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Review

A Review of Selected Types of Indoor Air Purifiers in Terms of Microbial Air Contamination Reduction

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Abstract: Aims: With the ongoing pandemic and increased interest in measures to improve indoor air quality, various indoor air purifiers have become very popular and are widely used. This review presents the advantages and disadvantages of various types of technologies used in air purifiers in terms of reducing microbial contamination. Methods: A literature search was performed using Web of Science, Scopus, and PubMed, as well as technical organizations dealing with indoor air-quality to identify research articles and documents within our defined scope of interest. Relevant sections: The available literature data focus mainly on the efficiency of devices based on tests conducted in laboratory conditions with test chambers, which does not reflect the real dimensions and conditions observed in residential areas. According to a wide range of articles on the topic, the actual effectiveness of air purifiers is significantly lower in real conditions than the values declared by the manufacturers in their marketing materials as well as technical specifications. Conclusions: According to current findings, using indoor air purifiers should not be the only measure to improve indoor air-quality; however, these can play a supporting role if their application is preceded by an appropriate technical and environmental analysis considering the real conditions of its use.

Keywords: indoor air; air purifiers; air cleaners; indoor air contamination; air filtration; UV; cold plasma; PCO

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1. Introduction

For many years, airborne bacteria present in indoor air in the form of various bioaerosols have been perceived as a probable or, in some cases, even a proven factor causing multiple communicable diseases. Indirectly, these have also been associated with the development and/or exacerbation of chronic respiratory system diseases, including asthma [1–6]. This problem mostly concerns industrialized countries as well as areas of urban infrastructure in developing countries, where people tend to spend about 85% of the day indoors [7–9]. Researchers conducting observations within the field of microbiological indoor air contamination prove that the variety of the genera and species of microbes present in indoor air can be substantial, depending on the facility type. A certain kind of microflora has been observed in schoolrooms, whereas different ones have been reported in residential houses or hospital facilities and other types of buildings [10–15].

It needs to be emphasized that indoor air-quality depends not only on the pollution present inside the indoor area, but also contaminants coming from the external environment. Atmospheric air can contain physical, chemical, as well as biological contamination; however, taking into consideration the contaminants generated inside buildings—besides the living activities of humans—construction materials, finishing materials, not to mention furnishing and accessories and the pollution these emit, also impact the air quality [16,17]. The most economical and effective way to address indoor air-pollution is usually to reduce or eliminate avoidable sources of pollutants and then to extract unavoidable particles, gases, and excessive water vapor that come from normal indoor activities to the outdoors. Increasingly often, ensuring proper indoor air-quality is a priority and the main health determinant for people staying indoors. Apart from minimizing the pollution sources and exhausting indoor pollutants to the outdoors, it is often possible to dilute pollutant concentrations by ventilating a house with cleaner outdoor air. However, opportunities for dilution using the outdoor air are frequently limited by weather conditions or by contaminants in the outdoor air [18].

Due to the SARS-CoV-2 pandemic, people now pay more attention to the prevalence of indoor air biological contamination in the form of aerosols. Microorganisms present in the air include viruses, bacterial cells or cellular fragments, mycelial fragments, and fungal spores [19–21]. People constitute one of the main sources emitting bioaerosols, as a person naturally emits bacteria, which are present in the skin microflora and can also be found on hair or clothes. Sneezing, coughing, and even normal human living activities (motion, moving) can result in producing aerosols. Pets and indoor plants are also considered significant internal sources of bioaerosols [22,23].

Society's growing awareness of the risks related to improper microbiological indoor air-quality, especially in light of the ongoing SARS-CoV-2 pandemic, increasingly drives various measures aiming to improve it. There are three main typical actions that may impact different types of indoor air-contaminants. These include:

Controlling the sources of pollution and undertaking measures to remove or reduce them

Many sources of pollutants in people's homes can be avoided or removed. For example, solid wood or alternative materials can be used in place of pressed wood products that are likely to be significant sources of formaldehyde. Combustion appliances can be adjusted to decrease their emissions. Any areas contaminated by microbial growth should not only be cleaned and dried, but the underlying moisture problem should also be addressed [18,24,25].

Improving the ventilation system capacity

Ventilation with outdoor air is a frequent strategy for diluting indoor air-pollutant concentrations, provided that the outdoor air is relatively clean and dry or that it can be made so through mechanical means, such as filtering. Outdoor air enters buildings in three ways. Small amounts of air are constantly entering by infiltration through the building envelope. Larger amounts enter when windows and doors are left open for extended periods and can also be brought in by continuous supply or exhaust fans [18,26–28].

Applying technologies for indoor air cleaning

Air cleaning has proven useful when used along with source control and ventilation, although it is not a substitute for either of the two methods. Air cleaning alone cannot ensure adequate indoor air-quality if significant sources are present, exhaust and outdoor air ventilation are insufficient, or the operating hours of an air-cleaning device are not sufficient to reduce indoor pollutant concentrations [17,27,29,30].

In the light of the ongoing SARS-CoV-2 pandemic, as well as due to considerable atmospheric air pollution with particulate matter, various indoor air-cleaning devices are becoming increasingly popular. These can be used both for removing or reducing the number of particulates—mainly the ones with diameters ranging from 2.5 to 10 μm, chemical contaminants such as volatile organic compounds (VOC) or ozone, as well as for reducing microorganisms present in indoor air [25]. Devices based on only one type of air-purification method are rarely seen. Combined technologies in many portable and in-duct air cleaners seem to be the most effective way to accomplish their purpose.

Depending on the technology used, in order to obtain expected goals, air purifiers should be placed in optimal places, at the right position and in a sufficient number. Factors to consider include the number of people permanently staying/working in the area, their safety air exchange, visiting people, and areas that the air purifier cannot reach.

This paper reviews articles concerned with the most popular technological solutions available on the market, factors important for effective use and future directions for expanding the knowledge about indoor air purification processes.

2. Methods

Searching Strategy

The literature search was carried out between November 2021 and February 2022 using Web of Science, Scopus, and PubMed to identify research articles within the defined scope. This database was searched simultaneously using (with "AND") the major terms "indoor air quality" and "indoor air", "air purifiers" and "air cleaners" as well as "indoor air contamination" together in the "Topic" field, which includes search within the title of the article, its abstract, and keywords. A total of 116 articles were identified as potential articles to include in the review, while 95 were used. In addition, the resources of technical organizations dealing with indoor air-quality in various countries were searched and several official guidelines or recommendations on the application of air cleaning devices were used.

3. Efficiency, Effectiveness, Clean Air Delivery Rates (CADR) for Air Cleaners

There are two crucial parameters that influence the performance of every air-cleaning device: efficiency and effectiveness.

Efficiency: a fractional measure of the device's ability to reduce the concentration of pollutants in the air that passes once through the device in a laboratory (controlled conditions).

Effectiveness: a measure of the device's ability to remove pollutants from the space in which it is located and operated. It is vital that the device's effectiveness be a function of its use in real-world conditions, and it depends on many factors, including its location, installation, airflow rate, and operating hours. In fact, these factors may have a stronger impact on its effectiveness than its laboratory-tested efficiency. For example, an air cleaner operating in a space with multiple opened windows may be less effective than when operating in a space with closed windows because ventilation through the open windows is likely to be a more dominant removal mechanism. A similar situation applies to indoor air microbial contamination. Spaces with increased people activity (shops, public transport, offices), constituting a constant and significant source of bacteria and viruses, may be difficult to clean with the device even with high efficiency because of its low effectiveness due to a high microbial load in the air [31,32].

Each air-purifying device, in order to ensure its effective operation, should be properly selected in terms of the efficiency in generating an appropriate volume of treated air. This parameter is referred to as the Clean Air Delivery Rate (CADR) and measures an air cleaner's effectiveness based on room space and the volume of clean air produced per minute. Particles removed to achieve "clean air" referred to in CADR include pollen (particles ranging from 5 to 11 μm), dust (particles ranging from 0.5 to 3 μm), and tobacco smoke (particles ranging from 0.09 to 1 μm). These three pollutants are used as examples representing large-, medium-, and small-sized particles, respectively. CADR labeled on the product packaging is typically the highest CADR achievable, which typically occurs at the highest airflow setting. It is also important to note that a portable air cleaner's removal rate also competes with other removal processes occurring within the space, including deposition of particles on surfaces, sorption of gases, indoor air chemical reactions and outdoor air exchange. The higher the CADR, the more particles the air cleaner will remove and the larger the area it can cover. Thus, although portable devices may not achieve their rated CADR under all circumstances, the CADR value does allow comparisons among portable air-cleaners [32–34].

4. Main Technologies Used in Air Purifiers

4.1. Air Purifiers with Mechanical Air Filtration

Mechanical filtration is a simple and widely used air-purification technique aiming to remove suspended particulate matter. Filters have become a standard element in most mechanical ventilation and air-conditioning systems, as well as indoor air-purifying devices. Filters can be made of various kind of fibers (paper, organic materials, glass fibers), nanofibrous membranes, and porous polymeric membranes. The efficiency of the filtering process depends mainly on the class of the air filter applied. The size, type, and shape of particles captured by the filtering material, as well as the scale and kind of filtering fiber cross-linking, air flow rate, and its humidity and temperature, are all factors that have a considerable impact on how efficiently these filters work. Mechanical media filters see improved efficiency with increasing loads [35]. Commercially available air purifiers have different kinds of mechanical filters, starting from prefilters made of plastic or metal net applied to capture large particles, such as hair or fur, big dust particles, or clothing fibers, through High Efficiency Particulate Air (HEPA) filters, the efficiency of which reaches 99.97% for particles featuring the greatest permeability (0.3 μm) according to PN-EN 1822:2009 [36]. Air purifiers are usually equipped with several types of intermediate filters with variable effectiveness, offering multilevel activity in order to capture smaller and smaller particles suspended in the air. Filters may have certain added accessories, providing biocidal properties against microorganisms suspended in indoor air. Silver ions or silver added in the form of nanoparticles, along with natural additives, such as essential oils or propolis, are popular additions since studies confirm their efficiency [37–39]. Over time, all mechanical filters lose their efficiency in terms of reducing the number of air-suspended particles, since a considerable number of these particles accumulate within the structure of the filter. This also leads to a reduction in pressure and reduced air flow through the matrix of the filter [40]. Incorrect filter application leads to the risk of leakage and decreased efficiency and effectiveness. In order to prevent this, mechanical filters need to be cleaned and changed according to their specified operating life. Additionally, microorganisms accumulated within the structure of the filter can remain alive. They may multiply in humid conditions and be released from the matrix of the filter into the air flow discharged from the device or the ventilation system, which poses the risk of creating a secondary source of microbiological air contamination inside the indoor area [41].

4.2. Air Purifiers with Cold Plasma Generators

Plasma is a strongly ionized gas created as a result of high-voltage electric discharges and generally contains electrons, positive ions, and neutral particles (atom constituents) [42]. Plasma not characterized by thermodynamic equilibrium is also known as cold plasma or nonthermal plasma. It is frequently utilized to improve indoor air-quality. Plasma has qualities enabling precipitation of particles due to electrostatic phenomena; it emits UV radiation and thus contributes to particle oxidation and removal of virus particles, bacterial cells, and other microorganisms [17,43–45]. However, the mechanism underlying microbial inactivation has not been fully tested yet [46]. Apart from the above, the process itself generates free radicals and other oxidants that break chemical bonds and lead to decomposition of substances, such as VOC to CO_2 and H_2O [47]. Cold plasma used in air filters is usually generated with continuous corona discharges [17]. It is a crucial fact that, apart from ozone produced during the process, the operation also leads to unwanted by-products, which in some case may even be more harmful for the building residents than the contaminants the air purifier should eliminate. The process may produce methyl nitrate and 2,3-butanedione, formic acid or carboxylic acids [48,49]. Cold plasma technology is becoming a very promising solution, which may successfully complement conventional indoor air-cleansing techniques in the future. Unfortunately, due to a large number of unknown issues associated with this technology, the matter begs for further investigation that will allow optimization of the parameters of the process and explain doubts concerning the mechanisms underlying the impact on microorganisms, along with the possible negative influence on human health and the environment [42,50].

4.3. Air Purifiers Utilizing Photocatalytic Processes (PCO)

Photocatalytic air-cleansing systems, including filters, constitute a dynamically growing market trend in the domain of indoor air purifiers. Titanium dioxide (TiO_2) is among the most well-known and most often used photocatalysts, especially in its nanoparticle form. Ultraviolet light (UV) falls on nanoparticles, which leads to the occurrence of free electrons on the surface of TiO_2 that then connect with oxygen from the air and create its active forms, along with electron holes. These, in hand, produce hydroxyl radicals when connected with water vapor and water. Hydroxyl radicals are characterized by very strong oxidizing properties, and that is why they can not only contribute to the decomposition of various organic contaminants, such as VOC, oils, fats, exhaust fumes, odorous and odorless gases, but they can also reduce the number of microorganisms present in indoor air [51–53]. The biggest issues associated with utilizing photocatalytic processes include the production of harmful by-products, such as formaldehyde or acetaldehyde, the necessity of using UV lamps, which may cause an additional ozone emission inside the room, as well as the limited lifespan of the photocatalyst [54,55]. It needs to be additionally emphasized that, unlike the reduction of chemical pollution, the efficiency of devices using photocatalytic processes intended for residential environments in reducing microorganisms is very poorly documented. What also cannot be ignored is the fact that recent studies have shown that long-term exposure of humans to titanium dioxide nanoparticles is not irrelevant as far as human health is concerned. When it comes to devices using photocatalytic processes, their activity is associated with possible release of nanoparticles to the air exhausted into the indoor area during operation. Even small doses of accumulated titanium dioxide particles may exert a negative influence on the intestinal mucosa, brain, heart, and other internal organs, which may lead to an increased risk of developing multiple diseases, including neoplasms. Nevertheless, the fact that nanoparticles used during the photocatalysis may possibly have an impact should be taken into consideration, especially in the situation when the market offers a wide range of air purifiers based on this technology [56].

4.4. Air Purifiers Using the UV Light Technology

Today, disinfection processes based on UV radiation are widely used in hospitals and healthcare facilities, as well as in malls, office areas, schools, residential areas, and means of public transportation [57–59]. Unfortunately, for marketing purposes, manufacturers or retailers place questionable statements without valid scientific grounds, concerning the efficiency of devices, which in the vast majority of cases is highly overvalued [60]. The radiation process mainly uses the UV wavelength spectrum ranging from 200 to 280 nm, the so-called UV-C spectrum [61]. This band causes critical damage to the genomic system of microorganisms, making it impossible for them to execute a proper DNA or RNA replication, and significantly reducing their viability as a result. That is why the impact of UV radiation on microorganisms is properly known as "inactivation", and not "killing". Although the efficiency of the process of inactivating microorganisms is widely known, the efficiency towards individual groups and species may differ significantly [62–65]. We can divide instruments operating based on UV radiation to directly acting devices (UV radiation is guided directly to the surface) and flow devices (the UV emitters are hidden inside the casing, through which the air is being channeled). As far as the first group is concerned, the skin or eyesight of humans staying indoors is directly exposed to UV radiation, which causes harmful photochemical reactions in tissues, causing skin burns (erythema), conjunctivitis and keratitis, cataract, or neoplastic skin lesions [66–68]. The direct impact of UV radiation may also damage and degrade materials, including plastic [69]. Another issue related to using these two types of UV-radiation-based air purifiers lies in the fact that these devices release ozone and oxygen free radicals into the air. In indoor air, their concentration may reach quite high levels, causing irritation in the human conjunctiva and mucous membrane lining the respiratory tract. What is more, ozone is a substance with strong oxidizing properties that reacts with VOC suspended in the air, causing the occurrence of derivative compounds that can have toxic properties. The amount of ozone generated is directly associated with the type of UV-C emitters used in a given device, as well as with their number, the type of radiation source, and the total output. The higher the power of the device, the greater the emission of ozone into the air [60,70,71].

4.5. Air Purifiers Using Electrostatic Filtration

Electrostatic air filters are filters combining electrostatic processes with mechanical filtration, and most of them are washable and can be cleaned on regular basis. These filters operate based on a strong electric field, the corona discharge phenomenon causing air ionization, along with the electrostatic attraction of charged particles. Particles suspended in the air are attracted and captured by the static load when the air passes through the cross-linked fibrous structure of the filter, as these fibers are susceptible to electrostatic loads. According to various estimates, depending on the ionizing power and filter types, the efficiency of filtration with electrostatic filters ranges from 82% to 94% [72,73]. The disadvantage of this solution lies in the fact that electrostatic filters operate in a manner that forces particle ionization, which is directly associated with the emission of ozone (O_3) and nitric oxide (NO_x) [74]. These two compounds, being harmful for human health, are commonly perceived as indoor air contaminants. Corona discharges also lead to electromagnetic disturbances. Apart from the aforementioned user health and safety limitations, the primary disadvantage associated with using these devices is the fact that household solutions usually feature low ionization levels, and hence, a considerably lower air-filtering efficiency. That is why these filters are most commonly used as one of several combined indoor air purification stages in air-cleansing devices, e.g., in combination with mechanical filtration or photocatalytic processes [72,74].

A short summary of the most popular devices intended for indoor air purification, including their advantages and disadvantages, can be found in Table 1.

Table 1. The summary of the advantages and disadvantages of air-cleaning technologies.

Air-Cleaning Technology	Advantages	Disadvantages
Air purifiers with mechanical air filtration	A simple, widely available, and relatively low-cost technique. High-rated efficiency; excellent extraction capabilities for many particle sizes. No additional emission of by-products.	The effectiveness depends on the flow rate, filter installation (its quality) and appropriate maintenance. Sensory air pollutions/odors. The risk of secondary source of microbiological air contamination. Microorganisms accumulated within the structure of the filter may be released into the air, causing secondary contamination of the indoor area.
Air purifiers with cold plasma generators	Depending on conditions–relatively high efficiency against microbial air contamination as well as VOC. Possibility to combine with other air cleaning technologies to improve performance and minimize by-product formation.	Production of O_3 and other unwanted by-products, such as formaldehyde, carbon monoxide, chloroform, nitrogen oxides.
Air purifiers utilizing photocatalytic processes	Reduction of a wide array of gaseous pollutants (e.g., aldehydes, aromatics, alkanes, olefins, halogenated hydrocarbons). Possibility to combine with adsorbent media to improve effectiveness.	Production of harmful by-products, such as formaldehyde or acetaldehyde and ozone. Often limited lifespan of the catalyst. No standard test methods for real-life effectiveness of the devices. Possible release of titanium dioxide nanoparticles to the air exhausted to the indoor area during operation.
Air purifiers using the UV light technology	Effective at high intensity with sufficient contact time. Effective inactivation of microbes on surfaces.	Emission of ozone. The risk of human skin and eye irritation. Inactivation but not removal of microbes. Possibility of damaging and degrading materials due to the direct impact of UV radiation.
Air purifiers using electrostatic filtration	High efficiency (82–94%)—depending on the ionizing power and filter types. Low pressure drop and minimal impacts on the HVAC systems. Low maintenance requirements.	Generation of ozone (O_3) and nitric oxide (NO_x). Efficiency typically decreasing with load and plates requiring cleaning.

5. Recommendations of International Organizations

In the face of the ongoing pandemic and increasing interest in measures to improve indoor air-quality, many international organizations specializing in and dealing with health and room ventilation have issued a series of recommendations. The European Centre for Disease Prevention and Control (ECDC) has issued guidelines on ventilation of indoor spaces in COVID-19 pandemic (except healthcare facilities), recommending good practices, such as increasing indoor-air exchange compared to the condition preceding the pandemic, avoiding air recirculation and maintaining mechanical ventilation systems under continuous operation, as well as ensuring frequent air exchange through regular ventilation/opening windows in indoor areas with gravitational ventilation. Nevertheless, the aforementioned guidelines do not recommend using mobile air-purifiers as a solution equivalent to the methods listed above, emphasizing limited data on their efficiency and doubts concerning their health safety, especially in the context of ozone emission. The guidelines do not forbid using these devices as a supplementary solution supporting ventilation of indoor spaces or their mechanical ventilation; however, it is indicated that these should not replace the suggested methods of conduct [75].

The British technical organization—the Chartered Institution of Building Services Engineers (CIBSE), an advisory board to the British government within the field of proper practices associated with ventilation and air-conditioning systems in the pandemic era—has stated that it is worth considering the use of mobile air-purifiers in poorly ventilated indoor spaces with high density and traffic volume. This guideline mainly includes devices filtrating the air with HEPA filters or ones that use UV radiation. At the same time, the document emphasizes that currently, there are no research results providing concrete evidence that UV-C radiation is effective against SARS-CoV-2 in indoor spaces under natural circumstances [76]. On the other hand, the American Environmental Protection Agency (EPA) argues that air purifiers and additional filters in ventilation and air-conditioning systems may help reduce bacteria and viruses in air aerosol, but only in combination with other recommended good hygiene practices, including social distancing, hand washing, and surface disinfection [77]. The Federation of European Heating Ventilation and Air Conditioning Associations (REHVA) also does not list air purifiers as one of the recommended measures to reduce microbiological air-contamination in indoor spaces, including SARS-CoV-2 infections [78]. The American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) takes into account the additional application of UV-radiating devices or additional air-filtering appliances, equipped with highly efficient HEPA filters; however, these recommendations focus mainly on healthcare. The UK Scientific Advisory Committee on Emergencies Environment and Modelling Group has concluded that the application of air-cleaning devices may be a useful strategy to reduce airborne transmission risks in poorly ventilated spaces. It has also noted that air cleaning devices have limited benefit in spaces that are already adequately ventilated and are not necessary for adequately ventilated buildings unless there are identified specific risks [79]. Furthermore, using these types of devices should always be preceded by a proper risk analysis, considering the possible negative influence that these devices may have on human health [80,81].

Available literature data focus mainly on tests conducted on the prototypes of air purifiers, which are performed in test chambers of small cubature (1–2 m^3), which does not reflect the real dimensions and conditions observed in residential areas or office spaces—real-world conditions. Moreover, test chambers have no sources constantly emitting microorganisms, such as the presence of people, which can be reported in real conditions under which air purifiers are used. It is also worth remembering that most commercially available devices have no scientifically confirmed efficiency for removing bioaerosol, VOC, or suspended particles [82]. Manufacturers and retailers offering air purifiers often state in their marketing leaflets that the efficiency in removing the given group of contaminants reaches the level of 99.99%, which is purely a marketing trick. Therefore, there are questions related to the effectiveness of various devices in terms of reducing the number of microorganisms in the air in real conditions, as well as the lack of clear recommendations regarding the prevalent use of such devices.

6. Discussion

The effectiveness of various air cleaners in terms of reducing microbiological air contamination (bacteria and fungi) might be considerably lower than the efficiency declared by the manufacturers/retailers in their marketing materials, usually based on test results obtained in model conditions, without the presence of people in the room or the test chamber. Under strictly defined model conditions, the majority of air purifiers can demonstrate a very high efficiency, reaching 100%, which does not reflect their efficiency in real conditions. Overall, field-testing and simulation studies show that high-CADR portable air cleaners can reduce the levels of airborne particles and, in some cases, gaseous pollutants in a house, but despite of high CADR values, air cleaner may not be as effective as expected based on the manufacturer's declarations [18,82]. Real conditions and some environmental factors can be crucial for the final effectiveness of every device. When it comes to cold plasma technology, depending on environmental working conditions, the obtained results of reduction ranged from 20% to 70% for various bacterial and fungal strains [43–45]. Lai et al. [83] indicated that with the low concentration of ions generated by the cold plasma activity, along with increased air humidity, the efficient inactivation of *E. coli* and *S. epidermis* bacteria was significantly lower than in the optimized process. The efficiency of the photocatalytic process during the process of purifying the air of microbiological contamination was confirmed during multiple model studies using specific bacterial and fungal strains. However, there are no reference methods that could be applied in order to confirm the efficiency of these devices, both the ones constituting a part of air-conditioning systems and mobile appliances—the so-called air purifiers [18,55]. Vohra et al. [84] and Mitoraj et al. [85] showed that *Bacillus cereus*, *Staphylococcus aureus*, and *Escherichia coli* strains were almost completely inactivated after various periods of exposure, lasting from 1 h to 24 h. On the other hand, *Aspergillus niger* fungal species demonstrated full inactivation after a 48 h-long exposure. Sánchez et al. [86] showed that properly selected technology using photocatalytic reactions, used in real conditions, proves to be efficient towards bacteria; however, in order to achieve complete fungal inactivation, it is important to perform a series of modifications to the process, covering the power of UV radiation activating the process, exposure time, and the size of the photocatalytic deposit. This confirms the previously cited data, indicating that the efficiency of the air-purification process with purifying devices depends mainly on the proper selection of the process parameters, including the proper selection of purification technology, along with environmental conditions and the devices' capacity as far as the air flow is concerned [26]. The health safety of people remaining within the premises where the devices containing photocatalytic deposits are operating is yet another important aspect, especially in the context of releasing nanoparticles of active compounds, such as TiO_2. Mechanisms responsible for the negative impact of nanoparticles have not been fully discovered yet, and this currently constitutes a crucial area for further research [56]. Guimera et al. [87] proved that UV-C flow lamps, used in various rooms within a healthcare facility, showed efficient reduction in bacterial and fungal count in the air of microbiologically pure premises, characterized by a small number of people remaining in these rooms, such as strictly medical areas. For publicly available areas, such as corridors, UV-C flow lamps did not show any influence on the bacterial and fungal concentration in the air. Kujundzic et al. [88] reported similar conclusions based on tests conducted with a UV-C flow lamp installed inside the tested air purifier. The lamp did not show any considerable impact on microorganism reduction in the air flowing through the device. However, a noteworthy impact of UV radiation was confirmed for the same lamp, which affected microorganisms suspended inside the air filter used in the purifier within 60 min. It has been shown that the low microbial reduction concerning air contamination resulting from the activity of a UV-C flow lamp may be associated with the short-lasting exposure of microbial cells to this radiation. Due to the confirmed action of UV-C radiation in terms of inactivating microorganisms, commercially available UV lamps are described as universal devices, with their efficient activity being universally confirmed. What tends to be overlooked is the fact that the efficiency of UV radiation always depends on the sensitivity of the given microbial genus or species, wavelength, and the power of emitters (lamps), along with the radiated air volume and humidity [89–92].

In order to fully evaluate this type of air purifier, taking into account their safety for the health of people staying in the premises, it is crucial to consider the emission levels of free radicals and ions, as well as ozone. From the point of view of the impact that indoor air pollution has on human health, it is essential to analyze the possible negative impact of by-products, especially in the case of high-power cleaning devices (plasma generators, UV lamps, electrostatic filters). Applying some technical solutions, such as activated carbon filters, after removing the potential source of emission may be effective for decreasing potential by-products [40]. Unfortunately, manufacturers and retailers very rarely have access to such data, and the possible negative impact on user health is completely overlooked in their advertising materials.

7. Conclusions and Future Directions

Using air purifiers, especially during the pandemic, should not be the only way to improve indoor air-quality. Available data do not confirm their real efficiency. Effective ventilation of premises should be the main strategy for diluting indoor air pollutants concentration, including microbiological contaminations.

There are no actual recommendations for using air purifiers in well-ventilated areas of buildings. Some guidelines published by technical organizations suggest the use of this kind of device in poorly ventilated indoor spaces with high density and traffic volume. The use of air purifiers should also be considered as a complementary approach for areas with special needs and in which a high cleanliness of the air is important to accomplish, e.g., hospital premises.

Actual legislation of the market does not include unified test methods confirming the efficiency of air purifiers in real conditions.

Using air purifiers to improve the microbial quality of indoor air should always be preceded with a fine selection of a proper device, including:

- ➢ CADR rate;
- ➢ Intended place of use limiting the possibility of airflow obstruction;
- ➢ Effectiveness confirmed by results of tests conducted by reliable third entity;
- ➢ Potential impact of the purifying technology on human health and safety.

Future studies and tests conducted by a reliable third party under real conditions are urgently needed to clarify the real benefits of air-purifier application.

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