

Article

# 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 ( $\text{CFU}\cdot\text{m}^{-3}$ ). The average concentration of fungal aerosol decreased the most when the ACLs were active for 24 min. The reduction was from  $474 \text{ CFU}\cdot\text{m}^{-3}$  to  $306 \text{ CFU}\cdot\text{m}^{-3}$ , and from  $582 \text{ CFU}\cdot\text{m}^{-3}$  to  $338 \text{ CFU}\cdot\text{m}^{-3}$  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

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

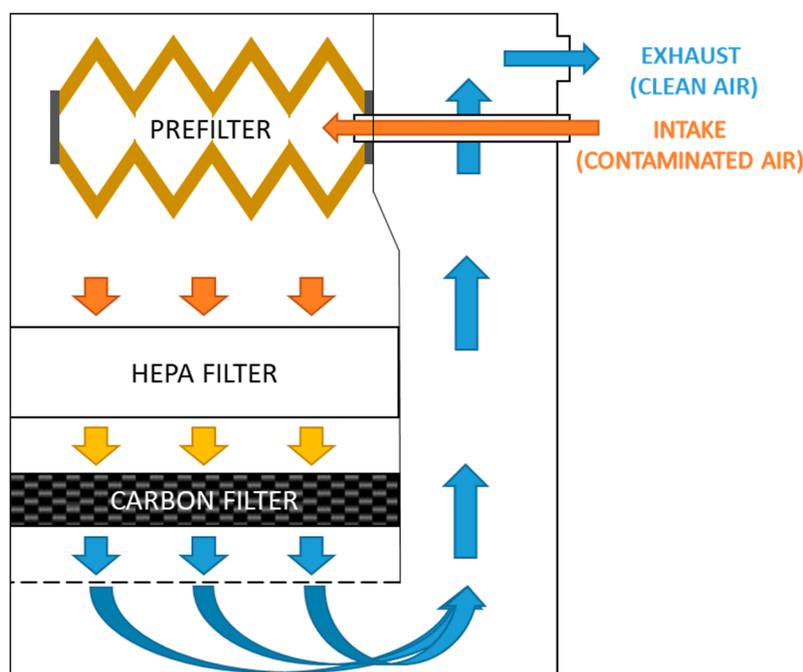
The study was carried out in two living rooms at two dwellings located in Bytom (18°54' E 50°23' N) in Southern Poland. Each analyzed living room was equipped with the same type of ACL, with a PET (polyester) pre-filter retaining larger air pollutants, HEPA-11 filter with an area of 2.2 m<sup>2</sup>, and an adsorption filter with active carbon (an absorbing area of 57,000 m<sup>2</sup>). 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 m<sup>3</sup>. 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 m<sup>3</sup>/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.

**Table 1.** Environmental parameters (mean  $\pm$  standard deviation), and a basic description of 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, m <sup>3</sup>	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 $\pm$ 5.1	20.5 $\pm$ 4.4
Indoor relative humidity, %	41. $\pm$ 8.1	48.2 $\pm$ 3.9
Outdoor temperature, °C	29.1 $\pm$ 4.2	28.6 $\pm$ 3.3
Outdoor relative humidity, %	39.1 $\pm$ 7.4	44.2 $\pm$ 8.9

The scheme of an ACL is presented in Figure 1.



**Figure 1.** The scheme of typical filters used in the air cleaner (ACL) device.

## 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  $\mu\text{m}$  with an air flow of 28.3  $\text{dm}^3/\text{min}$ , 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  $^\circ\text{C}$ . The concentration of living microorganisms was counted as the number of colony forming units in the volume of air ( $\text{CFU}\cdot\text{m}^{-3}$ ).

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.

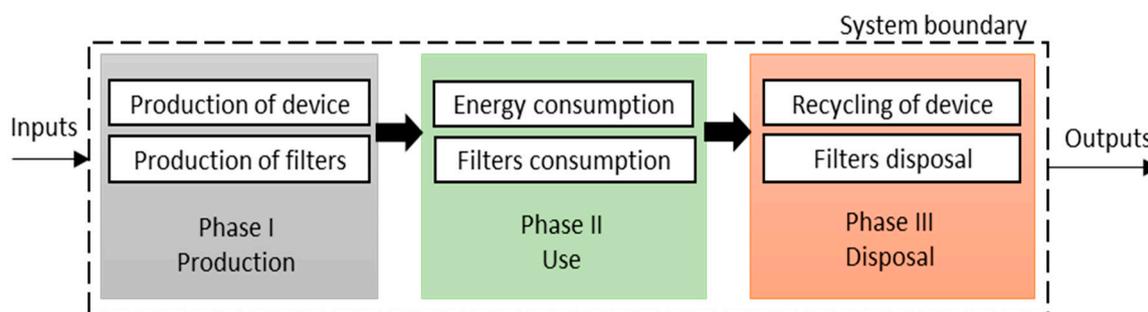


Figure 2. The scheme of life cycle assessment (LCA) phases in the process of air cleaning.

### 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<sup>-3</sup> to 306 CFU·m<sup>-3</sup>, and from 582 CFU·m<sup>-3</sup> to 338 CFU·m<sup>-3</sup> 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<sup>-3</sup> (ACLO) to 373 CFU·m<sup>-3</sup> 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<sup>-3</sup> (ACLO) to 419 CFU·m<sup>-3</sup> ( $p < 0.01$ ). 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].

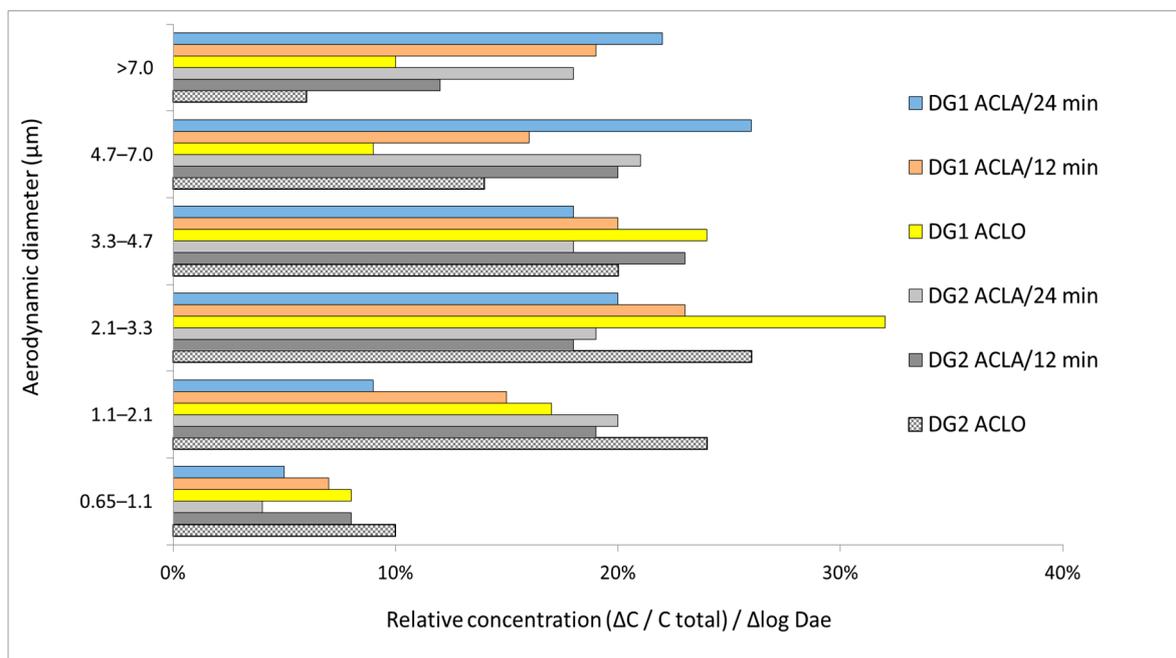
**Table 2.** Average concentration and standard deviation (SD) of fungal aerosol colony-forming units per cubic meter of air (CFU·m<sup>-3</sup>) inside two types of dwellings: dwelling 1 (DG1) and dwelling 2 (DG2), when the air cleaner was active (ACLA) for 12 min and 24 min, or when the air cleaner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

Location	Average Concentration CFU·m <sup>-3</sup> +/-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  $\mu\text{m}$ . Aerosols smaller than 5  $\mu\text{m}$  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).

We observed that while the air cleaner was active (ACLA), the respirable fraction of analyzed bioaerosol (particles less than 3.3  $\mu\text{m}$ ) 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 [52]. The symptoms caused by exposure to a fraction of fungal particles less than 3.3  $\mu\text{m}$  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 a still 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

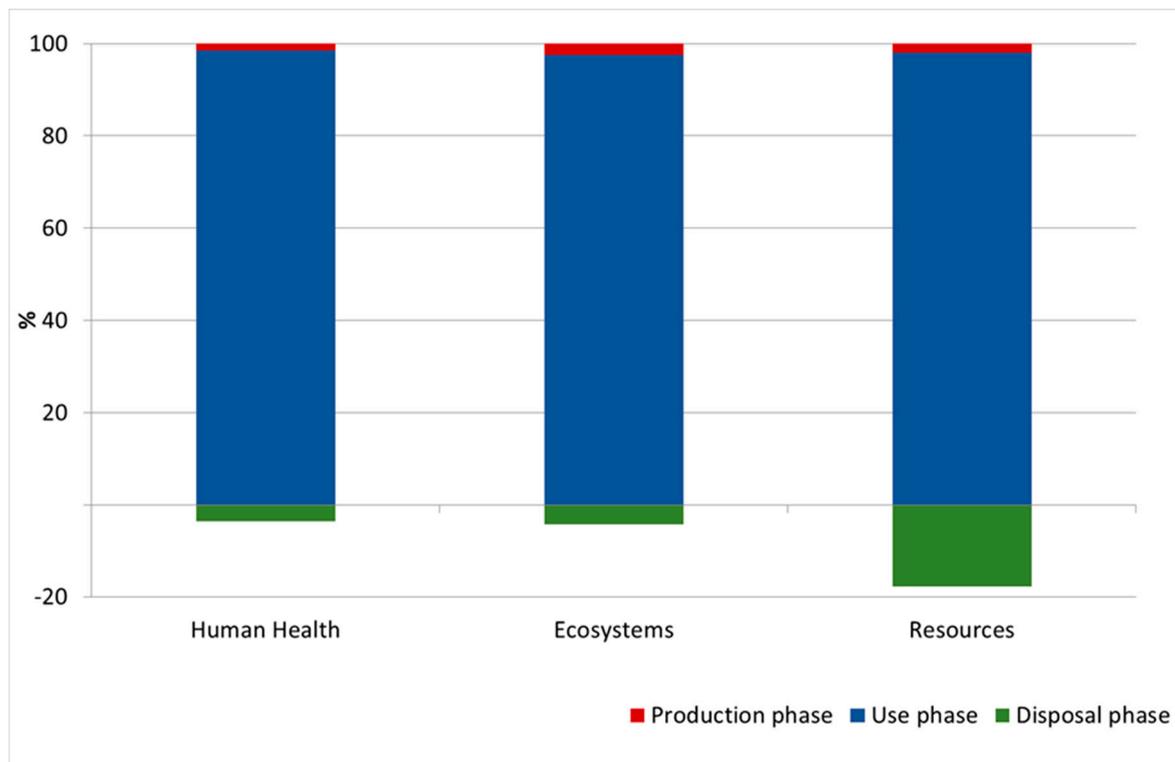
Table 3 presents a list of assumptions based on the Ecoinvent database. It shows the complex data that should be included, but with some limitations due to a lack in the database. Regarding the LCA phases, the three main phases are production, use, and disposal.

**Table 3.** Assumptions for LCA of air cleaning.

LCA	Product/Service	Assumption	Unit	Chosen Ecoinvent Database
Phase I Production	Production of the device	1	piece	Air filter, decentralized unit, 180–250 m <sup>3</sup> /h {RER}  production   Alloc Def, U
	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	_42 Recycling of plastics basic, EU27
	Recycling of metal	1	kg	_60 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.



**Figure 4.** The LCA analysis of ReCiPe Endpoint (H) and the damage assessment in %.

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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**Conflicts of Interest:** The authors declare no conflict of interest.

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