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Microbiological air quality in office buildings equipped with different ventilation systems

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Abstract

Proper hygienic conditions in office buildings are of a high importance for both health and well-being of the employees. The aim of this study was the direct comparison of different ventilation systems on microbiological environments in 15 office buildings. The results showed that both bacterial and fungal concentrations in the naturally ventilated office buildings were between 70 and 1600 cfu/m³, while in the offices equipped with air-conditioning and mechanical ventilation systems, concentrations were lower, that is, between 10 and 530 cfu/m³ and 20 and 410 cfu/m³, respectively. The size distribution analysis revealed that microorganisms were present in the air mainly as single cells (1.1–3.3 µm) and large aggregates (4.7–>7 µm). If deposited in the human respiratory tract, they may be responsible for nose and eyes irritations, asthmatic reactions, and allergic inflammations. The most prevalent bacterial species indoors were Gram-positive cocci (mainly from *Staphylococcus* and *Micrococcus/Kocuria* genera) and endospore-forming Gram-positive rods (from *Bacillus* genus). Among the most common fungal species were those from genera *Penicillium*, *Aspergillus*, and *Cladosporium*. Effectively working and regularly maintained mechanical ventilation or air-conditioning systems ensure a better hygienic quality in the office buildings than natural/gravitational ventilation.

KEYWORDS

bioaerosol, air conditioning, indoor air, mechanical ventilation, microbiological contaminants, natural ventilation

1 | INTRODUCTION

Rapid development of building industry results in a significant increase in the number of employees working in the premises intended or adapted for office activities. In this context, the indoor air quality becomes of a great importance for both the health and well-being of workers. Epidemiological data show that more than 30% of office workers complain about their health problems, linking them to the polluted indoor air.¹ They are often exposed to numerous harmful and/or burdensome factors which include chemical and biological contaminants, noise, mechanical vibration, electromagnetic fields, lighting, static electricity, and variable microclimate. As a result of such exposure, office employees usually report of tiredness,

breathlessness, headaches, dizziness, irritability, decreased ability to concentrate, memory disorders, irritation of mucous membranes of the eyes, and upper respiratory tract as well as skin lesions as major adverse health outcomes.² In the worst cases, some of them may be responsible for the development of harmful effects such as Sick Building Syndrome (SBS), tight building syndrome (TBS), or building-related illnesses (BRI).³

Buildings are at constant risk of microbial colonization. When microbiological agents are present in low concentrations, and no pathogens are found among them, they usually pose no hazard to humans. The problem of contamination arises when the level of microbiological contamination exceeds the certain limit which is considered “normal” (“natural”) for a particular environment.

Regarding microbial contaminants in office buildings, among their typical sources are employees, construction materials, ventilation (including air-conditioning) systems, and outdoor air penetrating particular building envelope.^{4,5} In this type of working environment, different microbiological agents (ie, bacteria, fungi, cell fragments, endotoxins, glucans, mycotoxins, or volatile organic compounds) being transported in the air can be responsible for numerous adverse health outcomes observed in exposed individuals.^{6,7}

Ventilation systems are a technical solution aimed at improving the indoor air quality. Apart from their health-oriented applications, modern ventilation systems reduce the microbiological contamination of the air. However, with time, they may get contaminated and become a secondary source of microbial pollution.

The aim of this study was the assessment of employees' exposure to bacterial and fungal aerosols in office buildings, taking into account the influence of different ventilation systems on the microbial quality of air in the studied premises.

2 | MATERIAL AND METHODS

2.1 | Building characteristics

This study was conducted in 15 randomly selected office buildings divided into three equal groups, that is, buildings equipped with an air-conditioning system, mechanical supply-and-exhaust ventilation, and natural (understood here as gravitational) ventilation. Both the air-conditioning system and mechanical supply-exhaust ventilation in studied buildings were central systems. Their detailed characteristics are given in Table 1.

2.2 | Sampling strategies

The measurements were taken during winter (a period of 6 months from October till March, when the average outdoor air temperature was below 10°C for at least 7 consecutive days) and summer (a period of 6 months from April till September, when the average outdoor air temperature was above 10°C for at least 7 consecutive days) seasons. At each studied office workplace, bioaerosol samples were collected in five office rooms in the morning at the beginning of work shift, to establish so-called indoor background and at noon, 4-5 hours from the beginning of work, during typical occupational activities. In addition, to determine the so-called outdoor background, the atmospheric bioaerosol was simultaneously collected outside each studied building (ie, in case of buildings equipped with an air-conditioning system or mechanical ventilation—near air intake on the roof; in case of naturally ventilated buildings—in their close vicinity on the street).

The viable (understood here as culturable) bioaerosol samples were taken simultaneously using both six-stage Andersen (model WES-710, Westech Instrument, Upper Stondon, Great Britain) as well as single-stage MAS (model 100 Eco, Merck KGaA, Darmstadt, Germany) impactors. The flow rates and sampling times were

Practical Implications

- The air quality in offices depends on the type and hygienic condition of the ventilation system used in the building.
- Offices where the mechanical ventilation or air-conditioning system operates properly and is maintained correctly are microbiologically less contaminated than those with natural/gravitational ventilation.
- The analysis of bioaerosol size distributions in the studied office buildings showed that air-conditioning systems filtered out the bioaerosol particles within 0.65-11 µm aerodynamic diameters with high efficiency.
- Both the MAS-100 Eco and 6-stage Andersen impactors may be successfully used in the hygienic evaluation of air quality in the office buildings.

28.3 L/min and 5 minutes as well as 100 L/min and 1.5 minutes, respectively. Standard Petri dishes filled with blood trypticase soy agar (TSA, 51044, bioMérieux, Marcy l'Etoile, France) and malt extract agar (MEA, Oxoid Ltd., Basingstoke, Great Britain) were used for bacterial and fungal sampling, respectively. Additionally, indoor bioaerosol samples were also taken using Button sampler (SKC Inc., Eighty-four, PA) to determine a total (viable and non-viable together) microbial count. The flow rate and sampling time were 4 L/min and 30 minutes, respectively.

During the measurements, all sampling instruments were placed at a height of 1-1.5 m above the floor, roof, or ground level to simulate aspiration from the human breathing zone. At each sampling point, all performed measurements were duplicated.

2.3 | Colony counting and microbiological analyses

All collected impactor samples were incubated as follows: bacteria—1 day at 37°C, followed by 3 days at 22°C and 3 days at 4°C; and fungi—4 days at 30°C followed by 4 days at 22°C.⁸ The appearance of the colonies was controlled during the whole incubation periods; however, the final concentrations of viable microorganisms in the air were calculated as colony-forming units (cfu), per 1 cubic meter of the air, counted at the end of the entire incubation period.

Bacterial and yeast strains were taxonomically identified after Gram staining (111885 Gram-color stain set, Merck KGaA) based on their morphology and biochemical analytical profile index (API) tests (bioMérieux).⁹ Filamentous fungi were identified according to their morphology using several identification keys.¹⁰⁻¹²

The most prevalent microbial isolates were additionally analyzed by molecular methods (polymerase chain reaction (PCR) followed by random amplification of polymorphic DNA-RAPD typing). DNA was isolated from pure bacterial/fungal cultures

TABLE 1 Characteristics of studied office buildings

Studied building	Date of building commissioning	Surface area, number of stories and number of rooms	Number of employees	Characteristics of ventilation system	Maintenance of ventilation system
Buildings with air-conditioning system					
Automatic regulation of temperature, humidity, air flow and proportion of fresh to the recirculated air					
In selected rooms: automatic registration of temperature, relative humidity and CO ₂ concentration					
Airtight (impenetrable for the outdoor air), non-openable windows					
AC I	2006	• 2800 m² • 4 stories • 65 rooms	120	• 1 air-conditioning unit for offices and 1 unit for toilets, corridors and halls • 50 m³/h of fresh air/employee	• Regular replacement of EU4 and EU8 exhaust filters • No mechanical cleaning of ventilation ducts
AC II	2000	• 5600 m² • 5 stories • 86 rooms	200	• 9 air-conditioning units • 20 m³/h of fresh air/employee	• Regular replacement of EU1, EU4 and EU8 filters • No mechanical cleaning of ventilation ducts
AC III	2003	• 12 532 m² • 13 stories • 296 rooms	370	• 10 air-conditioning units • 30 m³/h of fresh air/employee	• Regular replacement of EU1, EU4 and EU6 filters • No mechanical cleaning of ventilation ducts
AC IV	2004	• 7400 m² • 6 stories • 120 rooms	120	• 5 air-conditioning units • 30 m³/h of fresh air/employee	• Regular replacement of EU1, EU4 and EU6 filters • No mechanical cleaning of ventilation ducts
AC V	1999	• 10 500 m² • 10 stories • 280 rooms	260	• 15 air-conditioning units • 20 m³/h of fresh air/employee	• Regular replacement of EU1, EU4 and EU6 filters • 2005—comprehensive mechanical cleaning of ventilation ducts
Buildings with mechanical supply-and-exhaust ventilation					
Mechanical ventilation system with heat recovery					
The ability to manually control the system					
Airtight (impenetrable for the outdoor air), openable windows					
M VI	1998	• 10 270 m² • 8 stories • 420 rooms	700	20 m ³ /h of fresh air/employee	• Regular replacement of EU1 and EU2 filters • Mechanical cleaning and disinfection of selected sections of ventilation ducts (performed twice a year)
M VII	1997	• 1921 m² • 4 stories • 87 rooms	100	30 m ³ /h of fresh air/employee	• Regular replacement of EU2 filters (4-8 times per year) • No mechanical cleaning of ventilation ducts

(Continues)

TABLE 1 (Continued)

Studied building	Date of building commissioning	Surface area, number of stories and number of rooms	Number of employees	Characteristics of ventilation system	Maintenance of ventilation system
M VIII	1996	• 3040 m² • 7 stories • 126 rooms	210	• Heating or cooling of the air through ceiling-mounted ventilation units • Recirculation of the air • 20 m³/h of fresh air/employee	• Replacement of EU2 filters depending on the level of contamination • No mechanical cleaning of ventilation ducts
M IX	2002	• 8700 m² • 5 stories • 280 rooms	350	• Heating or cooling of the air through ceiling-mounted ventilation units • Recirculation of the air • 20 m³/h of fresh air/employee	• Regular replacement of EU2 filters • Mechanical cleaning and disinfection of selected sections of ventilation ducts (performed twice a year)
M X	1997	• 2500 m² • 5 stories • 125 rooms	180	20 m ³ /h of fresh air/employee	• Replacement of EU2 filters depending on the level of contamination • No mechanical cleaning of ventilation ducts
Buildings with natural (gravitational) ventilation					
Air penetrates inside through the building envelope (ie, through the leaks around windows and doors) and escapes via outlet grilles					
G XI	1970	• 1870 m² • 5 stories • 85 room	159	Leaky, openable windows	(if needed) vacuuming of outlet grilles
G XII	1992	• 6342 m² • 8 stories • 133 rooms	289	Airtight, openable windows	(if needed) vacuuming and washing of outlet grilles
G XIII	1995	• 1500 m² • 8 stories • 65 rooms	53	Airtight, openable windows	(if needed) vacuuming and washing of outlet grilles
G XIV	1957	• 2600 m² • 5 stories • 130 rooms	179	Airtight, openable windows	(if needed) vacuuming of outlet grilles
G XV	1985	• 7400 m² • 6 stories • 250 rooms	336	Leaky, openable windows	(if needed) vacuuming of outlet grilles

grown on TSA/MEA plates using QIAmp DNA Mini Kit (Qiagen, Hilden, Germany) or Fungi DNA Mini Kit (Syngen Biotech, Wrocław, Poland). The isolated bacterial DNA was used as a template in PCR using BAK11w (5'-AGTTTGATCMTGGCTCAG-3') and BAK2 (5'-GGACTACHAGGGTATCTAAT-3') primer set which allows the amplification of bacterial 16S rRNA gene fragment corresponding to *E. Coli* 16S rRNA gene positions from 10 to 806. The isolated fungal DNA was used as a template in PCR using ITS1 (5'-TCCGTAGGTGAACCTGCGG-3') and ITS4 (5'-TCCTCCGCTTATTGATATGC-3') primer set which allows the amplification of fungal genome fragment located between 18S and 28S rRNA genes, covering ITS1, 5.8S rRNA, and ITS2

fragments. The amplified PCR product was purified, sequenced using ABI3730 Genetic Analyzer (Applied Biosystems, Waltham, MA), and compared to GenBank database (National Center for Biotechnology Information, U.S. National Library of Medicine, USA) using BLAST algorithm (Basic Local Alignment Search Tool).^{13,14}

The total number of microorganisms (viable and non-viable bacteria and fungi together) was estimated using the CAMNEA method.^{15,16} Briefly, the microorganisms were sampled onto 25-mm gelatin filter with a pore size of 3 µm (SKC Inc.) housed in Button sampler inlet section. After sampling, the filter was removed from the sampler holder and dissolved in sterile water

TABLE 2 Microbial concentrations [cfu/m³] in office buildings with different ventilation systems and in outdoor air (symbols represent: "M"—median, "R"—range)

		Bacteria				Fungi			
		Summer		Winter		Summer		Winter	
Environment	Sampler	M	R	M	R	M	R	M	R
Air-conditioning system									
Indoor background (n = 50)	Andersen	130	40-410	40	10-80	20	0-100	10	0-70
	MAS	90	30-350	30	10-80	10	0-120	10	0-80
Workplaces (n = 50)	Andersen	130	60-460	60	10-250	60	0-250	20	0-180
	MAS	140	10-760	60	10-200	30	0-430	10	0-200
Mechanical ventilation									
Indoor background (n = 50)	Andersen	110	60-190	50	20-150	80	40-200	50	10-60
	MAS	120	50-200	50	40-120	60	50-100	40	10-60
Workplaces (n = 50)	Andersen	250	110-410	120	30-130	120	80-280	60	30-100
	MAS	220	100-320	120	100-200	150	80-280	60	20-100
Natural (gravitational) ventilation									
Indoor background (n = 50)	Andersen	140	90-560	60	30-100	150	110-340	100	40-140
	MAS	150	110-190	80	60-130	160	110-240	80	40-110
Workplaces (n = 50)	Andersen	350	190-1600	130	80-230	190	140-450	140	50-200
	MAS	330	190-730	150	80-320	180	112-510	150	70-210
Outdoor background (n = 30)	Andersen	140	110-180	40	40-130	200	150-1430	140	40-430
	MAS	330	130-840	60	10-190	350	100-640	160	40-400

containing 0.01% Tween 80 (Merck KGaA). Obtained suspension was treated with formaldehyde (37%) (POCH S.A., Gliwice, Poland), and the resulted fluid was stained with acridine orange (Sigma-Aldrich Co., St. Louis, MO) and then filtered through a black polycarbonate filter with a pore size of 0.4 μm (Whatman International Ltd., Maidstone, Great Britain); finally, dyed microorganisms were counted under an epifluorescence microscope (Eclipse E200, Nikon, Tokyo, Japan) at the wavelength of 490 nm. Their concentration was expressed as counts per 1 cubic meter of the air.

2.4 | Measurement of microclimate parameters

The environmental conditions (temperature and relative humidity of the air) in studied office buildings and atmospheric air were recorded during every sampling session with thermohygrometer (Omniport 20, E+E Elektronik GmbH, Engerwitzdorf, Austria).

2.5 | Statistical analysis

Due to a non-normal distribution of the collected data (analyzed by Shapiro-Wilk test), all the results were statistically processed based on the Kruskal-Wallis, Wilcoxon and Mann-Whitney tests as well as Spearman's correlation using the "STATISTICA data analysis software system" package version 7.1 (StatSoft Inc., Tulsa, OK). The relationships were treated as statistically significant at $P < 0.05$.

3 | RESULTS

3.1 | Quantitative analysis of bacterial and fungal aerosols

The concentrations of viable bacterial and fungal aerosols as measured using Andersen and MAS impactors in the air of studied office buildings and in the outdoor air in summer and winter seasons are presented in Table 2.

A comparison of concentration values for studied microbiota measured using both Andersen and MAS impactors at workplaces and in the indoor background in three buildings groups, in both studied seasons, demonstrated in all cases no statistically significant differences (Wilcoxon's test: $P > 0.05$). On the other hand, while comparing concentration values for bioaerosols in the outdoor background, it was found that in both the "summer" and "winter" seasons, the measurements taken using MAS impactor show higher concentration values than those obtained using Andersen impactor for bacterial microorganisms only (Wilcoxon's tests: $P < 0.01$ and $P < 0.05$, respectively).

A comparison of bacterial aerosol concentrations in the outdoor and indoor backgrounds in three studied building groups demonstrated no statistically significant differences in both measurement seasons. In turn, in both measurement rounds, the fungal aerosol concentrations were significantly higher in the outdoor environment than inside the studied buildings being equipped with air-conditioning system or mechanical ventilation

systems ($P < 0.05$). Regarding buildings equipped with natural ventilation, significantly higher fungal concentrations in outdoor air were recorded in the “summer” season only (Mann-Whitney test: $P < 0.05$).

There were no significant differences between bacterial aerosol concentrations in the indoor background in three building groups in both measurement seasons. To regard fungal aerosol, in both the “summer” and “winter” seasons, the highest concentrations were recorded in office rooms in the buildings with natural ventilation, while the lowest ones were measured in the rooms equipped with an air-conditioning system. Fungal aerosol concentrations measured in indoor background in the rooms with air-conditioning system were significantly lower (5.6 and 12 times, respectively) than those in the rooms with mechanical or natural ventilation (Kruskal-Wallis test: in both cases, $P < 0.01$).

The bacterial contamination of the air was significantly higher (about 2.2 times) at work places than in indoor background in both studied seasons in the buildings with mechanical as well as natural ventilation ($P < 0.01$). In case of fungal contamination of the air, no significant differences of this type were found. In the group of buildings with air-conditioning system, no statistically significant differences were recorded between concentrations of microorganisms at workplaces and in the indoor background.

The concentrations of bacterial aerosol measured at workplaces in the rooms with a air-conditioning system, in both seasons, were significantly lower (1.9 and 2.5 times, for “summer” and “winter” seasons, respectively) than those in the rooms with mechanical or natural ventilation systems (Kruskal-Wallis test: in both cases, $P < 0.01$). Also, in “summer” season, the bacterial contamination of the air was significantly higher (1.4 times) in the rooms with natural ventilation than in the mechanically ventilated rooms ($P < 0.05$).

The concentrations of fungal aerosol measured at workplaces in the rooms with natural ventilation, in both seasons, were significantly higher (3.7 and 2.5, respectively) than those in air-conditioned and mechanically ventilated buildings (Kruskal-Wallis test: $P < 0.01$ and $P < 0.05$, respectively). In the “winter” season, the concentrations of fungal aerosol in the rooms with mechanical ventilation system were usually 2.8 times higher than those in the rooms with air-conditioning system ($P < 0.01$).

The concentrations (median values and ranges) of viable and total microbial aerosols in the studied office buildings in “summer” and “winter” seasons are presented in Table 3.

Regardless of the type of ventilation system in building, the total concentrations of microorganisms were always significantly higher than the concentrations of culturable microorganisms. In our study, viable microorganisms constituted from 0.3% to maximally 1% of the total airborne microbiota in all studied offices. Furthermore, a comparison of the total microbial concentrations in three studied building groups, in both measurement periods, shows that in the rooms with natural ventilation, the recorded total bioaerosol concentrations were significantly higher than those in air-conditioned or mechanically ventilated premises (Kruskal-Wallis test: in both cases, $P < 0.01$). No significant differences were found for the concentrations of microorganisms between air-conditioned and mechanically ventilated rooms.

3.2 | Qualitative analysis of bacterial and fungal aerosols

All microbial species isolated from the air of examined offices are presented in Table 4. Qualitative analysis demonstrated that the most prevalent bacterial species in all studied premises were

TABLE 3 Concentrations of viable [bacteria and fungi, cfu/m³] and total [viable and non-viable bacteria and fungi together, counts/m³] microbial aerosols in office buildings with different ventilation systems

Sampler	Sample type	Microbial aerosol			
		Summer season		Winter season	
		Median	Range	Median	Range
Air-conditioning system					
Andersen	Viable	190	80-460	80	10-290
MAS	Viable	180	10-530	80	10-240
Button	Total	118 000	39 000-275 000	9800	31 000-157 000
Mechanical ventilation					
Andersen	Viable	200	80-410	70	30-130
MAS	Viable	180	80-320	100	20-200
Button	Total	177 000	138 000-216 000	96 000	59 000-138 000
Natural (gravitational) ventilation					
Andersen	Viable	330	140-1600	130	50-230
MAS	Viable	260	110-730	150	70-320
Button	Total	732 000	511 000-865 000	177 000	138 000-216 000

Button sampler results have been rounded to the nearest 1000 counts/m³.

TABLE 4 Microorganisms isolated from the air of office buildings (symbols represent: “S”—summer season, “W”—winter season, “+”—presence and “—”—absence of identified species and/or genus)

Bacteria	Air-conditioning system		Mechanical ventilation		Natural (gravitational) ventilation	
	S	W	S	W	S	W
Gram-positive cocci						
<i>Kocuria kristinae</i> ^a	+	+	—	+	—	+
<i>Kocuria rosea</i>	—	—	+	—	+	—
<i>Micrococcus luteus</i> ^a	+	+	+	+	+	+
<i>Micrococcus roseus</i>	+	+	+	+	+	+
<i>Micrococcus</i> spp.	+	+	+	+	+	+
<i>Staphylococcus aureus</i> ^b	—	—	—	—	—	+
<i>Staphylococcus auricularis</i>	+	+	—	—	+	+
<i>Staphylococcus capitis</i>	+	+	+	+	+	+
<i>Staphylococcus cohnii</i>	—	—	+	—	+	—
<i>Staphylococcus epidermidis</i> ^a	+	+	+	+	+	+
<i>Staphylococcus haemolyticus</i>	+	—	+	+	+	+
<i>Staphylococcus hominis</i> ^a	+	+	+	+	+	+
<i>Staphylococcus lugdunensis</i>	—	—	+	+	+	+
<i>Staphylococcus saprophyticus</i>	+	—	+	+	+	+
<i>Staphylococcus sciuri</i> ^a	+	+	+	+	+	+
<i>Staphylococcus warneri</i> ^a	+	+	+	+	+	+
<i>Staphylococcus xylosus</i>	—	—	+	+	+	+
Endospore-forming Gram-positive bacilli						
<i>Bacillus brevis</i>	—	—	—	—	+	—
<i>Bacillus cereus</i> ^a	+	+	+	+	+	+
<i>Bacillus licheniformis</i>	+	—	—	—	+	—
<i>Bacillus pumilus</i> ^a	+	+	+	+	+	+
Non-sporing Gram-positive rods						
<i>Arcanobacterium haemolyticum</i> ^a	+	+	+	+	+	+
<i>Arthrobacter</i> spp. ^c	+	+	+	+	+	+
<i>Brevibacterium epidermidis</i>	+	—	+	+	+	—
<i>Corynebacterium propinquum</i>	—	—	+	—	+	+
<i>Corynebacterium</i> spp. ^b	—	—	+	—	+	—
<i>Microbacterium</i> spp.	—	—	+	+	+	+
Mesophilic actinomycetes						
<i>Nocardia</i> spp. ^c	+	—	+	+	+	+
<i>Rhodococcus</i> spp. ^c	+	+	+	+	+	+
<i>Streptomyces</i> spp. ^b	+	—	+	+	+	+
Fungi	Air-conditioning system		Mechanical ventilation		Natural (gravitational) ventilation	
	S	W	S	W	S	W
Filamentous fungi						
<i>Acremonium</i> spp.	+	+	+	+	+	+
<i>Alternaria</i> spp.	—	—	—	—	+	+
<i>Aspergillus candidus</i> Link	+	+	—	—	—	—
<i>Aspergillus flavus</i>	—	—	+	—	+	—
<i>Aspergillus fumigatus</i> ^{a,b}	+	—	—	—	+	+

(Continues)

TABLE 4 (Continued)

Fungi	Air-conditioning system		Mechanical ventilation		Natural (gravitational) ventilation	
	S	W	S	W	S	W
<i>Aspergillus niger</i>	+	–	+	+	+	–
<i>Aspergillus ostianum</i>	–	–	+	+	+	+
<i>Aspergillus terreus</i> Thom ^a	+	+	+	+	+	+
<i>Cladosporium cladosporioides</i>	–	–	–	–	+	+
<i>Cladosporium herbarum</i>	+	–	–	–	–	–
<i>Cladosporium</i> spp.	+	+	–	–	–	–
<i>Mucor</i> spp.	–	+	–	–	+	–
<i>Penicillium atro-sanguineum</i>	–	–	–	–	+	–
<i>Penicillium brevicompactum</i>	+	–	+	+	+	+
<i>Penicillium chrysogenum</i> Thom	+	+	+	+	+	+
<i>Penicillium citrinum</i> Thom ^a	+	+	+	+	+	+
<i>Penicillium commune</i> Thom ^a	+	+	+	+	+	+
<i>Penicillium cyclopium</i>	–	–	+	–	+	+
<i>Penicillium funiculosum</i>	–	–	–	–	+	
<i>Penicillium griseoazurum</i>	+	–	–	–	+	+
<i>Penicillium marneffe</i> ^b	+	–	–	–	–	–
<i>Penicillium</i> spp.	+	+	+	–	+	–
<i>Verticillium</i> spp.	–	–	+	–	+	–
Yeasts						
<i>Candida famata</i>	+	–	–	–	+	–
<i>Geotrichum candidum</i> ^a	+	–	+	+	+	+
<i>Rhodotorula mucilaginosa</i> ^a (Jørgensen) Harrison (syn.: <i>R. biourgei</i> , <i>R. grinbergii</i> , <i>R. rubra</i>)	+	+	+	+	+	+

^aThe most prevalent microbial isolates characterized using molecular method.

^bPathogenic microorganisms from hazard group 2 according to their level of risk of infection.

^cGenus in which certain species are classified to the group 2 according to their level of risk of infection and allergy.^{17,18}

Gram-positive cocci (mainly from *Staphylococcus* and *Micrococcus/Kocuria* genera) and endospore-forming Gram-positive rods (from *Bacillus* genus). Among the most common fungal species were those from *Penicillium*, *Aspergillus*, and *Cladosporium* genera. The highest species diversity was found in the rooms with natural ventilation, where a total number of 30 bacterial species from 12 genera and 22 fungal species from 10 genera were identified. Twenty-one bacterial species from 10 genera and 18 fungal species from eight genera were identified in air-conditioned offices. In the offices with mechanical ventilation system, 26 species of bacteria from 12 genera and 14 species of fungi from six genera were identified.

The most prevalent microbial isolates identified using biochemical and microscopic techniques were additionally confirmed using molecular methods. The sequence similarity of 99–100% was achieved, comparing to GenBank-type material sequence database.

Percentage distributions of microbial groups identified in the air at workplaces are presented in Figure 1. The most prevalent microorganisms in the indoor air were Gram-positive cocci (from

48% to 49% of isolated microbiota), followed by filamentous fungi (from 20% to 26%) and endospore-forming Gram-positive bacilli (from 8% to 15%). There were no statistically significant differences between the percentage distributions of microbial groups in all studied buildings.

3.3 | Size distribution of microbial aerosols

The use of Andersen impactor in this study enabled to divide bio-aerosol particles into six fractions according to their aerodynamic diameters. The particle size distributions of collected airborne bacteria and fungi are presented in Figures 2A,B and 3A,B, respectively. The highest concentration of bacterial aerosol particles was observed within the range 1.1–4.7 μm of aerodynamic diameters in the “summer” season at workplaces in the rooms with natural ventilation (Kruskal-Wallis test: $P < 0.01$). Size distribution analysis shows that bacteria were present here mainly as single cells and small bacterial and/or bacterial-and-dust aggregates.

On the other hand, in the “winter” season, a statistically significant increase was observed for the concentrations of bacterial

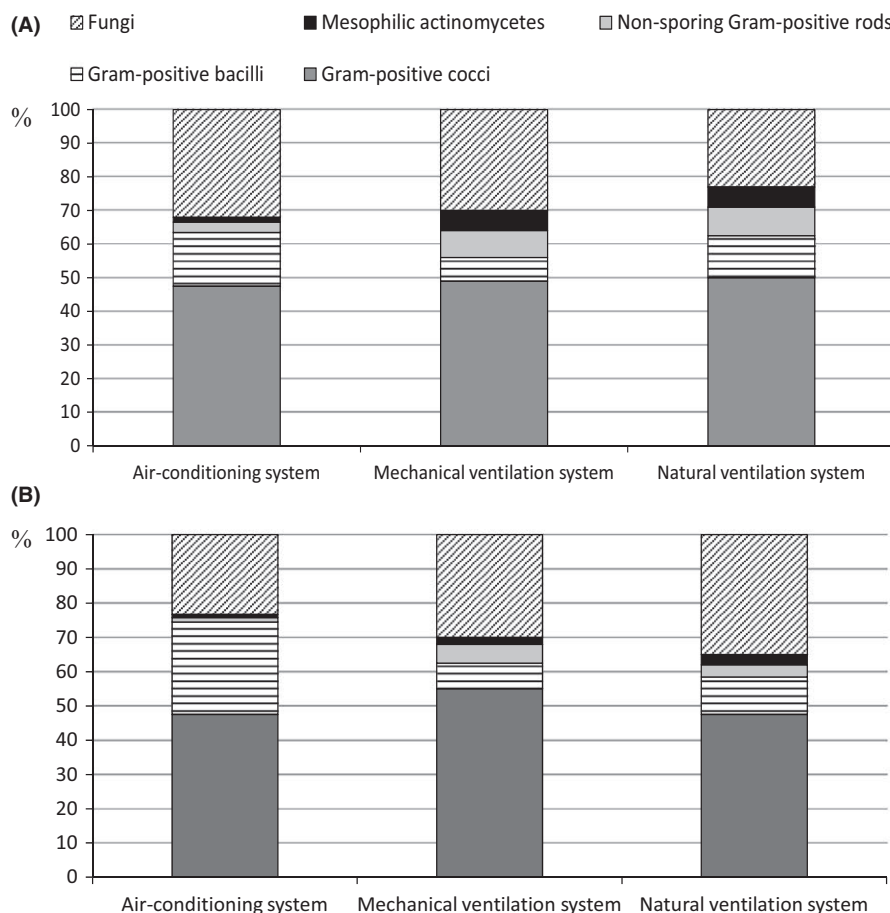


FIGURE 1 Percentage distributions of microbial groups in the air at workplaces in "summer" (A) and "winter" (B) seasons

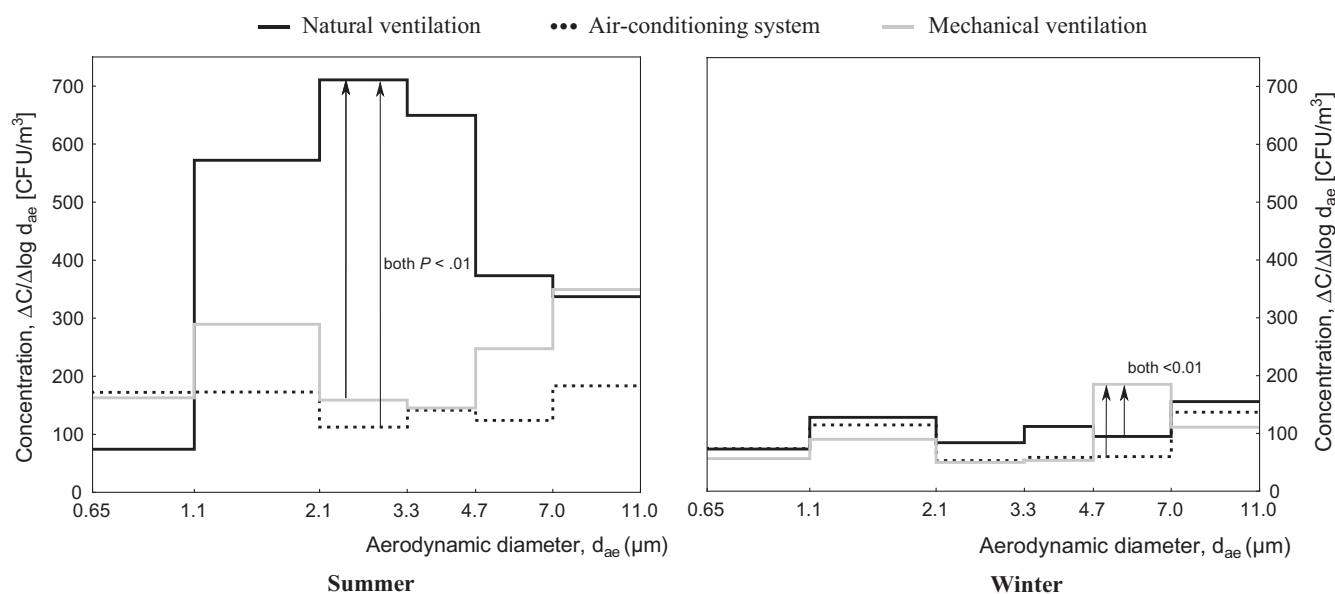


FIGURE 2 The size distribution of bacterial aerosols at workplaces in office buildings in "summer" and "winter" seasons

particles within the range of aerodynamic diameters of 1.1–2.1 μm , 3.3–4.7 μm , and above 7 μm in the naturally ventilated rooms compared to remaining groups of studied premises (Kruskal-Wallis test: $P < 0.01$). In the mechanically ventilated rooms, in the

"winter" period, a statistically significant increase was observed for the concentration of particles within the range of aerodynamic diameters of 4.7–7 μm . This demonstrates that mechanical ventilation is highly efficient only in the separation of large

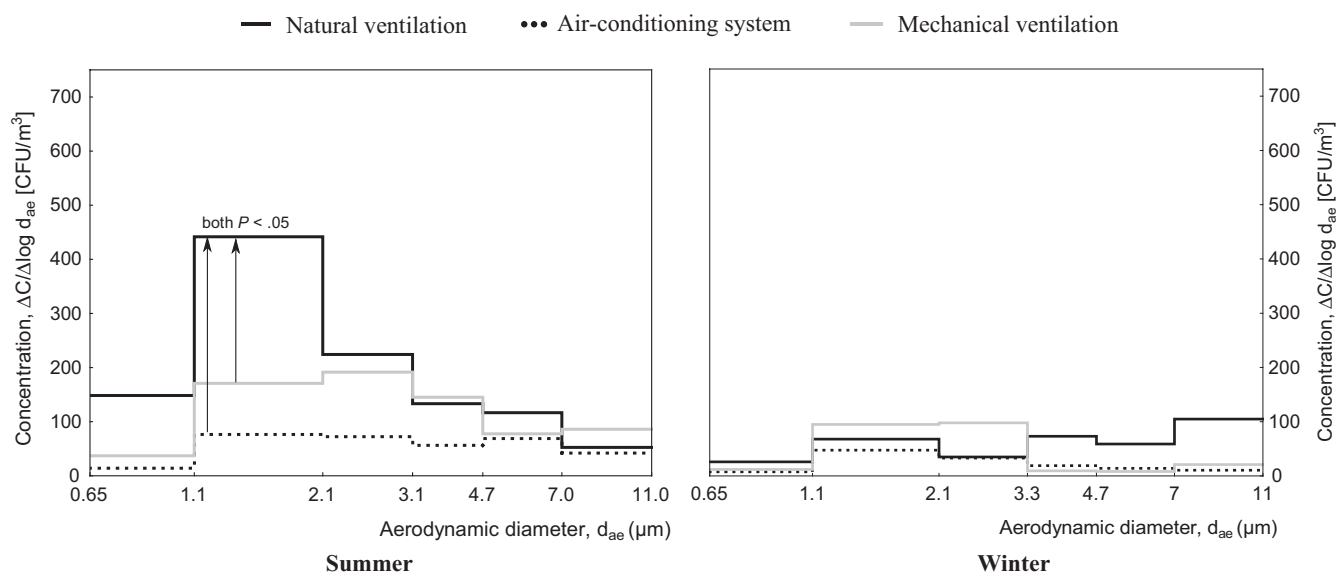


FIGURE 3 The size distribution of fungal aerosols at workplaces in office buildings in “summer” and “winter” seasons

TABLE 5 Air temperature and relative humidity inside and outside of office buildings in “winter” and “summer” seasons

Sampling season	Ventilation system	Temperature [°C]		Relative humidity [%]	
		Median	Range	Median	Range
Winter	Air-conditioning system	22	17-27	35	29-45
	Mechanical ventilation	23	21-25	36	33-40
	Natural ventilation	22	19-23	33	25-38
	Outdoor	2	2-4	37	26-48
Summer	Air-conditioning system	22	20-26	46	39-58
	Mechanical ventilation	25	24-26	52	50-54
	Natural ventilation	25	24-26	51	47-55
	Outdoor	25	22-27	49	47-56

bacterial and/or bacterial-and-dust aggregates. In both studied seasons, analysis of particle size distribution in air-conditioned rooms demonstrated, however, that such system efficiently separates particles within the full range of aerodynamic diameters of bacterial aerosol.

Analysis of fungal aerosol particle size distribution at workplaces shows that in the naturally and mechanically ventilated rooms, the concentrations of particles with aerodynamic diameters of 1.1–3.3 μm (in “summer” season) were significantly higher than those in air-conditioned premises (Kruskal-Wallis test: $P < 0.05$). This indicates that mechanical ventilation with a precise control of microclimate parameters is the most efficient system that keeps the indoor air pollution at the lowest level. Similarly, as in the case of bacterial aerosol, an air-conditioning system was able to eliminate fungal spores with high efficiency, practically regardless of their sizes and forms of occurrence.

Analyzing the impact of number of workers, presence on bacterial aerosol concentrations, significant correlations were only found

for the group of buildings with natural ventilation in the “summer” season (Spearman’s correlation: $R = 0.42$ at $P < 0.05$) and for mechanically ventilated buildings in both measurement seasons (Spearman’s correlations: $R = 0.51$ at $P < 0.05$ for “summer” and “winter”). There were no statistically significant correlations between fungal concentrations and the number of workers in three study office building groups.

In all three studied groups of office buildings, the size of office space did not significantly determine the observed concentrations of bacterial and fungal aerosols.

3.4 | Microclimate parameters

Air temperature and relative humidity recorded inside and outside of office buildings in “winter” and “summer” sampling seasons are presented in Table 5. Both microclimate parameters of the air did not significantly determine the observed concentrations of studied bioaerosols in all groups of buildings.

TABLE 6 The Polish proposals of threshold limit values for bioaerosols in public service buildings²⁹

Bioaerosol component	Threshold limit value [cfu/m ³]
Mesophilic bacteria	5000
Gram-negative bacteria	200
Thermophilic actinomycetes	200
Fungi	5000
Microbial agents from risk groups 3 and 4 ^a	0

^aAccording to the classifications in Directive 2000/54/EC.

4 | DISCUSSION

Analysis of the obtained results indicated that at workplaces in office buildings, the type of ventilation systems has a significant impact on the air quality. Among studied buildings, the highest bioaerosol concentrations (reaching 1.6×10^3 cfu/m³) were recorded in rooms with natural ventilation. In the premises equipped with mechanical ventilation or air-conditioning systems, the concentrations of microorganisms were lower and did not exceed 5.3×10^2 cfu/m³. Such type of analyses conducted by other researchers indicated that the concentrations of bacterial and fungal aerosols, measured using volumetric methods (eg, with Andersen impactor or Burkard sampler) in office rooms, usually fall within the range of 10^1 – 10^3 cfu/m³.^{19–26} Hence, the concentrations determined for the three groups of office buildings investigated in the present study fell within the range of values “normally” observed in the rooms intended for office work.

A properly functioning ventilation/air-conditioning system stops or, at least, effectively limits migration of bioaerosols from outdoors into the indoor environment. The outdoor air entering the system and being distributed to particular rooms is usually filtered to eliminate the possible contaminants.^{22,27} A lack of ventilation system maintenance, for example, too long filter changing intervals or poor filtration efficiency, may lead to dust deposition on the surfaces of the ducts turning them as a reservoir of pollutants. These dusty ducts may also release occasionally particles to supply air due to the process of secondary reaerosolization.^{27,28}

The quantitative interpretation of bioaerosol measurements conducted in the indoor environment is hampered due to the lack of acceptable hygienic standards for harmful microbiological agents (HMA). The main reason for this is the lack of well-documented dose-response relationship between the exposure to HMA and adverse health effects caused by their exact doses. Hence, for quantitative interpretation of the results and the classification of threshold limit values (TLV) for airborne microorganisms in public utility facilities, proposal by the Biological Agents' Expert Group at the Polish Interdepartmental Commission for Maximum Admissible Concentrations and Intensities for Agents Harmful to Health in the Working Environment was used (Table 6).²⁹ Data resulting from the present study showed that the concentrations of both viable bacterial and fungal aerosols in all examined office rooms did not exceed the TLV proposals.

The seasonal variability is an important factor influencing bioaerosol both in the outdoor environment and inside the buildings.

In the scientific literature, such studies are quite frequently presented.^{20,24,25,30–35} Based on them, it could be concluded that in summer, the concentrations of bacteria in the air range from 10^2 to 10^4 cfu/m³, while in winter they are lower and do not usually exceed the value of 10^2 cfu/m³. In the indoor environment, the concentration of bacterial aerosol falls within the range of 10^2 – 10^5 cfu/m³ in summer and 10^2 – 10^3 cfu/m³ in winter. Fungal aerosol, similarly to the bacterial one, also indicates quantitative differences in particular seasons of the year. The concentration ranges of fungi in atmospheric air are, in summer, at the level of 10^2 – 10^4 cfu/m³, while in winter they are below 10^2 cfu/m³. On the other hand, in the indoor environment, the concentration of such aerosols does not normally exceed the value of 10^4 cfu/m³ in the “summer” season and 10^3 cfu/m³ in the “winter” season. The results clearly showed that in the “summer” season, in the temperate climate zone, higher concentrations of bacterial and fungal aerosols are observed both in the indoor and in the outdoor air.^{20,25,32}

In the present study, the quantitative analysis of microbial contamination in the “summer” and “winter” seasons in buildings equipped with air-conditioning or mechanical ventilation systems showed that fungal aerosol concentrations were higher outdoors than indoors. In buildings with natural ventilation system, such relationship was only recorded in the “summer” season. For bacterial aerosol in both measurement seasons, in office rooms equipped with mechanical or natural ventilation systems, an opposite relationship was noted. As regards the buildings with an air-conditioning system, no significant differences were observed in bacterial aerosol concentration between indoor and the outdoor air.

The observed dependencies are in good agreement with data regarding the sources of bioaerosol origin. The most important emission sources of fungal aerosol are located in the outdoor environment (eg, soil, water reservoirs, and plants). The penetration of atmospheric air into buildings is usually the main process resulting in the contamination of the premises with fungal spores.³⁶ On the other hand, the biggest, and constantly active, emission sources for bacterial aerosol in the non-industrial indoor environments are humans and their activities.^{33,34,37,38}

Based on the obtained results, it can be concluded that the air-conditioning systems in studied buildings were highly effective (an appropriate number of air renewals per unit of time; adapting the number of air renewals to the number of employees; providing an adequate number of filtration stages) in the removal of airborne microbial contaminants.

Microbial aerosol concentrations in studied offices were measured using six-stage Andersen and MAS-100 *Eco* impactors. A six-stage Andersen impactor collects bioaerosol particles with the aerodynamic diameters from 0.65 μ m to above 7 μ m. This impactor is characterized by the high collection efficiency varying from 60% (for particles 0.65–2.5 μ m) to 90% (for particles > 4 μ m).³⁹ The MAS-100 *Eco* impactor is characterized by the collection efficiency from 10% (for particles bigger than 1 μ m) to 60% (for particles 3–7 μ m).^{39,40} However, a comparison of sampling performance

of both impactors did not indicate significant differences between them. Both types of impactors can be successfully used for the assessment of microbial aerosols, even, as it was shown, in relatively clean indoor environments.

A comparative analysis of viable (measured with Andersen and MAS impactors) and total (measured with the Button sampler) microbial concentrations showed that in the studied premises, viable microorganisms accounted for 0.02%-0.5% of the total airborne microbiota. The studies conducted in the non-industrial indoor environments (schools, flats) by Toivola et al⁴¹ revealed that the concentrations of viable microorganisms did not exceed 1% of the total number of airborne microorganisms. On the other hand, in agricultural environment contaminated with organic dust, the viable microorganisms constituted from 1% to 25% of airborne microbial particle.⁴² The atmospheric air is not the one which provides favorable conditions for growth and survival of microorganisms.⁴³ Hence, the difference in the concentrations between viable and total bioaerosols is obvious and clearly visible.⁴⁴ Usually, the use of only one measurement method does not give a comprehensive characteristic of bioaerosol contamination in the examined environment. Therefore, an application of the methods allowing simultaneous measurement of the total and viable bioaerosols for microbiological monitoring of the air enables to obtain a more complete qualitative and quantitative picture of air contamination covering both immunologically reactive particles, that is viable and non-viable (that still can maintain their, eg, toxic and/or allergic properties).

The qualitative analysis of bioaerosol demonstrated that the highest species diversity was found in the rooms with natural ventilation. However, irrespective of the type of ventilation system present in three studied groups of office buildings, the most prevalent in indoor air were the same microorganisms, that is, Gram-positive cocci of the *Staphylococcus*, *Micrococcus* and *Kocuria* genera, spore-forming *Bacillus* representatives, and fungi (*Penicillium*, *Aspergillus*, and *Cladosporium* genera). These species are usually the most prevalent indoors.²¹ Species of the genera *Staphylococcus*, *Micrococcus*, and *Kocuria* constitute a substantial part of the human microbiota. Bacteria of the *Bacillus* genus are usually of environmental origin, as they are abundant in soil and plants. Usually, they do not pose a hazard to humans, and they probably penetrate into the buildings with the atmospheric air or are carried indoors on employees (eg, on shoes, clothes, hands, or hair).³⁶

Among the most common fungal species were those from *Penicillium*, *Aspergillus*, and *Cladosporium* genera. They are broadly distributed in nature, including soil and decomposing and dead organic matter. Fungal spores may migrate into the buildings on the employees' clothes and hair, as well as, along with the atmospheric air, through open windows, doors, and due to the leakages of building envelope. After penetration, when enough water is available, they can easily colonize the indoor environment being readily found both in the indoor air and on surfaces.^{20,30,31,45,46} It is also well known from epidemiological studies that exposure to these molds has been associated with a variety of adverse health outcomes including

respiratory, hematological, immunological, and neurological system disorders and/or diseases.^{20,46-48}

To assess and control the indoor air quality, not only the data on bioaerosol concentrations are important, but also the size distribution of bioaerosol particles should be taken into account as both these parameters determine their deposition in the respiratory system.^{38,49} The use of the six-stage Andersen impactor in this study allowed for obtaining data on the bioaerosol particle size distribution in the investigated groups of offices. The health effect resulting from the inhalation of bioaerosol particles depends on the possibility for their penetration into the respiratory tract and the interaction with cells and tissues in the place of deposition. The mechanism of particle deposition in the respiratory system is influenced by their size, shape, density, chemical composition, and reactivity. Apart from the above-mentioned parameters, the depth of penetration in the respiratory track is also influenced by the rate of the air flow through the respiratory system, the manner of breathing, and the volume of lung ventilation depending on the age and the dynamics of activities performed by a given person.⁴⁹⁻⁵¹ Based on the results of the size distribution of bioaerosol particles, it can be stated that bioaerosols present in the studied office buildings, when inhaled, may be mainly deposited within the oral and nasal cavities, secondary bronchi, and bronchioles.⁵⁰ Hence, the adverse health outcomes associated with the immunological reactivity of the bioaerosol particles may cause the nose and eye irritations, asthmatic reactions, and allergic inflammations.⁴⁹

5 | CONCLUSIONS

1. Bacterial and fungal aerosol concentrations in the studied offices did not exceed 10^3 cfu/m³. This study showed that the air quality in offices depends on the type and maintenance condition of the ventilation system present in the building. Offices where the mechanical ventilation or air-conditioning systems operate properly and are correctly maintained become microbiologically less contaminated than those equipped with natural (gravitational) ventilation.
2. Both six-stage Andersen and MAS-100 Eco impactors may be successfully used in the hygienic control of air quality in the office buildings. The differences in impactor parameters characterizing their physical and biological sampling efficiencies of bioaerosol particles do not have a statistically significant impact on the result of the assessment of microbial quality in office premises.
3. The comparative analysis of viable and total airborne microbial counts showed that viable microorganisms accounted for 0.02% to 0.5% of the total airborne microbiota. Hence, the comprehensive hygienic assessment of the office workplaces should include an efficient control of both above-mentioned elements.
4. The qualitative analysis of microorganisms isolated from the air in office buildings revealed that the most prevalent bacteria belong to Gram-positive cocci of *Staphylococcus*, *Micrococcus*, and

Kocuria genera and endospore-forming *Bacillus* rods. Among the molds, the most frequently isolated were species of *Penicillium*, *Aspergillus*, and *Cladosporium* genera. All these microorganisms are typical for indoor environments.

5. The analysis of bioaerosol size distribution at studied office buildings shows that air-conditioning systems filtered out the bioaerosol particles with high efficiency within all studied aerodynamic diameters. The analysis of particle size distribution in the studied groups of buildings indicated that for the bacterial aerosol, the biggest load of such particles may reach the nasal and oral cavities, throat, trachea, and bronchi in the human respiratory system, while for the fungal aerosol—the trachea and bronchi. Such exposure might cause a variety of adverse health effects manifested by nose and eye irritation, asthmatic reactions, and allergic inflammation among office employees exposed to this type of bioaerosol particles.

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REFERENCES

1. Rylewski E. Health aspects of ventilation systems. In: *Indoor Air Quality Problems in Poland*. Institute of Heating and Ventilation at Warsaw University of Technology, Warsaw, Poland: Publishers of the Institute of Heating and Ventilation Warsaw University of Technology; 2004:321–329.
2. Seltzer JM. Building-related illnesses. *J Allergy Clin Immunol*. 1994;94:351–361.
3. Burge PS. Sick building syndrome. *Occup Environ Med*. 2004;61:185–190.
4. Robertson LD. Monitoring viable fungal and bacterial bioaerosol concentrations to identify acceptable levels for common indoor environments. *Indoor Built Environ*. 1997;6:301–308.
5. Pasanen A-L, Kasanen JP. Fungal growth and survival in building materials under fluctuating moisture and temperature conditions. *Int Biodeterior Biodegrad*. 2000;46:117–127.
6. EU-OSHA – European Agency for Safety and Health at Work. Expert forecast on emerging biological risks related to occupational safety and health. European risk observatory report. Luxembourg, Europe: Office for Official Publications of the European Communities; 2007.
7. WHO. Guidelines for indoor air quality: dampness and mould. Copenhagen, Denmark: World Health Organization, Regional Office for Europe; 2009.
8. Jensen PA, Schafer MP. Sampling and characterization of bioaerosols. In: *NIOSH Manual of Analytical Methods*. Atlanta, GA: NIOSH Publications; 1998:82–112.
9. Murray PR, Rosenthal KS, Pfaller MA. *Medical Microbiology*, 7th edn. Philadelphia, PA: Elsevier Saunders; 2013.
10. Fisher F, Cook NB. *Fundamentals of Diagnostic Mycology*. Philadelphia, PA: WB Saunders Company; 1998.
11. Samson RA, Hoekstra ES, Frisvad JC. *Introduction to Food- and Airborne Fungi*, 7th edn. Utrecht, the Netherlands: Centraalbureau voor Schimmeltculturen; 2004.
12. St-Germain G, Summerbell R. *Identifying Filamentous Fungi*. Belmont, MA: Star; 2011.
13. Bosshard PP, Zbinden R, Abels S, Böddinghaus B, Altwegg M, Böttger EC. 16S rRNA gene sequencing versus the API 20 NE system and the VITEK 2 ID-GNB card for identification of nonfermenting gram-negative bacteria in the clinical laboratory. *J Clin Microbiol*. Apr. 2006;44:1359–1366.
14. White TJ, Bruns T, Lee S, Taylor S. Amplification and direct sequencing of fungal ribosomal RNA genes for phylogenetics. In: Innis MA, Gelf DH, Sninsky JJ, White TJ, eds. *PCR Protocols. A Guide to Methods and Applications*. San Diego, CA: Academic Press Inc.; 1990:315–322.
15. Palmgren U, Ström G, Blomquist G, Malmberg P. Collection of airborne microorganisms on nucleopore filters: estimation and analysis - CAMNEA method. *J Appl Bacteriol*. 1989;61:401–406.
16. Wang Z, Reponen T, Grinshpun SA, Górny RL, Willeke K. Effect of sampling time and air humidity on the bioefficiency of filter samplers for bioaerosol collection. *J Aerosol Sci*. 2001;32:661–674.
17. Directive 2000/54/EC of the European Parliament and of the Council of 18 September 2000 on the protection of workers from risks related to exposure to biological agents at work. *Off J Eur Union L*. 2000; 262/21:21–45.
18. Ordinance of the Minister of Health of April 22, 2005, on hazardous biological agents in the work environment and the protection of health of workers occupationally exposed to them. *J Laws*. 2005;81:716.
19. Bonetta S, Mosso S, Sampò S, Carraro E. Assessment of microbiological indoor air quality in an Italian office building equipped with an HVAC system. *Environ Monit Assess*. 2010;161:437–483.
20. Giulio M, Grande R, Campli E, Bartolomeo S, Cellini L. Indoor air quality in university environments. *Environ Monit Assess*. 2010;170:509–517.
21. Gołofit-Szymczak M, Górny RL. Bacterial and fungal aerosols in air-conditioned office buildings in Warsaw. *Poland - the winter season*. *JOSE*. 2010;16:465–476.
22. Kemp PC, Neumeister-Kemp HG, Esposito B, Lysek G, Murray F. Changes in airborne fungi from the outdoors to indoor air; large HVAC systems in nonproblem buildings in two different buildings in two different climates. *AIHA J*. 2003;64:269–275.
23. Orosa JA, Baalina A, Garcia-Bustelo E. A practical case study of relationship between microbial air content and building parameters in humid climate flats. *Eur Open J Sci Res*. 2008;21:71–80.
24. Tsai FC, Macher JM, Hung Y-Y. Biodiversity and concentrations of air borne fungi in large US Office buildings from the BASE study. *Atmos Environ*. 2007;41:5181–5191.
25. Tseng CH, Wang HC, Xiao NY, Chang YM. Examining the feasibility of prediction models by monitoring data and management data for bioaerosols inside office buildings. *Build Environ*. 2011;46:2578–2589.
26. Wu PC, Li YY, Lee CC, et al. Changing microbial concentrations associated with ventilation performance in Taiwan's air-conditioned office buildings. *Indoor Air*. 2005;15:19–26.
27. Sundell J, Levin H, Nazaroff WW, et al. Ventilation rates and health: multidisciplinary review of the scientific literature. *Indoor Air*. 2011;21:191–204.
28. Noris F, Siegel JA, Kinney KA. Evaluation of HVAC filters as a sampling mechanism for indoor microbial communities. *Atmos Environ*. 2011;45:338–346.

29. Górny RL, Cyprowski M, Ławniczek-Wałczyk A, Gołofit-Szymczak M, Zapór L. Biohazards in the indoor environment - a role for threshold limit values in exposure assessment. In: Dudzińska MR, ed. *Management of Indoor Air Quality*. London: Taylor and Francis Group; 2011:1-20.
30. Bernasconi C, Rodolfi M, Picco AM, Grisoli P, Dacarro C, Rembges D. Pyrogenic activity of air to characterise bioaerosol exposure in public buildings: a pilot study. *Lett Appl Microbiol*. 2010;50:571-577.
31. Ejdzys E, Biedunkiewicz A. Fungi of the genus *Penicillium* in school building. *Pol J Environ Stud*. 2011;20:333-338.
32. Grinn-Gofroń A. Airborne *Aspergillus* and *Penicillium* in atmosphere of Szczecin, (Poland) (2004-2009). *Aerobiologia*. 2011;27:67-76.
33. Kummer V, Thiel WR. Bioaerosols - sources and control measures. *Int J Hyg Environ Health*. 2008;211:299-307.
34. Macher J, ed. *Bioaerosols: Assessment and Control*. Cincinnati, OH: ACGIH; 1999.
35. Stark PC, Celedon JC, Chew GL, et al. Fungal levels in home and allergic rhinitis by 5 years age. *Environ Health Perspect*. 2005;113:1405-1409.
36. Prussin AJ, Marr LC. Sources of airborne microorganisms in the built environment. *Microbiome*. 2015;3:78-88.
37. Kalogerakis N, Paschali D, Lekaditis V, Pantidou A, Eleftheriadis K, Lazaridis M. Indoor air quality - bioaerosol measurements in domestic and office premises. *J Aerosol Sci*. 2005;36:751-761.
38. Kulkarni P, Baron PA, Willeke K, eds. *Aerosol Measurement: Principles, Techniques, and Applications*. New York, NY: John Wiley and Sons, Inc.; 2011.
39. Hottell KA, Kesavan J. *Characteristics and Sampling Efficiencies of two Impactor Bioaerosol Samplers: MAS-100 (Microbial air Monitoring System) and Single-Stage Andersen Viable Microbial Samplers*. Aberdeen Proving Ground, MD: Chemical Biological Center, Edgewood; 2004.
40. Yao M, Mainelis G. Investigation of cut-sizes and collection efficiencies of portable microbial samplers. *J Aerosol Sci*. 2006;40:595-606.
41. Toivola M, Alm S, Reponen T, Kolari S, Nevalainen A. Personal exposures and microenvironmental concentrations of particles and bioaerosols. *J Environ Monit*. 2002;4:166-174.
42. Heikkilä P, Salmi T, Kotimaa M. Identification and counting of fungal spores by scanning electron microscopy. *Ann Occup Hyg*. 1988;32:241-248.
43. Hung LL, Miller JD, Dillon HK (eds). *Field Guide for the Determination of Biological Contaminants in Environmental Samples*, 2nd edn. Fairfax, VA: AIHA; 2005.
44. Górny RL. Microbial fragments as hidden indoor contaminants. *Allergy Immun*. 2012;9:135-138.
45. Goncalves FL, Bauer H, Cardoso MRA, et al. Indoor and outdoor atmospheric fungal spores in the Sao Paulo metropolitan area (Brazil): species and numeric concentrations. *Int J Biometeorol*. 2010;54:347-355.
46. Holme J, Hägerhed-Endgman L, Mattsson J, Sundel C, Bornehag G. Culturable mold in indoor air and its association with moisture-related problems and asthma and allergy among Swedish children. *Indoor Air*. 2010;20:329-240.
47. Jones R, Recer GM, Hwang SA, Lin S. Association between indoor mold and asthma among children in Buffalo. *New York. Indoor Air*. 2011;21:156-164.
48. Rylander R, Fogelmark B, Ewaldsson B. Moldy environments and toxic pneumonitis. *Toxicol Ind Health*. 2008;24:177-180.
49. Owen MK, Ensor DS, Sparks LE. Airborne particles size and sources found in indoor air. *Atmos Environ*. 1992;12:2149-2162.
50. Górny RL, Dutkiewicz J, Krysińska-Traczyk E. Size distribution of bacterial and fungal bioaerosols in indoor air. *Ann Agric Environ Med*. 1999;6:105-113.
51. Reponen T. Aerodynamic diameters and respiratory deposition estimates of viable fungal particles in mold problem dwellings. *Aerosol Sci Technol*. 1995;22:11-23.

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