Effectiveness and Eco-Costs of Air Cleaners in Terms of Improving Fungal Air Pollution in Dwellings Located in Southern Poland—A Preliminary Study

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Abstract: Epidemiological evidence shows that air pollution is responsible for several million premature deaths per year. By virtue of being responsible for these deaths, economic evidence shows that air pollution also imposes a so-called economic cost to society of several trillion dollars per year. The diseases caused by biological air pollutants are of primary global concern for both social and economic reasons, and given that people may spend more than 90% of their time in enclosed spaces, the investigation into methods to remove indoor air pollutants is of paramount importance. One of the methods to improve indoor air quality (IAQ) is to use air cleaners (ACLs) with high-efficiency particulate air filters (HEPA) that remove biological indoor air pollutants from indoor environments. This work presents the results of a study of fungal aerosol samples collected during the summer season from inside two dwellings (DG1 and DG2) before and after starting the use of ACLs. The fungal aerosol samples collected from each of the six stages of the sampler were incubated on agar plates at 26 °C, and the colony forming units (CFU) were manually counted and statistically corrected. The concentration of living airborne fungi was expressed as the CFU in the volume of air (CFU·m⁻³). The average concentration of fungal aerosol decreased the most when the ACLs were active for 24 min. The reduction was from 474 CFU·m⁻³ to 306 CFU·m⁻³, and from 582 CFU·m⁻³ to 338 CFU·m⁻³ in DG1 and DG2, respectively. The use of ACLs was assessed by the life cycle assessment (LCA) methodology. This study highlights the benefits of controlling biological air pollutants in order to keep occupants of buildings happy and healthy.

Keywords: biological air pollutants; fungal aerosol; air cleaner; life cycle assessment; indoor air quality

1. Introduction

With the ongoing improvements in quality of life, indoor air quality (IAQ) has become an area of concern for researchers in the last few decades [1]. People spend the majority of their time indoors, and lowering the indoor concentrations of air pollutants is fundamental for our health and wellbeing, while conserving energy in residential indoor environments [2]. In particular, poor IAQ can be harmful to vulnerable groups such as children, young adults, the elderly, or those suffering from chronic respiratory and/or cardiovascular diseases [3]. Therefore, the development of indoor air decontamination technologies is highly desirable [4–6].

In recent years, a growing number of studies have focused on the assessment of exposure to biological air pollutants in indoor spaces with respect to the various negative effects on human health [7,8]. Interest in exposure to biological air pollutants (e.g., bacteria, fungi, and viruses) has increased in the 21st century, because they are associated with a wide range of health problems with a
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major impact on public health. These health problems include infection by disease, acute toxic effects,
allergies, and even cancer [9–12]. The spread of infectious is of worldwide concern for social and
economic reasons, e.g., seasonal influenza kills 200–500 thousand people annually [13].

Among biological air pollutants, the particles of fungal aerosols may be transported into buildings
on the surface of new materials or on clothing [14–17]. They may also penetrate buildings through
active or passive ventilation [18,19]. Symptoms of tiredness and memory loss, as well as common
diseases such as allergies, asthma, and hypersensitivity pneumonitis, are caused by fungal aerosol
exposure [20–22]. Fungal diversity is enormous, with more than an estimated one million species
that produce airborne spores, conidia, hyphae, and other fragments that can affect human health [23].
Almost 10% of people worldwide suffer from a fungal allergy [24]. Therefore, the reduction of exposure
to indoor fungal aerosols represents a particular challenge.

Natural ventilation is a common method used in homes to remove harmful toxins that may arise
from the activity of the occupants. Its zero-energy cost is also important. Nowadays, when outdoor
air pollution is an increasing problem, HVAC (heating, ventilation, and air conditioning) systems
are used more and more often, which help to obtain the appropriate quality of indoor air [25,26].
However, one of the major drawbacks in this case is the high energy cost of operating these systems [13].
As an intermediate solution, air cleaners (ACLs) are becoming more and more popular in households,
the operation of which increases the energy cost to a lesser extent, and at the same time ensures cleaning
of the internal air [27]. One of the common methods of air purification is filtration, and the materials
commonly used are high efficiency particulate filters (HEPAs). The use of activated carbon filters is
equally popular [28].

The American Household Appliances Association (AHAM) established an air purifier standard in
1984, describing the method used to test the particle removal efficiency of air filters [29]. Three key
elements contribute to the efficiency of an air filter, namely: room size, clean air delivery rate (CADR),
and particle size category. CADR is the product of the filter removal efficiency and the airflow rate
through the device, experimentally determined as the difference between the decay constants with and
without the ACL running, multiplied by the effective indoor mixing volume [30].

HEPA filters are typically constructed from two media choices—polytetrafluoroethylene (PTFE)
membrane or micro glass fibers. The thickness of the media can play a large role in the filter operating
performance [31]. As public awareness of air pollution increases, HEPA filters in ACLs are becoming
widely used in Poland by the growing middle class. In an ACL, the air is forced through the HEPA
filter and the particles are physically captured. The key mechanisms of this action are diffusion,
interception, inertial impaction, and sieving [32]. Studies have shown that HEPA filters can reduce
particle concentrations by more than 50% [4,33,34].

There is also some evidence to suggest that these reductions lead to improvements in
cardiorespiratory health [35,36]. Moreover, studies have reported that the use of indoor ACLs may be
associated with a reduction in blood pressure, oxidative stress, and systemic inflammation, and may
also improve lung function [4]. Therefore, it is important to reduce and control the concentrations of
harmful microorganisms in the air in order to ensure good IAQ [37]. However, contaminated HEPA
filters serve as an ecological niche for indoor microorganisms [38,39]. Moreover, the bulky structure of
the HEPA filter requires a large working space and causes a large pressure difference between the inlet
and outlet of the filter, and limits the efficiency of the air circulation [39].

This study includes four aspects. Our main goal was to evaluate of the impact of ACLs on the
fungal IAQ. Therefore, we investigated the concentration and size distribution of fungal aerosols in
two dwellings located in Southern Poland. We also calculated the ecological cost of air purification
using the life cycle assessment (LCA) technique.
2. Experiments

2.1. Sampling Sites

The study was carried out in two living rooms at two dwellings located in Bytom (18°54’ E 50°23’ N) in Southern Poland. Each analyzed living room was equipped with the same type of ACL, with a PET (polyester) pre-filter retaining larger air pollutants, HEPA-11 filter with an area of 2.2 m², and an adsorption filter with active carbon (an absorbing area of 57,000 m²). The research was conducted over a period of two months during the summer season of 2020. The sampling was performed once a week. A sample was taken when the ACLs were turned off, and again 12 min and 24 min after the ACLs were turned on. Samples were collected between 16:00 p.m. and 18:00 p.m. in order to check the efficiency of the tested device. Three sets of measurements were performed in each living room with the ACL turned on and turned off. Samples of airborne fungi were collected from the center of each room at a height of about 1.5 m in order to simulate aspiration from the human breathing zone. Each sample included six impaction stages with Petri dishes. In total, 864 Petri dishes (without blanks) with biological material were analyzed during the study.

The measurement was conducted in two living rooms, each with a volume of approximately 64 m³. The assessment of the effectiveness of the air decontamination was carried out in the natural conditions of the residents’ routine activities. Each living room was equipped with an ACL, with a Clean Air Delivery Rate (CADR) of 310 m³/h. The windows in the rooms were closed during the study, and the air change per hour (ACH) was 0. Table 1 presents a description of the analyzed dwellings.

| Parameters and Basic Description of DG1 and DG2 | Dwelling 1 (DG1) | Dwelling 2 (DG2) |
|-----------------------------------------------|-----------------|-----------------|
| Home localization                             | close the city center | close the city center |
| Building built-in                              | 1990s           | 1980s           |
| Equipment                                      | table, chairs, sofa | table, chairs, sofa, 2 armchairs |
| Ventilation system                             | natural         | natural         |
| Volume, m³                                     | 64              | 62              |
| Number of occupants                            | 4 (2 adults and 2 children) | 4 (2 adults and 2 children) |
| Number of animals                              | -               | 2 dogs          |
| Floor covered with                             | PVC and carpet  | PVC and carpet  |
| Indoor temperature, °C                         | 22.5 +/- 5.1    | 20.5 +/- 4.4    |
| Indoor relative humidity, %                    | 41. +/- 8.1     | 48.2 +/- 3.9    |
| Outdoor temperature, °C                        | 29.1 +/- 4.2    | 28.6 +/- 3.3    |
| Outdoor relative humidity, %                   | 39.1 +/- 7.4    | 44.2 +/- 8.9    |

The scheme of an ACL is presented in Figure 1.
2.2. Sampling and Analysis Methods

Measurements of the fungal aerosol concentrations were conducted using a six-stage Andersen impactor with cut-off diameters of 7.0, 4.7, 3.3, 2.1, 1.1, and 0.65 µm with an air flow of 28.3 dm³/min, and the sampling time was 10 min (calculated following Nevalainen et al. [40]). For sampling the fungal particles, we used Petri dishes containing a solid nutrient medium located on all of the impactor stages. Malt extract agar (MEA 2%, Biocorp, Warsaw, Poland) culture media with chloramphenicol was used to speciate the fungal aerosol. The samples were incubated for five to six days at 26 °C. The concentration of living microorganisms was counted as the number of colony forming units in the volume of air (CFU·m⁻³).

According to our previous studies [41,42], the quality control procedure was practiced using PN-EN12322 [43] and ISO 11133:2014 [44] standards.

2.3. Statistical Analysis

Based on the Shapiro–Wilk test results, it was found that all of the samples had a normal distribution in terms of the tested parameters. Student’s t-test ($p < 0.05$) was used to detect the presence of a statistically significant difference between when the ACL was turned off (ACLO) and the samples when the air cleaner was active (ACLA) for 12 min and 24 min. The statistical analysis was performed using Statistica v.12.

2.4. LCA Methodology

In an environmental analysis, many LCA methodologies are used. One LCA methodology practiced here was ReCiPe 2008, with the same operation details as in our previous studies [41]. The next part of the analysis was the environmental aspect. In order to calculate the impact on the environment, the analysis should follow the ISO 14040: 2006 standard [45]. This methodology is based on the full life cycle, which includes three main stages, namely: production, use, and disposal. Figure 2 presents the phases in the case of air ventilation linked with purification in terms of reducing fungal air pollution in dwellings. Depending on the individual case, the description of these phases should be more precise. The LCA includes transportation, different waste scenarios, and so on. In order to
assess the real impact, the analysis should include all materials, pollution, and consumption involved in making the product. LCA is based on assumptions and it reveals the most important negative inputs or outputs [46,47]. In this study, the analysis was conducted using SimaPro software with the Ecoinvent 3.0 database. The results are given as percentages so as to visualize the impact of each of the phases in the complete analysis.

![Figure 2. The scheme of life cycle assessment (LCA) phases in the process of air cleaning.](image)

### 3. Results and Discussion

#### 3.1. The Concentration of Culturable Fungal Aerosol and the Effectiveness of ACLs

The average concentrations of airborne fungi collected from the indoor air are presented in Table 2. The average concentration of fungal aerosols significantly \((p < 0.01)\) decreased when the ACL was active for 24 min, from 474 CFU·m\(^{-3}\) to 306 CFU·m\(^{-3}\), and from 582 CFU·m\(^{-3}\) to 338 CFU·m\(^{-3}\) in DG1 and DG2, respectively. So, the reduction of fungal aerosols was 35% in DG1 and 42% in DG2. In the case of the average concentration of culturable fungal spores when the ACL was active for 12 min, in DG1 we observed a decrease from 474 CFU·m\(^{-3}\) (ACLO) to 419 CFU·m\(^{-3}\) with a significant difference \((p = 0.04)\), while in DG2 with the same operation time for the ACL, we observed a decrease from 582 CFU·m\(^{-3}\) (ACLO) to 419 CFU·m\(^{-3}\) \((p < 0.01)\). The reduction of fungal particles after 12 min of ACL operation was 21% and 28% in DG1 and DG2, respectively. Both times of purification proved to be effective for the removal of fungal aerosols. However, the reduction of fungal aerosols was more effective after the extended use of the air cleaner.

The results obtained in our study correspond with our earlier research in which we determined the effect of ACLs in eliminating bacterial microorganisms; when ACLs were enabled, the concentration of bacterial aerosols was reduced by about 50% [41]. Similar studies conducted in central Poland indicate that the effectiveness of filters in air decontamination in nursery schools is 41% [48]. However, the ACL is only effective during the operation period; it does not eliminate sources of fungal contamination. ACLs do not provide a fundamental solution to fungal contamination [49].

### Table 2. Average concentration and standard deviation (SD) of fungal aerosol colony-forming units per cubic meter of air (CFU·m\(^{-3}\)) inside two types of dwellings: dwelling 1 (DG1) and dwelling 2 (DG2), when the air cleaner was active (ACLA) for 12 min and 24 min, or when the air cleaner was turn off (ACLO).

| Location       | Average Concentration CFU·m\(^{-3}\) +/- SD | Minimum | Maximum |
|---------------|--------------------------------------------|---------|---------|
| DG1 ACLA/12 min | 373 +/- 101                               | 21      | 410     |
| DG2 ACLA/12 min | 419 +/- 124                               | 14      | 544     |
| DG1 ACLA/24 min | 306 +/- 92                                | 18      | 404     |
| DG2 ACLA/24 min | 338 +/- 86                                | 4       | 419     |
| DG1 ACLO       | 474 +/- 134                               | 14      | 522     |
| DG2 ACLO       | 582 +/- 141                               | 7       | 640     |
Moreover, under the current COVID-19 pandemic situation, ACLs could be used as a supplementary and precautionary method after other more significant activities have been taken, such as local source control, frequent disinfection of the room and furnishing surfaces, and ventilation [50].

3.2. The Size Distribution of Fungal Aerosol and the Effectiveness of ACLs

The mean distributions of the aerodynamic diameters of the airborne fungi are shown in Figure 3. It can be seen that the size distribution of fungi when the air cleaner was turned off (ACLO) in the analyzed dwellings was characterized by a large share of particles in an aerodynamic diameter (d_{ae}) range of 2.1–3.3 µm. Aerosols smaller than 5 µm in the aerodynamic diameter contribute to airborne infection [51]. An increase in the share of the coarser fraction of airborne fungi when the air cleaner was active (ACLA) may be as a result of the reemission process generated by the air blowing from ACLs.

![Figure 3. The size distribution of fungal aerosols in dwelling 1 (DG1) and dwelling 2 (DG2) when the air cleaner was active (ACLA) for 12 min and 24 min, or when the air cleaner was turned off (ACLO).](image)

We observed that while the air cleaner was active (ACLA), the respirable fraction of analyzed bioaerosol (particles less than 3.3 µm) decreased compared with the results when the air cleaner was turned off (ACLO) in DG1 by approximately 13% and 19%, and decreased in DG2 by approximately 15% and 17% when the ACLA for 12 min and 24 min, respectively.

The HEPA filters built into ACLs are made of intertwined fibers, where the smallest particles or bioaerosols become retained in three ways, namely: interception, impaction, or diffusion. The fine fraction of biological particles are most likely trapped in the fibers by means of diffusion [29].

Exposure of residents to respirable fungal particles may result not only in infections related directly to contact with microbial pathogens, but may also cause diseases associated with the exposure to mycotoxins and fungal glucans [32]. The symptoms caused by exposure to a fraction of fungal particles less than 3.3 µm include bronchitis, allergic asthma, obstructive pulmonary disease, alveolitis, or organic dust toxic syndrome [53].

Fungal aerosols do not grow well indoors if there is insufficient water and moisture in the materials and substrates. The current recommended procedures for controlling indoor fungal growth in the dwelling are to stop and control all moisture and water problems, remove contaminated materials under containment so as to avoid the dispersal of fungal spores, and the use of HEPA filters in indoor environments [54].
There is still a lack of global standards and guidelines for microbiological indoor air quality. Therefore, measurements of indoor bioaerosols should be conducted much more intensely and on a larger scale. Portable and affordable ACLs have the potential to reduce the exposure of people to bioaerosols in indoor environments, but further work is needed, particularly focused on the reemission process generated by the air blowing from ACLs. The elucidation of this relationship will be an important foundation from which to develop air cleaning technologies.

3.3. LCA—The Ecological Cost of Emission Reduction

Table 3 presents a list of assumptions based on the Ecoinvent database. It shows the complex data that should be included, but with some limitations due to a lack in the database. Regarding the LCA phases, the three main phases are production, use, and disposal.

| LCA          | Product/Service | Assumption | Unit         | Chosen Ecoinvent Database                                                                 |
|--------------|-----------------|------------|--------------|------------------------------------------------------------------------------------------|
| Phase I      | Production of the device | 1 piece | Air filter, decentralized unit, 180–250 m³/h (RER) | Production of the device | 1 piece | Included in device production |
|              | Production of the carbon filter | 1 piece | Included in device production                                                                 |
|              | Production of the HEPA filter | 1 piece | Included in device production                                                                 |
| Phase II Use| Electricity consumption | 85.5 kWh/year | Electricity, low voltage [PL], market for [Alloc Def, U]                                        |
|              | Filter changes   | 1 piece/year | Not included (for the first year the original filter is used)                                    |
| Phase III Disposal | Recycling of plastic | 2 kg | Recycling of plastics basic, EU27                                                             |
|              | Recycling of metal | 1 kg | Recycling of metals basic, n.e.c., EU27                                                        |
|              | Disposal of filters | 1 kg | Not included (lack of database)                                                                |

Of course, in the disposal phase, only recycling options are presented, but more scenarios can be predicted like the landfill or a scenario where only half of the materials will be recycled. However, regarding the regulations of the Waste Electrical and Electronic Equipment Directive (WEEE) [55], it should be collected by dedicated companies, and because of this, this scenario is presented as the most probable. In the article, the LCA analysis should show the main value of LCA and that everything has an impact on the environment; even people who think about our health and that it is the most important issue, we always have an impact on the environment. In other scenarios, we can predict that the impact on the environment will be higher than what is presented. The analysis was based on SimarPro software. The results are presented in Figure 4.

In each category, the “use phase” has the biggest impact on the environment. Taking into account the assumption that metals and plastics are recycled at the end of the life of the device, in each category, the impact is negative, which means that it has positive results, particularly when linked to the replacement effect. The impact of the production of the device is less than 1% per category. The main conclusion is that the impact of cleaning air is mostly associated with electricity consumption. For the test carried out in Poland, the electricity mix comes from coal, and therefore its impact is huge. If it is compared with the environmental impact of another electricity mix, for example in France, the total impact will be much lower.
Environmental impact is a very important issue that could be treated as a form of external cost, which is currently high on the agenda and should be taken into account in order to deliver a better picture of the processes under analysis. This is not a question of whether or not should we sacrifice human health for a lower carbon footprint. It is rather a question of a more holistic view that would lead to more informed decisions and better scientific credibility. LCA is very important in every field. Like economic analysis, each measure should be calculated and analyzed as broadly as possible. LCA analysis allows us to assess the impact on the environment, but also on human health in the full life cycle, i.e., from the extraction of natural resources, through production, transport, use, and management. During this analysis, the real results on the environment and human health can be predicted, taking into account all of the stages and the many dimensions of the problem, and not only the benefits of using certain products. The article presents this problem more generally because the aim of the article is to present the research and results of the removal of fungi from the air. However, the LCA can indicate that this also affects the environment and human health in another dimension.

4. Conclusions

A study of the quantity of fungal aerosols and the ecological cost of pollution reduction was carried out in dwellings in Southern Poland during the summer season. Although the presented research is the result of preliminary studies, it allows for the following conclusions to be drawn.

Air purification has an impact on the environment. Electricity and materials, including chemicals, are needed in almost every process, but this cost is much lower than the cost of contaminated air on health. This problem is also linked with waste; the filters are contaminated with pollutants and should be disposed of with special care.

In our study, both analyzed of the times of purification (12 min and 24 min) proved to be effective for the removal of fungal aerosols. However, the reduction in the average concentration of fungal aerosols was more effective after an extended use of air cleaners.
The current findings suggest the need for further work, particularly focused on a reemission process generated by air blowing from ACLs. The elucidation of this relationship will be an important foundation from which to develop air cleaning technologies.

Microbial pollution is one of the most fundamental indoor environmental quality problems indoors. Therefore, we believe that our study will point out the need for implementing a strategy to control and improve microbiological air quality in indoor environments.

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**References**

1. Saini, J.; Dutta, M.; Marques, G. A comprehensive review on indoor air quality monitoring systems for enhanced public health. Sustain. Environ. Res. 2020, 30, 1–12. [CrossRef]
2. Simoni, M.; Jaakkola, M.S.; Carrozz, L.; Baldacci, S.; Di Pede, F.; Vieg, G. Indoor air pollution and respiratory health in the elderly. Eur. Respir. J. 2003, 21, 155–208. [CrossRef]
3. Cincinelli, A.; Martellini, T.; Cincinelli, A.; Martellini, T. Indoor Air Quality and Health. Int. J. Environ. Res. Public Health 2017, 14, 1286. [CrossRef] [PubMed]
4. 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]
5. Yang, Y.; Zhang, B.; Feng, Q.; Cai, H.; Jiang, M.; Zhou, K.; Li, F.; Liu, S.; Li, X. Towards locating time-varying indoor particle sources: Development of two multi-robot olfaction methods based on whale optimization algorithm. Build. Environ. 2019, 166, 106413. [CrossRef]
6. Brauer, M.; Hoek, G.; Smit, H.A.; De Jongste, J.C.; Gerritsen, J.; Postma, D.S.; Kerkhof, M.; Brunekreef, B. Air pollution and development of asthma, allergy and infections in a birth cohort. Eur. Respir. J. 2007, 29, 879–888. [CrossRef] [PubMed]
7. Qian, J.; Hospodsky, D.; Yamamoto, N.; Nazaroff, W.W.; Peccia, J. Size-resolved emission rates of airborne bacteria and fungi in an occupied classroom. Indoor Air 2012, 22, 339–351. [CrossRef] [PubMed]
8. Van Leuken, J.P.G.; Swart, A.N.; Droogers, P.; Van Pul, A.; Heederik, D.; Havelaar, A.H. Climate change effects on airborne pathogenic bioaerosol concentrations: A scenario analysis. Aerobiologia 2016, 32, 607–617. [CrossRef] [PubMed]
9. Fröhlich-Nowoisky, J.; Kamp, C.J.; Weber, B.; Huffman, J.A.; Pöhlker, C.; Andreea, M.O.; Lang-Yona, N.; Burrows, S.M.; Gunthe, S.S.; Elbert, W.; et al. Bioaerosols in the Earth system: Climate, health, and ecosystem interactions. Atmos. Res. 2016, 182, 346–376. [CrossRef]
10. Reinmuth-Selzle, K.; Kampf, C.J.; Lucas, K.; Lang-Yona, N.; Fröhlich-Nowoisky, J.; Shiraiwa, M.; Lakey, P.S.; Lai, S.; Liu, F.; Kunert, A.T.; et al. Air Pollution and Climate Change Effects on Allergens and Adjuvants. Environ. Sci. Technol. 2017, 51, 4119–4141. [CrossRef]
11. Samake, A.; Uzu, G.; Martins, J.M.F.; Calas, A.; Vince, E.; Parat, S.; Jaffrezo, J.L. The unexpected role of bioaerosols in the Oxidative Potential of PM. Sci. Rep. 2017, 7, 1–10. [CrossRef] [PubMed]
12. Kim, K.-H.; Kabir, E.; Jahan, S.A. Airborne bioaerosols and their impact on human health. J. Environ. Sci. 2018, 67, 23–35. [CrossRef] [PubMed]
13. Aliaibadi, A.A.; Rogak, S.N.; Bartlett, K.H.; Green, S.I. Preventing Airborne Disease Transmission: Review of Methods for Ventilation Design in Health Care Facilities. Adv. Prev. Med. 2011, 2011, 1–21. [CrossRef] [PubMed]
14. Kildeso, J.; Würtz, H.; Nielsen, K.F.; Kruse, P.; Wilkins, K.; Thrane, U.; Gravesen, S.; Nielsen, P.A.; Schneider, T. Determination of fungal spore release from wet building materials. Indoor Air 2003, 13, 148–155. [CrossRef]
15. Li, D.-W.; Yang, C.S. Fungal Contamination as a Major Contributor to Sick Building Syndrome. Adv. Appl. Microbiol. 2004, 55, 31–112. [CrossRef]
16. Kulkarni, P.; Baron, P.; Willeke, K. Aerosol Measurement: Principles, Techniques, and Applications, 3rd ed.; Wiley: Hoboken, NJ, USA, 2011.

17. Shelton, B.G.; Kirkland, K.H.; Flanders, W.D.; Morris, G.K. Profiles of airborne fungi in buildings and outdoor environments in the United States. *Appl. Environ. Microbiol.* 2002, 68, 1743–1753. [CrossRef]

18. WHO. Guidelines for Indoor Air Quality: Dampness and Mould; WHO Regional Office for Europe: Copenhagen, Denmark, 2009; ISBN 7899289041683.

19. Ghosh, B.; Lal, H.; Srivastava, A. Review of bioaerosols in indoor environment with special reference to sampling, analysis and control mechanisms. *Environ. Int.* 2015, 85, 254–272. [CrossRef]

20. King, M.D.; Lacey, R.E.; Pak, H.; Fearing, A.; Ramos, G.; Baig, T.; Smith, B.; Koustova, A. Assays and enumeration of bioaerosols—traditional approaches to modern practices. *Aerosol Sci. Technol.* 2020, 54, 611–633. [CrossRef]

21. Siersted, H.C.; Gravesen, S. Extrinsic allergic alveolitis after exposure to the yeast Rhodotorula rubra. *Allergy* 1993, 48, 298–299. [CrossRef]

22. Selman, M.; Lacasse, Y.; Paré, A.; Cormier, Y. Hypersensitivity Pneumonitis Caused by Fungi. *Proc. Am. Thorac. Soc.* 2010, 7, 229–236. [CrossRef]

23. Lee, J.H.; Hwang, G.B.; Jung, J.H.; Lee, D.H.; Lee, B.U. Generation characteristics of fungal spore and fragment bioaerosols by airflow control over fungal cultures. *J. Aerosol Sci.* 2010, 41, 319–325. [CrossRef]

24. Yassin, M.F.; Almouqatea, S. Assessment of airborne bacteria and fungi in an indoor and outdoor environment. *Int. J. Environ. Sci. Technol.* 2010, 7, 535–544. [CrossRef]

25. Liu, Z.J.; Ma, S.Y.; Cao, G.Q.; Meng, C.; He, B.J. Distribution characteristics, growth, reproduction and transmission modes and control strategies for microbial contamination in HVAC systems: A literature review. *Energy Build.* 2018, 177, 77–95. [CrossRef]

26. Liu, Z.; Zhu, Z.; Zhu, Y.; Xu, W.; Li, H. Investigation of dust loading and culturable microorganisms of HVAC systems in 24 office buildings in Beijing. *Energy Build.* 2015, 103, 166–174. [CrossRef]

27. Cheng, K.-C.; Park, H.-K.; Tetteh, A.O.; Zheng, D.; Ouellette, N.T.; Nadeau, K.C.; Hildemann, L.M. Mixing and sink effects of air purifiers on indoor PM2.5 concentrations: A pilot study of eight residential homes in Fresno, California. *Aerosol Sci. Technol.* 2016, 50, 835–845. [CrossRef]

28. Gunschera, J.; Markewitz, D.; Bansen, B.; Salthammer, T.; Ding, H. Portable photocatalytic air cleaners: efficiencies and by-product generation. *Environ. Sci. Pollut. Res.* 2016, 23, 7482–7493. [CrossRef] [PubMed]

29. Lee, J.H.; Kim, J.Y.; Cho, B.-B.; Anusha, J.R.; Sim, J.Y.; Raj, C.J.; Yu, K.-H. Assessment of air purifier on efficient removal of airborne bacteria, Staphylococcus epidermidis, using single-chamber method. *Environ. Monit. Assess.* 2019, 179, 70. [CrossRef]

30. Shaughnessy, R.J.; Sextro, R.G. What Is an Effective Portable Air Cleaning Device? A Review. *J. Occup. Environ. Hyg.* 2006, 3, 169–181. [CrossRef]

31. Hiner, S. Not all HEPA filters are the same. *Power Eng.* 2017, 121, 5.

32. Yang, C. Aerosol Filtration Application Using Fibrous Media—An Industrial Perspective. *Chin. J. Chem. Eng.* 2012, 20, 1–9. [CrossRef]

33. 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] [PubMed]

34. Wheeler, A.J.; Gibson, M.D.; MacNeill, M.; Ward, T.J.; Wallace, L.A.; Kuchta, J.; Seaboyer, M.; Dabek-Zlotorzynska, E.; Guernsey, J.R.; Stieb, D.M. Impacts of Air Cleaners on Indoor Air Quality in Homes Impacted by Wood Smoke. *Environ. Sci. Technol.* 2012, 46, 720. [CrossRef]

35. Fisk, W.J. Health benefits of particle filtration. *Indoor Air* 2013, 23, 357–368. [CrossRef] [PubMed]

36. Morishita, M.; Thompson, K.C.; Brook, R.D. Understanding Air Pollution and Cardiovascular Diseases: Is It Preventable? *Curr. Cardiovasc. Risk Rep.* 2015, 9, 1–9. [CrossRef]

37. Onmek, N.; Kongcharoen, J.; Singtong, A.; Penjumrus, A.; Junnoo, S. Environmental Factors and Ventilation Affect Concentrations of Microorganisms in Hospital Wards of Southern Thailand. *J. Environ. Public Health* 2020, 2020, 1–8. [CrossRef]

38. Guo, J.; Xiong, Y.; Kang, T.; Xiang, Z.; Qin, C. Bacterial community analysis of floor dust and HEPA filters in air purifiers used in office rooms in ILAS, Beijing. *Sci. Rep.* 2020, 10, 1–11. [CrossRef]
39. Choi, S.-J.; Kim, K.H.; Kim, H.J.; Yoon, J.S.; Lee, M.J.; Choi, K.-S.; Sung, U.-D.; Park, W.-T.; Lee, J.; Jeon, J.; et al. Highly Efficient, Flexible, and Recyclable Air Filters Using Polyimide Films with Patterned Thru-Holes Fabricated by Ion Milling. Appl. Sci. 2019, 9, 235. [CrossRef]

40. Nevalainen, A.; Willeke, K.; Liebhafner, F.; Pastuszka, J.S.; Burge, H.; Henningson, E. Bioaerosol sampling. In Aerosol Measurement: Principles, Techniques and Applications; Willeke, K., Baron, P., Eds.; Van Nostrand Reinhold: New York, NY, USA, 1993; pp. 471–492.

41. Brągoszewska, 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]

42. Brągoszewska, E.; Biedroń, I. Indoor Air Quality and Potential Health Risk Impacts of Exposure to Antibiotic Resistant Bacteria in an Office Rooms in Southern Poland. Int. J. Environ. Res. Public Health 2018, 15, 2604. [CrossRef]

43. PN-EN 12322 In Vitro Diagnostic Medical Devices. Culture Media for Microbiology. Performance Criteria for Culture Media. 2005. Available online: https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/iv-diagnostic-medical-devices_en (accessed on 1 October 2020).

44. ISO 11133 Microbiology of Food, Animal Feed and Water—Preparation, Production, Storage and Performance Testing of Culture Media. 2014. Available online: https://www.iso.org/standard/53610.html (accessed on 1 October 2020).

45. Environmental Management—Life Cycle Assessment—Principles and Framework; ISO 14040; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.

46. Bogacka, M.; Pikoń, K. Best Practice In Environmental Impact Evaluation Based On Lca—Methodologies Review. In Proceedings of the 14th International Multidisciplinary Scientific GeoConference-SGEM, Albena, Bulgaria, 17–26 June 2014.

47. Pikoń, K.; Bogacka, M. Local Specificity in Environmental Impact Assessment—End-Point Local Evaluation Indicators. In Proceedings of the 14th International Multidisciplinary Scientific GeoConference-SGEM, Albena, Bulgaria, 17–26 June 2014.

48. Gayer, A.; Mucha, D.; Adamkiewicz, Ł.; Badyda, A. Children exposure to PM2.5 in kindergarten classrooms equipped with air purifiers—A pilot study. In Proceedings of the International Conference on Fire and Environmental Safety Engineering (FESE 2018), Lviv, Ukraine, 7–8 November 2018.

49. Hashimoto, K.; Kawakami, Y. Effectiveness of Airborne Fungi Removal by using a HEPA Air Purifier Fan in Houses. Biocontrol Sci. 2018, 23, 215–221. [CrossRef]

50. Zhao, B.; Liu, Y.; Chen, C. Air purifiers: A supplementary measure to remove airborne SARS-CoV-2. Build. Environ. 2020, 177, 106918. [CrossRef] [PubMed]

51. Tellier, R. Aerosol transmission of influenza A virus: A review of new studies. J. R. Soc. Interface 2009, 6, S783–S790. [CrossRef] [PubMed]

52. Lacey, J.; Dutkievicz, J. Bioaerosols and occupational lung disease. J. Aerosol Sci. 1994, 25, 1371–1404. [CrossRef]

53. Owen, M.; Ensor, D.; Sparks, L. Airborne particle sizes and sources found in indoor air. Atmos. Environ. Part A Gen. Top. 1992, 26, 2149–2162. [CrossRef]

54. Institute of Medicine. Damp Indoor Spaces and Health; The National Academies Press: Washington, DC, USA, 2004; ISBN 10-0-309-09193-4.

55. European Parliament and the Council of the European Union. Directive 2012/19/EU of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE). Off. J. Eur. Union 2012, 55, 38–71. Available online: http://eur-lex.europa.eu/ (accessed on 14 November 2020).

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