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## Particulate matter in indoor spaces: known facts and the knowledge gaps\*

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**Abstract:** *Particulate matter in indoor spaces: known facts and the knowledge gaps.* As people spend most of the time in closed spaces (flats, workplaces, schools etc.), the indoor air has been researched for many years all over the world. Particulate matter (PM) is one of the most often examined pollutants in the indoor and outdoor air. The following study presents the facts about PM in closed spaces and the most often taken actions. The least known aspects related to the indoor air pollution with PM are demonstrated. The indoor space of various service and office buildings/facilities (not related to production, i.e. offices, shops, beauty parlours, restaurant kitchens, restaurants, pubs etc.) seem to be an unrecognized area in the air pollution studies. Importantly, a great number of people work in such spaces all over the world and thus spend there a large part of their lives.

*Key words:* indoor aerosol, buildings, flats, sources of dust emissions, resuspension

### INTRODUCTION

Atmospheric aerosol (an acronym for the atmospheric aerosol used in the literature is PM – particulate matter) can be investigated in terms of its chemical compo-

sition, the ability to absorb and scatter light, the affinity to various chemical compounds, but the critical feature of the particles constituting the dispersed phase is their size (Hinds 1998). In the atmospheric air in every selected point of observation particles with aerodynamic diameters in the range from  $10^{-3}$  to  $100 \mu\text{m}$  can be found. The fraction of particles of the specific sizes (range of diameters –  $\text{PM}_{10}$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$  are examined mostly, which means particles with aerodynamic diameter not greater than 1, 2.5 and  $10 \mu\text{m}$ , respectively) in the given place depends on a large number of factors, including the origin of the particles (Whitby 1978). On the other hand, the main factor determining the deposition of inhaled particle in the respiratory tract is its aerodynamic diameter. Fine particles, belonging to the respirable fraction ( $\text{PM}_{10}$  or  $\text{PM}_{2.5}$ ), are able to reach the deepest areas of lungs what makes their effects on human health much more serious than the effects of coarse particles

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(Englert 2004, Wichmann 2004, Ostro et al. 2007, Zhang et al. 2011).

The origin of PM also determines its chemical composition. Generally, the chemical substances, constituting almost the entire mass of PM in urbanized regions, can be divided into six groups (Chow 1995, Sillanpää et al. 2006, Rogula and Klejnowski 2013, Rogula-Kozłowska et al. 2014): geological matter (oxides of aluminum, silicon, calcium, titanium and iron), organic carbon (hundreds of compounds), elemental carbon, sulfates, nitrates and ammonia. In the regions that are industrialized and exposed to the effects of traffic emission the atmospheric aerosol also contains trace elements (Schroeder et al. 1987, Pastuszka et al. 2010). When the relative humidity of air is higher than 70%, water is absorbed by soluble compounds and becomes a component of the aerosol. In coastal regions also water-soluble salts of sodium and chlorides are absorbed (Chow 1995, Sillanpää et al. 2006). In the areas where fossil fuels are the main sources of energy, sodium and chlorides originate from the combustion processes, what is particularly pronounced in the heating season (Rogula-Kozłowska et al. 2014).

The most common anthropogenic sources of dust include: industrial processes, energy production, transport and household emissions. Among the natural sources, the ones deserving special attention include: volcanic eruptions, resuspension of dust from soil and desert areas, marine aerosol, forest and steppe fires (Chow 1995, Hinds 1998). On a global scale the majority of PM

in the atmosphere is of a natural origin. In urbanized areas natural sources have smaller contribution to the dust emission than the anthropogenic ones (Sówka et al. 2012, Majewski and Ćwiek 2013, Rogula-Kozłowska et al. 2013).

#### BRIEF OVERVIEW OF THE INFORMATION ON PARTICULATE MATTER IN INDOOR AIR

Particulate matter in indoor spaces may originate from both outdoor and indoor sources. The most significant indoor sources of aerosol include: tobacco smoking, combustion heating devices (burning of coal, wood, biomass), food preparation, building materials cleaning agents, different kinds of habitation-related activities. Bioaerosol particles (mainly bacteria) can be emitted indoors from human (as well as from pets) respiratory tract, skin and hair, as well from the plants present in the indoor environment.

In Table 1 the most important sources of indoor aerosol taken from Lippman (2009) are listed together with the methods recommended for reducing emission from these sources.

The atmospheric air can be considered as a substantial source of suspended dust for the closed spaces. Correlations between concentrations in the atmospheric air and in the closed spaces are interfered by the existence of indoor sources and different ventilation conditions (Monn 2001). In the summer concentrations of total suspended particulates in closed spaces are higher than in the winter. The influence of outdoor PM concentrations on the concentrations in

TABLE 1. Indoor sources of aerosol (adapted from Lippman 2009)

Category / Common sources	Mitigation and control
<b>Housekeeping and Maintenance</b>	
Cleanser	Use low-emitting products
Waxes and polishes	Avoid aerosols and sprays
Disinfectants	Dilute to proper strength
Air fresheners	Do not overuse; use during unoccupied hours
Adhesives	Use proper protocol when diluting and mixing
Janitor's/storage closets	Store properly with containers closed and lid tight
Wet mops	Use exhaust ventilation for storage spaces (eliminate return air)
Drain cleaners	Clean mops, store mop top up to dry
Vacuuming	Avoid "air fresheners" – clean and exhaust instead
Paints and coatings	Use high-efficiency vacuum bags/filters
Solvents	Use integrated pest management
Pesticides	–
Lubricants	–
<b>Occupant-related sources</b>	
Tobacco products	Smoking policy
Office equipment (printers/copiers)	Use exhaust ventilation with pressure control for major local sources
Cooking/microwave	Low-emitting art supplies/marketing pens
Art supplies	Avoid paper clutter
Marking pens	Education material for occupants and staff
Paper products (e.g. perfume)	–
Tracked-in dirt/pollen	–
<b>Building uses as major sources</b>	
Print/photocopy shop	Use exhaust ventilation and pressure control
Dry cleaning	Use exhaust hoods where appropriate; check hood airflows
Science laboratory	–
Medical office	–
Hair/nail salon	–
Cafeteria	–
Pet store	–
<b>Building-related sources</b>	
Plywood/compressed wood	Use low-emitting sources
Construction adhesives	Air out in an open/ventilated area before installing
Asbestos products	Increase ventilation rates during and after installing
Insulation	Keep material dry prior to enclosing
Wall/floor coverings (vinyl/plastic)	–
Carpets/carpet adhesives	–
Wet building products	–
Transformers	–
Upholstered furniture	–
Renovation/remodeling	–

TABLE 1 (continued)

Category / Common sources	Mitigation and control
HVAS system	
Contaminated filters	Perform HVAC preventive maintenance
Contaminated duct lining	Change filter
Dirty drain pans	Clean drain pans; proper slope and drainage
Humidifiers	Use portable water for humidification
Lubricants	Keep duct lining dry; move lining outside of duct if possible
Refrigerants	Fix leaks/clean spills
Mechanical room	Maintain spotless mechanical room (not a storage area)
Maintenance activities	Avoid back drafting
Combustion appliances (boilers/furnaces/stoves/generators)	Check/maintain flues from boiler to outside
Moisture	
Mold	Keep building dry
Vehicles	
Underground/attached garage	Use exhaust ventilation Maintain garage under negative pressure relative to the building Check airflow patterns frequently Monitor carbon monoxide

closed spaces is characterized by the I/O ratio (indoor / outdoor) of the PM concentration in a closed space to the concentration in the atmospheric air.

The I/O ratio for various fraction of PM can lie within the range from 0.1 to 31.4.  $PM_{2.5}$  I/O ratios in the large-scale studies (larger than 20 homes) in different cities are in the range between 0.8 and 3.4 (Chen and Zhao 2011). Values of the I/O ratio for  $PM_{10}$  encountered in the literature are in the range between 1.14 and 3.91 (Morawska and Salthammer 2006). In air-conditioned spaces where dust filters are used this ratio can be low, between 0.1 and 0.3 (Yocom 1982).

Although in a given area atmospheric PM can constitute a relatively steady (in terms of concentration) background for

particular houses, the indoor PM concentrations in this region can vary for the different buildings and spaces. The dispersed fraction of the atmospheric aerosol can have a contribution to the concentration of suspended dust in the air of closed spaces reaching 70% for naturally ventilated spaces and 30% for spaces with air conditioning (Dockery and Spengler 1981). In houses with no substantial indoor sources of emission the atmospheric air contributes 75% to the  $PM_{2.5}$  and 66% to the  $PM_{10}$  indoor concentration (Özkaynak et al. 1996). In houses with substantial indoor sources of dust (cooking, tobacco smoking) atmospheric air can contribute about 55–60% to the indoor  $PM_{10}$  and  $PM_{2.5}$  concentrations.

Cigarette smoking is a very effective source of particles suspended in the air in closed spaces. The I/O ratio of the indoor dust concentration to the concentration in atmospheric air for spaces in which tobacco is smoked is greater than unity, e.g. generally I/O for PM in spaces where tobacco is smoked can reach  $2.7 \pm 6.7$  and for  $PM_{10}$  it can be between  $1.8 \pm 0.9$  (May) and  $2.9 \pm 3.0$  (September) in a rural area, and  $3.9 \pm 7.8$  (March) in an urban flat (Jones et al. 2000), while in the case of spaces where tobacco is not smoked the ratio is equal to unity (Monn 2001). Mean 48-hour indoor concentration of  $PM_{2.5}$  (in the winter) can increase by  $33 \mu\text{g}/\text{m}^3$  under the influence of cigarette smoking (Simoni et al. 1998), 24-hour concentration can rise by  $25\text{--}32 \mu\text{g}/\text{m}^3$ , and 12-hour concentration by  $30\text{--}35 \mu\text{g}/\text{m}^3$  (Özkaynak et al. 1996).

The use of gas stoves (cooking) causes a significant increase in the I/O ratio only during meal preparation (Jones et al. 2000).

Also cleaning with the use of vacuum cleaners and wood burning (in fireplaces) are substantial sources of solid particles in the air of closed spaces (Monn 2001).

Human activity alone is an important factor affecting the concentration levels of dust particles in closed spaces. Activities performed by users of the spaces, their movement, cause continuous movement of dust particles present in the spaces: suspending, mixing in the air, re-settling. These phenomena contribute to the increase in concentrations of particles with the aerodynamic diameter smaller than  $2.5 \mu\text{m}$ . They cause

a rise in the I/O ratio, and although not in every case (Jones et al. 2000) in one of the houses no relationship between the rise in mean  $PM_{10}$  concentrations and movement of people was found), but in (Jones et al. 2000) in the majority of cases, an increase in the  $PM_{10}$  mean concentration from 10 to  $40 \mu\text{g}/\text{m}^3$  caused by the movement of residents was observed.

In the environments of closed spaces occupied by people and animals usually dust particles of animal origin are present in the air (from acari, insects, dogs, cats, birds etc.).

It should not go unmentioned that, apart from suspended dust, indoor sources also emit other pollutants. The most important groups of indoor pollutants and their sources are given in Table 2.

Air inside accommodation spaces (Table 3), spaces in public utility buildings (schools, kindergartens, theatres, hospitals, museums, library; Table 4), and inside public transport vehicles as well as the relationships between indoor and outdoor sources of dust and gaseous pollutants and air quality have already been studied quite thoroughly (Dockery and Spengler 1981, Yocom 1982, Lis and Pastuszka 1997, Levy et al. 1998, Simoni et al. 1998, Pastuszka et al. 1998, 2000, 2005, Godish, 2000, Long et al. 2000, Li and Lin 2003, Morawska and Salthammer 2006, Colbeck et al. 2010, Dudzińska 2011, Liroy et al. 2011, Gurley et al. 2013, Zwoździak et al. 2013, Célia et al. 2014, Pollard et al. 2014).

TABLE 2. The most important groups of pollutants emitted from selected indoor sources (adapted from Lippman 2009)

Pollutant or Pollutant class	Potential sources
Combustion contaminants	furnaces, generators, gas or kerosene space heaters, tobacco products, outdoor air, vehicles
Biological contaminants	wet or damp materials, cooling towers, humidifiers, cooling coils or drain pans, damp duct insulation of filters, condensation, re-entrained sanitary exhausts, bird droppings, cockroaches or rodents, dust mites on upholstered furniture or carpeting, body odors
Volatile organic compounds (VOCs)	paints, stains, varnishes, solvents, pesticides, adhesives, wood preservatives, waxes, polishes, cleansers, lubricants, sealants, dyes, air fresheners, fuels, plastics, copy machines, printers, tobacco products, perfumes, dry cleaned clothing
Formaldehyde	particleboard, plywood, cabinetry, furniture, fabrics
Soil gases (radon, sewer gas, VOCs, drain leak, drain methane)	soil and rock (radon), sewer traps, leaking underground storage tanks, landfill
Pesticides	termiticides, insecticides, rodenticides, fungicides, disinfectants, herbicides

TABLE 3. Comparison of PM<sub>1</sub> and PM<sub>2.5</sub> concentrations in ambient (outdoor) and indoor (accommodation spaces) air (mean ±standard deviation)

Site	PM concentration (µg/m <sup>3</sup> )	
	indoor	outdoor
<sup>a</sup> Hong Kong (PM <sub>2.5</sub> )	50.4	–
<sup>a</sup> Southern California (PM <sub>2.5</sub> )	15.45	15.2
<sup>a</sup> Birmingham (PM <sub>2.5</sub> )	summer 16.1 ±5.7	summer 26.5 ±9.5
	winter 11.2 ±5.4	winter 12.2 ±5.1
<sup>a</sup> Athens (PM <sub>2.5</sub> )	35.6 ±29.4	37.3 ±27.4
<sup>a</sup> Basel (PM <sub>2.5</sub> )	21.0 ±16.7	19.3 ±11.5
<sup>a</sup> Helsinki (PM <sub>2.5</sub> )	9.5 ±6.1	10.5 ±7.1
<sup>a</sup> Prague (PM <sub>2.5</sub> )	34.4 ±28.7	27.3 ±10.4
<sup>a</sup> Birmingham (PM <sub>1</sub> )	9.9 ±3.3	8.3 ±4.1
<sup>a</sup> Taipei (PM <sub>1</sub> )	summer 25.4 ±8.9	summer 28.8 ±9.8
	winter 26.4 ±14.1	winter 27.0 ±14.4
<sup>a</sup> Taipei (PM <sub>2.5</sub> )	summer 36.6 ±12.6	summer 36.3 ±12.7
	winter 38.7 ±19.5	winter 38.3 ±20.7
<sup>b</sup> Katowice (TSP <sup>c</sup> )	100	156
<sup>b</sup> Katowice (fine PM)	69	59
<sup>b</sup> Bytom (TSP <sup>c</sup> )	102	289
<sup>b</sup> Bytom (fine PM)	72	105
<sup>b</sup> Sosnowiec (TSP <sup>c</sup> )	82	213
<sup>b</sup> Sosnowiec (fine PM)	74	50
<sup>b</sup> Chorzów (TSP <sup>c</sup> )	93	405
<sup>b</sup> Chorzów (fine PM)	81	124

<sup>a</sup> Li and Lin 2003; <sup>b</sup> Górny et al. 1995; <sup>c</sup> TSP – total suspended particles (total PM).

TABLE 4. Comparison of PM concentrations in ambient (outdoor) and air in some public utility buildings (indoor)

Site	PM concentration ( $\mu\text{g}/\text{m}^3$ )			
	indoor	outdoor		
<sup>a</sup> School in Wrocław	Summer			
	PM <sub>1</sub>	8.5 ±3.6	8.9 ±3.4	
	PM <sub>2.5</sub>	13.5 ±4.1	16 ±9.1	
	PM <sub>10</sub>	43.1 ±17.9	24.7 ±10.5	
	Winter			
	PM <sub>1</sub>	21.2 ±5.3	25.5 ±7.8	
	PM <sub>2.5</sub>	59.8 ±21.6	49.1 ±15.6	
PM <sub>10</sub>	68.5 ±21.8	56.8 ±17.3		
<sup>b</sup> Wawel Castle museum	Winter (TSP <sup>d</sup> )			
	Room 1 (ground floor)	73 ±2	59 ±2	
	Room 2 (1st floor)	79 ±2		
	Room 3 (2nd floor)	61 ±2		
	Summer (TSP <sup>d</sup> )			
	Room 1 (ground floor)	22 ±2	19 ±2	
	Room 2 (1st floor)	7 ±2		
Room 3 (2nd floor)	11 ±2			
<sup>c</sup> Classrooms in the 1st school	winter	summer	-	
	occupied; biology			
	PM <sub>1</sub>	47		59
	PM <sub>2.5</sub>	48		60
	PM <sub>10</sub>	105		78
	TSP	297		132
	occupied; physic			
	PM <sub>1</sub>	118		78
	PM <sub>2.5</sub>	119		78
	PM <sub>10</sub>	191		104
	TSP	363		192
	vacant; biology			
	PM <sub>1</sub>	22		34
	PM <sub>2.5</sub>	23		34
	PM <sub>10</sub>	39		48
	TSP	59		87
vacant; physic				
PM <sub>1</sub>	61	52		
PM <sub>2.5</sub>	62	52		
PM <sub>10</sub>	72	62		
TSP	85	82		

<sup>a</sup>Zwoździak et al. 2013, <sup>b</sup>Worobiec et al. 2010, <sup>c</sup>Połędnik 2013; <sup>d</sup>TSP – total suspended particles (total PM).

## GAPS IN THE CURRENT STATE OF KNOWLEDGE

It appears that non-production spaces, i.e. offices, photocopy shops, kitchens, restaurants, hair salons, beauty parlours, etc., are the most poorly characterized in this regard. On one hand, they constitute the most common workplaces

door sources (e.g. from secondary emission of settled dust) – Table 5.

The changes in size distribution can be particularly significant in the case of hygroscopic dusts penetrating into spaces with high air humidity (e.g. kitchen rooms). The above mentioned phenomena were only partially characterized in

TABLE 5. Possible changes in the structure of the atmospheric aerosol in non-production spaces. Own analysis

Mechanism of the changes	Examples of the spaces	Changes in aerosol structure
Condensation on particles	beauty parlours, kitchens, photocopy shops	a, b, d, e, f
Nucleation	beauty parlours, kitchens	a, b, c, d, e, f
Absorption of water vapour by hygroscopic particles	kitchens	a, b, d, f
Gas adsorption on particles	beauty parlours, kitchens, photocopy shops, offices	a, b, d, e, f
Emission and re-emission of dust	beauty parlours, kitchens, offices	a, b, c, d, e, f

Designations: a – change of the morphology of the particles, b – change of the mass concentration, c – change of the number concentration, d – change of the size distribution, e – change of the chemical composition, f – change of the optical parameters.

nowadays in developed countries, and thus are the environment of prolonged residence for a vast number of people, while on the other hand they are an environment, completely different than the atmospheric air, in which mutual interactions of pollutants already present in the spaces with those migrating from the outdoor air takes place.

Migration of the atmospheric aerosol into indoor spaces may cause measurable changes in the level of concentrations and in the size distribution of dust particles, which will overlap with changes resulting from dust emission from out-

a quantitative manner. For the majority of indoor spaces qualitative or semi-quantitative characterizations are predominant in the subject literature. It seems that this kind of changes should be expected particularly in an urbanized and highly industrialized area. Atmospheric aerosol in such areas contains a large proportion of elemental carbon (Rogula-Kozłowska et al. 2014), especially in the surface layer (Pastuszka et al., 2003, Klejnowski et al. 2012), what makes it particularly susceptible to adsorption of gaseous substances, such as volatile organic compounds (VOCs), polycyclic aromatic compounds (PAHs)



or oxides of various metals. Processes of this type, consisting in the enrichment of aerosol particles in adsorbed gaseous pollutants, have not yet been studied in the indoor environment.

Research in this mainstream would allow to detect and describe general patterns in the evolution of the atmospheric aerosol, resulting from it being contacted with an indoor stream of gaseous pollutants, in relation to the characteristics of indoor emitters and parameters of the indoor environment, what would fill the gap in the current state of knowledge.

If the changes in aerosol structure in indoor spaces, that are to be the subject of the studies, turn out to be significant, there will be a necessity to modify the methods for prognosis health effects of exposure of the general population to the outdoor aerosol.

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**Streszczenie:** *Pył zawieszony w pomieszczeniach: znane fakty i luki w stanie wiedzy.* Ponieważ większość życia ludzie spędzają w pomieszczeniach zamkniętych (mieszkania, miejsca pracy, szkoły, itp.), powietrze wewnętrzne jest od wielu lat przedmiotem zainteresowania grup badaczy na całym świecie. Jednym z najczęściej badanych zanieczyszczeń w powietrzu wewnętrznym jest, podobnie jak w powietrzu zewnętrznym, pył zawieszony, PM. W pracy przedstawiono udokumentowane fakty dotyczące PM w pomieszczeniach zamkniętych i najczęściej podejmowane kierunki działań w tym zakresie. Wskazano również obszar najslabiej rozpoznany pod względem zanieczyszczenia powietrza pyłem zawieszonym. Przestrzeń wewnętrzna różnego rodzaju obiektów usługowo-biurowych (nieprodukcyjnych, tj. biura, sklepy, salony urody, kuchnie restauracyjne, restauracje, puby itp.) wydaje się być zupełnie nierozpoznanym obszarem jeżeli chodzi o zanieczyszczenie powietrza. Tymczasem, właśnie w takich obiektach pracuje i tym samym spędza dużą część swojego życia mnóstwo osób na całym świecie.

*Słowa kluczowe:* aerozol wewnętrzny, budynki, mieszkania, źródła emisji pyłu, resuspensja

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