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Particulate matter and health effects in offices - A review

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ABSTRACT

As a growing percentage of the population is working in office buildings worldwide, air quality in these indoor environments is becoming of particular importance for assessing health impacts from exposure to different pollutants. Apart from the common indoor air pollution sources, the presence of a variety of electronics such as printers, copier machines and other equipment in office buildings may present a high health risk because of their emissions of gases and particles. The aim of this study is to review and compare available measurements of the most commonly reported indoor particulate matter (PM) fractions in office environments and the methodological approaches that were used for the assessment of air quality and associated health effects. Data from forty-nine studies conducted in twenty-four countries around the world were included in this review. Half of these studies report measurements of indoor air pollution concentrations at a fixed point, with half of those using portable devices for assessing the personal exposure of employees in a direct way. The results showed that indoor concentrations for all air pollutants were higher than those measured outdoors, and that they increased during working hours. The average PM levels in offices ranged from 14 to 333 μg/m^3 for particles having diameters up to 10 μm (PM_{10}), and 4–227.44 μg/m^3 for particles having diameters up to 2.5 μm ($PM_{2.5}$). Results also showed that many health effects like eye irritation, dry throat, runny nose, sneezing, cough, tiredness, irritability, difficulty concentrating, headache, dizziness, and skin irritation reported through questionnaires by employees were associated with these pollutants, while being influenced by gender and environmental factors such as temperature and relative humidity.

1. Introduction

Indoor air pollution constitutes a major problem for both the developing and industrially developed countries. People in the developed world are indoors on average 80–90% of their time, much of which is spent in offices (Baccarelli et al., 2011; Karakatsani et al., 2010). Indoor air pollution is characterized by a large variability in the concentrations of pollutants among different indoor environments and depends on factors such as the emission characteristics of the sources, the behavior of the office occupants, and the microclimatic and ventilation conditions [1]. Studies using questionnaires [2] indicate that the four most frequently reported symptoms in offices are tiredness, headaches, irritated, dry or itchy eyes, as well as stuffy or runny nose and sneezing [3]. It has been estimated that such building-related symptoms (BRS) are responsible for reduction in productivity and consequent economic loss. Analyses suggest that BRS are responsible for a 2% reduction in productivity, which translates to an economic loss in the order of $60 billion per year in the United States alone [4–6]. The growing evidence relating poor indoor air quality in offices and BRS has lead to the provision of guidelines for selected indoor air pollutants, including particulate matter (PM), ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) (WHO, 2005; SCHER, 2007) [7].

Office buildings are often located in big cities near traffic intersections and busy roads so that they are easily accessible to employees. These buildings are usually equipped with heating, ventilation and air conditioning (HVAC) systems to create an acceptable feeling of comfort for the workers [8–10]. Although more recent HVAC systems include components for improving indoor air quality, the indoor space pollution will be the result of several factors including the pollutants penetrating from outdoors through the mechanical ventilation systems, and indoor sources, as well as the different microclimatic conditions (i.e., temperature, relative humidity). All these factors have an influence on the concentration, the size and the chemical composition of the indoor particles as well as the penetration of particles from the outdoor

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Abbreviations

BP	Blood pressure
BMI	Body Mass Index
BRS	Building Related Symptoms
CO	Carbon monoxide
CO_2	Carbon dioxide
ETS	Environmental tobacco smoke
HR	Heart Rate
HVAC	Heating Ventilation and Air Conditioning
I/O	Indoor/Outdoor
NO_2	Nitrogen dioxide
O_3	Ozone
OC	Organic carbon
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate matter
PM_1	Particles of diameter less than 1 µm (µm)
PM_{10}	Particles with a diameter of 10 µm (µm) or less
$PM_{2.5}$	Fine particles with a diameter of 2.5 µm (µm) or less
RH	Relative Humidity
SBS	Sick Building Syndrome
SO_2	Sulfur dioxide
SVOCs	Semivolatile organic compounds
TSP	Total Suspended Particulates
UFPs	Ultrafine particles
VOCs	Volatile organic compounds

environment [11,12].

The last few decades have seen major changes in the home and work environments. Advances in information technology have increased the quantity and transformed the nature of equipment used in proximity to office workers. There is growing concern about the levels of potentially harmful pollutants that may be emitted from office equipment (Kalantzi et al., 2011), such as PM, ozone, volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) [13]. The increasing use of office equipment in combination with poor indoor air quality may cause numerous health problems such as rhinitis, sore throat, initiation of asthma attacks, and allergic inflammations of the respiratory tract, as well as irritations of the skin and eyes, headaches and cardiovascular diseases, reducing the quality of life [10].

The aim of this study is to review and compare available measurements of the most commonly reported indoor PM fractions (i.e., corresponding to particles smaller than 10, 2.5, and 1.0 µm, as well as the ultrafine fraction; abbreviated as PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and ultrafine particles (UFPs) from this point forward) in office environments and the methodological approaches that were used for the assessment of air quality and associated health effects. Other indoor air pollutants and their sources, monitoring strategies, and approaches for future research are also discussed.

2. Methodology

2.1. Inclusion and exclusion criteria

In this review we incorporate studies on indoor air quality in office environments and their human health effects, which have been carried out and reported in the scientific literature over the last 16 years. The following inclusion criteria were considered: 1) the studies are published in a scientific journal, 2) they refer to indoor air quality in offices and how they affect the health of the employees, 3) they are in English, 4) they refer to occupational exposure during working hours, 5) they exclude employees who are not working full time in an office environment such as truck drivers or mail carriers.

2.2. Search strategy description

A PubMed, Scopus, Science Direct and Web of Science literature search was carried out covering studies published from 2002 to August 2017 using the following keywords (and their combinations) "particulate matter", "sick building syndrome", "office workers", "office employees", "occupational exposure", indoor air quality", "health effects" and "offices".

2.3. Data collection

From all the studies retrieved using the above-mentioned keywords, we removed those that did not meet the inclusion criteria, while the rest were recovered and further evaluated. Data from the selected studies was collected, incorporated in the review and organized into tables. The data from these final eligible studies contains the following information:

- Sampling period
- Studied country
- Measured air pollutants
- Number of offices and employees
- Sampling duration
- Instrumentation used
- Questionnaires assessing health effects
- Age of the building
- Ventilation type

It should be mentioned here that some of the studies have employed gravimetric methods for assessing the concentration of Total Suspended Particulates (TSP), PM_{10}, $PM_{2.5}$ and/or $PM_{1.0}$ while others have used online instruments that probe the optical properties of the sampled aerosol in order to obtain the same information [14–16]. To convert the measured variable (which is particle number concentration) from these optical instruments to mass concentration, one has to assume the size (if not measured in parallel), the morphology and the optical properties (i.e., the refractive index) of the particles, which can introduce a higher uncertainty to the measurements compared to the gravimetric method [14,17,18].

3. Results and discussion

3.1. Total Suspended Particulates

A limited number of studies monitored TSP levels in offices, compared to other air pollutants included in this review [19]. took measurements in eleven offices using different ventilation systems in Sydney (Australia). Mean TSP concentrations ranged from 14 to 42 µg/m^3 throughout the year. Although no significant variability was found in TSP concentrations, notable trends were observed, with mixed-ventilated buildings generally exhibiting higher PM concentrations than those with other ventilation systems. Two studies were conducted in Europe, one in the city of Kosice (Slovakia) and one in Antwerp (Belgium). In the Slovakian study, the average TSP concentration measured in eight offices was 68.6 µg/m^3 and the median 46.1 µg/m^3, respectively. Higher mass concentrations were observed in the office with no human activity (no occupancy) than the office with human activity for all size fractions, except for TSP [20]. This is likely related to the lower air exchange intensity in room without human activity and accumulation of PM in the indoor air and was likely caused by a higher deposition of the largest particles in the office with no activity. In the Belgian study, TSP ranged from 7 to 31 µg/m^3 with an average of 18 µg/m^3 in nine offices from Antwerp [21].

In Asia [22], measured TSP concentrations in an office in Shanghai (China), which used a central air conditioner and had closed windows during the measurements. The average concentration of TSP in this office was 50.3 μg/m^3, which is slightly higher than in the previously mentioned European and Australian studies. A cross-sectional study was performed by Ref. [15] in Rio de Janeiro, Brazil, to compare the prevalence of sick building syndrome (SBS) symptoms among 1736 office workers of a sealed office building (with HVAC ventilation) and 950 of a non-sealed one (with natural ventilation). The results showed that although the mean TSP concentrations in the non-sealed building with the HVAC were 776 μg/m^3, which were paradoxically higher compared to the sealed building, some symptoms such as eye dryness, runny nose, dry throat, and lethargy were more prevalent in the sealed building. It should be noted, however, that other factors, such as undetected VOCs, mites, molds and endotoxin concentrations can contribute to the greater prevalence of symptoms in the sealed building.

3.2. PM_{10}

One of the earliest studies that reported PM_{10} measurements in office environments was in the United States [23]. Six large office buildings in metropolitan areas were selected in Iowa, Minnesota, and Nebraska. Mean PM_{10} concentrations in these buildings ranged from 14 to 36 μg/m^3. The majority of later studies reported PM_{10} measurements in office buildings have been conducted in Asia and Europe, with very few in Australia, the Middle East and none from Central and South America or Africa (Table 1). In Europe mean PM_{10} concentrations in offices ranged from 11.3 μg/m^3 in Italy [24] to 56.5 μg/m^3 in Athens, Greece [31]. In Asian offices mean PM_{10} concentrations were higher compared to Europe, ranging from 27.2 μg/m^3 in Shanghai, China [22] to 333 μg/m^3 in Xian, China [45]. Some of the highest values for PM_{10} were observed in China, in different studies conducted in Beijing and Xian (cf. Table 1). In most studies, the indoor to outdoor ratio of PM_{10} was < 1, indicating limited indoor sources and/or effective removal of particles through the buildings.

Various studies tested different ventilation types. As expected, offices using mechanical ventilation exhibited the lowest PM_{10} concentrations, in comparison to natural (open windows) or mixed (mechanical and natural) ventilation [19,41] [41]. observed that mechanical ventilation prevented the infiltration of outdoor PM_{10}, but also aided the accumulation of PM_{10} from indoor sources. Window-type air conditioners and HVAC systems showed higher indoor/outdoor (I/O) ratios (1.3 and 1.2, respectively) than natural ventilation and exhaust fan systems (0.8 and 0.7, respectively), indicating that the filtration processes of the latter two were relatively effective in removing the particles. HVAC systems are usually equipped with air filters and were found to be the most effective to remove coarse particles [44]. This study was also the only one that used samples collected during different seasons, and found higher values in the winter than in the summer, which were attributed to the higher frequency of high pollution episodes during wintertime [20]. observed that open-space offices had lower levels than closed-design offices, with higher PM_{10} concentrations being observed in offices during periods with intense human activity (i.e., during office-hours occupancy). As the authors explain, this could be attributed to the fact that either most of the air exchange was actually from the street level, or that these buildings also contained some internal source. The duration of the measurements varied from 2 h (https://www.sciencedirect.com/science/article/pii/S0160412003001739 [56], to 8 h during the work shift (http://iopscience.iop.org/article/10.1088/1755-1315/18/1/012008/pdf, [43]; https://www.witpress.com/elibrary/wit-transactions-on-ecology-and-the-environment/191/29609 [24,57]; https://www.sciencedirect.com/science/article/pii/S1309104215302993 [26]; https://link.springer.com/article/10.1007/s11356-011-0647-5 [10] and up to 24 h for 15 days (https://journal.gnest.org/journal-paper/indoor-outdoor-pm-levels-and-ec-surrogate-typical-microenvironments-athens-area [31].

Except for PM_{10} measurements in offices, some studies reported measurements using personal passive samplers or lightweight portable monitors, in order to assess the personal exposure of employees in a more direct manner. The duration of personal measurements varied from 8 h (during the work shift [10,26,51,52]; to 24 h [14,47,54,61]. The mean personal PM_{10} concentration reported during the 8-h working shift ranged from 39.4 to 160 μg/m^3, whereas in the 24-h sampling studies PM_{10} concentrations ranged from 32 to 530 μg/m^3 per day, with the highest values being measured in offices where the employee was either an active or passive smoker. No differences were observed between the PM_{10} concentrations measured by personal passive samplers and portable monitors.

3.3. $PM_{2.5}$

The first study to report $PM_{2.5}$ and associated health effects in offices was conducted in France [34]. After that, the majority of the studies have been conducted in Asia (especially in China) and in Europe, with few in the United States, Australia and the Middle East and none in Central and South America or the African continent (Table 1). In Europe, mean $PM_{2.5}$ concentrations ranged from 4 μg/m^3 in offices from Italy [24] to 37.6 μg/m^3 in a smoking office in Athens, Greece [30]. In Asia the mean $PM_{2.5}$ concentrations measured in office buildings ranged from 5.3 μg/m^3 in Hsinchu, Taiwan [55] to 213 μg/m^3 in an office from Xian, China [45]. Typically, $PM_{2.5}$ concentrations in offices from Asia were higher compared to those typically observed in Europe (Table 1). The highest values for $PM_{2.5}$ were recorded in two naturally ventilated offices in Agra, India with a mean concentration of 227.4 μg/m^3 [58].

In most studies the I/O was < 1, indicating possible outdoor influence on indoor $PM_{2.5}$ levels. In those studies with an I/O of > 1, either human activities such as smoking or printing were taking place [40], or there was natural and/or combination ventilation (HVAC and natural ventilation) used in the offices [19,35,44]. In a study from Korea [44], window-type air conditioners and HVAC systems showed high I/O ratios of 1.2 and 1.3 for $PM_{2.5}$, respectively, while natural ventilation and the exhaust fan system showed lower I/O ratios of 0.9 and 0.8 for $PM_{2.5}$, respectively. The different ventilation types used in offices during the winter and summer periods, as reported in the studies included in this review, can be seen in Table 2.

One study that measured $PM_{2.5}$ in different types of offices, observed lower PM mass and number concentrations in open-space offices compared with closed-design offices [20]. Comparing measurements during occupancy (with human activity) and non occupancy (without human activity), higher mass concentrations were observed in the office with no activity [62]. also found increased I/O ratios overnight compared to during the day, which could be due to the accumulation of PM trapped in the buildings overnight. With the exception of one study from Taiwan [55], all the studies that sampled during both summer and winter seasons found consistently higher mean concentrations of $PM_{2.5}$ in the winter than in the summer months [27–29,44,46]. This is also evident from Table 2. The duration of the measurements varied from 8 h (http://journals.sagepub.com/doi/pdf/10.1177/1420326X15604349 [42]; https://www.witpress.com/elibrary/wit-transactions-on-ecology-and-the-environment/191/29609 [24]; https://www.sciencedirect.com/science/article/pii/S0048969716323798?via%3Dihub [27]; https://www.sciencedirect.com/science/article/pii/S0160412016301453 [28,62], to 24 h for 3 months (https://www.sciencedirect.com/science/article/pii/S2352340915004060 [63].

Except for $PM_{2.5}$ indoor and outdoor measurements in different indoor office environments, some studies focused on personal measurements using personal portable samplers. The duration of personal measurements varied from 8 h (during the work shift [39,48–50,55,60]; to 24 h [33,34,38,53,59,63]. The mean personal $PM_{2.5}$ concentration reported in the 8-h working shift studies ranged from 4.9 to 140.4 μg/m^3 and the 24-h

Table 1
Mean concentration and range (in parentheses) of TSP, PM_{10}, $PM_{2.5}$, PM_1, and UFPs in offices worldwide.

Continent	Country	Sampling Date	Type	Duration	TSP (μg/m^3)	PM_{10} (μg/m^3)	I/O	$PM_{2.5}$ (μg/m^3)	I/O	PM_1 (μg/m^3)	UFPs (particles/cm^3)	Type of ventilation	References
Europe	Italy	2014	3 offices	8 h work shift	NA	Office 1: 11.3 (NA) Office 2: 28.5 (NA) Office 3: 17.1 (NA)	NA	Office 1: 9.5 (NA), Office 2: 13.4 (NA),Office 3: 4 (NA)	NA	Office 1: 8.8 (NA), Office 2: 10.2(NA), Office 3: 3.2 (NA)	NA	Combined	[24]
	Romania	2014	40 offices	24 h, 7 days	NA	NA (1.84–43.5)	NA	9.82 (NA)	NA	NA	NA	Natural	[25]
	Athens, Greece	2013	4 employees, 2 offices	8 h work shift	NA	160 (NA)	NA	NA	NA	NA	NA	Natural, (personal measurements)	[26]
	Finland, Hungary	Summer 2012-Winter 2012–2013	38 offices: 16 summer, 22 winter	8 h work shift, 5 days	NA	NA	NA	Summer: 9.7 (2.7–17), Winter: 15 (3.4–32)	Summer: 9.2 Winter: 16	NA	NA	Combined	[27]
	Finland	Summer 2012-Winter 2012	3 offices	8 h work shift	NA	NA	NA	Summer: 3.4 (2.6–5.3), Winter: 4.8 (3.4–6.3)	Summer: 8.7, Winter: 12.9	NA	NA	Combined	[28]
	Greece		5 offices					Summer: 13.3 (8.7–16.8), Winter: 14.3 (5.5–18.5)					
	Hungary		5 offices					Summer: 9.4 (5.5–17.1), Winter: 21.3 (12.9–32.3)					
	Italy		4 offices					Summer: 10.5 (8.9–12.6), Winter: 11 (6.1–17.7)					
	Netherlands		3 offices					Summer: 5.2 (4.2–6.1), Winter: 8.4 (5–12.8)					
	Budapest, Hungary	Summer 2012	5 offices	8 h work shift	NA	NA	NA	Office 1: 5.3 (2.9–8.4), Office 2: 13.1 (12.2–15.5), Office 3: 6.7 (4.7–8.2), Office 4: 13 (6.4–22.7), Office 5: 8.3 (5.9–11.4)	0.45–0.96	NA	NA	Mechanical	[29]

(continued on next page)

Table 1 (*continued*)

Continent	Country	Sampling Date	Type	Duration	TSP (μg/m^3)	PM$_{10}$ (μg/m^3)	I/O	PM$_{2.5}$ (μg/m^3)	I/O	PM$_1$ (μg/m^3)	UFPs (particles/cm^3)	Type of ventilation	References
	Kosice, Slovakia	November 2011	8 offices	24 h, 8 days	68.58 (35.8–131.6)	57.04 (28–113.4)	NA	10.37 (4.6–17)	NA	7.33 (1.9–11.4)	NA	Natural, 1 office closed windows during the measurements	[20]
	Dublin, Ireland	February 2009–June 2011	59 office employees	24 h	NA	32 (10–214)	NA	NA	NA	NA	NA	Natural, personal measurements	[14]
	Belgium	2008	9 offices	8 h work shift	18 (7–31)	NA	NA	NA	NA	NA	NA	Natural	[21]
	Athens, Greece	July 2007	2 offices	24 h	NA	NA	NA	smoking office: 37.6 (17.3–94.3) non smoking office: 30.7 (25.3–40.5)	non smoking office: 1.2–1.7	smoking office: 30.4 (13.2–66.4), non smoking office: 26.8 (23.3–35.7)	NA	Natural	[30]
	Germany	January 2006, October 2006	63 offices in 9 buildings	8 h work shift	NA	53 (19.1–231)	NA	36 (19.1–231)	NA	NA	18923 (NA)	Natural, Frequently A/C	[10]
	Athens, Greece	2006	1 office	24 h, 15 days	NA	56.5 (28.6–185.5)	0.61 (0.47–0.82)	37.4 (24.3–83.2)	0.87 (0.64–0.99)	NA	NA	Natural	[31]
	Athens, Greece	February 2004–April 2005	73 office employees	8 h work shift	NA	39.4 (NA)	NA	NA	NA	NA	NA	Natural, personal measurements	[32]
	Bradford, UK	2004	40 employees	48 h	NA	NA	NA	Summer: 21.5 (6.7–80.1), Winter: 37.4 (6.4–78.7)	NA	NA	NA	Natural, personal measurements	[33]
	Wolverhampton, UK	September 2000–May 2001	1 office building	24 h, 23 weekdays	NA	NA	NA	9.8 (5–22)	0.4	NA	NA	Mechanical	[16]
	Paris, France	December 1999–September 2000	62 office employees	24 h, 1 day	NA	NA	NA	34.5 (4.7–265.1)	NA	NA	NA	Natural, personal measurements	[34]
N. America	Chicago, USA	September 2014, October 2014	1 office building	120 h	NA	NA	NA	5 (NA)	1.10–2.88	NA	NA	Mechanical	[35]
	California, USA	2012	37 office buildings	24 h, 40 days	NA	16.2 (NA)	< 1	6.4 (NA)	< 1	0.1 (NA)	5900 (NA)	Mechanical	[36]
	Detroit, USA	August 2005, December 2005, January 2006, April 2006	1 office	24 h	NA	NA	NA	NA	NA	NA	20000	Mechanical	[37]
	USA	2005	8 office employees	24 h, 9 days	NA	NA	NA	42 (NA)	NA	NA	NA	Mechanical	[38]
	Detroit, USA	February 2003	32 office employees	8 h work shift	NA	NA	NA	42.5 (14.5–110.6)	NA	NA	NA	Natural, personal measurements	[39]
	Iowa, Minnesota, Nebraska, USA	November 1996–April 1997	6 office buildings	1 week	NA	(NA) 14 -36	NA	NA	NA	NA	NA	Mechanical	[23]

(*continued on next page*)

Table 1 (*continued*)

Continent	Country	Sampling Date	Type	Duration	TSP (μg/m^3)	PM_{10} (μg/m^3)	I/O	$PM_{2.5}$ (μg/m^3)	I/O	PM_1 (μg/m^3)	UFPs (particles/cm^3)	Type of ventilation	References
Asia	Guangzhou, China	March–June 2015	5 offices in 1 building	24 h	NA	NA	NA	Office 1: 43 (NA), Office 2: 34.1 (NA), Office 3: 102 (NA), Office 4: 112 (NA), Office 5: 22.4 (NA)	Office1: 0.61, Office 2: 0.49, Office 3: 1.45, Office 4: 1.60, Office 5: 0.32	NA	NA	Combined, natural	[40]
	Seremban, Malaysia	May–August 2014	2 office buildings	24 h, 4 days	NA	Office 1: 63.6 (NA), Office 2: 59 (NA)	0.69	NA	NA	NA	NA	Mechanical	[41]
	Beijing, China	February 2014–March 2014	1 office	8 h work shift	NA	NA	NA	17- 60 (NA)	0.81–2.94	NA	NA	Mechanical	[42]
	Kuala Lumpur, Malaysia	2014	3 office buildings	3 days, 8 h work shift	NA	NA (0.393–1.667)	NA	NA	NA	NA	NA	Combined	[43]
	Seoul, Korea	July–September 2013, December 2013–February 2014	1 office	24 h	NA	Summer: 70.9 (NA), Winter: 76.2 (NA)	0.4–2.3	Summer: 32 (NA), Winter: 62 (NA)	1.2–1.9	NA	NA	Combined	[44]
	Shanghai, China	Summer 2012-Winter 2012	10 office buildings	24 h, 7 days	50.3 (NA)	27.2 (NA)	NA	20.4 (NA)	NA	NA	NA	Mechanical	[22]
	Xian, China	October–November 2011	1 office	24 h, 6 days	NA	333 (NA)	0.89	213 (NA)	0.86	213 (NA)	NA	Natural	[45]
	Singapore	July 2010, October 2010	5 office workers	24 h, 6 days	NA	NA	NA	Summer: 51.3 (NA), Autumn: 93.5 (NA)	Summer: 0.44, Autumn: 0.62	NA	NA	Natural	[46]
	Seoul, Korea	December 2009–March 2010	2 office employees	24 h, 7 days	NA	177.7 (124.8–296.7)	NA	125.7 (76.1–170)	NA	109.8 (46.1–138.2)	NA	Natural, personal measurements	[47]
	Taipei, Taiwan	April 2009, June 2011	53 office employees	8 h work shift	NA	NA	NA	70.82 (56.3–99.2)	NA	NA	NA	Natural, personal measurements	[48]
	Beijing, China	June–July 2008	60 office employees	8 h work shift	NA	NA	NA	94.69 (22.4–183.4)	NA	NA	NA	Natural, personal measurements	[49]
	Beijing, China	June–July 2008	60 office employees	8 h work shift	NA	NA	NA	94.6 (NA)	NA	NA	NA	Natural, personal measurements	[50]
	Beijing, China	June–July 2008	60 office employees	8 h work shift, 2 days	NA	121.5 (72–186)	NA	NA	NA	NA	NA	Natural, personal measurements	[51]
	Beijing, China	June–July 2008	120 office employees	8 h work shift	NA	119.5 (84.9–146.5)	NA	94.6 (22.4–183.4)	NA	NA	NA	Natural, personal measurements	[52]
	Daejeon, Korea	April–May 2008, September 2008	2 buildings	24 h	NA	NA	NA	47.6 (14.4–90.9)	1.37 (0.86–2.21)	NA	NA	Natural	[9]
	Beijing, China	October 2006, November 2007	32 office employees	24 h, 13 days	NA	NA	NA	83.5 (NA)	NA	NA	NA	Mechanical	[53]

(*continued on next page*)

Table 1 (*continued*)

Continent	Country	Sampling Date	Type	Duration	TSP (μg/m^3)	PM$_{10}$ (μg/m^3)	I/O	PM$_{2.5}$ (μg/m^3)	I/O	PM$_1$ (μg/m^3)	UFPs (particles/cm^3)	Type of ventilation	References
Rest of the World	Beijing, China	October 2006, November 2007	114 offices	24 h, 13 days	NA	NA	NA	118.5 (28.5–327.8)	NA	NA	NA	Mechanical	[17]
	Thailand	September 2006–January 2007	76 office employees	24 h	NA	Respirable dust concentrations: 0.02–2.18	NA	NA	NA	NA	NA	Natural	[54]
	Hsinchu, Taiwan	August 2003, November 2003	121 office employees	8 h work shift	NA	NA	NA	August: 5.3 (3.8–7.8), November: 4.9 (3.9–6)	NA	NA	NA	Mechanical	[55]
	Beijing, China	October 2002–March 2003	11 offices	9:00 and 11:00 a.m.	NA	63 (14.0–166.3)	NA	28.1 (2.5–102.9)	NA	15.5 (1–54.5)	NA	Natural	[56]
	Doha, Qatar	April–June 2015	1 office building	24 h	NA	21.2 (6.92–141)	0.09	15.5 (4.95–79.4)	NA	NA	NA	sealed	[57]
	Sydney, Australia	August 2014–July 2015	11 office buildings	24 h	NA (14–42)	NA (13–34)	0.99 (0.53–2.40)	NA (6-23)	0.53–2.48	NA	NA	5 mechanical, 3 natural, 3 combined	[19]
	Agra, India	September–December 2011	2 offices	24 h, 7 days	NA	Office 1: 300.6 (274.9–333.9), Office 2: 288.5 (266–306.4)	NA	Office 1: 227.44 (194–245.6), Office 2: 200.44 (194–245.6)	NA	Office 1: 139.2 (105.6–157.7), Office 2: 117.9 (105.6–157.7)	NA	Natural	[58]
	Brisbane, Australia	August 2009	3 Office Buildings	24 h	NA	NA	NA	Building 1: 8.62 (NA), Building 2: 5.22 (NA), Building 3: 5.16 (NA)	Building 1: 0.8, Building 2: 0.86, Building 3: 0.86	NA	NA	Mechanical	[12]
	Brazil	June 2003, August 2003	1736 employees in 2 buildings	8 h work shift	Sealed Building: NA (133–1933), Non Sealed Building: NA (300–1933)	NA	NA	NA	NA	NA	NA	1 sealed, 1 natural	[15]
	Iran	November 2002–November 2003	40 office employees	48 h	NA	NA	NA	30.3 (NA)	NA	NA	NA	Natural, personal measurements	[59]
	Mexico City and Puebla, Mexico	April–May 2002	23 office employees	8 h work shift	NA	NA	NA	Mexico City: 140.4 (NA), Puebla: 74.3 (NA)	NA	NA	NA		https://www.sciencedirect.com/science/article/pii/S1352231007005110 [60]

NA: Not Available.

1. The exact date was not provided.
2. The city was not provided.
3. Mean concentration or Range.

Table 2
Average concentrations of PM2.5 (μg m-3) in summer and winter with different types of ventilation.

Continent	Country	City	Type of ventilation	Sampling Year	Summer	Winter	Reference
Europe	Finland		Combined	2012–2013	17	32	[27]
	Hungary				9,7	15	[27]
	Finland		Combined	2012–2013	3,4	4,8	[28]
	Greece				13,3	14,3	
	Hungary				9,4	21,3	
	Italy				10,5	11	
	Netherlands				5,2	8,4	
	Hungary	Budapest	Mechanical	2012	13,1		[29]
	Slovakia	Kosice	Natural	2011		10,4	[20]
	Ireland	Dublin	2 natural, 4 mechanical	2010–2012	34*		[62]
	Greece	Athens	Natural	2007	37,6 **		[30]
	Greece	Athens	Natural	2006	37,4*		[31]
	Germany		Natural	2006		36	[10]
	UK	Wolverhampton	Mechanical	2000–2001		9,8	[16]
N.America	USA	Chicago	Mechanical	2014	9,9		[35]
	USA	Detroit	Natural, personal measurements	2003		110,4	[39]
Asia	China	Guangzhou	Combined, natural	2015	112**		[40]
	China	Beijing	Mechanical	2014		60	[42]
	India	Agra	Natural	2013–2014		125,8	[63]
	Korea	Seoul	Combined	2013–2014	32	62	[44]
	Singapore		Natural	2013	47		[46]
	China	Shanghai	Mechanical	2012	20,4*		[22]
	India	Agra	Natural	2011		227,4	[58]
	China	Xian	Natural	2011		213	[45]
	Taiwan	Taipei	Natural, personal measurements	2009–2011	70,8* ***		[48]
	China	Beijing	Natural, personal measurements	2008	94,6		[51]
	Korea	Daejeon	Natural	2008	47,6		[9]
	China	Beijing	Mechanical	2006, 2007		118,5	[17]
	Taiwan	Hsinchu	Mechanical	2003	5,3	4,9	[55]
	China	Beijing	Natural	2002–2003		28,1	[56]
Rest of world	Qatar	Doha	Mechanical	2015	15,5		[57]
	Australia	Sydney	5 mechanical, 3 natural, 3 combined	2014–2015	23*		[19]
	Australia	Brisbane	Mechanical	2009		8,62	[12]

* mean of winter and summer measurements.
** ETS office.
*** median.

sampling studies $PM_{2.5}$ concentrations ranged from 23 to 316 μg/m^3 per day, with the highest values being measured in offices where the employees were either active or passive smokers.

3.4. $PM_{1.0}$ and UFPs

Relatively fewer studies measured UFPs and $PM_{1.0}$ concentrations in office indoor environments. Mean $PM_{1.0}$ mass concentrations ranged from 3.2 to 148 μg/m^3 in offices in Italy [24] and China [45], respectively. As expected, offices with activities that are likely to result in higher levels of PM such as smoking, printing, and photocopying exhibited higher $PM_{1.0}$ levels than those without activities [20,30,56]. One study reported the negative effect of fitted carpets in offices, as these capture the dust and release it later on during the transit of people [24]. Heavy traffic conditions outdoors and frequently opening doors were also factors that resulted in higher indoor office $PM_{1.0}$ mass concentrations [45,56]. In most studies the I/O ratio for $PM_{1.0}$ was < 1, with the exception of an office where smoking was taking place [30].

Median UFP mass concentrations in offices ranged from 5.9×10^3 particles/cm^3 in offices from the USA [36] to 15.5×10^3 particles/cm^3 in offices in Germany [10]. Ultrafine particle concentrations were measured each minute using portable condensation particle counters (CPC) [37]. measured ultrafine and fine PM inside and outside of mechanically ventilated buildings in Denver, USA, and observed that indoor particle levels were highly correlated with outdoor levels. The I/O ratio for $PM_{1.0}$ was weakly but positively correlated with the amount of ventilation provided to the indoor environment, and was similar for each period of the week. Their results suggest that improved filtration is warranted in mechanically ventilated buildings, particularly for ultrafine particles, and that nighttime infiltration is significant depending on the building design.

It should be noted here that studies reporting number concentrations of UFPs are scarce primarily because they have not yet been sufficiently linked to adverse health effects – despite their higher relevance – compared to mass concentrations, but also due to the relatively high cost of the associated instruments. This paradigm, however, is changing as new low-cost and portable instruments are becoming available or are currently being developed. In this respect low-cost optical sensors (cf [64,65]. and/or particle mobility segregators [66,67] and classifiers [68] can be use to measure respectively the number-based size distributions of particles larger than ca. 0.3 μm, and/or smaller particles having diameters down to the sub-10-nm range.

4. Indoor office PM concentrations and associated health effects

4.1. Determinants of human exposure to PM

Sixteen studies in our review used personal samplers to assess employee exposure to PM and other indoor air pollutants. About half of these studies used samples collected over the 8- to 10-h (depending on the type of work performed) work shift, while the rest sampled continuously for 24 h. Sampling duration ranged from 2 to 7 days. Only five of these studies used a time-activity log and a few used spirometry [32,49,69], blood pressure and heart rate measurements [51] and biological measurements such as blood or urine [48,50,52]. In those cases, the time activity logs showed that most participants spent close to 90% of their day in indoor environments, whether at work or at home, irrespective of the sampling season. The most common determinants of PM in offices were smoking, commute mode, ambient concentrations, body mass index (BMI), temperature, humidity, and person density.

[34] were the first to report the significant contribution of smoking to individual exposure in the office, in the absence of which (i.e., in non-smoking indoor environments), ambient air pollution and person density (the ratio between the number of persons in the room and the surface area as a surrogate of particle resuspending) became significant factors (both $p < 0.05$) [17]. found that personal exposure concentrations on workdays were higher than those on weekends ($p < 0.05$). Ventilation was found to be another determinant of exposure to indoor air pollutants [60]. Office employees working in a naturally ventilated library (with some indoor sources of PM such as resuspended dust, and photocopiers present) had lower exposure to PM than those working in an air-conditioned building with no natural ventilation and presence of environmental tobacco smoke (ETS). Compared to other microenvironments such as homes and recreational spaces, offices result in the largest uptake of PM_{10}, as shown in the study by Ref. [14] [47]. observed the same important contribution of the office environment during the weekdays to the inhalation mass of PM_{10}, $PM_{2.5}$ and $PM_{1.0,}$ compared to homes and other microenvironments in Korea.

The studies by Refs. [50,52] were the only ones that sampled employees' blood, in addition to personal PM measurements; the former measured mitochondrial DNA (MtDNAcn) and the latter measured DNA methylation (SATα) as biomarkers for environmental exposure to PM. In office workers MtDNAcn decreased in association with increased levels of 5-day and 8-day means of ambient PM_{10}. Each 10 μg/m^3 increase in the 5-day mean of ambient PM_{10} was associated with an average decrease of 0.011 relative units in MtDNAcn (95% CI: −0.025;-0.004, $p = 0.01$) [52]. In office workers, SATα methylation was positively associated with concentrations of S (0.115, 95%CI: 0.034; 0.196), which is likely to represent the exposure to coal combustion, a typical urban air pollution source in China [50].

[48] collected post-shift urine samples for 1-OHPG and 8-OHdG as biomarkers of DNA damage from 53 office workers to investigate whether exposure to $PM_{2.5}$ is a determinant of urinary levels. They observed that the median $PM_{2.5}$ concentration in the exposed group was 70.82 μg/m^3, in comparison to 82.87 μg/m^3 in the control group, suggesting that elevated levels of $PM_{2.5}$ may increase urinary levels. The authors however were not able to find any associations between urinary 1-OHPG nor urinary 8-OHdG levels and DNA strand breaks, which was contrary to their initial hypothesis. Their results provide an indication that PM could be associated with DNA damage, and particulate PAHs could be the biologically active constituent of $PM_{2.5}$ with regarding to the induction of oxidative DNA damage.

[51] also measured blood pressure (BP) and heart rate (HR) and found increases in BP associated with ambient PM_{10} concentrations averaged over five and eight days before the BP examination. The authors did not find any significant associations of BP with personal measurements of $PM_{2.5}$ during work hours on the day of the examination, nor with ambient PM_{10} averaged over 1–2 days before the examination days, suggesting that higher levels of PM exposure exert effects on BP that may require 5–8 days to become detectable.

In most cases temperature and humidity were generally kept constant at a comfortable level for the employees (around 22–25 °C and 40–60% for RH). The important role of micrometeorological parameters such as mean temperature and relative air humidity to indoor air quality was explored by several studies [33,59] found that the ambient temperature during the monitoring period and PM_{10} concentrations were the strongest predictors for both indoor office and indoor home $PM_{2.5}$ concentrations [70]. observed that humidification of the air resulted in an RH increase from 12% to 39%, which led to fewer complaints about thermal discomfort at temperature settings below 22.0 °C.

Finally [49], found that higher concentrations of Si, Al, Ca, and Ti in $PM_{2.5}$ particles were associated with decreased lung function as assessed by forced expiratory volume in 1 s (FEV1) in office workers in Beijing, China. Si, Al, and Ca were also negatively associated with forced vital capacity (FVC) [32]. also observed decreased lung function of office workers in Athens, Greece, exposed to higher concentrations of PM_{10} (> 39.35 μg/m^3) as assessed by FEV1 and FVC.

4.2. Studies assessing SBS with questionnaires

Questionnaires can be a cost-effective research tool for use in data collection, as they contain large amounts of information and can be collected from a large number of people in a short period of time (Mc Coll et al., 2001). Nine studies in our review used self-reported questionnaires to assess SBS-related symptoms in office workers caused by exposure to PM_{10}, $PM_{2.5}$ and other pollutants. The most commonly reported symptoms were eye irritation, tired and/or dry eyes, dry throat, runny nose, sneezing, cough, tiredness, irritability, difficulty concentrating, headache, dizziness, skin irritation, pain/stiffness in shoulders and/or neck, and nausea [15,22,23,32,38,54,55,63,70]. Some associations between indoor air pollutants and self-reported SBS symptoms have been reported in several studies. Adjusting for age, gender, smoking habits and education [32], did not find statistically significant odds ratios (OR) for symptoms and diseases in office employees for NO_2, O_3 and PM_{10}. On the other hand [22], found that adjusted OR per 100 ppb increase in indoor TVOCs were slightly significant for upper respiratory syndrome (OR = 1.06; 95% CI = 1.04–1.07), stuffy nose (OR = 1.01; 95% CI = 1.01–1.02), dry throat (OR = 1.06; 95% CI = 1.03–1.09) and lower respiratory syndrome (OR = 1.01; 95% CI = 1.00–1.01), non-specific syndrome (OR = 1.03; 95% CI = 1.02–1.05), tiredness (OR = 1.02; 95% CI = 1.01–1.04), angry easily (OR = 1.02; 95% CI = 1.01–1.04) and dizziness (OR = 1.01; 95% CI = 1.00–1.02).

[55] also reported that compared with workers exposed to CO_2 concentrations of less than 500 ppm, workers exposed to CO_2 concentrations of greater than 800 ppm were more likely to report the symptoms of two of the five SBS groups: eye irritation (ORs = 1.7; 95% CI = 1.1–2.7) and upper respiratory symptoms (ORs = 1.7; 95% CI = 1.0–2.7). Across all 17 SBS symptoms, workers exposed to indoor CO_2 concentrations of greater than 800 ppm were likely to report more tired or strained eyes (ORs = 1.7, 95% CI = 1.1–2.7), dry, itching, or irritated eyes (ORs = 1.8, 95% CI = 1.2–2.8), and difficulty in remembering things or in concentrating (ORs = 1.7, 95% CI = 1.0–2.9) than those exposed to CO_2 concentrations of less than 500 ppm.

The combined exposure of air pollutants in indoor office air may become significant in the prevalence of health symptoms [38]. found that dry eyes, sleepiness and skin irritation as reported by office workers were either absent or marginally reported during individual ozone of dust exposures, but significant at combined exposures, suggesting an interaction between the exposures. The authors pointed out that while a strong response to the combined exposure in the time course of general irritation was found, accumulation of responses reached equilibrium after about 12 h exposure. However, the individuals used in that study were all atopic persons, with a higher than average sensitivity to exposures. As a result, the observed effects may overestimate the responses of the general population to the same exposures.

An interesting observation in some studies is the difference in reporting SBS symptoms between male and female office workers. In a study by Ref. [55]; female employees, and particularly those suffering from allergies, reported more SBS symptoms than their male counterparts. According to the study, female employees were more likely to report SBS symptoms than male employees for eye irritation (ORs = 5.6; 95% CI = 2.2–14.1), nonspecific symptoms (ORs = 2.6; 95% CI = 1.2–6.0), higher respiratory symptoms (ORs = 3.1; 95% CI = 1.3–7.0), and skin irritation (ORs = 3.5, 1.3–9.2). In addition, workers who had a history of allergies were more likely to report eye irritation, nonspecific symptoms, and lower respiratory symptoms than workers who did not suffer from any allergies [23]. also found significant relations between a number of SBS symptoms and exposure to indoor air pollution (as well as temperature, and endotoxin) for males. For females, elevated number of symptoms was only associated with relative humidity and endotoxin. The higher number of females reporting SBS work-related symptoms is consistent with empirical observations reported for cases of SBS. As the authors explain, the difference between males and females in the relation of symptoms to psychosocial parameters is probably not unexpected, given the differences in male and female behavior and other patterns of gender-specific behavior.

In contrast to the above [70], observed a different pattern of complaints between people of different genders, with men having a higher prevalence of symptoms compared to women. Men reported the effect of indoor air exposure more often than women, which as the authors explain, may have been due to different hierarchical positions in the office. On the other hand, they found that dust complaints (associated with PM_{10} fraction) were significantly higher in female than male employees, possibly due to the fact that women are more sensitive to smoking activities, resulting in higher concentrations of PM_{10} in their workplace. The authors used a symptom score, where they replaced the perceived physical environments (subjective perception score) with objective assessments (airborne physical parameters such as air movement, air temperature, and relative humidity), with three sub-scores for symptoms (general, mucosal, and dermal). Men reported making all three types of complaint (total, general, mucosal, and dermal) after exposure to TVOCs or aldehyde content, while women only reported having mucosal discomfort from exposure to this chemical. The most common complaints related to the exposure of TVOCs were fatigue and cough.

Building ventilation was shown by Ref. [15] to be an important factor in SBS symptoms. They reported a higher prevalence of work-related upper respiratory symptoms and tiredness in the HVAC sealed building than in the naturally ventilated building. The average mean concentration of VOCs during working hours in the sealed building was 774 $\mu g/m^3$ and 463 $\mu g/m^3$ in the non-sealed building. In the sealed building the frequency of some symptoms were more prevalent such as eye dryness 33.3% and 27.1%, runny nose 37.3% and 31.3%, dry throat 42% and 36%, and lethargy 58.5% and 50.5% respectively. In addition, workers from the sealed building reported a significantly higher frequency of improvement (of SBS symptoms) out of the office than the ones working in the naturally ventilated building. The authors note however that some potential biases such as job satisfaction, amount of work, job-related stress and other unknown job-related factors that could influence the outcomes should also be considered.

Finally, seasonal differences in SBS symptoms were explored by Ref. [55]; who found significant increases in the prevalence of eye irritation, nonspecific symptoms, and upper respiratory symptoms in November 2003 (the respective increases for these three groups were 13.5%, 10.9%, and 9.9% between August and November 2003). The authors observed that the prevalence rates of tired or strained eyes, dry, itching, or irritated eyes, and difficulty in concentrating had significantly increased by November 2003 (the respective increases of these three groups between August and November were 14.5%, 10.8%, and 10.8%).

5. Conclusions

In this study we review and evaluate existing information on the presence of PM of various size fractions in office environments. There is suggestive evidence that certain conditions, commonly found in offices, can significantly deteriorate the quality of the air and therefore the health of the occupants. The consensus from all these studies is that the location, the age and air-tightness of office buildings, the room design, the ventilation rate, the occupant's personal activities and outdoor air pollution as well as temperature (both indoor and ambient) and relative humidity, play an important role on the indoor pollutants concentrations and subsequently the perceived health effects by the workers. The results also show that differences in the concentrations of PM among different countries are associated with ventilation rates, relative humidity values, the use of different ventilation facilities, various office equipment, and construction and building materials.

We also noted a distinct gap in the measurement of the elemental composition of PM, which may be an important factor when considering the associated health effects of indoor air pollution exposure. When considering ventilation, it appears that use of combined and natural ventilation could provide an indoor environmental quality of a sufficient standard, saving the infrastructure and running costs associated with mechanical ventilation. The construction of office buildings, equipped with adequate ventilation systems to improve air exchange, as well as the use of low-emitting building and furniture materials, would be an important step in the protection of employees from SBS symptoms.

Certain literature gaps and issues that need to be considered in future studies of indoor air pollution in offices and associated human health effects are also revealed in this review. While some studies assessing SBSs utilized standardized questionnaires (e.g., NIOSH/EPA questionnaire, European Community Respiratory Health survey questionnaire, NIOSH indoor air quality and work environment symptoms questionnaire), most were developed in-house and some were modified versions of standardized questionnaires without further details. For comparison purposes, it would be preferable to use standardized questionnaires that can be accessed at any time, in a more systematic way. Furthermore, when designing management strategies to prevent and respond to indoor air pollution problems, there needs to be consideration of the differences between the two genders with regards to perceived SBS symptoms, exposures, and other psychosocial factors, since many studies found significant differences between males and females and reported SBS symptoms. In addition, other chemicals present in indoor air such as VOCs and CO, as well as environmental factors such as temperature and relative humidity should also be considered when evaluating an indoor office environment. A more holistic approach, which considers these aforementioned factors, as well as psychological and personality factors, is advisable when dealing with indoor occupational environments. There are other pollutants besides particulate matter that may cause significant health effects in an office environment, which were not measured or considered in many studies included in this review. Measurements of all possible pollutants are therefore required in order to better understand the relation between of health effects and indoor air quality in offices.

Finally, it is important to put this review in the context of exposure, health implications, energy costs, and technology options. In this regard, new miniaturized and inexpensive sensors that can be installed at the offices to monitor PM concentrations continuously hold great promises for providing dense and reliable datasets for linking air quality measurements with occupational health. Apart from mass and/or number concentration measurements, of particular importance in this direction will be the development and exploitation of low-cost systems capable of probing the size distributions of the inhaled particles. This can be achieved with new low-cost optical sensors for particles larger than ca. 0.3 μm, or electrical mobility segregators and classifiers for particle having diameters down to the sub-10-nm range as described in section 3.

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