| 2 | 273.75 | 144.68 | 43.54 | 503.96 |
| 3 | 84.50 | 14.29 | 61.75 | 107.25 |
| 4 | 77.50 | 23.70 | 39.79 | 115.21 |

Table 2 shows the cfu/m³ mean values of the MD8 sampler over the 5 working days. The decrease in airborne bacterial contamination between the 2nd hour of sampling (AEROK off) and the 3rd hour (AEROK on) was 56%; between the 2nd hour and the mean between the values of 3rd and 4th hour (AEROK on), it was 57%.

Table 2. Bacterial air contamination (cfu/m³) assessed by MD8 sampler.

| Hour | Mean | Standard Deviation | 95% Confidence Interval | |
|------|--------|--------------------|-------------------------|--------|
| | | | Upper | Lower |
| 1 | 348.80 | 129.411 | 188.12 | 509.48 |
| 2 | 321.20 | 122.381 | 169.24 | 473.16 |
| 3 | 142.80 | 19.422 | 118.68 | 166.92 |
| 4 | 135.20 | 56.136 | 65.50 | 204.90 |

Regarding passive sampling, Figure 2 shows IMA values obtained at point E (center of the room). There was a decrease between the values of the 2nd hour (AEROK off) and the 3rd hour (AEROK on) of 44% and between the 2nd hour compared to the mean of 3rd and 4th hour (AEROK on) of 56%; moreover, IMA values obtained at the same time in the adjacent corridor in the absence of air treatment are shown.

Figure 3 shows bacterial air contamination values assessed by active sampling using DUOSAS and MD8, expressed as cfu/m³, and the results of passive sampling performed at point E, expressed as IMA.

Figure 4 shows the IMA median values and interquartile ranges referring to IMA values measured in the different sampling hours for each sampling point (Figure 1). At points A, B, and E a reduction in IMA values during the third and fourth hour (AEROK on) compared to the first two hours (AEROK off) was observed.

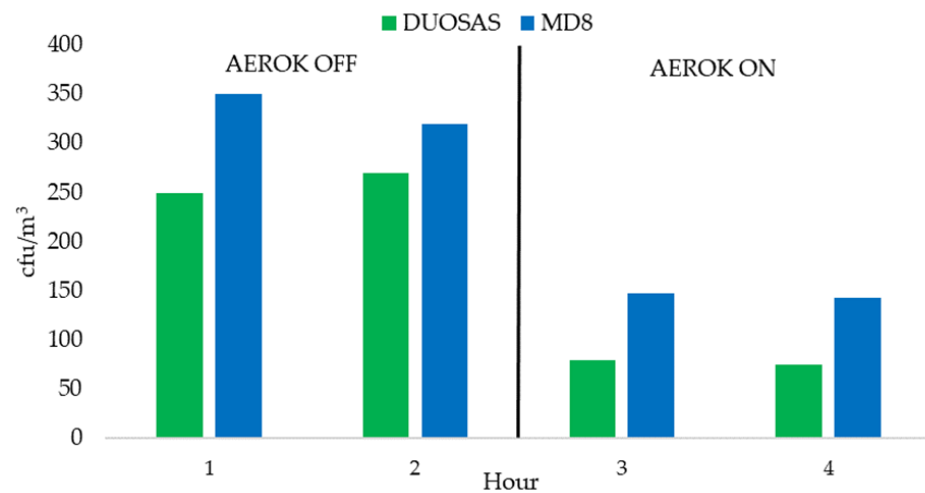


Figure 3. Cfu/m³ mean values obtained by DUOSAS and MD8.

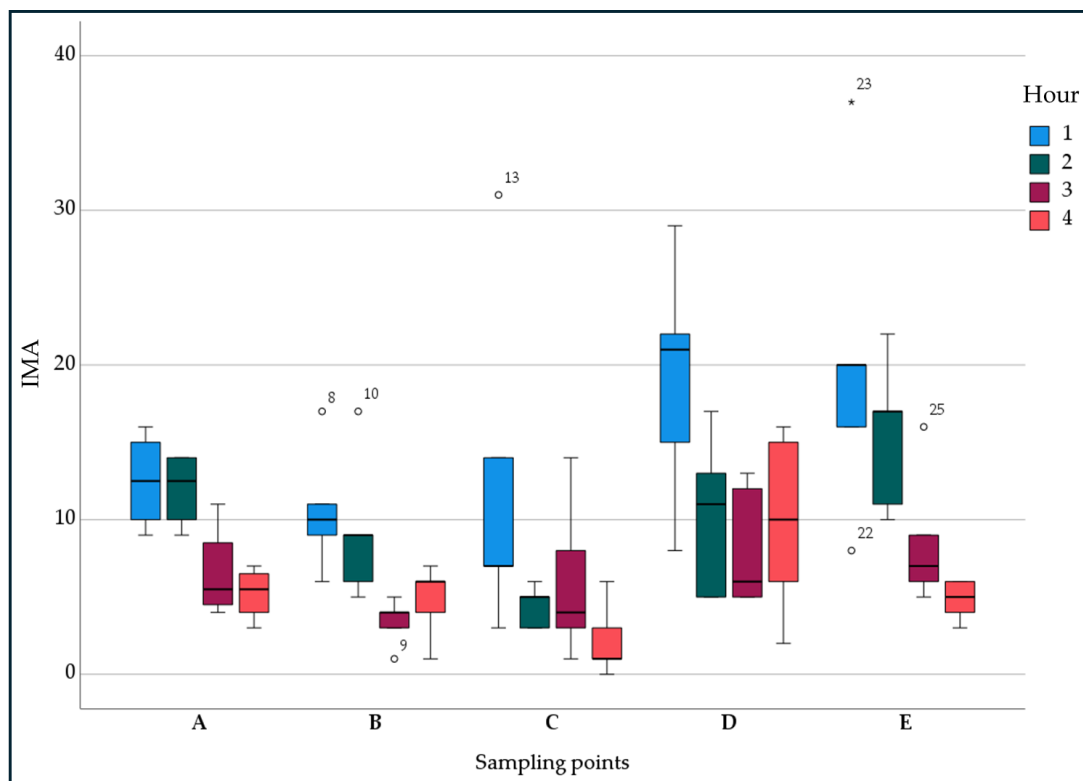


Figure 4. IMA median values and interquartile range at the different sampling points and times. ° Outliers; * Extreme outliers.

3.1.2. Fungi

Fungal airborne contamination detected by DUOSAS significantly decreased between the 2nd hour (AEROK off) and the 3rd and 4th hour (AEROK on) ($p = 0.013$), from 27.1 cfu/m³ to 16.6 cfu/m³ (39% of reduction). Regarding the passive sampling carried out at point E, the fungal contamination decreased, although not significantly, between the 2nd hour (1.6 IMA) and the mean of the 3rd hour and the 4th hour (1.2 IMA).

3.1.3. Door Openings

Table 3 shows the number of door openings per hour recorded during microbial sampling over 5 days of sampling, used as an indicator of the attendance in the room and adjacent spaces ($p < 0.05$). The highest number of openings was observed at the fourth hour.

Table 3. Number of door openings over 5 days of microbial sampling.

| Hour | Mean | Standard Deviation | Minimum | Maximum |
|------|-------|--------------------|---------|---------|
| 1 | 24.40 | 4.16 | 19 | 28 |
| 2 | 19.60 | 2.07 | 17 | 22 |
| 3 | 23.20 | 7.46 | 14 | 32 |
| 4 | 30.25 | 3.27 | 27 | 35 |

3.2. Particles

Table 4 shows particles/m³ values according to the particle size assessed with AEROK off and with AEROK on during the 200 min of observation for each of the two conditions.

Table 4. Maximum, minimum, mean, standard deviation of particles according to their size.

| AEROK | Particle Diameter (µm) ≥ | Numbers of Detections | Maximum | Minimum | Mean | St. Deviation |
|-------|--------------------------|-----------------------|--------------------|--------------------|--------------------|--------------------|
| Off | 0.5 | 200 | 3.81×10^6 | 2.89×10^6 | 3.29×10^6 | 2.34×10^5 |
| | 1 | | 6.91×10^5 | 1.96×10^5 | 5.12×10^5 | 1.34×10^5 |
| | 2 | | 2.66×10^5 | 6.19×10^4 | 1.39×10^5 | 3.53×10^4 |
| | 5 | | 3.63×10^4 | 5.50×10^2 | 2.69×10^3 | 5.62×10^3 |
| | 10 | | 1.94×10^4 | 0 | 4.96×10^2 | 1.89×10^3 |
| On | 0.5 | 200 | 5.43×10^6 | 4.32×10^5 | 2.08×10^6 | 8.60×10^5 |
| | 1 | | 1.57×10^6 | 1.09×10^5 | 4.81×10^5 | 2.43×10^5 |
| | 2 | | 5.96×10^5 | 3.16×10^4 | 1.30×10^5 | 8.79×10^4 |
| | 5 | | 3.92×10^4 | 1.70×10^3 | 1.86×10^3 | 5.28×10^3 |
| | 10 | | 1.09×10^4 | 0 | 3.43×10^2 | 1.37×10^3 |
| | 25 | | 7.50×10^2 | 0 | 0.16×10^2 | 0.78×10^2 |

With AEROK turned on, a significant reduction of particles with diameters 1.0 and 2.0 µm was observed ($p < 0.001$). For particles with diameters ≥0.5, 5, 10, and 25 µm, no significant differences were found between the results obtained with AEROK off and with AEROK on.

3.3. Pollen and Fungal Spores

Figure 5 shows the mean values of the indoor-to-outdoor concentration ratio (I/O) of total pollen and fungal spores of *Alternaria* spp. Over the 7 days of sampling during the sampling period: 7 days with AEROK off and 7 days with AEROK on.

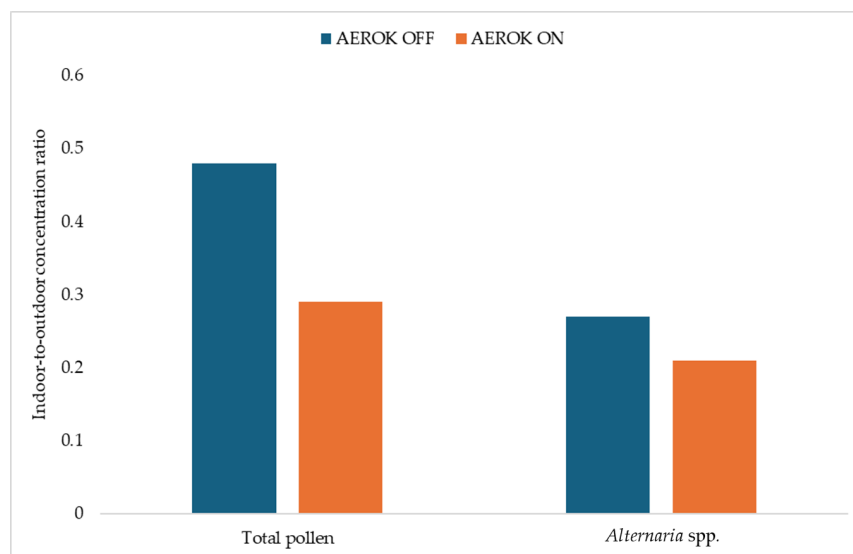


Figure 5. Mean values of the weekly indoor-to-outdoor concentration ratio of total pollen and fungal spores of *Alternaria* spp. with AEROK off and with AEROK on.

Significantly, the concentration ratio I/O of total pollen ($p < 0.001$) and spores of *Alternaria* spp. ($p < 0.05$) decreased with AEROK on.

3.4. Monitoring of Microclimatic Parameters

No significant changes in temperature, relative humidity, and CO₂ values were observed between AEROK off and AEROK on.

4. Discussion

Microbial contamination of indoor environments is considered a public health concern due to the spread of pathogens or in general, aerosols harmful.

In recent years, portable (stand-alone) air purifiers have been increasingly adopted, also due to the SARS-CoV-2 pandemic, with widespread use in different confined spaces and not always sure of their effectiveness in reducing airborne contamination [31,66–68].

The characteristics of these devices can be very different in the mechanisms of action (HEPA filters, electrostatic decontamination, chemical, UV-C radiation, plasma, ozone, plasma, disinfection, etc., all the more so if it is a combination of different systems) [40–48,54]. Each mechanism of action has strengths and weaknesses (noise, high energy costs, pressure drop, disposal of chemicals, residues, or by-products). The goal has been to demonstrate the effectiveness of removing airborne contamination from particulate matter, viruses, bacteria, fungi, VOCs, allergens, etc.

Most of the studies have analyzed only one device at a time or a comparison between several devices with the same or different decontamination methods [32–39]. Often, the studies were limited to well-controlled laboratory situations or in rest conditions, but also field tests are important, because laboratory tests may not run with the complexities of the real situations (airflow patterns, occupant behaviors, interactions with the interior environment, etc.). A recent systematic review and meta-analysis [53] refers to 48 studies on stand-alone-air purifiers of which 36 performed in residential buildings, 6 in health care settings, 4 in schools, and 2 in daycares. The research focused on pet allergens (11 papers), bioaerosols (9 papers), house dust mite allergen (8 papers), fungal spores (8 papers), SARS-CoV-2 RNA (5 papers), cockroach allergen (2 papers), pollen (2 papers), and airborne endotoxin (1 paper). The air-cleaning technologies applied in these studies were different, but a majority focused on HEPA filters. The tests have often been carried out without a vision of standardization regarding the methods used and the contaminants considered [21,32–39].

Based on previous experiences [69–74], we evaluated the effectiveness of an air treatment device with a global approach including the assessment of microbial, particle, pollen, and fungal contamination.

- As for microbial contamination, active and passive sampling were used to have a complete assessment of air biological quality. They have different purposes: active sampling provides information about airborne viable particle concentration, whereas passive sampling measures the rate at which airborne viable particles settle on surfaces. Passive sampling provides a measure of the contribution of airborne contamination to the contamination of the surfaces.
- The results obtained highlight the effectiveness of the tested device in reducing airborne microbial contamination. This effectiveness is also supported by the observation of the trend of microbial contamination detected in the room where the device was operating compared to that of the contamination detected in the adjacent corridor, with similar activity. The presence of people and their activity are the main factors that increase airborne microbial contamination [75–77]. Between the 1st and 2nd hour, in both environments a reduction in microbial contamination was observed, corresponding to the reduction of administrative activity; during the 3rd and 4th hours, in correspondence with the increased administrative activity, an increase in microbial contamination was observed in the corridor, while in the room with AEROK on, microbial contamination continued to decrease. Regarding passive sampling, no reduction

in airborne microbial contamination was observed at points C and D, contrary to what was observed at point E, probably affected, respectively, by the presence of a copier in continuous operation and the opening of the door.

- AEROK was also effective in reducing airborne particle contamination for particles with diameters ≥ 1.0 and $2.0 \mu\text{m}$.
- Moreover, AEROK reduced the concentration of airborne pollen ($p < 0.001$) and fungal spores of *Alternaria* spp. ($p < 0.05$). This result is particularly relevant because it is obtained with windows constantly open and therefore in a condition that favors the replenishment of pollen and *Alternaria* spores.
- The tested device does not use chemical compounds with biocidal activity, resulting in the absence of chemical by-products to be disposed of. Therefore, the need for maintenance activities for filter cleaning is reduced, minimizing the risk of environmental contamination or exposure of personnel. The effectiveness of air-handling devices is usually assessed through laboratory tests and not through field studies within living or working environments, as carried out in this study. In addition, only some of the aspects considered in this study (bacterial, fungal, particulate contamination, pollen, and fungal spores) are often analyzed. Based on the literature, no converged conclusions can be drawn regarding the effectiveness of air purification technologies in practice. The documented and well-controlled laboratory studies do not adequately represent the practical situation in which the purifier systems are used [40]. Air cleaners are generally found to be effective in removing PM_{2.5} and PM₁₀, with mean aggregated reductions of 49% and 44%, respectively [59]. These findings are in line with our results using an AEROK electrostatic copper filter device showing a slightly higher reduction of microbial contamination, and pollen and fungal spores I/O ratio.

5. Conclusions

This study provided an assessment of the effectiveness of the AEROK copper electrostatic filtration system for air disinfection in a working environment under real working conditions. It can also represent a useful contribution to the definition of a standardized model for evaluating the effectiveness of devices to be used for air disinfection.

Author Contributions: Conceptualization, R.A., C.P. and M.E.C.; methodology, R.A., C.P., M.E.C., I.V. and E.C.; statistical analysis, R.A., C.P., M.E.C., L.V., M.M.M.I. and A.C.; investigation, R.A., C.P., M.E.C., I.V., E.C. and M.S.; data curation, A.C. and M.M.M.I.; writing—original draft preparation, R.A., C.P. and M.M.M.I.; writing—review and editing, R.A., C.P., M.E.C., I.V., R.Z., P.A., L.V., A.C. and M.M.M.I. All authors have read and agreed to the published version of the manuscript.

Funding: The AERSAFE s.r.l., Trento, Italy supported this study with a liberal grant.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request.

Acknowledgments: The authors are grateful to Rosslynne Milburn for her linguistic advice.

Conflicts of Interest: All the authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript. The funding sponsor did not have any role in the choice of research project, design of the study, collection and analysis or interpretation of data, and in the writing of the manuscript.

References

1. Mbareche, H.; Morawska, L.; Duchaine, C. On the Interpretation of Bioaerosol Exposure Measurements and Impacts on Health. *J. Air Waste Manag. Assoc.* **2019**, *69*, 789–804. [[CrossRef](#)] [[PubMed](#)]
2. Raaschou-Nielsen, O.; Andersen, Z.J.; Beelen, R.; Samoli, E.; Stafoggia, M.; Weinmayr, G.; Hoffmann, B.; Fischer, P.; Nieuwenhuijsen, M.J.; Brunekreef, B.; et al. Air Pollution and Lung Cancer Incidence in 17 European Cohorts: Prospective Analyses from the European Study of Cohorts for Air Pollution Effects (ESCAPE). *Lancet Oncol.* **2013**, *14*, 813–822. [[CrossRef](#)] [[PubMed](#)]

3. Haddrell, A.E.; Thomas, R.J. Aerobiology: Experimental Considerations, Observations, and Future Tools. *Appl. Environ. Microbiol.* **2017**, *83*, e00809–e00817. [[CrossRef](#)] [[PubMed](#)]
4. Cincinelli, A.; Martellini, T. Indoor Air Quality and Health. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1286. [[CrossRef](#)] [[PubMed](#)]
5. Kumar, P.; Singh, A.B.; Singh, R. Comprehensive Health Risk Assessment of Microbial Indoor Air Quality in Microenvironments. *PLoS ONE* **2022**, *17*, e0264226. [[CrossRef](#)]
6. Cedeño Laurent, J.G.; Macnaughton, P.; Jones, E.; Young, A.S.; Bliss, M.; Flanigan, S.; Vallarino, J.; Chen, L.J.; Cao, X.; Allen, J.G. Associations between Acute Exposures to PM_{2.5} and Carbon Dioxide Indoors and Cognitive Function in Office Workers: A Multicountry Longitudinal Prospective Observational Study. *Environ. Res. Lett.* **2021**, *16*, 094047. [[CrossRef](#)]
7. Buters, J.; Prank, M.; Sofiev, M.; Pusch, G.; Albertini, R.; Annesi-Maesano, I.; Antunes, C.; Behrendt, H.; Berger, U.; Brandao, R.; et al. Variation of the Group 5 Grass Pollen Allergen Content of Airborne Pollen in Relation to Geographic Location and Time in Season the HIALINE Working Group. *J. Allergy Clin. Immunol.* **2015**, *136*, 88–95. [[CrossRef](#)]
8. Ridolo, E.; Albertini, R.; Giordano, D.; Soliani, L.; Usberti, I.; Dall’Aglia, P.P. Airborne Pollen Concentrations and the Incidence of Allergic Asthma and Rhinoconjunctivitis in Northern Italy from 1992 to 2003. *Int Arch Allergy Immunol.* **2007**, *142*, 151–157. [[CrossRef](#)]
9. Borrego Alonso, S.F.; Molina, A. Behavior of the Cultivable Airborne Mycobiota in Air-Conditioned Environments of Three Havanan Archives, Cuba. *J. Atmos. Sc. Res.* **2020**, *3*, 16–28. [[CrossRef](#)]
10. Pasquarella, C.; Barchitta, M.; D’Alessandro, D.; Cristina, M.L.; Mura, I.; Nobile, M.; Auxilia, F.; Agodi, A. Heating, ventilation and air conditioning (HVAC) system, microbial air contamination and surgical site infection in hip and knee arthroplasties: The GISIO-Siti Ischia study. *Ann. Ig.* **2018**, *30*, 22–35.
11. Chawla, H.; Anand, P.; Garg, K.; Bhagat, N.; Varmani, S.G.; Bansal, T.; McBain, A.J.; Marwah, R.G. A comprehensive review of microbial contamination in the indoor environment: Sources, sampling, health risks, and mitigation strategies. *Front. Public Health* **2023**, *11*, 1285393. [[CrossRef](#)]
12. Bonadonna, L.; Briancesco, R.; Coccia, A.M.; Meloni, P.; La Rosa, G.; Moscato, U. Microbial Air Quality in Healthcare Facilities. *Int. J. Environ. Res. Public Health* **2021**, *18*, 6226. [[CrossRef](#)]
13. Sessa, R.; Di Pietro, M.; Schiavoni, G.; Santino, I.; Altieri, A.; Pinelli, S.; Del Piano, M. Microbiological Indoor Air Quality in Healthy Buildings. *New Microbiol.* **2002**, *25*, 51–56.
14. Zoni, R.; Capobianco, E.; Viani, I.; Colucci, M.E.; Mezzetta, S.; Affanni, P.; Veronesi, L.; Di Fonzo, D.; Albertini, R.; Pasquarella, C. Fungal Contamination in a University Building. *Acta Biomed.* **2020**, *91*, 150–153.
15. World Health Organization. Regional Office for Europe. *Indoor Air Quality Research: Report on a WHO Meeting, Stockholm, 27–31 August 1984*; World Health Organization, Regional Office for Europe: Copenhagen, Denmark, 1986; ISBN 9289012692.
16. Berglund, B.; Lindvall, T. Sensory reactions to sick buildings. *Environ. Int.* **1986**, *12*, 147–159. [[CrossRef](#)]
17. Redlich, C.A.; Sparer, J.; Cullen, M.R. Sick-Building Syndrome. *Lancet* **1997**, *349*, 1013–1016. [[CrossRef](#)]
18. Zhang, L.; Ou, C.; Magana-Arachchi, D.; Vithanage, M.; Vanka, K.S.; Palanisami, T.; Masakorala, K.; Wijesekara, H.; Yan, Y.; Bolan, N.; et al. Indoor Particulate Matter in Urban Households: Sources, Pathways, Characteristics, Health Effects, and Exposure Mitigation. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11055. [[CrossRef](#)]
19. Cabral, J.P.S. Can We Use Indoor Fungi as Bioindicators of Indoor Air Quality? Historical Perspectives and Open Questions. *Sci. Total Environ.* **2010**, *408*, 4285–4295. [[CrossRef](#)]
20. Bhui, K.; Newbury, J.B.; Latham, R.M.; Ucci, M.; Nasir, Z.A.; Turner, B.; O’Leary, C.; Fisher, H.L.; Marczylo, E.; Douglas, P.; et al. Air quality and mental health: Evidence, challenges and future directions. *BJPsych Open* **2023**, *5*, e120. [[CrossRef](#)]
21. Oh, H.-J.; Nam, I.-S.; Yun, H.; Kim, J.; Yang, J.; Sohn, J.-R. Characterization of Indoor Air Quality and Efficiency of Air Purifier in Childcare Centers, Korea. *Build. Environ.* **2014**, *82*, 203–214. [[CrossRef](#)]
22. Van Tran, V.; Park, D.; Lee, Y.C. Indoor Air Pollution, Related Human Diseases, and Recent Trends in the Control and Improvement of Indoor Air Quality. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2927. [[CrossRef](#)]
23. UNI 11425:2011; Impianto di Ventilazione e Condizionamento a Contaminazione Controllata (VCCC) per il Blocco Operatorio—Progettazione, Installazione, Messa in Marcia, Qualifica, Gestione e Manutenzione. Ente Nazionale Italiano di Unificazione: Milano, Italia, 2011; pp. 1–32.
24. Wu, J.; Alipouri, Y.; Luo, H.; Zhong, L. Ultraviolet Photocatalytic Oxidation Technology for Indoor Volatile Organic Compound Removal: A Critical Review with Particular Focus on Byproduct Formation and Modeling. *J. Hazard. Mater.* **2022**, *421*, 126766. [[CrossRef](#)]
25. Bragoszewska, E.; Biedroń, I. Efficiency of Air Purifiers at Removing Air Pollutants in Educational Facilities: A Preliminary Study. *Front. Environ. Sci.* **2021**, *9*, 709718. [[CrossRef](#)]
26. Kelly, F.J.; Fussell, J.C. Improving Indoor Air Quality, Health and Performance within Environments Where People Live, Travel, Learn and Work. *Atmos. Environ.* **2019**, *200*, 90–109. [[CrossRef](#)]
27. Li, Y.W.; Ma, W.L. Photocatalytic Oxidation Technology for Indoor Air Pollutants Elimination: A Review. *Chemosphere* **2021**, *280*, 130667. [[CrossRef](#)]
28. Bragoszewska, E.; Bogacka, M.; Pikoń, K. Efficiency and Eco-Costs of Air Purifiers in Terms of Improving Microbiological Indoor Air Quality in Dwellings—A Case Study. *Atmosphere* **2019**, *10*, 742. [[CrossRef](#)]
29. Lombini, M.; Schreiber, L.; Albertini, R.; Alessi, E.M.; Attinà, P.; Bianco, A.; Cascone, E.; Colucci, M.E.; Cortecchia, F.; De Caprio, V.; et al. Solar Ultraviolet Light Collector for Germicidal Irradiation on the Moon. *Sci. Rep.* **2023**, *13*, 8326. [[CrossRef](#)]

30. Grinshpun, S.A.; Adhikari, A.; Honda, T.; Kim, K.Y.; Toivola, M.; Rao, K.S.R.; Reponen, T. Control of Aerosol Contaminants in Indoor Air: Combining the Particle Concentration Reduction with Microbial Inactivation. *Environ. Sci. Technol.* **2007**, *41*, 606–612. [[CrossRef](#)]
31. Otter, J.A.; Clark, L.; Taylor, G.; Hussein, A. Comparative evaluation of stand-alone HEPA-based air decontamination systems. *Infect. Dis. Health* **2023**, *28*, 246–248. [[CrossRef](#)]
32. Griffiths, W.D.; Bennett, A.; Speight, S.; Parks, S. Determining the Performance of a Commercial Air Purification System for Reducing Airborne Contamination Using Model Micro-Organisms: A New Test Methodology. *J. Hosp. Infect.* **2005**, *61*, 242–247. [[CrossRef](#)]
33. Uhde, E.; Salthammer, T.; Wientzek, S.; Springorum, A.; Schulz, J. Effectiveness of Air-Purifying Devices and Measures to Reduce the Exposure to Bioaerosols in School Classrooms. *Indoor Air* **2022**, *32*, e13087. [[CrossRef](#)]
34. Polidori, A.; Fine, P.M.; White, V.; Kwon, P.S. Pilot Study of High-Performance Air Filtration for Classroom Applications. *Indoor Air* **2013**, *23*, 185–195. [[CrossRef](#)] [[PubMed](#)]
35. Heredia-Rodríguez, M.; Álvarez-Fuente, E.; Bustamante-Munguira, J.; Poves-Alvarez, R.; Fierro, I.; Gómez-Sánchez, E.; Gómez-Pesquera, E.; Lorenzo-López, M.; Eiros, J.M.; Álvarez, F.J.; et al. Impact of an Ultraviolet Air Sterilizer on Cardiac Surgery Patients, a Randomized Clinical Trial. *Med. Clin.* **2018**, *151*, 299–307. [[CrossRef](#)]
36. Batterman, S.; Du, L.; Mentz, G.; Mukherjee, B.; Parker, E.; Godwin, C.; Chin, J.Y.; O’Toole, A.; Robins, T.; Rowe, Z.; et al. Particulate Matter Concentrations in Residences: An Intervention Study Evaluating Stand-Alone Filters and Air Conditioners. *Indoor Air* **2012**, *22*, 235–252. [[CrossRef](#)]
37. Liu, D.T.; Phillips, K.M.; Speth, M.M.; Besser, G.; Mueller, C.A.; Sedaghat, A.R. Portable HEPA Purifiers to Eliminate Airborne SARS-CoV-2: A Systematic Review. *Otolaryngol. -Head. Neck Surg.* **2022**, *166*, 615–622. [[CrossRef](#)]
38. Riederer, A.M.; Krenz, J.E.; Tchong-French, M.I.; Torres, E.; Perez, A.; Younglove, L.R.; Jansen, K.L.; Hardie, D.C.; Farquhar, S.A.; Sampson, P.D.; et al. Effectiveness of Portable HEPA Air Cleaners on Reducing Indoor Endotoxin, PM10, and Coarse Particulate Matter in an Agricultural Cohort of Children with Asthma: A Randomized Intervention Trial. *Indoor Air* **2021**, *31*, 1926–1939. [[CrossRef](#)]
39. Medical Advisory Secretariat. Air cleaning technologies: An evidence-based analysis. *Ont. Health Technol. Assess. Ser.* **2005**, *5*, 1–52.
40. Kompatscher, K.; van der Vossen, J.M.B.M.; van Heumen, S.P.M.; Traversari, A.A.L. Scoping Review on the Efficacy of Filter and Germicidal Technologies for Capture and Inactivation of Micro-Organisms and Viruses. *J. Hospital Infect* **2023**, *142*, 39–48. [[CrossRef](#)]
41. Yan, S.; Liu, C.; Hou, L.A.; Wang, B.; Zhang, Y. A new filterless indoor air purifier for particulate matter and bioaerosol based on heterogeneous condensation. *Environ. Res.* **2023**, *218*, 115034. [[CrossRef](#)]
42. Wang, C.; Lu, S.; Zhang, Z. Inactivation of airborne bacteria using different UV sources: Performance modelling, energy utilization, and endotoxin degradation. *Sci. Total Environ.* **2019**, *655*, 787–795. [[CrossRef](#)]
43. Buonanno, M.; Kleiman, N.J.; Welch, D.; Hashmi, R.; Shuryak, I.; Brenner, D.J. 222 nm far-UVC light markedly reduces the level of infectious airborne virus in an occupied room. *Sci. Rep.* **2024**, *14*, 6722. [[CrossRef](#)] [[PubMed](#)]
44. Piletić, K.; Linšak, D.T.; Kovač, B.; Mežnarić, S.; Repustić, M.; Radmanović-Skrbić, M.; Gobin, I. Ozone disinfection efficiency against airborne microorganisms in hospital environment: A case study. *Arh. Hig. Rada Toksikol.* **2022**, *73*, 270–276. [[CrossRef](#)] [[PubMed](#)]
45. Hernández-Díaz, D.; Martos-Ferreira, D.; Hernández-Abad, V.; Villar-Ribera, R.; Tarrés, Q.; Rojas-Sola, J.I. Indoor PM2.5 removal efficiency of two different non-thermal plasma systems. *J. Environ. Manag.* **2021**, *278*, 111515. [[CrossRef](#)] [[PubMed](#)]
46. Nie, L.; Li, S.; Cao, M.; Han, N.; Chen, Y. A brief review of preparation and applications of monolithic aerogels in atmospheric environmental purification. *J. Environ. Sci.* **2025**, *149*, 209–220. [[CrossRef](#)] [[PubMed](#)]
47. Marchand, G.; Wingert, L.; Barbeau, B.; Lacombe, N.; Xiao, Y.; Alameddine, M.; Moschin, D.E. Evaluation of the decay rate of airborne viruses in an exposure chamber during air treatment by a UV-C based technology. In Proceedings of the WorldAerobiology Congress, Vilnius, Lithuania, 1–5 July 2024.
48. Allen, J.G.; Ibrahim, A.M. Indoor Air Changes and Potential Implications for SARS-CoV-2 Transmission. *JAMA* **2021**, *325*, 2112–2113. [[CrossRef](#)]
49. Nardell, E.A.; Nathavitharana, R.R. Airborne Spread of SARS-CoV-2 and a Potential Role for Air Disinfection. *JAMA* **2020**, *324*, 141–142. [[CrossRef](#)]
50. Schuit, M.; Ratnesar-Shumate, S.; Yolitz, J.; Williams, G.; Weaver, W.; Green, B.; Miller, D.; Krause, M.; Beck, K.; Wood, S.; et al. Airborne SARS-CoV-2 Is Rapidly Inactivated by Simulated Sunlight. *J. Infect. Dis.* **2020**, *222*, 564–571. [[CrossRef](#)]
51. Lindsley, W.G.; Derk, R.C.; Coyle, J.P.; Martin, S.B.; Mead, K.R.; Blachere, F.M.; Beezhold, D.H.; Brooks, J.T.; Boots, T.; Noti, J.D. Efficacy of Portable Air Cleaners and Masking for Reducing Indoor Exposure to Simulated Exhaled SARS-CoV-2 Aerosols—United States, 2021. *MMWR* **2021**, *70*, 972–976. [[CrossRef](#)]
52. Cortes, A.A.; Zuñiga, J.M. The use of copper to help prevent transmission of SARS-coronavirus and influenza viruses. A general review. *Diagn. Microbiol. Infect. Dis.* **2020**, *98*, 115176. [[CrossRef](#)]
53. Ebrahimifakhar, A.; Poursadegh, M.; Hu, Y.; Yuill, D.P.; Luo, Y. A systematic review and meta-analysis of field studies of portable air cleaners: Performance, user behavior, and by-product emissions. *Sci. Total Environ.* **2024**, *20*, 912168786. [[CrossRef](#)]

54. INAIL. Il Monitoraggio Microbiologico negli Ambienti di Lavoro. *Campionamento E Anal.* **2010**, 1–90; Tipolitografia INAIL – Milano - 1/2010 ISBN 978-88-7484-162-2.
55. *Standardization ISO 14698-1*; Cleanrooms and Associated Controlled Environments—Biocontamination Control—Part 1: General Principles and Methods. International Organization: Geneva, Switzerland, 2003.
56. *EN 17141*; Cleanrooms and Associated Controlled Environments. Biocontamination Control. iTeh Inc.: San Francisco, CA, USA, 2021.
57. CDC Guidelines for Environmental Infection Control in Health-Care Facilities; NO:RR-10. 2003. Available online: <https://www.cdc.gov/infection-control/media/pdfs/Guideline-Environmental-H.pdf> (accessed on 5 September 2024).
58. Pitzurra, M.; Savino, A.; Pasquarella, C. Il monitoraggio ambientale microbiologico (MAM). *Ann. Ig.* **1997**, *9*, 439–454.
59. Pasquarella, C.; Pitzurra, O.; Savino, A. The Index of Microbial Air Contamination. *J. Hosp. Infect.* **2000**, *46*, 241–256. [[CrossRef](#)] [[PubMed](#)]
60. Pasquarella, C.; Albertini, R.; Dall’Aglio, P.; Saccani, E.; Sansebastiano, G.E.; Signorelli, C. Air microbial sampling: The state of the art. *Ig. Sanità Pubbl.* **2008**, *64*, 79–120. [[PubMed](#)]
61. *Standardization ISO 14644-1:2015*; Cleanrooms and Associated Controlled Environments—Part 1: Classification of Air Cleanliness by Particle. International Organization: Geneva, Switzerland, 2015.
62. *Standardization ISO 14644-2:2015*; Cleanrooms and Associated Controlled Environments—Part 2: Monitoring to Provide Evidence of Cleanroom Performance Related to Air Cleanliness by Particle Concentration. International Organization: Geneva, Switzerland, 2015.
63. *Standardization ISO 21501-4:2018*; Determination of Particle Size Distribution—Single Particle Light Interaction Methods—Part 4: Light Scattering Airborne Particle Counter for Clean Spaces. International Organization: Geneva, Switzerland, 2018.
64. Hirst, J.M. An automatic volumetric spore trap. *Ann. Appl. Biol.* **1952**, *39*, 257–265. [[CrossRef](#)]
65. *EN 16868:2019*; Ambient Air—Sampling and Analysis of Airborne Pollen Grains and Fungal Spores for Networks Related to Allergy—Volumetric Hirst Method. iTeh Inc.: San Francisco, CA, USA, 2019.
66. Pisharodi, M. Portable and Air Conditioner-Based Bio-Protection Devices to Prevent Airborne Infections in Acute and Long-Term Healthcare Facilities, Public Gathering Places, Public Transportation, and Similar Entities. *Cureus* **2024**, *11*, e55950. [[CrossRef](#)] [[PubMed](#)]
67. Banholzer, N.; Jent, P.; Bittel, P.; Zürcher, K.; Furrer, L.; Bertschinger, S.; Weingartner, E.; Ramette, A.; Egger, M.; Hascher, T.; et al. Air cleaners and respiratory infections in schools: A modeling study using epidemiological, environmental, and molecular data. *Open Forum Infect. Dis.* **2024**, *21*, ofae169. [[CrossRef](#)]
68. Salmons-Smith, J.; Ducci, A.; Balachandran, R.; Guo, L.; Torii, R.; Houlihan, C.; Epstein, R.; Rubin, J.; Tiwari, M.K.; Lovat, L.B. Use of portable air purifiers to reduce aerosols in hospital settings and cut down the clinical backlog. *Epidemiol. Infect.* **2023**, *151*, e21. [[CrossRef](#)]
69. Pasquarella, C.; Balocco, C.; Pasquariello, G.; Petrone, G.; Saccani, E.; Manotti, P.; Ugolotti, M.; Palla, F.; Maggi, O.; Albertini, R. A Multidisciplinary Approach to the Study of Cultural Heritage Environments: Experience at the Palatina Library in Parma. *Sci. Total Environ.* **2015**, *536*, 557–567. [[CrossRef](#)]
70. Pasquarella, C.; Vitali, P.; Saccani, E.; Manotti, P.; Bocconi, C.; Ugolotti, M.; Signorelli, C.; Mariotti, F.; Sansebastiano, G.E.; Albertini, R. Microbial Air Monitoring in Operating Theatres: Experience at the University Hospital of Parma. *J. Hospital Infect.* **2012**, *81*, 50–57. [[CrossRef](#)]
71. Pasquarella, C.; Saccani, E.; Sansebastiano, G.E.; Ugolotti, M.; Pasquariello, G.; Albertini, R. Proposal for a Biological Environmental Monitoring Approach to Be Used in Libraries and Archives. *Ann. Agric. Environ. Med.* **2012**, *19*, 209–212. [[PubMed](#)]
72. Pasquarella, C.; Veronesi, L.; Napoli, C.; Castiglia, P.; Liguori, G.; Rizzetto, R.; Torre, I.; Righi, E.; Farruggia, P.; Tesauro, M.; et al. SItI Working Group Hygiene in Dentistry. Microbial environmental contamination in Italian dental clinics: A multicenter study yielding recommendations for standardized sampling methods and threshold values. *Sci. Total Environ.* **2012**, *420*, 289–299. [[CrossRef](#)] [[PubMed](#)]
73. Buters, T.M.; Thibaudon, M.; Smith, M.; Kennedy, R.; Rantio-Lehtimäki, A.; Albertini, R.; Reese, G.; Weber, B.; Galán, C.; Brandao, R.; et al. Release of Bet v 1 from birch pollen from 5 European countries. Results from the HIALINE study. *Atmos. Environ.* **2012**, *55*, 496–505. [[CrossRef](#)]
74. Viani, I.; Colucci, M.E.; Pergreffi, M.; Rossi, D.; Veronesi, L.; Bizzarro, A.; Capobianco, E.; Affanni, P.; Zoni, R.; Saccani, E.; et al. Passive Air Sampling: The Use of the Index of Microbial Air Contamination. *Acta Biomedica.* **2020**, *91*, 92–105.
75. Qian, J.; Peccia, J.; Ferro, A.R. Walking-Induced Particle Resuspension in Indoor Environments. *Atmos. Environ.* **2014**, *89*, 464–481. [[CrossRef](#)]
76. McDonagh, A.; Byrne, M.A. The Influence of Human Physical Activity and Contaminated Clothing Type on Particle Resuspension. *J. Environ. Radioact.* **2014**, *127*, 119–126. [[CrossRef](#)]
77. Whyte, W.; Hejab, M. Particle and microbial airborne dispersion from people. *Eur. J. Parent. Pharm. Sc.* **2007**, *12*, 39–46.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.