Review Article

Journal of Occupational Health and Epidemiology

Journal Homepage: https://johe.rums.ac.ir/

Rafsanjan University of Medical Sciences

Effects of Photocatalysts on the Efficiency and Pressure Drop of HEPA Filters in Removing Airborne Microorganisms: A Scoping Review

Akbar Ahmadi Asour[1], Fatemeh Fasih-Ramandi[2], Mehdi Mohammadian[2], Sepideh Keyvani[2], Malihe Kolahdouzi[2], Zahra Beigzadeh[2], Farideh Golbabaei[3*]

1. Ph.D. Student in Occupational Health and Safety, Dept. of Occupational Health Engineering, School of Health, Tehran University of Medical Sciences, Tehran, Iran; Instructor, Dept. of Occupational Health Engineering, School of Health, Sabzevar University of Medical Sciences, Razavi Khorasan, Iran.
2. Ph.D. Student in Occupational Health and Safety, Dept. of Occupational Health Engineering, School of Health, Tehran University of Medical Sciences, Tehran, Iran.
3. Professor, Dept. of Occupational Health Engineering, School of Health, Tehran University of Medical Sciences, Tehran, Iran.

Citation: Ahmadi Asour A, Fasih-Ramandi F, Mohammadian M, Keyvani S, Kolahdouzi M, Beigzadeh Z, Golbabaei F. Effects of Photocatalysts on the Efficiency and Pressure Drop of HEPA Filters in Removing Airborne Microorganisms: A Scoping Review. J Occup Health Epidemiol. 2023;12(3):201-12.

Article Info

*** Corresponding author:**
Farideh Golbabaei,
E-mail:
golbabaei@tums.ac.ir

Article history
Received: Feb 2023
Accepted: Aug 2023

10. 61186/johe.12.3.201

Print ISSN: 2251-8096
Online ISSN: 2252-0902

Peer review under responsibility of Journal of Occupational Health and Epidemiology

Abstract

Background: Recent years have seen many attempts to increase the efficiency and reduce the pressure drop of High-Efficiency Particulate Air Filter (HEPA) filters in removing microorganisms through shape change and the use of photocatalysts. This study is the first scoping review of the effects of photocatalysts on increasing the efficiency of HEPA filters in the elimination of airborne microorganisms.

Materials and Methods: PubMed, Scopus, Irandoc, and Magiran databases were searched for relevant articles. Based on select keywords and the study objectives and applying the inclusion and exclusion criteria, eight from a total of 315 articles were identified, two of which were typical in the review of efficiency and pressure drop. These articles investigated the effect of photocatalyst and filter shape on the efficiency and pressure drop of HEPA filters.

Results: These studies were released from 2000 to 2021. TiO_2, with its long-term interactions with microorganisms, the attack of superoxide radicals ($O_2•^-$), and the release of K^+, RNA, proteins, and other essential components will cause their destruction. Ultraviolet rays at a wavelength of 254 nm remove bacteria on the surface of the filter. The synergy of the inherent ability of UV radiation with TiO_2 through nucleic acid and protein damage in microorganisms and the generation of oxidative radicals increases the efficiency of HEPA filters compared to either one alone.

Conclusion: The photocatalysts with ultra-violet rays on the HEPA filter can reduce the problem of microorganism growth and increase indoor air quality.

Keywords: HEPA, TIO2, UV, Microorganisms, Efficiency.

Introduction

The development of the filtration industry has been attributed to the years after World War I (1915) and the start of using masks and respirators to control chemical pollutants, especially in miners and firemen. Since 1946 and along with the official entry of HEPA filters on the market under the abbreviation "High-Efficiency Particulate Air Filter" (HEPA), this industry has seen significant growth.

The first HEPA filters were developed in the 1940s by the Arthur D. Little Research and Development Company under government contract and through the Manhattan Project [1]. At the beginning, HEPA filters, similar to paper-making, used borosilicate fine fiber media in a flat and pleated form to increase the total surface area and baffles to separate pleats for better air flow transmission [2]. As defined by the United States Department of Energy (DOE) standard adopted by most American industries, HEPA filters remove at least 99.97% of aerosols 0.3 micrometers (μm) in diameter [2].
Some microorganisms, such as Aspergillus Niger, Penicillium citrinum, Staphylococcus epidermidis, and Bacillus subtilis, were captured using photocatalytic oxidative (PCO) HEPA filters. A HEPA filter can also capture some viruses and bacteria which are ≤0.3 μm [3] as well as floor dust containing bacteria, clostridia, and bacilli [4].

- HEPA-Type (Grade E): About 99% efficiency.
- True HEPA (Grade H): 99.97% efficiency.
- Absolute HEPA (Grade A): 99.99% efficiency or more.
- Ultra-HEPA (Grade U): More than 99.999% efficiency.

According to the 2009 European standard EN, HEPA filters are classified based on E, H, and U labels; E and H filters have the lowest and high rates of efficiency(99% and 99.97%), respectively, and U17 has highest efficiency, greater than 99.9999% [5]. Since the development of HEPA filters and their use in air purification systems and equipment, efforts have been made to improve the efficiency of these filters and reduce their pressure drop. Although various studies in this field have used strategies such as changing the shape, size, and material of fibers [6], the approach that has received the most attention in recent years is the photocatalyst technique with layers of nanoparticles or metal coatings for improving the retention and removal of aerosols and microorganisms on HEPA filters.
Photocatalysts are semiconductors that absorb light, reach a higher energy level, and initiate a chemical reaction by transferring energy to the reactant. Photocatalysts break down various chemicals (organic, petrochemical, pharmaceutical, etc.) and disinfect a variety of pathogens (bacteria, viruses, fungi, and protozoa cells). The process of photocatalytic inactivation is a function of the nature, morphology, and concentration of the catalyst. Metallic oxide nanoparticles like zinc oxide (ZnO), titanium (TiO_2), zinc acetate (Zn_2SnO_4), and tungsten oxide (WO_3) based semiconductor materials have antibacterial activities. Luna et al. initiated studies on developing and increasing the efficiency of HEPA filters in 2008 by adding photocatalysts and ultraviolet radiation [3]. Studies continued in the following years by other researchers such as Chuaybamroong (2010). Goswami et al. used a system containing P25 TiO_2 and UV-A with an intensity of 10 mW/cm2 (at a wavelength of 350 nm) and a relative humidity of 50% to inactivate the gram-negative bacteria Serratiamarcescens. After 8 hours of photocatalysis with a velocity of 0.376 m/s, 82% of bacteria were inactivated. Keller et al. first reported 99.1-99.8% removal of non-pathogenic E. coli in air using UV-A (380 nm wavelength) and TiO_2 [3, 7, 8]. Pal et al. demonstrated that TiO_2 photocatalysis could be used to deactivate bioaerosols. Vohra et al. used an advanced TiO_2 catalyst with silver ion combined with UV-A (10 mW/cm2) and succeeded in inactivating various microbes such as Bacillus cereus, Staphylococcus aureus, E.coli, Aspergillus niger, and bacteriophage MS2 in the air [9].
Candiani et al. (2011) modified the HEPA filter by impregnating it with isopropyl alcohol, and Lakshmi and Muthukumaran added a coating of copper on the surface of the filter in 2017. Its modification has continued, but few studies were conducted with such approaches until 2021. Given the fact that to date, no comprehensive research has been conducted on the methods of improving the performance of HEPA filters in removing microorganisms, the current systematic review investigated the impact of structural changes, the use of photocatalysts and nanoparticles, and types of metal coatings, radiation, etc., on the performance of the HEPA filler (efficiency and pressure drop) in controlling and removing microorganisms from polluted airflow.

Materials and Methods

This scoping review is underpinned by Arksey and O'Malley's [10] five-stage framework, which adopts a rigorous process of transparency, enabling replication of the search strategy and increasing the reliability of the study findings. The five stages of Arksey and O'Malley's framework are (1) identifying the initial research questions, (2) identifying relevant studies, (3) study selection, (4) charting the data, and (5) collating, summarizing, and reporting the results.
Identifying the initial research questions: The current review focused on exploring critical aspects of the HEPA filter that influence its efficacy and contribute to the effectiveness of microorganism capture. To ensure that a wide variety of documents relevant to the topic of interest are

included, the following initial research questions were asked:
What effect can TiO2 have on filter performance?
What is the combined performance of UV and TiO2 in reducing microorganisms?
What effect does copper coating have on reducing microorganisms?
How does isopropyl alcohol affect the efficiency of HEPA filters?
How does the filter work in reducing microorganisms?
How do microorganisms affect the efficiency of HEPA filters?
What effect do photocatalysts have on HEPA filter pressure drop and efficiency?
Key concepts and theories of a particular research topic and research into the types of available evidence can be considered a scoping review. A scoping review can particularly be implemented when investigating issues that have not been comprehensively reviewed or have been less thoroughly investigated. Scoping studies are performed instead of systematic reviews in cases that aim to identify knowledge gaps, scope a body of literature, clarify concepts, or investigate research conduct. Scoping reviews may also be helpful precursors to systematic reviews and can be used to confirm the relevance of inclusion criteria and potential questions [11]. The current study was conducted to investigate the development process of HEPA filter efficiency in the removal of microorganisms from the years 2000 to the end of 2022. The search strategy and selection of studies were based on PRISMA, a guide that develops and enhances structured reports and meta-analysis reviews. Searches were performed in PubMed, SCOPUS, Irandoc, and Magiran databases. Different mesh combinations were used to search for studies that include:
((microorganism [MeSHTerms] OR "Organisms "[Title/Abstract] OR Bacteria"[Title/Abstract]) AND (filter ("HEPA"[MeSH Terms] OR " HEPA "[Title/Abstract] OR" pressure "[MeSH Terms] OR " pressure drop [Title/Abstract]) AND (" Efficiency "[MeSH Terms] OR " Efficiency "[Title/Abstract]) AND (" Photocatalyst "[Title/Abstract] OR " TIO2 "[Title/Abstract]) AND ("UV "[Title/Abstract]))

Identifying relevant studies: To find more studies, Google Scholar was searched using the references mentioned in the relevant articles, and those found were reviewed.

Inclusion and Exclusion Criteria: Articles from 2000 to 2021 were reviewed. Original full-text articles in Persian or English with at least one of the desired keywords in the title, abstract, and keywords section and that examined HEPA filter performance and effectiveness in removing microorganisms were included in the current research. Also included were articles investigating factors affecting the performance of these filters (such as efficiency and pressure drop) and combined systems, such as photooxidation or ultraviolet disinfection systems, in reducing microbial load and microorganism particles. Articles of which the full text was unavailable, those that focused only on the use of HEPA filters and its development goals, and duplicate articles were excluded from the review process. Unrelated articles were also excluded based on the PRISMA statement. The titles, abstracts, and keywords of all the collected articles were checked carefully, and irrelevant items were removed according to the primary purpose of this study.

Quality Assessment: To avoid any uncertainty in the findings, selected articles were evaluated by two experts independently for method validity, and a consensus between the current reviewers was reached about what could be included or excluded from the study. The third author resolved any disagreement between ratings.

Data extraction: Based on the chosen keywords and study objectives and after applying the inclusion and exclusion criteria and reviewing the text of the articles, the following information was extracted: author, year of publication, study purpose, modifications made to the HEPA filter, main results, and interpretation of results (Table 1). Out of a total of 315 articles, 229 articles due to repetitiveness, and 201 articles were excluded from the review process due to the lack of coverage of the study objectives in the abstract and text or irrelevance despite the presence of some keywords in the title. Another 20 articles were excluded,as they lacked the necessary quality (12 articles), full text (1 article), and essential information (7 articles)). Finally, eight articles were selected from the databases. Among those, one (reference 23) shared the topics of efficiency and pressure drop, so the articles in Table 1 are listed in 9 rows. Of these, one article was published in 2008, four in 2010, one in 2011, two in 2017, and one in 2018.

Study selection

Characteristics of selected studies: Out of the 8 final articles, in 7 articles the efficiency of HEPA filters is mentioned, in one of these articles the pressure drop was also investigated, and the eighth article is dedicated to the investigation of pressure drop.Out of 7 articles, one article referred to the use of TIO2, two articles to the use of UV, two articles the combined use of TIO2 and UV, one article the effect of the materials and shape, and one article the coating of the filter with metals have discussed.

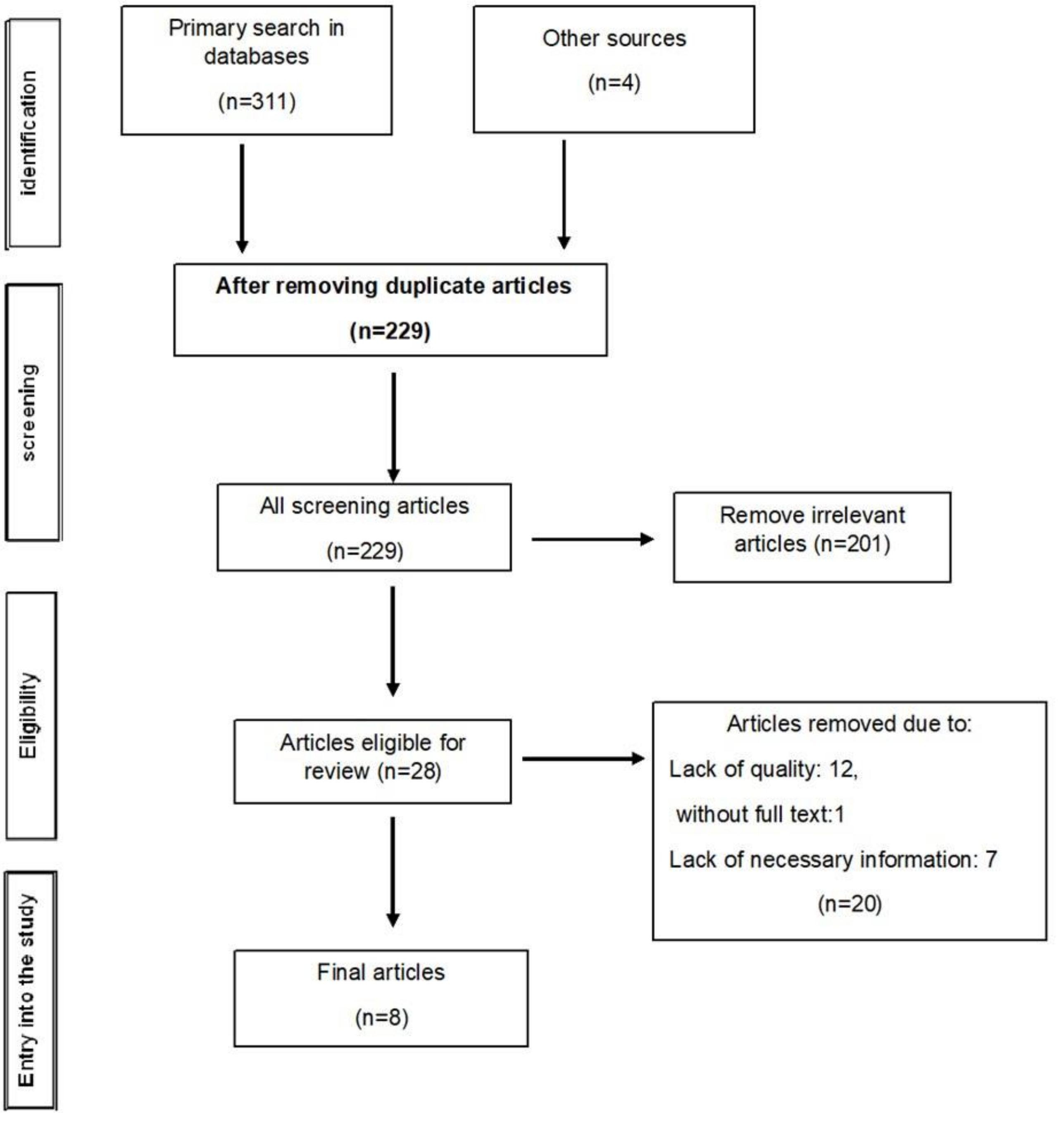

Fig. 1. Flow diagram of the screening process and study selection (5)

Data charting and collation: The process of selecting articles based on the PRISMA checklist is shown in Fig. 1.

Results

The review of the studies (Table 1) showed that since entering the commercial market (1946), HEPA filters have consistently been undergoing structural and functional changes to increase efficiency. Modifications began with folding as a turning point in improving the performance of these filters and continued into changing the shape of folds such as U and V shape. The recent satisfactory performance of HEPA filters in removing and eliminating various particles and microorganisms from public places, medical centers, clean rooms, and various industries confirms that these filters have been improved with the addition of different chemical compounds such as photocatalyst UV radiation, metal coatings, etc., individually or combined.

Table 1. Characteristics of the included studies (Efficiency)

	Ref.	Authors	Aim	microorganism	Modifications made to the HEPA filter	Results
Efficiency	16	Luna, 2008	Deactivation and removal of endospores of species	Bacillus	Adding TiO2 nanoparticles to the inner surface of the HEPA filter along with UVC radiation	TiO2 nanoparticles along with UVC radiation increased the inactivation rate of Bacillus spores. The combined use of UVC and HEPA filters in the air channel of our air conditioning system can kill and deactivate microorganisms and particles.
	3	P. Chuaybamroong, 2010	The effectiveness of HEPA photocatalytic filter	Niger	Surface coating of Hepa by TiO2 filters with UVA radiation	The inactivation of microorganisms on the TiO2 photocatalytic filter (by 60-80%)and their less penetration into the filter due to oxidative damage to cellular DNA caused by UV-A.
	23	Chotigawin,R. et al., 2010	Determining the effectiveness of photocatalytic HEPA filters (TiO2) in reducing microorganisms in the closed chamber.	Epidermidis	Load TiO2 on the HEPA filter	TiO2 loading at the rate of 1870 ± 169 mg/m2 with There was no significant difference in the loading of 3.140 ± 67 mg/m/m2 for microorganism disinfection in this study. Photolysis can kill bacteria, especially S. epidermidis, but cannot affect fungi. The presence of light-sensitive molecules in their cells causes differences.
	12	G. Candiani et al., 2011	Development of cardboard filters to remove airborne bacteria	E. coli	Dip pleated filters in isopropanol	Cardboard filters impregnated with isopropanol had negligible flow loss. Unimpregnated filters showed a maximum 77% reduction in airborne bacteria, but impregnated filters were 14% more efficient because of the more complex surface.
	31	Lakshmi LD andMuthukumaranV 2017	Covering the HEPA filter with copper and investigating its antimicrobial properties		Filter cover with copper	The pore size of the copper-coated HEPA filter (Cu-HEPA) was reduced from 17.4 to 4.3 micrometers. As a result, the removal efficiency increased and its antimicrobial properties improved
	22	Mousavi et al. 2017	Evaluation of the effect of UVC radiation on the surface of Hepa-plated filters to remove microorganisms		UV radiation on the surface of the HEPA filter	Reducing the density of penetration of airborne microorganisms, including bacteria and fungi, by UVC radiation on the surface of the HEPA filter
	13	Pourhassan B. et al 2018	Investigating the performance of HEPA photocatalytic filter		Photocatalysis of HEPA filters with UVC radiation	Photocatalysis of HEPA filters and UVC radiation at lower surface speeds have a positive and significant effect on reducing microorganisms and increasing the efficiency of HEPA filters.

Various studies investigating the efficiency and pressure drop of HEPA filters have identified the most important microorganisms as Staphylococcus epidermidis, Bacillus subtilis, Bacillus atrophies, Aspergillus niger, Penicillium, E. coli, and Picitrinium. To remove these microorganisms ultraviolet rays A or C combined with TiO2 have been used in the studies of ChotiGawin et al.; Rotruedee, Chuaybamroong, Luna, Mousavi, et al.; and Pourhasan et al. HEPA filters with photocatalytic coatings and the simultaneous use of ultraviolet rays have a higher efficiency in removing microorganisms than uncoated HEPA filters.

Some studies have mentioned using isopropyl alcohol and metal coatings such as copper. Lakshmi and Muthukumaran used copper metal as the coating layer, and Candiani et al. impregnated HEPA filters with isopropyl alcohol; both studies observed satisfactory improvements in the performance of these filters. The accumulation of microorganisms on the surface of HEPA filters and the increase in the thickness of the cake and its coating with photocatalysts or metal coatings cause significant changes in the pressure drop of these filters, an issue addressed by ChotiGawin, Rotruedee et al. and Joubert.

Out of the eight articles reviewed herein, seven mentioned the efficiency of HEPA filters, and two articles mentioned pressure drop. The discussed items are listed in Tables 1 and 2. The efficiency and effectiveness of HEPA filters in reducing microorganism contamination in indoor environments depend on the type of surface coating (type of photocatalyst), type of microorganism, amount and source, intensity and duration of light radiation, type, shape, environmental conditions such as temperature and humidity, opening speed and pressure drop, and the various ways in which it is done, such as cleaning by outside air, filtration, containment through pressure control, use of ultraviolet radiation and ozone, and chemical oxidation. Nonetheless, limitations are still encountered in using each of these methods alone. For example, filtration cannot remove or destroy biological species and only increases air concentration [3].

Table 2. Characteristics of the included studies (Pressure loss)

	Fef.	Authors	Aim	Microorganism	Modifications made to the HEPA filter	Results
Pressure loss	23	Chotigawin, et al., 2010	Determining the effectiveness of photocatalytic HEPA filters (mmm2) in reducing microorganism and filter pressure drop	Epidermidis	TiO2 loaded on the HEPA filter	- The maximum increase in pressure drop of the coated HEPA filter compared to the uncoated filter was about 0.26-0.34 inches of water depending on the rate of abduction. In addition, the penetration of microorganisms was reduced with the coated filter. - The change in pressure drop depends mainly on the forward speed. At the surface velocity of 0.m/m1, the pressure drop of low loading and high loading was significantly different from the uncoated filter (p = 0.791 for 45% relative humidity). (p = 0.0001),
	37	Joubert, A. 2010	The effect of humidity on the clogging of smooth and pleated HEPA filters		Moisture added to pleated and flat filters	In pleated filters, the effect of humidity on pressure drop changes depending on the clogging stage. - When it is possible to reduce the level of filtration, the presence of moisture accelerates the process of closing the folds. - The higher the humidity is, the faster the folds close, leading to a greater pressure drop in the filter. - At the same humidity, pleated filters close earlier than flat ones

Discussion

In the method of cleaning of outside air, a lot of energy is needed, and the disinfection technique by ultraviolet radiation alone has limitations such as low operational power (efficiency), high energy consumption, and reliance on lamps with a radiation wavelength less than 254 nm [12]. Catalytic oxidation technology is an effective alternative technique that works at room temperature and under ultraviolet radiation. This type of oxidation is the most common disinfection process of airborne microorganisms. Much research has been done on the use of PCO on different layers, such as HEPA filters to remove bacteria and fungi, which understand the principles of photocatalysts, including mass transfer in the porous medium, electron excitation, photochemical reaction mechanisms as well as adsorption on photocatalyst surfaces, to interpret experimental data and analyze parameters affecting PCO efficiency. Finally, system optimization is of fundamental importance and is discussed in this review study [13].

The effect of TiO2 on filter performance: Titanium dioxide (TiO2) is one of the most important photocatalytic compounds because of its long-term stability, low price, and high safety for humans and the environment [14]. This photocatalyst operates by reducing microorganisms. TiO2 electrons, receiving the necessary energy, are transferred to the conduction band and leave the previous layers, and the electrons of this band react with oxygen to produce superoxide radical anions. Because of the very short lifetime of these radicals, detoxification of the main organic compounds is carried out on the catalyst's surface (Jacoby et al., 1996); however, because microorganisms are much larger than single molecules, the microbicidal effect of TiO2 involves long-term interactions between the reactants (microorganisms) and this photocatalyst [15]. The mentioned radicals will attack the cell walls of microorganisms and release K+, RNA, proteins, and other important components, ultimately causing cell death [6]. The duration of the reaction as an effective factor can increase the efficiency in the filters coated with TiO2, as mentioned in the studies of Lin and Li [16].

Effect of copper coating on reducing microorganisms: In recent years, to increase the efficiency of HEPA filters impregnated with TiO2 nanoparticles in the target of microorganisms in indoor air, the use of ultraviolet rays (UV) has been increased as a practical and cost-effective controller. The destructive effect of ultraviolet rays depends on the sensitivity of microorganisms and the amount of radiation [17]. Special and high doses of ultraviolet rays at 254 nm have been shown to deactivate bacteria in the air. Ultraviolet emitting lamps may cause the inactivation of microorganisms in two ways: 1) Adequate exposure to unfixed bacteria on the HEPA filter (suspended in air), and 2) Adequate exposure to immobile bacteria on the filter surface [18]. The disinfection effect of ultraviolet rays depends on the sensitivity of microorganisms and the intensity of ultraviolet radiation [17]. Many studies have mentioned the combined use of ultraviolet rays and the TiO2 photocatalyst as one of the most widely used approaches because of its cost-effectiveness and environmental compatibility [19- 21].

Furthermore, the combined use of ultraviolet rays and TiO2 photocatalyst, while increasing the efficiency of air filters, will also increase the useful life of the HEPA filter, because bacteria and organic compounds that typically block the filter pores are destroyed on the surface of TiO2 and with the effect of ultraviolet rays. Nanoparticles of titanium dioxide produce radicals' superoxide and hydroxyl after exposure to UVC radiation causing the destruction of microorganisms on the surface of the filter. Therefore, it can be said that photocatalytic oxidation (TiO2 + UVC) significantly affects the reduction of microorganisms' penetration compared to using UVC alone (photolysis). Chotigawin et al. showed that PCO was more successful in disinfecting microorganisms than UVA photolysis alone [21]. According to Greist et al. (2002), when spores are exposed to PCO, their hydrophobic exteriors mineralized, and external changes of spores occur, producing radicals that allow the hydrophilic interiors to interact with the photocatalytic inactivation of cells [22].

The reason for the destruction of bacteria is based on the synergism between the inherent ability of ultraviolet rays to inactivate viral particles and bacteria directly through nucleic acid and protein damage and the production of oxidative radicals produced through TiO2 surface radiation [23]. According to Greist et al. (2002), when spores are exposed to PCO, their hydrophobic exteriors are mineralized, and external changes in spores occur, producing radicals that allow the hydrophilic interiors to interact with the photocatalytic inactivation of cells [22]. In this process, after UV rays are absorbed by titanium dioxide particles, electrons are mobilized by UV and leave their orbit, leaving holes with very high oxidizing ability. At the same time, electrons with strong reductive properties produce oxygen and hydroxyl free radicals after contact with H2O and O2 in the air.

Because of their high oxidizing properties, these free radicals, are able to destroy the outer membrane of bacteria, which includes phospholipids, proteins, and lipophosphosaccharides, and will eventually destroy cells by breaking down their DNA structure [24]. Cadet believes this destruction depends on the nature of microorganism cells and the intensity of ultraviolet radiation [25]. The results of various studies have pointed out the positive effect of the combined use of photocatalysts and ultraviolet rays on the performance of HEPA filters in reducing the number of microorganisms [13, 15, 26]. Evaluations of the state of deactivation and removal of endospores of Bacillus species using HEPA photocatalytic filters (TiO2) and UV-C radiation studies have shown that the difference in the number of spores is significant in the primary and secondary tests [27]. Furthermore, UVC radiation on the HEPA filter surface had a more significant effect in reducing microorganisms compared to UVA, because of the shorter wavelength and higher energy of UVC compared to other UV rays (such as UVA), such that UVA affects the layer surface and UVC the deep layers [3]. Therefore, the intensity of ultraviolet rays on the photocatalysis of bacteria can be considered an essential factor and has an optimal limit. The photocatalytic inactivation of Bacillus cereus Using UVA with an intensity of 3 mW/cm2 on Bacillus cereus has achieved significant photocatalytic inactivation, but at higher intensities, no significant change in its inactivation has been observed [27]. This can be explained by the competition between UVA rays and photocatalysis to obtain dissolved oxygen. In other words, UVA combines with the production of strong oxidizing species and superoxide radicals in high intensities with hydroxyl radicals on the surface of titanium dioxide and reduces the level of inactivation of microorganisms. In addition to the intensity of the rays, the amount of photocatalyst doped on the filter is also effective in the removal efficiency of microorganisms. Various studies have investigated the effects of TiO2 loading. Some bacteria, such as B. subtilis, show a constant rate of inactivation when the loading of TiO2 is increased up to 2300 mg/m2 on the acetate membrane filter, but more than this amount did not have a positive effect. Instead, it caused a reduction in the disinfection of Paenibacillussp, Macrobacterium, Microbacteria ceaester, and Pseudomonas fluorescens. The optimal loading was reported to range from 511 to 1666 mg/m2 [9].

In Pal's study, the inactivation rate of E. coli at a fixed amount of 1516 mg/m2 of TiO2 increased with the increase of UV-A intensity from 0.5 to 3.4 mW/cm. Moreover, the higher intensity of UV-A led to a higher rate of destruction of Gram-negative bacteria S. marcescens [9]. The effectiveness of microorganisms from TiO2 with the simultaneous irradiation of UV rays is different; it is related to the structure and cellular nature of the microorganisms and the exposure duration. A 2010 study investigated the effectiveness of HEPA photocatalytic filters with titanium dioxide coating in two levels (1870 ± 169 ± 2 mg/m and 3140 ± 67 mg/m) and UVA radiation with intensities of 0.85 and 4.85 mW/cm2 in inactivating four microorganisms, namely Aspergillus Niger, Penicitrinum, Staphylococcus epidermidis, and Bacillus subtilis. The criterion of effectiveness of the studied filter for disinfection was the comparison of the colonies of microorganisms on the photocatalytic filter before and after UVA radiation [3]. The results showed that the inactivation rate of bacteria was not the same. The disinfection efficiency during 8 hours of UVA radiation was 77%, 73%, 80%, and 60-80% for Aspergillus Niger, S. epidermidis, P. citrinum epidermidis, and Bacillus subtilis, respectively. Bacillus subtilis, an endospore-forming bacterium, is less vulnerable to UVA rays than S. epidermidis. The greater vulnerability of S. epidermidis is due to its Gram-positivity and UVA sensitivity, which, as it has a network-like cell wall made of peptidoglycan, is easily destroyed by the impact of radiation [3]. Therefore, because of the low energy of UVA, this ray can cause cell damage through oxidative stress caused by oxygen radicals, thereby stimulating light-sensitive molecules inside the cell. As a result, active species such as 2H2O2, Oº, and OHº are produced, which affect the genome and intracellular molecules and lead to inactive mutations and growth delay [26].

The speed of destruction of bacteria in the use of TiO2 and ultraviolet rays combined is significant compared to the use of each alone. The rate of destruction of B. subtilis under UVA radiation with an intensity of 4 mW/cm 79 per minute and when used together with TiO2 was 0.197 per minute [3].

The effect of copper coating on reducing microorganisms: Since 2017, some studies on increasing the efficiency of HEPA filters in the removal of microorganisms have used metals such as copper as an antibacterial substance to create a positive charge on the surface of nanoparticles, which is significantly effective in the removal of living organisms [28]. The ability of copper nanocomposite to slow down or even prevent the growth of living organisms such as fungi and other pathogenic microorganisms such as S. enteric and C. jejuni have been observed [29]. Increasing the spraying duration of copper on the surface of the filter also leads to an increase in the thickness of the sediment and a decrease in the size of the pores. The results of a 2017 study to investigate and understand the efficiency of HEPA filters by coating them with copper and investigating the antimicrobial properties of copper showed that the size of the pores (pore size) of the HEPA filter is minimized through the copper spraying process using the DC method. The time of copper spraying on the filter caused the pore size to decrease significantly in 30 seconds from 17.43 microns in HEPA filter without coating to 6.62 microns in HEPA filter with single layer coating, in 60 seconds to 33.5 microns in HEPA filter with double layer coating and in 90 seconds to 4.38 microns in HEPA filter with triple coating.

Three-layer coatings have greater efficiency than single-layer coatings, as they lead to greater contact between copper and the microorganisms, i.e., lethal contact. This can be attributed to the larger volume of copper [28].

The large cross-sectional area of copper leads to greater contact and effective destruction of microorganisms. The impossibility of cell division on the surface of copper after direct and long-term exposure and dry surfaces of copper are more effective in killing bacteria [30] and will increase the efficiency of HEPA filters. This ability of copper nanocomposite is also the cause of deceleration and prevention of the growth of living organisms, such as fungi and other pathogenic microorganisms such as S. enteric and C. jejuni [31].

Despite the high efficiency of HEPA filters with three layers of copper compared to those with two and single layers and the proof of effective antimicrobial activity for this filter (Cu-HEPA), contradictory results have been seen in some studies caused by long-term immersion Cu-HEPA filters which are wet in the feeding environment, which causes instability of copper contact on HEPA filters. Therefore, the possibility of copper separation from the HEPA substrate is higher in a humid environment. In standard levels of humidity, however, such an event will not occur, and humidity is less likely to influence Cu-HEPA performance [28].

The role of isopropyl alcohol on the efficiency of HEPA filters: In addition to photocatalysts, methods such as impregnating filters with alcoholic substances can increase the HEPA filters' efficiency and effectiveness in removing microorganisms such as E. coli. In the study of Candiani (2011), pleated cardboard filters impregnated with isopropanol (isopropyl alcohol) performed at 91%, which is about 14% better than filters without alcohol, in reducing bacteria in the air. Isopropyl alcohol increased the survival rate of microorganisms by increasing the roughness of the filter surface and reducing the moisture content of the cardboard and, as a result, creating a more heterogeneous surface compared when it is not used [12]. The relatedness of the filter is another factor that will have a positive effect on increasing the efficiency of isopropyl alcohol in removing microorganisms.

How the filter works in reducing microorganisms: While making HEPA filters, changing the shape of the filter into the pleated type will increase their overall surface and efficiency. One study (2018) used the immersion method to kill the Gram-positive bacteria Staphylococcus epidermidis and Bacillus subtilis. The amount of bacteria penetration in the ordinary non-plate and photocatalytic HEPA filter with different intensities of UVC radiation were significantly reduced in comparison to the absence of radiation. In this study, UVC radiation with an intensity of 1.8 mW/cm compared to an intensity of 1.2 mW/cm caused a greater reduction in bacteria penetration in both filters. With an increase in speed from 0.1 meters per second to 0.3 m/s in the case of UVC radiation and without UVC radiation, the rate of penetration of bacteria increased significantly ($p<0.05$) [13].

How microorganisms affect the efficiency of HEPA filters: Studies have shown that the diversity of microorganisms is also significant in addition to the combined use of TiO_2 and ultraviolet rays. The microorganisms most commonly investigated are Staphylococcus epidermidis, Bacillus subtilis, Bacillus atrophius, Aspergillus niger, Penicillium, E. coli, and Positronium [32]. Results have shown that under identical conditions, the lowest and highest removal rates were related to Aspergillus Niger and S. epidermidis, respectively, because of the cellular DNA's lower and higher sensitivity to oxidative damage caused by ultraviolet rays, respectively [3]. In another study, the difference in the average density of the four types of microorganism, Staphylococcus epidermidis, Bacillus subtilis, Aspergillus niger, and Penicillium, in the case of UVC radiation to the surface of the HEPA filter compared to the absence of this radiation in three time periods (60, 90, and 120 minutes) was significant ($p <0.05$), which indicates a decrease in the density of penetration of airborne microorganisms such as bacteria and fungi caused by UVC radiation on the surface of the HEPA filter [33]. The effects of environmental factors such as humidity on the removal of microorganisms can lead to improvement in the effectiveness of the filtration mechanism [34].

A microorganism such as B. subtilis in 45% humidity after 5 hours under UVA radiation is about 80% photolyzed, because after exposure to PCO, their hydrophobic outer parts are mineralized and external changes occur to spores, allowing the hydrophilic interior to interact with radicals produced by the photocatalyst, which ultimately leads to cell inactivation [35].

The effects of photocatalysts on HEPA filter pressure drop and efficiency: Air filters are widely used to reduce particle concentrations because of their effective performance in absorbing incoming particles. The increase in pressure drop of filters and filter media caused by adsorbed particles has attracted wide attention because of its significant effect on the useful life of filters and the energy consumption of ventilation systems [35]. Study results have shown that the pressure drop throughout the filter without coating with photocatalysts increased with increases in the deposited mass of aerosol particles. At the point of cake formation, the increase in pressure drop is linearly proportional to the mass of the deposited aerosol particles [35]. While filter efficiency and pressure drop remain constant in the initial stage of filtration, during filtration, aerosol particles gradually accumulate on the surface of the fiber, blocking the filter and resulting in a sharp increase in pressure drop and a change in filter efficiency [36]. In uncoated filters, pressure drops increase with surface speed; at low speeds (less than 0.4 cm/s), the pressure drop changes very slowly [37].

Various studies have investigated the effect of surface velocity on pressure drop. In filters both with and without cover, increases in surface velocity correspond with increases in pressure drop. At the velocity of 0.1 m/s for the uncoated filter with photocatalysts, the pressure drop was 15.57 pa and for the filter coated with a combination of TiO_2 and Ag was 25.95 pa. At a velocity of 1 m/s, it was 33.36 pa and 46.71 pa, respectively. In HEPA filters at a velocity of 0.1 m/s, without coating with photocatalysts, however, the pressure drop rate was 31.14 pa, and for the filter coated with a combination of TiO_2 and Ag was 46.71 pa. At a velocity of 1 m/s, it was 57.09 pa and 72.65 pa, respectively. The results showed that the increase in pressure drop due to increased surface velocity in HEPA filters was greater than in other filters. This can probably be attributed to the more complex structure of HEPA filters, which are more effective in removing microorganisms than other filters [7].

Other studies have reported an increase in pressure drop due to increased surface velocity. In the study of Pour Hasan, the pressure drop of ordinary and photocatalytic HEPA filters at a velocity of 0.1 m/s and an airflow rate of 240 l/m was equal to 2.48 and 3.23 pa, respectively, and at a velocity of 0.3 m/s and a flow rate of 720 l/m, it was equal to 3.73 and 4.72 pa, respectively. As a result, the increase in surface velocity produces a linear increase in pressure drop and increased efficiency of the HEPA filter in removing microorganisms ($p<0.05$). This result is similar to that of other studies as well [13].

Studies have demonstrated the relationship between pressure drop, surface velocity, and relative humidity on the performance of coated filters. A change in pressure drop depends on the forward speed. At a surface velocity of 0.1 m/s, the pressure drops in the uncoated filter with low loading and high loading and relative humidity of 45% showed a significant difference ($p<0.05$). Between the filters with and without TiO_2 coating, at 45% humidity, the maximum pressure drop was 0.26 inches of water. Still, at 75% humidity, the maximum pressure drop increased to 0.34 inches of water [3].

The effect of humidity on increasing pressure drops in filters, especially pleated ones, has been investigated in studies. The results showed the effect of humidity on clogging and pressure drop depends on the stage of clogging on the filter surface. At the beginning of clogging, pressure drop changes in pleated filters are similar to those in flat filters. When the filtration surface is significantly reduced, the presence of moisture accelerates the process of closing the wrinkles, and the adhesion forces between the particles due to the capillary forces caused by vapor condensation are intensified by increasing relative humidity, especially when the aerosol is hydrophilic [35]. The higher the capillary forces are, the less likely the aerosol will penetrate much into the folds. Thus, particles accumulate on the surface of the folds and cause the folds to close, resulting in a pressure drop in the filter [38].

Thus, adding a coating of different materials, such as photocatalysts, or increasing the humidity on the surface of the HEPA filter due to limiting the passage of microorganisms will increase the pressure drop and the efficiency of the filters in removing these factors.

Some studies have reported contradictory results. Ludwig et al. (2018) investigated the effects of the size and morphology of nanoparticles released by TiO_2 and SiO_2 in filtration and reported that clogging caused by the deposition of nanoparticles on the filtering fibers is significant; however, it has no significant effect on pressure drop [39]. This difference can be attributed to the particle size, which was 30-50 nm in Ludwig's study and 17 nm in the study by Pourhassan et al. (12, 39). Thus, the larger size of the particles, which causes more continuity and less distance between them, will have less effect on the pressure drop on the filter surface.

Conclusion

Filter efficiency and pressure drop are the most important parameters of fibrous filters. A good filter using fine fibers is expected to show high efficiency and low-pressure drop. By adding nanomaterials to filters, it is possible to potentially overcome the inherent limitation of the relationship between filter efficiency and pressure drop that traditional filters have. Also, ultraviolet radiation leads to competition between different types of this radiation and photocatalysis for soluble O2, which is required to produce strong oxidant species. One of the factors affecting the pressure drop of filters is the amount of humidity and the surface speed, which increases the pressure drop, regardless of the shape and structure of the filter (pleated or flat), coated or uncoated. Using different coatings individually or together on the HEPA filter increases their efficiency in reducing and removing microorganisms. Therefore, it is possible to reduce the problem of microorganism growth and indoor air quality by using HEPA photocatalytic filters. According to studies done on improving the performance of HEPA filters, photocatalysts, ultraviolet rays, and metal coatings have all been used. What has not yet been investigated, however, is the effect of MOF on improving the performance of HEPA filters. It is recommended that researchers pay special attention to this issue in future research.

Acknowledgement

The authors express their gratitude to all who assisted with this study.

Conflict of interest: None declared.

References

1. Ogunseitan O. Green Health: An A-To-Z Guide. 1ed. Los Angeles, California, United States: SAGE Publishing Inc; 2011. P.13.
2. Roy A. A Review of general and modern methods of air purification. J Therm Eng. 2019;5(2):22-8.
3. Chuaybamroong P, Chotigawin R, Supothina S, Sribenjalux P, Larpkiattaworn S, Wu CY. Efficacy of photocatalytic HEPA filter on microorganism removal. Indoor Air. 2010;20(3):246-54.
4. Guo J, Xiong Y, Kang T, Xiang Z, Qin C. Bacterial community analysis of floor dust and HEPA filters in air purifiers used in office rooms in ILAS, Beijing. Sci Rep. 2020;10(1):6417.
5. International Organization for Standardization. High-efficiency filters and filter media for removing particles in the air – Part 5: Test method for filter elements. Geneva, Switzerland: International Organization for Standardization; 2022. Report No.:29463-5:2022
6. Tan J, Abu Bakar NZ. Design improvement of an airbox for a passenger vehicle. Proceedings of the 15th International Engineering and Computing Research Conference (EURECA 2021); 2021 Jun 30; Subang Jaya, Malaysia. (J Phys Conf Ser. 2021;2120(1):012010).
7. Goswami DY. Engineering of solar photocatalytic detoxification and disinfection process. Adv Sol Energy. 1995;10.
8. Keller V, Keller N, Ledoux MJ, Lett MC. Biological agent inactivation in a flowing air stream by photocatalysis. Chem Commun (Camb). 2005;(23):2918–20.
9. Pal A, Pehkonen SO, Yu LE, Ray MB. Photocatalytic inactivation of airborne bacteria in a continuous-flow reactor. Ind Eng Chem Res. 2008;47(20):7580–5.
10. Arksey H, O'Malley L. Scoping studies: Towards a methodological framework. Int J Soc Res Methodol. 2005;8(1):19-32.
11. Munn Z, Peters MDJ, Stern C, Tufanaru C, McArthur A, Aromataris E. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC Med Res Methodol. 2018;18(1):143.
12. Candiani G, Del Curto B, Malloggi C, Cigada A. Development of novel cardboard filters very effective in removing airborne bacteria from confined environments. J Appl Biomater Biomech. 2011;9(3):207-13.
13. Pourhassan B, Golbabaei F, Pourmand MR, Dehghan SF, Masoorian E. Examining performance of the conventional and photocatalytic HEPA filters on the removal of the airborne microorganisms. J Health Saf Work. 2018;8(3):251-64.
14. Weir A, Westerhoff P, Fabricius L, Hristovski K, von Goetz N. Titanium Dioxide Nanoparticles in Food and Personal Care Products. . Environ Sci Technol. 2012;46(4):2242-50.
15. Dunlop PSM, Byrne JA, Manga N, Eggins BR. The photocatalytic removal of bacterial pollutants from drinking water. J Photochem Photobiol A Chem. 2002;148(1-3):355-63.
16. Luna VA, Cannons AC, Amuso PT, Cattani J. The inactivation and removal of airborne Bacillus atrophaeus endospores from air circulation systems using UVC and HEPA filters. J Appl Microbiol. 2008;104(2):489-98.
17. Walker CM, Ko G. Effect of Ultraviolet Germicidal Irradiation on Viral Aerosols. Environ Sci Technol. 2007;41(15):5460-5.
18. Kujundzic E, Zander DA, Hernandez M, Angenent LT, Henderson DE, Miller SL. Effects

of Ceiling-Mounted HEPA-UV Air Filters on Airborne Bacteria Concentrations in an Indoor Therapy Pool Building. J Air Waste Manag Assoc. 2005;55(2):210-8.
19. Huang X, Wang H, Yin S, Chen X, Chen W, Yang H. Sterilization system for air purifier by combining ultraviolet light-emitting diodes with TiO2. J Chem Technol Biotechnol. 2009;84(10):1437-40.
20. Mousavi T, Golbabaei F, Helmi Kohneshahri M, Pourmand MR, Rezaie S, Hosseini M, et al. Efficacy of photocatalytic HEPA filter on reducing bacteria and fungi spores in the presence of UVC and UVA lights. Pollution. 2021;7(2):309-19.
21. Song YW, Kim MY, Chung MH, Yang YK, Park JC. NOx-reduction performance test for TiO2 paint. Molecules. 2020;25(18):4087.
22. Chotigawin R, Sribenjalux P, Supothina S, Johns J, Charerntanyarak L, Chuaybamroong P. Airborne microorganism disinfection by photocatalytic HEPA filter. EnvironmentAsia. 2010;3(2):1-7.
23. Greist HT, Hingorani SK, Kelley K, Goswami DY. Using scanning electron microscopy to visualize photocatalytic mineralization of airborne microorganisms. In: Levin H, ed. Indoor Air 2002- 9th International Conference on Indoor Air Quality and Climate. Proceedings of the 9th International Conference on Indoor Air Quality and Climate; 2002 Jun 30 - 2002 Jul 05; Monterey, California, United States. Rotterdam, Netherlands; 2002. P.712-7.
24. Buonanno M, Welch D, Shuryak I, Brenner DJ. Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. Sci Rep. 2020;10(1):10285.
25. Marouzi S, Sabouri Z, Darroudi M. Greener synthesis and medical applications of metal oxide nanoparticles. Ceram Int. 2021;47(14):19632-50.
26. Cadet J, Sage E, Douki T. Ultraviolet radiation-mediated damage to cellular DNA. Mutat Res. 2005;571(1-2):3-17.
27. Block SS, Seng VP, Goswami DW. Chemically enhanced sunlight for killing bacteria. J Sol Energy Eng. 1997;119(1):85-91.
28. Zhao J, Krishna V, Hua B, Moudgil B, Koopman B. Effect of UVA irradiance on photocatalytic and UVA inactivation of Bacillus cereus spores. J Photochem Photobiol B. 2009;94(2):96-100.
29. Dhiviya Lakshmi L, Muthukumaran V. Investigation of antimicrobial activity of medical grade hepa filter with copper deposition. Int J Civil Eng Technol. 2017;8(9):262-70.
30. Ben-Sasson M, Zodrow KR, Genggeng Q, Kang Y, Giannelis EP, Elimelech M. Surface Functionalization of Thin-Film Composite Membranes with Copper Nanoparticles for Antimicrobial Surface Properties. Environ Sci Technol. 2014;48(1):384-93.
31. Liu YS, Cole HS. Laser surface modification for copper deposition on polyimide. MRS Online Proc Libr. 1988;129:579-84.
32. Ereth MH, Hess HD, Driscoll A, Hernandez M, Stamatatos F. Particle control reduces fine and ultrafine particles greater than HEPA filtration in live operating rooms and kills biologic warfare surrogate. Am J Infect Control. 2020;48(7):777-80.
33. Mousavi T, Golbabaei F, Pourmand MR, Rezaei S, Hosseini M, Helmi Kohneshahri M, et al. Evaluating the efficiency of UVC radiation on HEPA filters to remove airborne microorganisms. J Health Saf Work. 2017;7(2):111-20.
34. Novick VJ, Monson PR, Ellison PE. The effect of solid particle mass loading on the pressure drop of HEPA filters. J Aerosol Sci. 1992;23(6):657-65.
35. Joubert A, Laborde JC, Bouilloux L, Chazelet S, Thomas D. Modeling the pressure drop across HEPA filters during cake filtration in the presence of humidity. Chem Eng J. 2011;166(2):616-23.
36. Payatakes AC. Model of the dynamic behavior of a fibrous filter. Application to the case of pure interception during a period of hindered growth. Powder Technol. 1976;14(2):267-78.
37. Kanaoka C, Hiragi S. Pressure drop of the air filter with dust load. J Aerosol Sci. 1990;21(1):127-37.
38. Ricketts CI, Ruedinger V, Wilhelm JG. HEPA-filter behavior under high humidity airflows. In: First MW, ed. Proceedings of the 19th Doe/Nrc Nuclear Air Cleaning Conference. Paper presented at: The 19th DOE/NRC Nuclear Air Cleaning Conference; 1986 Aug 18-21; Seattle, Washington, United States. Washington: United States; May 1987. P. 319.
39. Vinches L, Hallé S. Effects of Size and Morphology of TiO2 and SiO2 Airborne Nanoparticles on their Filtration Through Chemical Protective Clothing. J Theor Appl Nanotechnol. 2018;6:11-20.