Chapter

Impact of Air-Conditioning Filters on Microbial Growth and Indoor Air Pollution

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Abstract

Contemporary lifestyles dictate that people spend between 60 and 90% of their daily lives indoors. For those living in warm climates, air conditioning is thus considered a necessity. Air conditioners function by removing hot and humid air from building interior and replacing it with cooler air. Microorganisms are considered among the most important sources of poor quality of indoor air, and contamination of this air by microbial pollutants is being increasingly recognized as a public health problem and a probable cause of the so-called sick building syndrome. In this regard, microfiber glass panel filters are considered to provide an effective solution for air filtration and have been demonstrated to improve air quality in many applications. However, recent research has demonstrated that certain microorganisms are able to colonize panel filter surfaces. Studies on selected microbes isolated from the most commonly used filters have revealed that the bacterial and fungal moist masses carried on sponge-type filters are greater than those carried on polyester and high-efficiency particulate air (HEPA) filters. Moreover, microbial moist mass has been found to increase with increasing incubation time. In addition, recent research has shown that certain microorganisms, particularly fungi, can colonize the materials used in heating, ventilation, and air-conditioning systems (HVAC).

Keywords: colonization, air-conditioning system, filter, HEPA, indoor, sick building syndrome

1. Introduction

Microorganisms are among the most important sources of poor indoor air quality, and contamination of indoor air by microbial pollutants is being increasingly recognized as a public health problem and as one of the factors contributing to sick building syndrome. Bioaerosols, such as those comprising fungi, bacteria, and viruses, in indoor air can cause allergic and infectious diseases, respiratory problems, and hypersensitivity reactions. People who are sensitive to indoor environmental problems complain of a wide variety of symptoms, ranging from headache, tiredness, nausea, and sinus congestion to eye, nose, and throat irritations [1].

Although invisible to the naked eye, the atmosphere is populated by a diversity of microorganisms, including bacteria, fungi, algae, and protozoa. Researchers have estimated that the total bacterial count within the troposphere layer ranges from 1×10^3 to

1×10^5 cells/m^3. Dust is formed during the passage of organic and inorganic particles from external and internal resources, which subsequently aggregate and precipitate. House dust, for example, consists of cotton fibers, hair, bacteria, molds, and remaining paint particles [2, 3]. The findings of a previous study have indicated that the average number of fungi contaminating 820 indoor air-conditioning units was 1252 CFU/m^3, with range of 17–9100 CFU/m^3. In addition, Baxter [4] found that the average number of spores isolated from 85 buildings was 913 cells/m^3, ranging from 68 to 2307 cells/m^3. Daily and seasonal numbers of contaminant microorganisms in the air vary and depend primarily on environmental factors, such as vegetation, human activities, and seasonal fluctuations [5]. Most of these microorganisms are bacteria and fungi [6].

These microbial contaminants affect the residents of enclosed and humid buildings, particularly in the case of toxic hygrophytic fungi, such as *Phoma* sp., *Exophiala* sp., *Aureobasidium pullulans*, *Acremonium* sp., and *Sporobolomyces*, that are frequently isolated from the cooling pipes of air-conditioning systems. Gram-negative bacteria and their toxins are also isolated from leaks in air-conditioning pipes. Yang [7], for example, identified *Legionella pneumophila*, which is the causal agent of legionnaires disease, as a dominant bacterium in the water leaking from cooling systems. In addition, *Pseudomonas aeruginosa*, which has also been isolated from water leaking from air-conditioning systems, is an opportunistic bacterium responsible for several diseases. Many studies have proven that the heating, ventilation, and air-conditioning (HVAC) systems can become contaminated with organic pollutants, bacteria, and fungi, as well as by particulate matter derived from mice, insects, and nematodes. The bacteria and fungi colonizing these systems tend to saprophytic and thrive in areas that meet their environmental requirements [7]. Fungi have been proven to be a source of airborne contamination in air-conditioning systems [8], including *Alternaria*, *Aspergillus flavus*, *Aspergillus fumigatus*, *Aspergillus niger*, *Aspergillus ochraceus*, *Aspergillus versicolor*, *Botrytis cinerea*, *Cladosporium herbarum*, *Epiccocum purpurascens-sterilia*, *and Penicillium* spp., among which *A. fumigatus*, which has been isolated from air-conditioning filters, is responsible for many dangerous infections. With regard to bacteria, *Propionibacterineae*, *Staphylococcus*, *Streptococcus*, and *Corynebacterineae* (17, 17.5, 20, and 3%, respectively) have been detected in aeration pipes and air filters installed in indoor areas [9, 10]. In addition small percentages of species from the genera *Fusobacterium* and *Veillonella* (0.02 and 0.1%, respectively), which are associated with the mouth cavity and saliva, have also been identified as air-conditioning system contaminants [11–13].

With a view toward providing clean indoor air, several studies have been conducted to investigate measures that can be used to control the levels of microorganisms that colonize filtering, heating, ventilation, and air-conditioning systems. In this regard several types of air filters have been studied with the aim of preventing the penetration of particles. However, although high-efficiency particulate air (HEPA) filters are widely used in hospitals, *Aspergillus*-associated infections continue to occur [14]. Currently, most indoor air-conditioning systems contain internal filters that extract microorganisms from the air (**Figure 1**). However, these microbes often remain viable and can be returned to the surrounding atmosphere under certain circumstances, such as inefficient operation, during periods of maintenance, or due to temporary malfunction [15].

It is widely acknowledged that air-conditioning filters do not remove all the particles from the air. Even the use of HEPA filters will not completely eliminate the problem of microbial contamination, as this material will only retain particles of a minimum of 3 microns in size. Thus, dust particles with sizes smaller than 3 microns will pass through unhindered. Furthermore, when the filters become excessively wet, they can provide a fertile environment for the proliferation of molds and bacteria [16, 17].

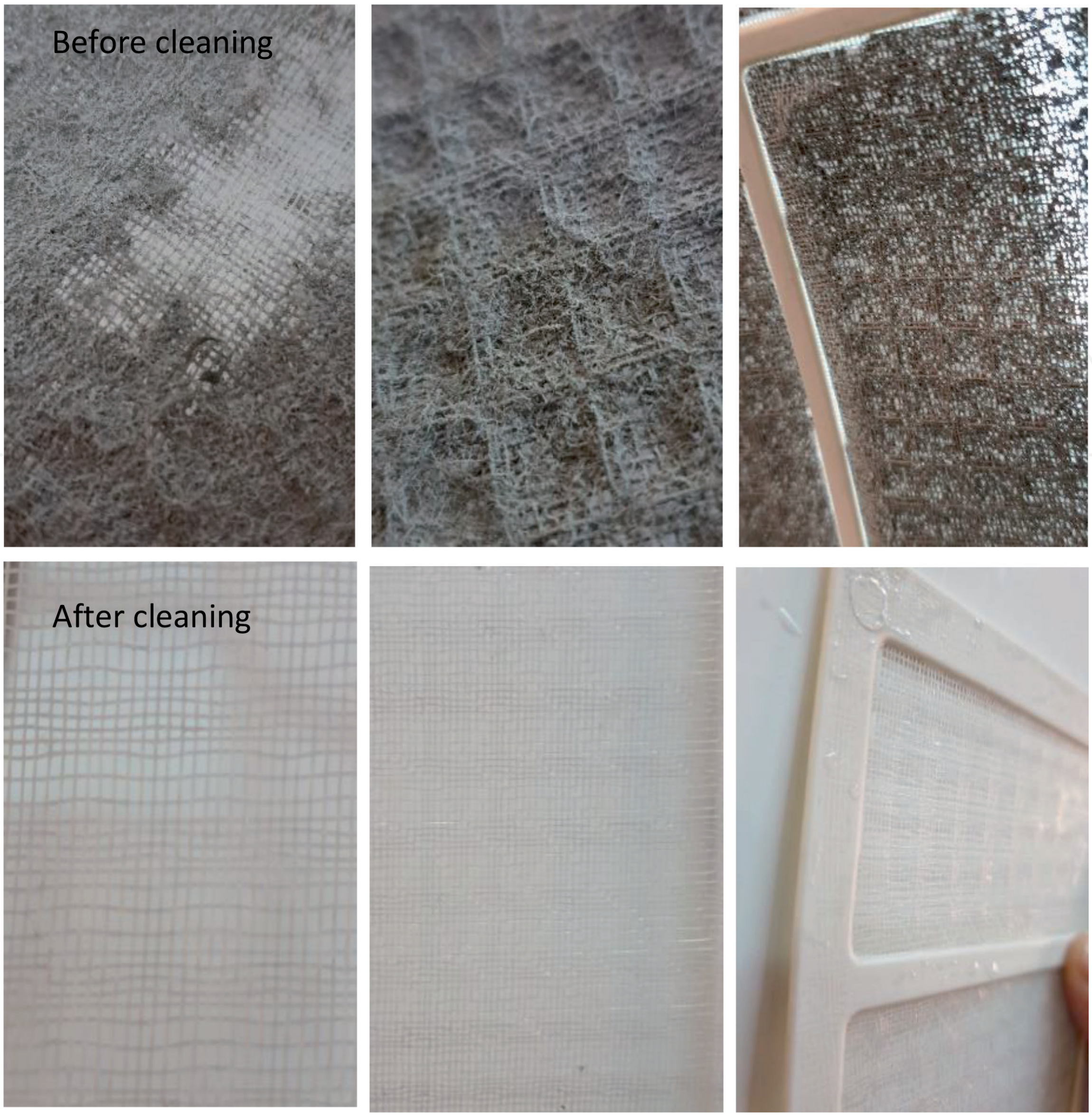

Figure 1.
Accumulated dust on discarded polyester filters.

In this chapter, several new topics related to environmentally sustainable buildings were presented, as it clearly describes the potential impact of HVAC systems on the indoor air quality with the aim to enhance the healthy buildings. The chapter is structured as follows: besides the Introduction (Section 1), Section 2 introduces the principle of air filtration, Section 3 is concerned with presenting the traditional air filters, Section 4.5 demonstrates a comparison between the most common and modern HVAC filters, Section 6 provides the impact of HVAC filters on indoor air quality, and Section 7 is concerned with presenting several results for research progress about the relationship between microbes and traditional filters and microbial colonization of the types of filters commonly used in air-conditioning systems.

2. Principle of air filtration

2.1 How filters work

There are five different collection mechanisms that determine air filtering performance: straining, interception, diffusion, inertial separation, and electrostatic attraction.

The first of these mechanisms applies mainly to mechanical filters and is influenced by particle size. **Figures 6** to **10** illustrate the five mechanical principles of particle capture and their contribution to the retention of particles of different sizes.

Straining (sieving) occurs when the opening between the media components (e.g., fibers, screen mesh, and corrugated metal) is smaller than the diameter of the particle the filter is designed to capture. This principle spans across most filter designs and is entirely related to the size of the particle, media spacing, and media density (**Figure 2**).

Interception occurs when a large particle, because of its size, collides with a fiber in the filter that an air stream is passing through (**Figure 3**).

Diffusion occurs when the random (Brownian) motion of a particle causes that particle to come into contact with a fiber. When a particle vacates an area within the media, by attraction and capture, it creates an area of lower concentration within the medium into which another particle diffuses, only in turn to be captured itself. To enhance the likelihood of this attraction, filters employing this principle operate at low media velocities and/or high concentrations of microfine fibers, glass, or otherwise (**Figure 4**).

Inertial separation is based on a rapid change in air direction and the principles of inertia to separate particulate matter from the air stream. Particles moving at a certain velocity tend to remain at that velocity and travel in a continuous direction. This principle is normally applied when there is a high concentration of coarse particulate matter and in many cases represents a pre-filtration stage prior to the passage of air through higher-efficiency final filters (**Figure 5**).

Electrostatic attraction is obtained by charging the media as a part of the manufacturing process (**Figure 6**). However, it plays a minor role in mechanical filtration. After fiber contact is made, smaller particles are retained on the fibers by a weak electrostatic force. The force may be created through a manufacturing process or be dependent upon airflow across media fibers. The force is eradicated as media fibers collect contaminants that act as an insulator to a charge. Electrostatic filters, which are composed of polarized fibers, may lose their collection efficiency over time or when exposed to certain chemicals, aerosols, or high relative humidity. A decrease in pressure in an electrostatic filter generally increases at a slower rate than it does in a mechanical filter of similar efficiency.

Inertial separation and interception are the dominant collection mechanisms for particles greater than 0.2 μm in size, whereas diffusion is dominant for particles less than 0.2 μm in size.

As mechanical filters become loaded with particles over time, their collection efficiency and reduction in pressure typically increase. Eventually, the decrease

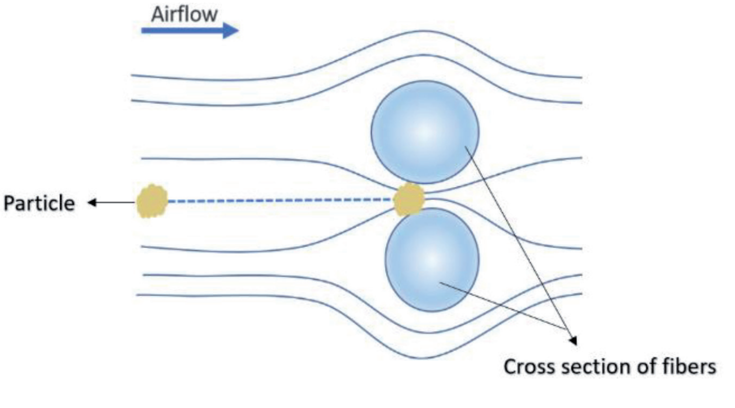

Figure 2.
Model of straining (sieving) mechanism, depends on the space between the fibers.

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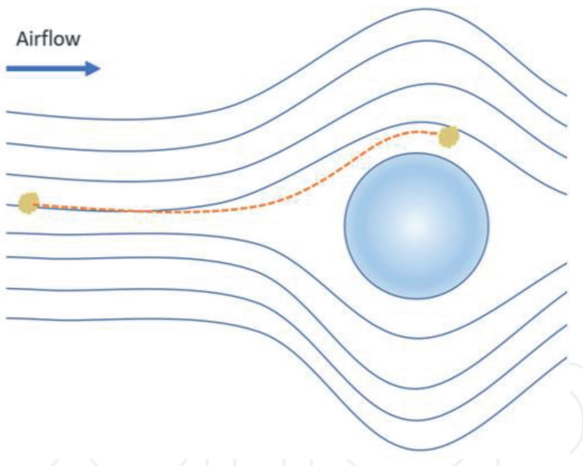

Figure 3.
Model of interception effect mechanism, depends on the collision between the fiber and the particle passing through the filter.

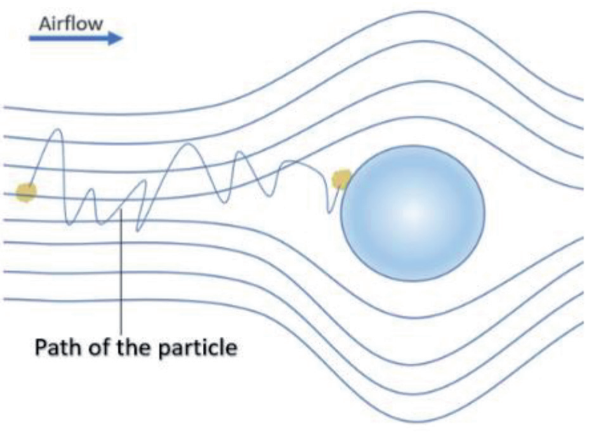

Figure 4.
Model of diffusion mechanism, depends on the motion of the particle causing contact with a fiber.

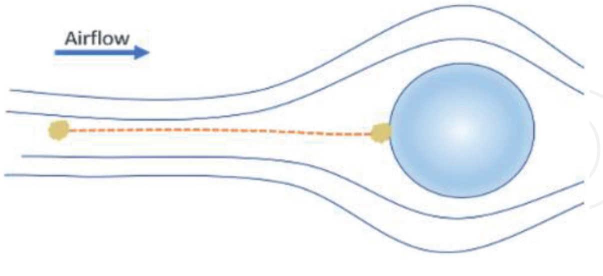

Figure 5.
Model of inertial separation mechanism, depends on the collision between the fiber and the small particles for reducing its velocity.

in pressure significantly inhibits airflow, and when this occurs, the filters must be replaced. For this reason, a decrease in pressure across mechanical filters is often monitored, as this can provide an indication of when the filters need to be replaced. Thus, unlike mechanical filters, a decrease in the pressure of electrostatic filters is a poor indicator of the need to change filters. When selecting an HVAC filter, these differences between mechanical and electrostatic filters should be borne in mind because they will have an impact on filter performance (collection efficiency over time), as well as on maintenance requirements (changeout schedules).

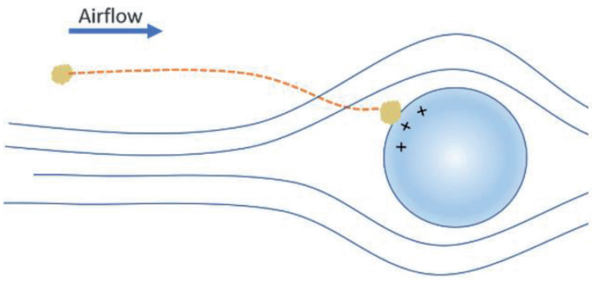

Figure 6.
Model of electrostatic attraction mechanism, depends on charging the fiber to retain the small particles by a weak electrostatic force.

3. Traditional types of household air filters

Humans consume approximately 30 liters of oxygen per hour. Hence, our requirement for air is relatively small: 0.15 m^3/h. However, because we also produce carbon dioxide, our bodies require approximately 5 m^3/h of fresh air in order to maintain carbon dioxide concentrations below life-threatening levels. When installing an air-conditioning system, it is advisable to determine the amount of air needed, and this will generally be set at between 15 and 20 m^3 per individual per hour. However, larger volumes of air might be necessary for managing temperature or drawing off polluted air.

Ensuring that air is free of dust and aerosols is not only important for maintaining buildings and their interior but also essential for maintaining the health and well-being of the human inhabitants.

This may be due to the higher foot traffic during business hours. The air output of these places is relatively high, and the cleaning of air-conditioning units may prove difficult, which could favor microbial growth and increased accumulation of dust on filters and in ducts. With respect to building contamination, it has been found that hospitals tend to have higher levels of contamination than other types of building examined. Given that hospitals are permanently inhabited by patients, this accordingly increases the potential for contamination and possibly infection by opportunistic pathogens [18, 19].

Al-Abdalall and Al-Abkari [20] examined the most commonly used filters incorporated in air-conditioning systems, namely, sponge, polyester, and HEPA, in order to assess the efficiency with which these filters can prevent the passage of fungi and bacteria. They accordingly found that complex filters were the most efficient in terms of purifying air, with efficiency rates up to 91.8% for bacteria and 100% for fungi. Sponge filters were deemed to be the least efficient filters, with estimated filtration rates of 2 and 50% for bacteria and fungi, respectively. This difference can probably be explained in terms of the passage of air through filters, with filters containing smaller pores being able to trap the larger cells of bacteria or fungi more efficiently. In other words, sponge filters are less efficient for air purification due to the large filter pores, whereas the filters of HVAC systems are able to capture particles smaller than 0.5 microns and prevent all particles with sizes greater than 3 microns from passing through [21].

In this regard, there are a number misconceptions concerning the relationship between filter efficiency and particle size, and in order to resolve this issue, a number of companies have developed certain filter-related standards based on particle counts at the most penetrating particle size (MPPS). The European Standard applies to HEPA ULPA filters used in the field of ventilation and for technical processes (e.g., for clean room technology or applications in the nuclear and pharmaceutical industries).

Many indoor air quality problems can be solved or avoided by cleaning or replacing air filters on a regular basis. Since using air filters is one of the most common methods of purifying air, it is recommended that filters be checked at 3-month intervals or that arrangements are made for a certified technician to change the filter at the beginning of each season.

Filters tend to become clogged, and once their holding capacity has been reached, particulate matter tends to be released downstream in the system and into the heat exchanger and can thereby cover the interior of the ductwork and the blower motor. This matter can subsequently cause problems and malfunctions in the mechanical and electrical parts of the system, resulting in high repair costs and even the need for replacement. The dispersed matter will circulate back into the house, potentially resulting in the proliferation of molds and other fungi. Dirty filters can also have a detrimental effect on energy consumptions due to impeded airflow, resulting in an increased in fan runtime.

4. Types of most common HVAC filters

4.1 Minimum efficiency reporting value (MERV)

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 52.2-2007 [22], the performance of an air filter is determined by measuring the particle counts on both the upstream and the downstream sides of the air filter device being tested. Through provided capture efficiency values for a range of particle sizes, it facilitates the selection of a filter that has the best efficiency with regard to removal of the target contaminant.

To simplify filter selection, the Standard defines a minimum efficiency reporting value. The MERV is a single number that simplifies the filter selection process by providing the specifier, or the user, with a single value of specification for filter selection. For most filters with mechanical-based filter operation, this number will most probably be a minimum value at installation and throughout the life of the filter. The particle size ranges specified by Standard 52.2 and an illustration of how to read an ASHRAE 52.2-2007 [22] test report are shown in **Tables 1** and **2** and **Figure 5**, respectively (**Figure 7**).

Range	Size (microns)
1	0.3–0.4
2	0.4–0.55
3	0.55–0.7
4	0.7–1.00
5	1.00–1.30
6	1.30–1.60
7	1.60–2.20
8	2.20–3.00
9	3.00–4.00
10	4.00–5.00
11	5.00–7.00
12	7.00–10.00

Table 1.
Particle size ranges of Standard 52.2.

Example particle	Size (μm)
Hair	20–200
Pollen	10–100
Spores	10–25
Toner	5–20
Oil fog	0.3–5
Bacteria	0.2–25
Tobacco smoke	0.01–1
Virus	0.002–0.05

Table 2.
Particle size ranges of common pollutants specified by Standard 52.2.

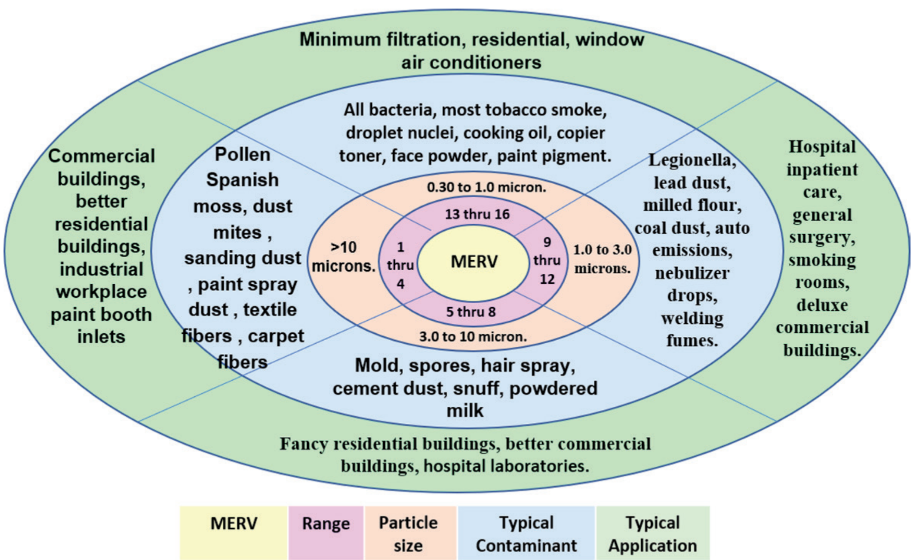

Figure 7.
How to read an ASHRAE 52.2-2007 test report.

Unfortunately, filters that use the principle of electrostatic attraction can "fool" the test by providing a high MERV during tests. However, due to the loss of electrostatic attraction during operation, a much lower value is obtained during application. Hence, the user may not be getting the particle removal efficiency that they originally specified.

Multiple studies have shown that coarse-fiber media (charged synthetic media), unlike fine-fiber media (fiberglass media), perform differently in real-life applications. Coarse-fiber media depends on an electrostatic charge to achieve the published filter efficiency. When atmospheric air, in which 99% of the particulate matter less than 1.0 micron in size, passes through a filter, the very fine particulate matter will dissipate the charge, and the filter rapidly loses efficiency.

Qian [23] isolated Streptophyta from dust samples collected from the filters of air-conditioning systems at a rate of 45%, whereas the rate in the indoor air was found to be only 2.4%, which provides an indication of the efficiency of HVAC filter systems (preventing particles sizes that are larger than 3 μm).

4.2 Types of most common HVAC filters

There are six types of filters, which are briefly described below.

4.2.1 Flat fiberglass filters

The main advantage of fiberglass filters is they are very cheap, easy to install, and readily available in stores. Accordingly, although they have a lifespan of only 1 month, replacing them on a monthly basis would not pose an inordinate financial burden. Unfortunately, they are not particularly effective in terms of trapping particles.

4.2.2 Pleated filters

These filters are more effective with regard to trapping dust than fiberglass filters. They can trap approximately 45% of airborne debris. Their MERV rating typically lies somewhere between 10 and 13. They also have a 1-month lifespan but tend to be more expensive than fiberglass filters.

4.2.3 Electrostatic air filters

These filters use electricity to attract charged particles, which are trapped internally. They are very efficient at trapping dust particles and debris and have a 6-month lifespan.

4.2.4 Washable filters

They are the most economical type of filter, which can be removed and cleaned as directed, dried, and then reinstalled. Furthermore, they do not need replacing at monthly intervals. These filters can prevent the passage of debris and tend to function better when dirty. However, they have a MERV rating of only 1–4.

4.2.5 Disposable filters

These filters comprise a cardboard frame and filter material. As their name implies, it is necessary to replace them when they become dirty.

4.2.6 HEPA filters

HEPA filters are considered the best type of filter because they trap even the smallest particles and keep premises smelling fresh. They can capture up to 97% of all particulate matter and remove all allergens from indoor air.

5. Modern HVAC filters

The type of air filter is the first factor people take into consideration before deciding on which air purifier to purchase.

Air filters and electrostatic filter cleaners are typically rated according to the minimum efficiency reporting value, commonly known as the MERV rating. The MERV scale is a measurement scale developed in 1987 by ASHRAE to rate the effectiveness of air filters, which determines efficiency in terms of the size of particle that the filter will capture. Values vary from 1 to 16, with a higher number indicating the greater efficiency of the filter in trapping airborne particles.

5.1 UV lights and filtration systems for cleaner indoor air

Recently, UV lights have been widely employed in the ducts of HVAC filtration systems. These lights facilitate effective and inexpensive control and solve the problem of microbial outgrowth in HVAC systems, eliminating up to 99.9% of the microorganisms and destroying airborne viruses, bacteria, and fungi. The types and quantities of microorganisms killed depend on the length of exposure and the output of the lamps. Nowadays, more advanced UV lights, such as air scrubbers, are employed, which can kill both airborne viruses and bacteria and those growing on surfaces.

There are two main types of UV lights used for HVAC systems, the most common of which are coil sterilization UV lights, which are installed near the return ducts, so as to kill mold that may grow on the air handler coil. These UV lights operate 24 h a day and eliminate the need for removing mold from the air handler coils. The second main type of UV lights is air sterilizer UV lights that function by sterilizing the air passing through the return ducts [24].

5.2 Activated carbon air filters

Also referred to as charcoal-impregnated air filters, these types of filters are used to effectively remove odors and fumes from the air during the air recirculating process.

Commercial activated carbon filters provide high-efficiency odor, fume, and gas removal and are fabricated using the finest quality coatings, including bulk air filter media and pads cut to size, pleats, panels, and high-density granular carbon packs.

Synthetic media substrates, such as non-woven polyester, are impregnated with finely ground coatings, including activated carbon, zeolite, or alumina, and a heat set to retain these coatings even when the activated carbon filter media is rinsed or vacuumed. Just as a sponge soaks up water, the media of activated carbon air filters absorb odors and fumes. Moreover, the odor-causing molecules are permanently removed from the air, rather than simply being masked with a different odor.

The rate of adsorption depends on the relationship between the pore structure, or surface area, and the shape of the contaminating molecules. Activated carbon filters are disposable air filters, and once they have become saturated with odors, fumes, or gases, after approximately 3 to 6 months of use, they must be replaced. The amount of activated carbon required will depend on the amounts of odors, fumes, or gases to be removed [24].

5.3 Deodorizing filters

Deodorizing air filters use acidified titanium, activated carbon, ceramic fiber, pulp, and other advanced materials that are prepared using a variety of rigorous refinement processes. They function by purifying the air and maintaining air fresh and show superior efficacy when used in conjunction with UV irradiation [24].

5.4 Antibacterial filters

Antibacterial filters are prepared by incorporating a bactericidal substance in the filter media. However, doubts remain regarding the effectiveness of these filters. One type is prepared by simply spraying the additive onto the surface of the filter medium, and therefore effective coverage is often not achieved, and not all of the filter layers will kill bacteria. A second type is prepared by application of a bacteriostatic agent, which does not kill the bacteria and may indeed promote the development of drug resistance among the bacteria. A third type may generate certain gaseous substances or odors that are potentially harmful to humans. Furthermore, it should be emphasized that it is difficult to capture bacteria on the windward side of the HEPA filters fabricated from inorganic materials, into which the bacteria may even penetrate. However, these microorganisms are only likely to survive under suitable conditions of temperature and humidity. Accordingly, the efficacy of these antibacterial filters remains inconclusive, and ASHRAE has recommended that HVAC systems incorporating antibacterial filters should be used with caution, so as not to produce any additional chemical pollution within indoor environments [24].

Although air filters often show excellent removal efficiency with regard to pathogens, the captured microorganism can remain viable within the filter and subsequently grow and become re-dispersed in the air flow, thereby generating a secondary source of pollutants and unpleasant odors. In an effort to resolve this issue, a large number of studies have been conducted with the objective of improving the effectiveness of air filters with antibacterial properties, and some of these studies have demonstrated that such air filters can be successfully prepared by incorporating inorganic nanoparticles and natural plant extracts [25].

Kim [26] also evaluated the efficacies of various functional filters coated with antimicrobial chemicals in deactivating representative microorganisms on filters or as bioaerosols. Specifically, they examined the effectiveness of functional filters coated with different chemicals, including ginkgo and sumac; Ag-apatite and guanidine phosphate; SiO_2, ZnO, and Al_2O_3; and zeolite, using a model ventilation system to evaluate the efficiency in which bacteria (*Escherichia coli* and *Legionella pneumophila*), bacterial spores (*Bacillus subtilis* spore), and viruses (MS2 bacteriophage) were removed. Their result showed that although the functional filters could facilitate the biological removal of various bioaerosols, physical removal was minimal. Appropriate use of chemical-coated filter materials could reduce exposure to these agents.

5.5 Electrostatic and HEPA filters

Electrostatic filters: Static electricity attracts dirt and dust to vertical and overhead surfaces. The static is often generated when two surfaces rub together and are then separated. Electrostatic filters generate a static electrical charge on all particles in the air that passes through eight filter layers. The discharged particles are then attracted to collector plates with an opposite electrical charge. These filters have the advantage of being washable.

High-efficiency particulate air filters: HEPA filters have a strong particle-trapping capacity that facilitates the removal of a high percentage (99.97%) of airborne particles that pass through an air purifier and accordingly meet US government standards. This contrasts with the 60–90% efficiency of medium filters [27]. Furthermore, HEPA filters perform significantly better than electrostatic air cleaners, in which filtering is based on ionic processes. HEPA filters are therefore often used in medical facilities and in households in which the residents suffer from severe allergies.

5.6 Microbial filtration efficiency of HEPA filters

Photocatalysts are nanoscale metal oxide materials (commonly titanium dioxide) that are applied to substrate surfaces, forming a film after drying under the action of light. They have a strong catalytic degradation function and can be used to degrade hazardous atmospheric gases. They can also be used to effectively kill a variety of bacteria, with an antibacterial rate of 99.99%. Furthermore, toxins released during the degradation of bacteria and fungi can be rendered harmless. These catalysts also have a range of other properties, including deodorant and dirt removal functions.

Exposure to bioaerosols can cause various adverse health effects, including infectious and respiratory diseases and hypersensitivity. Consequently, controlling the exposure to bioaerosols constitutes an important aspect of disease control and prevention.

Photocatalytic oxidation systems use a UV light source and a titanium dioxide photocatalyst to produce oxidants that destroy gaseous contaminants. When the photocatalyst is irradiated with UV light at wavelength of 254–365 nm, a photon from the light excites a catalyst electron in the valence band to jump to the conduction band, leaving a hole. This photocatalytic oxidation process converts organic pollutants into carbon dioxide and water. Using this technique, pollutants, particularly volatile organic carbons, are preferentially adsorbed on a catalyst surface and oxidized. The hole generated by photocatalysis can further react with surrounding water to produce a hydroxyl radical (ÆOH), whereas the electron in the conduction band reacts with oxygen to yield a superoxide radical anion (ÆO2). These radicals can attack the cell membranes of microorganism, thereby causing the release of K^+ ions, RNA, proteins, and other important components and eventually resulting in cell death [28]. Given these properties, researchers have applied photocatalytic oxidation to many substrates and achieved impressive results, indicated by the affective control of test microbes.

To date, however, photocatalytic oxidation has yet to be applied to HEPA filters in HVAC systems [27]. HEPA filters have been mandated for use in the removal of airborne microorganisms in many codes adopted in the field of healthcare, including the American Institute of Architects Guidelines for Design and Construction of Hospital and Health Care Facilities (AIA Guidelines), the American Society of Heating, Refrigerating and Air-Conditioning Engineers standards, the Joint Commission on Accreditation of Healthcare Organizations Environment of Care standards, the Centers for Disease Control and Prevention (CDC) guidelines, and recommended practices [29]. Although HEPA filters can efficiently capture aerosolized microorganisms, the area downstream of the filter can become a breeding ground for microbes. Under conditions of suitable temperature and humidity, microbes retained within a filter can multiply using particulates adhered to the filter as a food source, and the microbial progeny can ultimately disperse into the filtered air [30, 31]. Thus, instead of being an apparatus to control air quality, these systems can potentially become a source of pathogens. Efforts have accordingly been made to eliminate the breeding ground problem. For example, Goswami [32] examined four microbial species (*Aspergillus niger*, *Penicillium citrinum*, *Staphylococcus epidermidis*, and *Bacillus subtilis*) that are representative of the genera most commonly detected in hospitals in Thailand, a country characterized by a hot and humid climate, with an average temperature of 27°C and average relative humidity ranging from 62 to 84% [33, 34].

Very high relative humidity not only reduces the probability of microorganisms coming into contact with hydroxyl radicals but also provides sites conducive to microbial survival. Excessive amounts of water can also occlude the reactive sites of filter surfaces and subsequently reduce the photocatalytic oxidation efficiency [32, 34, 35]. Hence, the effect of relative humidity has been investigated.

Chuaybamroong [27] examined the application of photocatalytic oxidation to HEPA filters for disinfection of airborne microorganisms. Experiments were conducted at two TiO_2 loadings on HEPA filters irradiated with UV-A under two relative humidities. They assessed the inactivation of two fungal (*Aspergillus niger* and *Penicillium citrinum*) and two bacterial (*Staphylococcus epidermidis* and *Bacillus subtilis*) isolates and found that, on average, 60–80% of microorganisms retained on a photocatalytic filter were inactivated, although in the case of *S. epidermidis,* 100% inactivation was observed.

These authors suggested that high humidity may induce the reactivation of organisms, whereas water may occupy most of the TiO_2 sites, leaving fewer available sites for microbial colonization. These conjectures are consistent with the opinions of [36], who noted that although the presence of water vapor enhances the likelihood of hydroxyl radical formation, at certain humidity levels, radical formation would not increase with increasing water vapor and even decrease due to the occlusion of adsorption site on the TiO_2 surface. Consequently, high humidity would decrease filter efficiency. Furthermore, Peccia [37] indicated that high levels of relative humidity may promote changes in the biopolymers within microbial cells, including cell wall components, or alter protein structure, thereby affecting DNA repair enzymes, and hence could protect the microorganism from desiccation and/or attenuate the incident UV irradiation.

6. Impact of HVAC filters on indoor air quality

Filtration technology is currently an integral aspect of air purification techniques that focus on particulate matter, the most common examples of which are fibrous filters [38]. The use of glass fiber filters is another mature filtration technique with a proven high efficiency (99.0%), similar to that of the HEPA filters [39]. Furthermore, wire mesh filters can also provide good filtration efficiency down to sizes of 2–10 μm [40].

On the basis of particle filtration efficiency, air filters can be divided into four types: prefilters, medium filters, HEPA filters, and ultralow particulate air (ULPA) filters [41]. The filtration efficiency of ULPA filters is greater than 99.999%, with particles of diameters down to 0.12–0.17 μm being effectively trapped [42]. Similarly, HEPA material has a strong ability for trapping particles and can remove 99.97% of particulate matter, smog, and bacteria with sizes down to 0.3 μm (**Figure 8**). In contrast, the efficiency of medium filters is only between 60 and 90% [27, 43]. Most air purifiers currently on the market incorporate HEPA filters, as these are internationally recognized as the most efficient filters, capturing particles of different diameters. HEPA filters are designed to be over 99.99% efficient and are used in a diverse range of situations, including in theaters, hospitals, respirators, and vehicles [44]. Furthermore, filtration based on the use of non-woven nano-fiber material is an emerging filtration technique with an extremely high efficiency that is comparable to, or even superior to, HEPA-based filtration in the smaller particle size range [45].

According to the Environmental Protection Agency (EPA), pollutant levels may be two to five times higher indoors than outdoors, which indicates that the poor quality of indoor air is mainly attributable to the inefficient circulation of air. In regions characterized by hot summer, there is a heavy reliance on air-conditioning systems for maintaining comfortable conditions during the hot summer months. Accordingly, windows tend to remain shut, and little fresh air enters into our homes and places of work. The EPA warns that high temperatures and humidity can increase the concentrations of certain pollutants, with young children and the elderly being at particular risk from the detrimental effects of indoor air pollution.

Mechanisms for trapping dust in air using a standard filter, killing almost of all airborne microbes using UV lamps, and removing fine particles (dust) and died microbes using a high-efficiency particulate air filter (**Figure 8**).

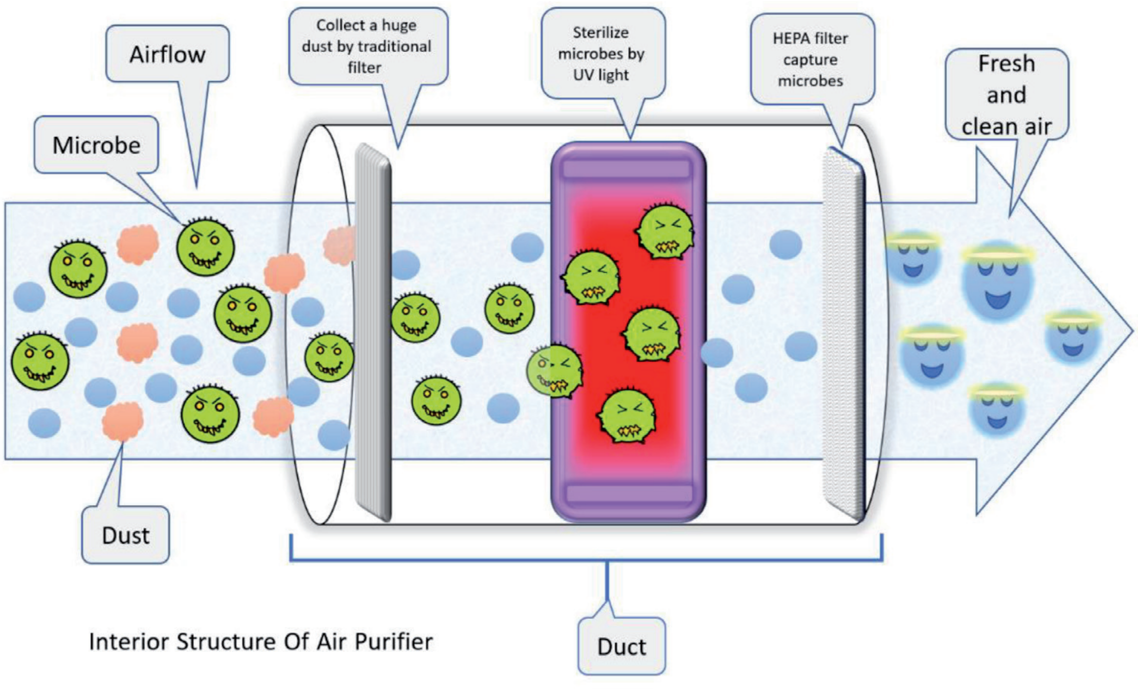

Figure 8.
A standard filter traps large dust particles in internal structure of an air purifier. HEPA filter captures microbes.

6.1 Air duct cleaning services

Given that dirty HVAC units have been proven to be less efficient, it is essential that air-conditioning ducts are periodically cleaned through employing an air duct cleaning service. Such cleaning should include complete care of the internal elements of the HVAC unit.

Ductwork would only be essential if there has been renovation, asbestos abatement, lead paint removal, or a significant accumulation of dust debris. Cleaning would be considered essential in the presence of the following: animal feces, mold, foul odors, noticeable debris, or pet hairs. Furthermore, if occupants suffer from an unexplained allergy, then it would be advisable to consider cleaning. Abe [46] noted that it is possible to remove fungi and bacteria from filters by washing with water and detergent; however, if the fan and heat exchanger are also contaminated, specialist cleaning would be required (**Figure 9**).

Kujundzic [47] mentioned that cleaning room air could contribute to reducing the levels of particulate matter within the home and that this can be achieved by using filters that retain the filtered particles.

6.2 Air-conditioning systems and mold

Mold is a pervasive problem, of which many property owners are fully unaware. In the Eastern Province of Saudi Arabia, the average annual humidity level is approximately 74%, but can be notably higher during certain times of the day and year. Many types of mold require a humidity of only 50% to commence growth, and air-conditioning systems are a common source of mold in many households. One of the causal factors in this respect is the fact that HVAC systems do not operate continuously, which can result in a fluctuation in humidity levels. The EPA warns that if an HVAC system is turned off before occupants perform tasks such as mopping, the humidity levels can suddenly surge and cause moisture and mold problems. If an HVAC system is improperly programed (which is a common problem), then the air-conditioning system may cycle off when the air is cooled but before it has had time to dry sufficiently, causing moisture problems. HVAC maintenance issues can be a further source of mold-related problems, such as when excessive moisture accumulates on the air-conditioning coils, resulting in the growth of mold. This mold can subsequently be blown through the air-conditioning ducts and released into the surrounding air. Holes or gaps in air ducts can also lead to the formation of condensation, which creates a perfect breeding ground for mold to grow. Such mold can cause numerous health-related problems, including respiratory problems, skin rashes, and allergic reactions [17].

In a study designed to examine the efficiency of various filters used for trapping microorganisms, Al-Abdalall and Al-Abkari [20] isolated the bacteria and fungi colonizing air-conditioning systems in different types of buildings during each of the four season s, in the provinces of Dammam and Qatif in eastern Saudi Arabia, and determined the respective frequency distributions. The air-conditioning systems were found to be contaminated by different types of bacterial and fungal species. Specifically, the isolated bacteria included *Serratia*

Figure 9.
Ducts should be cleaned periodically.

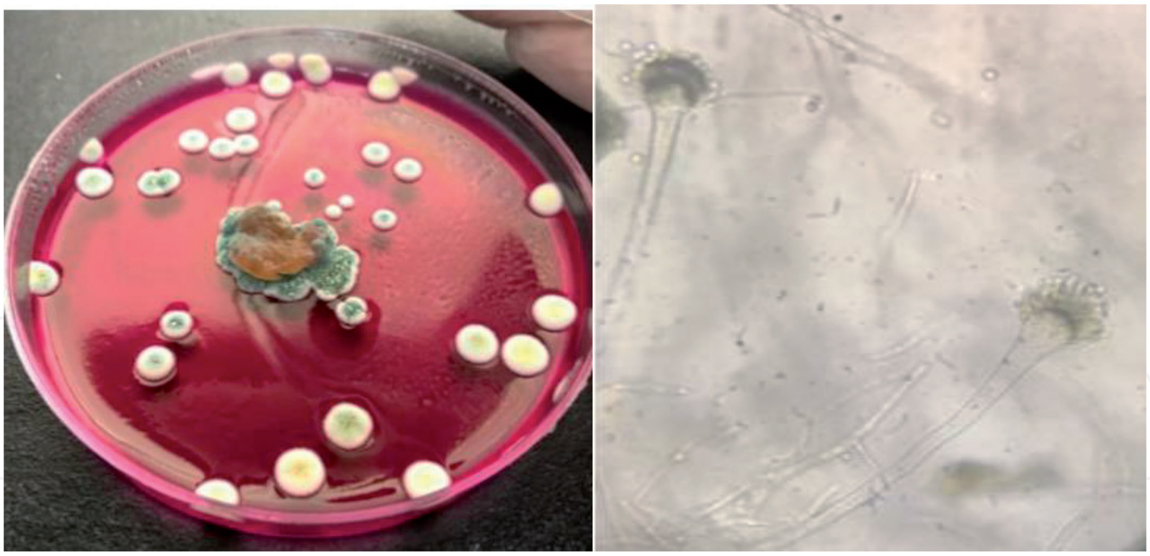

Figure 10.
Microorganisms collected by swabbing an air-conditioning duct and using the swabs to inoculate a fungal growth medium. The left-hand panel shows Aspergillus fumigatus growth on inoculated medium. The right-hand panel shows the mycelial growth and conidiophores of A. fumigatus viewed under a compound microscope.

liquefaciens, *Bacillus pumilus*, *Bacillus cereus*, *Bacillus subtilis*, *Staphylococcus lentus*, and *Oligella ureolytica,* whereas the common fungal taxa included *Cryptococcus laurentii*, *Aspergillus niger*, *Aspergillus flavus*, *Cladosporium* sp., and *Rhizoctonia* sp. Ironically, the findings of the study indicated that buildings that were in good condition were those likely to have the highest levels of microbial contamination (**Figure 10**).

Among the microparticles suspended in air, there is an abundance of biological material, including fungal spores, pollen grains, bacteria, and viruses. Air-conditioning systems can readily become polluted by these biological contaminants, which disperse throughout indoor areas and raise the risk of infection among the occupants [48]. The amounts of bacteria and fungi harbored by these systems tend to differ according to location, and numbers and frequencies also show seasonal differences [49]. Furthermore, differences in the number of microorganisms isolated and the distribution of different types of isolates can also depend on the type of filter used and the frequency of cleaning. In this regard, [20] found *Cladosporium* sp. to be a dominant contaminant and also identified *Alternaria* sp., *Aspergillus flavus*, *Aspergillus niger*, and *Rhizoctonia* sp. with frequencies of 24.16, 12.96, 12.8, 8.29, and 4.96%, respectively. Similar results were obtained by [50–53]. Consistently, Al-Suwaine et al. [54] mentioned that *Aspergillus* and *Cladosporium* spp. were the common isolates detected in closed systems in Riyadh, KSA, whereas other fungal genera, including *Fusarium* and *Rhizopus*, were isolated in low frequency, similar to findings of [51, 55].

6.3 HVAC systems and indoor pollution

Heating, ventilating, and air-conditioning (HVAC) systems function by drawing in air through a network of intake ducts, cooling the air, and then releasing the cooled air back into the home through return ducts. The constant recirculation of air in HVAC systems means that pollutants are continuously blown through indoor areas. In the eastern region of Saudi Arabia, given that the summer is generally very hot and humid, many properties are at risk from the growth of mold within air ducts.

7. The microbial colonization of traditional filters

7.1 The relationship between microbes and traditional filters

We have previously examined the nature of the relationship between filters and airborne microbes, using small pieces (1 × 1 cm) of traditional filters (sponge, polyester, and HEPA) These materials were sterilized with alcohol, then dried, and subsequently moistened with glucose yeast extract medium. We then prepared suspensions of the examined fungal strains (*Aspergillus niger*, *Aspergillus flavus*, *Cladosporium* sp., and *Rhizoctonia* sp.). These were retained in sterilized petri dishes, whereas other groups were prepared for carbon-free sources. They were monitored for 1 to 3 months and thereafter examined under a microscope. Heavy growth of mycelium was observed. The fungal filaments are looped around filter fibers also assembled into the filter cavities, forming a tangled knot of fungal mycelium and filters fibers (**Figure 11**).

Figures 12–**15** show that the microscopic structures of the filters shown in **Figure 11** have been colonized by *Aspergillus niger* in (**Figure 12**), *Aspergillus flavus* in (**Figure 13**), *Rhizoctonia* in (**Figure 14**) and *Cladosporium* in (**Figure 15**) which indicate that these fungi use the filters as a support for fungal mycelium.

Microorganisms can exploit various parts of air-conditioning systems, including filters, as sheltered sites, which are conducive to rapid grow and reproduction [16, 17, 56]. The high levels of humidity in air-conditioning systems [16, 57] and the accumulated dust in the filters and other parts of these systems provide an environment that is suitable for the growth of a range of different microbes.

Microorganisms can secrete a diverse array of extracellular enzymes to exploit the various available filter materials, such as cellulose, as sources of nutrition [56, 58].

Kuehn [57] pointed out that moisture promotes fungal growth in filter tissues and can also favor bacterial reproduction leading to subsequent transmission to and dispersal within indoor environments. Such moisture often originates from the drops of condensate that form air-conditioning towers [59].

Maus [60] have suggested that the spores of some bacteria and fungi trapped within air filters can retain their viability and reproduce under the prevailing environmental conditions. These microorganisms can be dispersed through purification and air-conditioning systems and be inhaled by workers and residents in buildings [48].

Microbiological particles constitute one of the most important sources of air pollution that determine the purity of the air. It is known that atmospheric air is a carrier of disease-causing organisms, including fungal spores and microbial

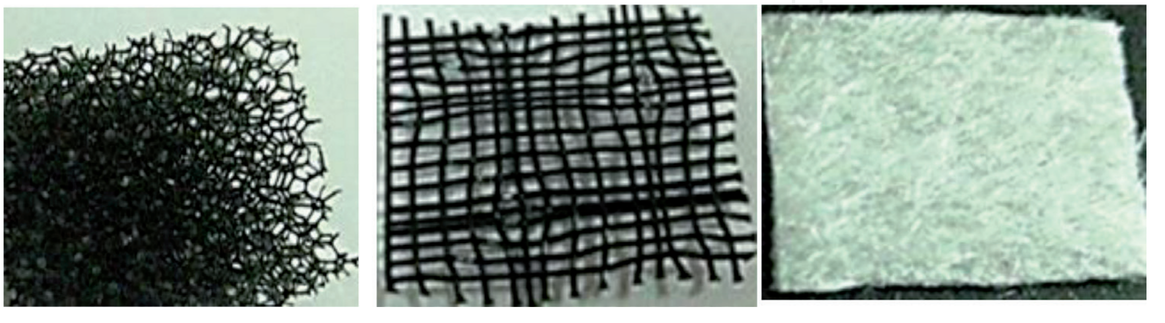

Figure 11.
Structure of filters observed under an optical compound microscope. The right-hand panel shows sponge filter cavities of different sizes. These openings are wider than those of other filters. The middle panel shows a polyester filter, which is characterized as a network installation with narrower openings than the sponge filter that are regular in shape. The left-hand panel shows a HEPA filter, characterized by complex knit and numerous narrow openings that increase efficiency by preventing the passage of fine particles.

cells, the concentrations of which vary widely according to environmental condition, particularly the nature of the internal environment and the various activities of humans who reside or work therein [61]. In order to achieve the desired level of microbial contamination control in air-conditioning systems and develop suitable air purification techniques, it is generally necessary to conduct extensive studies [17].

Hamada and Fujita [62] noted that the contamination of filters tends to be very low during the first year after installation, reaching 257 cells/m^3 of room air, whereas by the sixth year of use, they found that the number of contaminating cells had increase threefold to 692.

Durand [63] demonstrated that species of *Aspergillus* and *Penicillium* are the fungi most commonly isolated from the filters of air-conditioning systems, whereas species of *Cladosporium* and other types tend to be detected at relatively low rates.

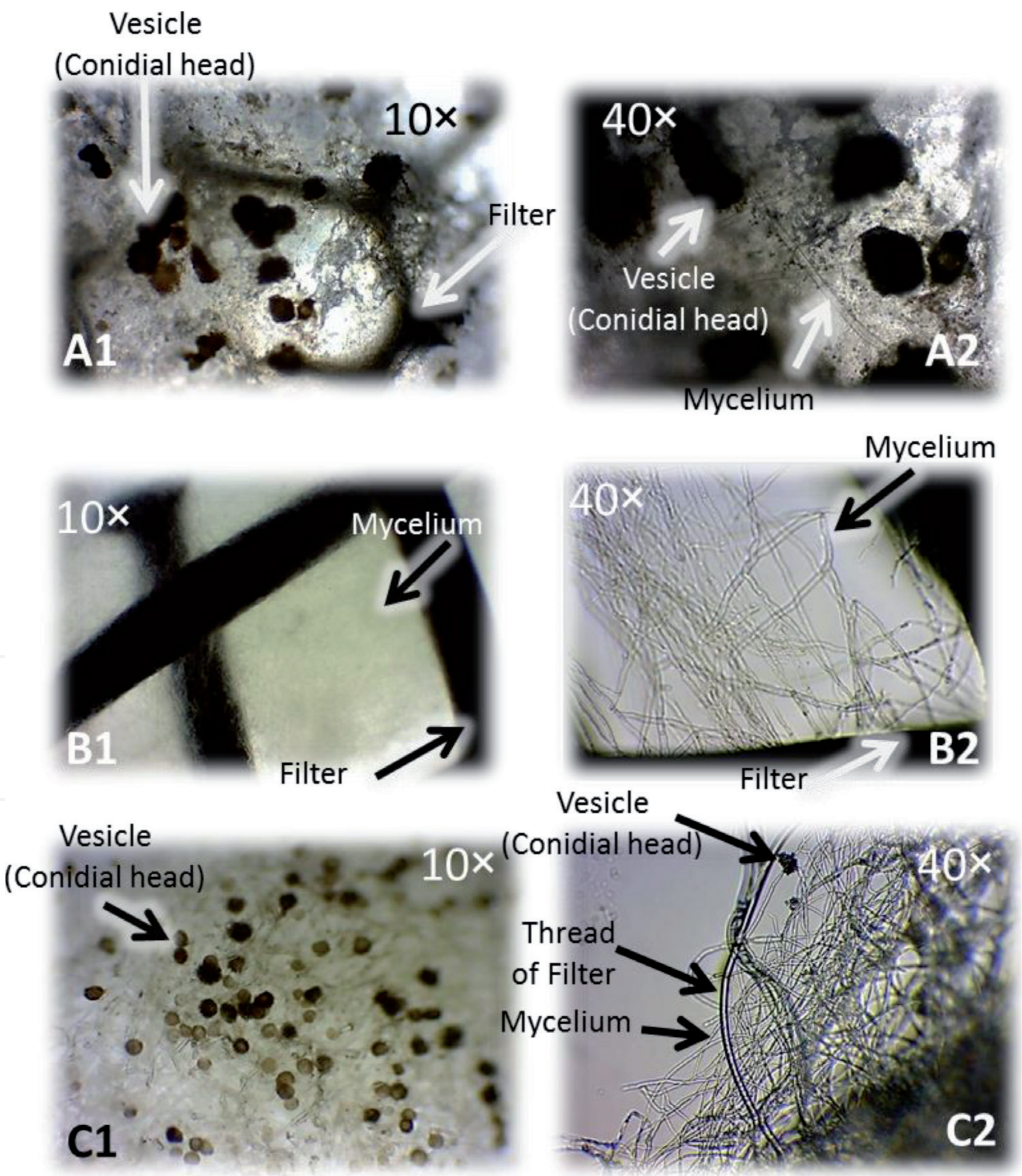

Figure 12.
The mycelial growth and conidiophores of Aspergillus niger on the studied filters: (a) sponge, (b) polyester, and (c) HEPA.

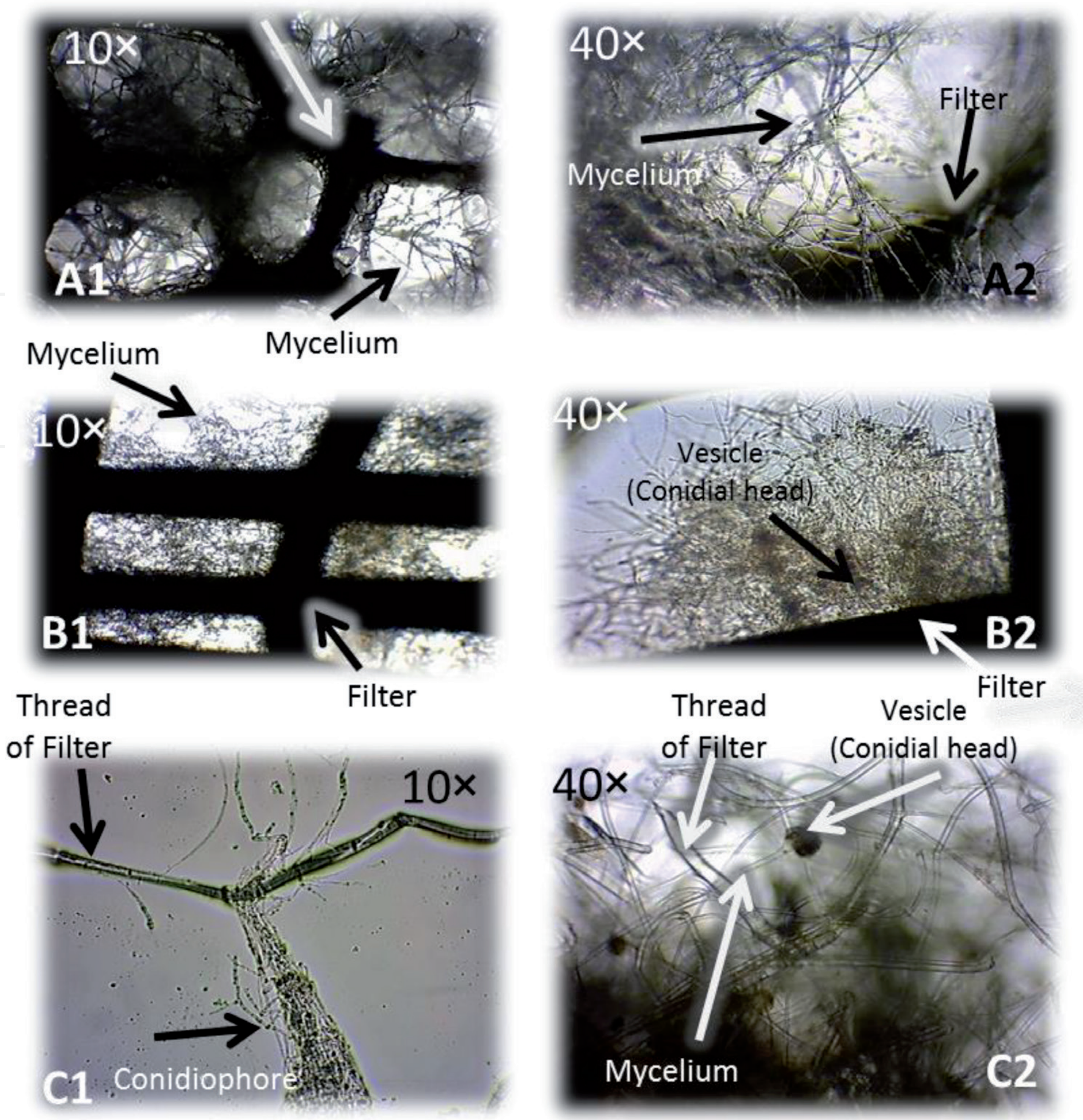

Figure 13.
The mycelial growth and conidiophores of Aspergillus flavus on the studied filters: (a) sponge, (b) polyester, and (c) HEPA.

For bacteria, species of *Actinomycetes* and *Bacillus* (cocci and Gram-negative types) tend to be the most commonly isolated.

Al-Abkari [17] recommended that air-conditioning filters should be cleaned regularly and that regular maintenance is necessary to prevent an accumulation of contaminants and to remove the suspended dust. In this regard, spongy filters can be readily washed and cleaned with detergents, and be reused after cleaning. In contrast, HEPA filters, which consist of interlocking fibers, are very difficult to wash and clean and should thus be replaced on a regular basis. Furthermore, it has been demonstrated that the number of microbial colonies (bacteria and fungi) growing on culture dishes that were exposed to air that had passed through different filters increased after 30 min and then decreased after 60 min. This indicates an inverse relationship between the period of operation of the air-conditioning system and the quantity of air that had been purified [64].

Al-Abkari [17] examined the extent of microbial growth on the most common types of filter used in the eastern region of Saudi Arabia (sponge, polyester, and HEPA) and found that sponge filters harbored the highest microbial moist mass, reaching 0.177 and 0.257 gm for bacteria and fungi, respectively.

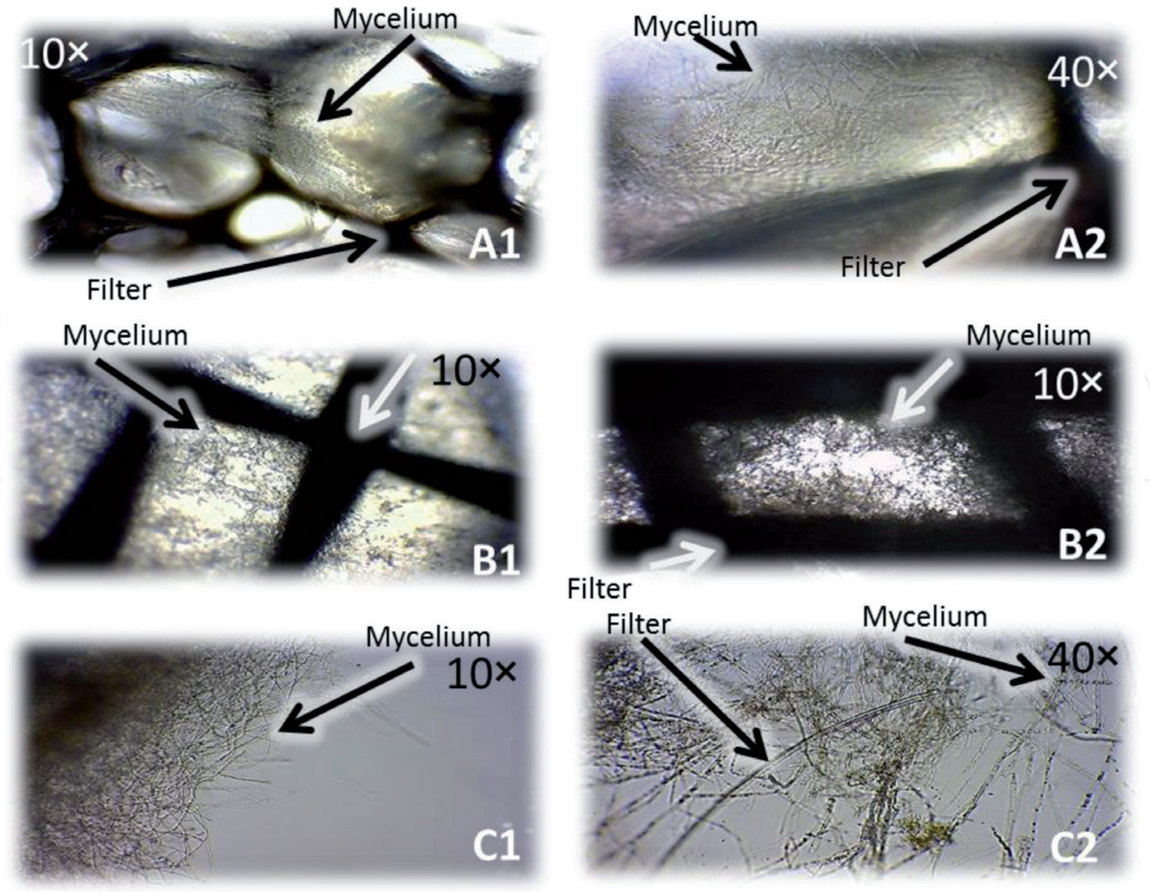

Figure 14.
The mycelial growth of Rhizoctonia sp. on the studied filters: (a) sponge, (b) polyester, and (c) HEPA.

Comparatively, the bacterial mass recorded on polyester and HEPA reached 0.024 and 0.037 gm, respectively, and the corresponding fungal mass on these filters was 0.072 and 0.047 gm, respectively. Douwes [65] isolated polysaccharide compounds known to be excreted by various fungi that grow on dust in residential homes, and the detection of these compounds is accordingly considered to be a good indicator of the presence of these fungi.

Moray and Williams [66] performed direct microscopic observations of the porous soft filters typically used in air-conditioning systems and accordingly identified pollen grains, cellulose fibers, synthetic fibers, decayed plant leaves, hairs, parts of insects, dust, mites, and numerous organic compounds, all of which can provide a refuge for microbes.

7.2 Microbial colonization of the types of filters commonly used in air-conditioning systems

Microorganisms that are captured by filters can thrive on the filters and can potentially be released into the air, thereby resulting in sick building syndrome [67]. Furthermore, it has been determined that the number of microbes found in indoor air is less than that colonizing the surface of filters used in air-conditioning systems [68]. Foarde [69] and Kowalski [68] examined the efficiency of these systems and provided solutions for the HEPA filters. In addition, they noted that the tested filter samples trapped *Bacillus subtilis*, with efficiencies ranging from 19 to 100%, whereas in contrast the efficiency in trapping viruses was low, ranging from 0.7 to 20%.

Al-Abkari [17] examined the ability of microorganisms (bacteria and fungi) to degrade various types of filter commonly used in air-conditioning systems,

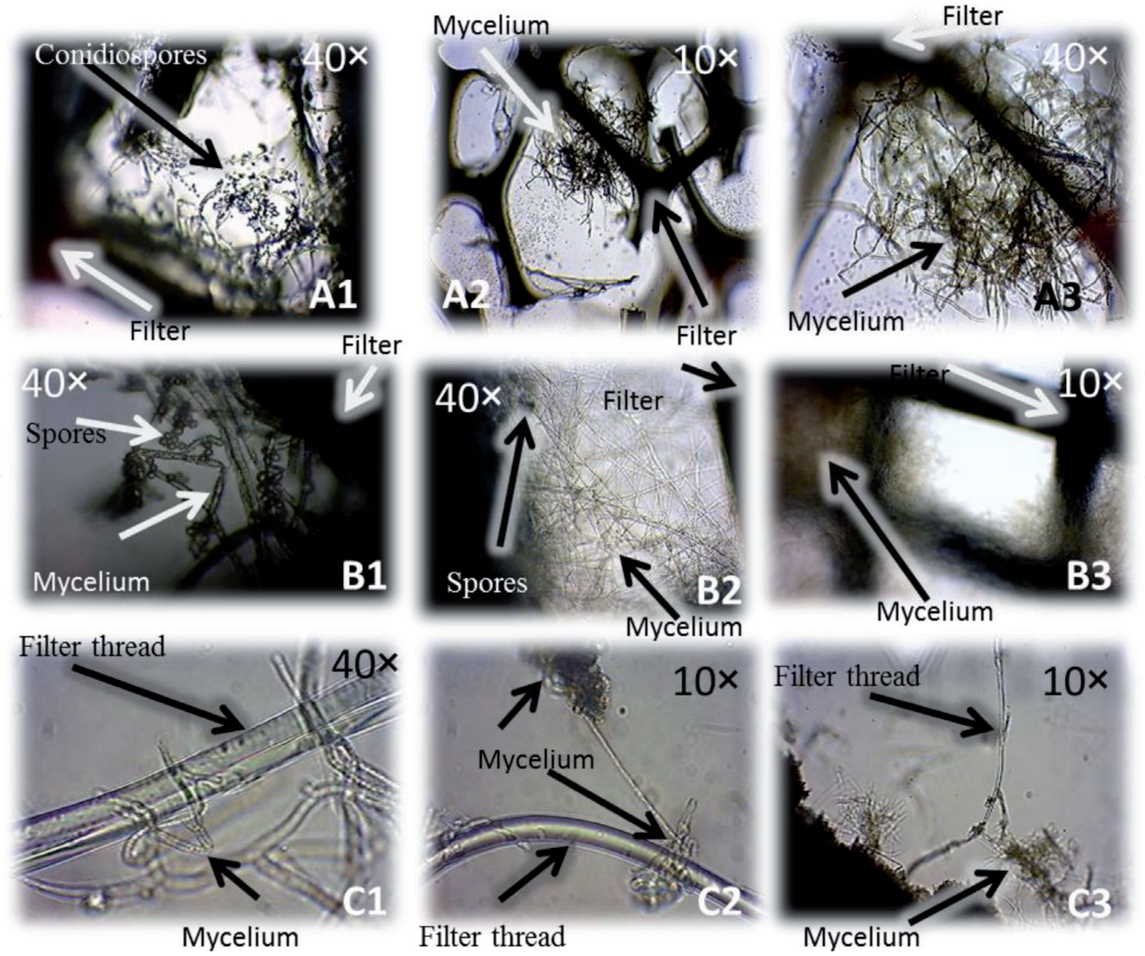

Figure 15.
The mycelial growth and conidia of Cladosporium sp. on the studied filters: (a) sponge, (b) polyester, and (c) HEPA.

namely, sponge, polyester, HEPA, and the environmental conditions, such as dust, temperature, and moisture, which enable these organisms to take refuge, grow, and reproduce. The results indicated that the growth of bacterial strains was dependent on the filter media containing a carbon source. The average of bacterial moist mass loading on different filters was found to be positively related to the length of incubation period (1, 2, and 3 months), with weights reaching 0.061, 0.09, and 0.101 g after incubations for 1, 2, and 3 months, respectively. Furthermore, it was found that the average microbial mass detected on sponge filters (0.177 g) was larger than that on either polyester (0.024 g) or HEPA (0.037 g).

Generally, it was observed that the average of moist weights of bacterial mass on all filters increases with an increase in the length of the incubation period, with recorded averages of (0.134, 0.169, and 0.228 g) and (0.019, 0.024, and 0.03 g) and (0.031, 0.035, and 0.046 g) for sponge, polyester, and HEPA filters, respectively. In contrast, it was found that the moist mass of microbial growth on culture medium lacking a carbon source remained essentially constant with increasing incubation time, with values of 0.023, 0.023, and 0.028 g; 0.03, 0.035, and 0.039 g; and 0.163, 0.171, and 0.162 g) for sponge, polyester, and HEPA filters, respectively.

With regard to the growth of fungal strains, when these were grown in a medium containing a carbon source, the average moist fungal mass loading on different filters showed a positive relationship with incubation period (1, 2, and 3 months), with weights reaching 0.87, 0.118, and 0.142 g, respectively. Similar to bacterial growth, the average weight of fungal biomass growing on sponge filters (0.257 g) was larger than that on polyester (0.072 g) and HEPA (0.047 g). The weight of fungal mass on polyester and HEPA filters was 0.05, 0.082, and 0.085 g and 0.022, 0.04, and 0.078 g, respectively. Notably, however, fungal growth on sponge filters increased with increasing incubation time, reaching 0.181 and 0.324 g, following incubation for 1 and 2 months, respectively, whereas after incubation for 3 months, it had decreased to 0.265 g.

8. Conclusion

Microbial pollution is one of the most fundamental indoor environmental quality problems in buildings. Therefore, this chapter has presented several solutions for indoor air quality monitoring in an effort to enhance the healthcare by describing the potential impact of HVAC systems on the indoor air quality. The principles of air filtration and traditional air filter types were presented.

Also, the chapter covered the filtration technology and the indoor air quality topics. Subsequently, the air duct cleaning devices, mold formation, and HVAC systems and indoor pollution were illustrated. Moreover, this chapter provided the ASHRAE standards, which was used to select the suitable HVAC filters. The six most common designs of HVAC filters were briefly described. This chapter was followed by the modern filters. All advanced air filters, UV lights, activated carbon, deodorizing, antibacterial, electrostatic and HEPA filters, microbial filtration efficiency of HEPA filters were discussed extensively.

A brief description of the microbial colonization on the commonly used traditional filter types for air-conditioning systems were provided, followed by a detailed explanation of the relationship between traditional filters and microbe's formation.

Even though there is highly development in designing advanced filters to overcome microbial pollution, we are still facing indoor air pollution problems. The most challenging step is providing an affordable construction, easy to install, made of environmentally friendly and long-term materials, available in different designs and able to avoid the existence of microbial growth.

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