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EXPOSURE TO COARSE PARTICLES AND FLOOR DUST CHEMICAL AND BIOLOGICAL CONTAMINATION INSIDE JORDANIAN INDOOR ENVIRONMENTS

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Androniki Maragkidou,
Helsinki, August 2018

Exposure to coarse particles and floor dust biological and chemical contamination inside Jordanian indoor environments

Androniki Maragkidou

University of Helsinki, 2018

Abstract

This thesis consists of two parts where Indoor Environmental Quality is studied in the first part by analyzing polycyclic aromatic hydrocarbons (PAHs) and biological contamination levels in floor dust inside an educational building and dwellings within the capital city of Jordan (Amman). Exposure, dose and health risk assessments of PAHs were also performed. The second part investigates particle distribution of accumulation and coarse particles as well as workers'/students' exposure to coarse particles inside an educational workshop.

For the first part of the thesis, floor dust samples were taken from the living room and the entrance area inside eight houses as well as from four offices, two lecture rooms, two corridors and two areas of a workshop inside a university building. For the second part, the inhaled deposited dose of coarse particles inside an educational workshop was estimated.

The total PAHs concentrations at the living rooms ranged from around 641–65422 ng/g and at the entrance area from 241–9266 ng/g. Half of the dwellings had higher total PAHs concentrations at the living rooms than at the entrance area. Our findings indicated that both outdoor and indoor sources contributed to high PAHs concentrations. Based on the answers of the occupants of the dwellings, the main sources of indoor PAHs included indoor smoking, cooking activities, heating system and traffic, correlating with the results from other studies. However, more studies are needed to make a confirm conclusion regarding the specific source(s) of PAHs in household floor dust.

The total PAHs concentrations inside the educational building varied from around 714–5246 ng/g. The PAHs concentrations inside offices, where tobacco smoking took place, were higher than those observed inside lecture rooms and the workshop area. This finding indicated that exposure to tobacco smoking inside poorly ventilated and small indoor environments can be seriously harmful.

Especially important was the fact that our results revealed that Jordanian occupants inside residential and occupational environments were less exposed to toxic PAHs via dust ingestion than occupants in similar indoor environments in Europe and Asia.

The bacterial and fungal concentrations varied significantly among and within the studied environments indoors, indicating that that the origin of bio-contaminants differs depending on the locations within the city. In addition to occupancy, human's activities and outdoor sources, environmental conditions, are also responsible for the increase of bacterial and fungal concentrations indoors.

Inside the workshop area, the highest mean and maxima $PN_{0.3\text{-}1}$ ($PM_{0.3\text{-}1}$) and $PN_{1\text{-}10}$ ($PM_{1\text{-}10}$) concentrations were detected during welding activities. The variation in the accumulation mode and coarse mode aerosol concentrations could be attributed to the type of activity (i.e. specific source) and the particle loss rate (i.e. dry deposition and removal via ventilation). During an 8-hour exposure to particles produced during welding and other activities, the total estimated inhaled deposited dose would be less than 750 μg. The mass regional deposition was: ~ 53% in the alveolar region, ~ 29% in the tracheobronchial and ~ 18% in the head/throat region. The results obtained for the inhaled deposited dose could be used in epidemiological studies and in the creation of risk assessment models during welding or related processes.

Keywords: indoor air quality, particulate matter, polycyclic aromatic hydrocarbons, fungi, bacteria, inhaled deposited dose, Estimated Daily Intake

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List of publications

This thesis consists of an introductory review, followed by 4 research articles. In the introductory part, the publications are cited according to their roman numerals. **Paper I** is reproduced with permission of the Journal of Chemical Engineering & Process Technology. **Papers II, III** and **IV** is reproduced with permission of Elsevier.

I. **Maragkidou A**, Ma Y, Jaghbeir O, Faouri D, Harrad S, Al-Hunaiti A, Arar S, Hämeri K, Hussein T. : PAHs in Household Floor Dust Collected in Amman, Jordan. Journal of Chemical Engineering & Process Technology 7: 292, 2016.

II. **Maragkidou A**, Arar S, Al-Hunaiti A, Ma Y, Harrad S, Jaghbeir O, Faouri D, Hämeri K, Hussein T.: Occupational health risk assessment and exposure to floor dust PAHs inside an educational building. Science of the Total Environment, 579, 1050–1056, 2017.

III. Al-Hunaiti A, Arar S, Täubel M, Wraith D, **Maragkidou A**, Hyvärinen A, Hussein T.: Floor dust bacteria and fungi and their coexistence with PAHs in Jordanian indoor environments. Science of The Total Environment, 601-602, 940-945, 2017.

IV. **Maragkidou A**, Jaghbeir O, Hämeri K, Hussein T.: Aerosol particles (0.3–10 μm) inside an educational workshop−Emission rate and inhaled deposited dose. Building and Environment, 40, 80-89, 2018.

1 Introduction

Since the beginning of this century, Indoor Air Quality (IAQ) has been in the spotlight of many scientific studies due to the fact that people spend most of their time (approximately 80-90%) in indoor environments (i.e. dwellings, offices, educational buildings, hospitals, restaurants, bars, gyms, etc.) than outdoors (Sundell, 2004; Gaidajis and Angelakoglou, 2009; Yassin et al., 2012; De Gennaro et al, 2014; Mercier et al., 2014; Saad et al., 2015; Javid et al., 2016; see also references from **Papers I** and **II**). Therefore, special attention needs to be given to people's exposure to indoor air pollution and its implications on their health (WHO, 2016; GBD, 2017; HEI, 2017). A matter of great concern is also the safety and the comfort provided by the indoor environment as well as its indoor air quality (Saad et al., 2015).

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defined in Standard 62-2001: Ventilation for Acceptable Indoor Air Quality that acceptable indoor air quality is the "air in which there are no known contaminants, as harmful concentrations are determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed to it do not express dissatisfaction." In fact, the majority of the guidelines issued with respect to indoor air quality determine the minimum percentage of people displeased with the air indoors based on factors such as discomfort and annoyance (Frontczak and Wargocki, 2011).

Poor IAQ is mostly associated with lack of building operations (lighting, heating, etc.), improper maintenance, poor ventilation mechanisms, emission of building materials and of chemicals from cleaning products, furnishings, high occupancy and occupants' activities (Daisey et al., 2003; Moglia et al., 2006, De Gennaro et al., 2014; **Paper IV**). People are exposed to indoor contaminants mainly via inhalation, hence, resulting in serious respiratory infections (Hulin et al., 2012). Numerous investigations evidenced that exposure to poor IAQ is strongly correlated with adverse health implications, such as sore eyes, headache, morbidity, illnesses, fatigue, disability, allergies, asthma and lung cancer (Samet and Spengler, 1991; Jones, 1999; Sundell, 2004; Saad et al., 2015).

In principal, indoor air pollution is a combination of indoor contaminants originating mainly from furnishings, building materials, poor building design and maintenance, combustion mechanisms such as heating and cooking systems (i.e. kerosene, oil, fuel wood), chemicals products for cleaning, electronic devices, biocides and human activities such as tobacco smoking, cooking, walking, vacuuming, burning candles and incenses (Franck et al, 2011; Hulin et al., 2012; Yassin et al., 2012; Mercier et al, 2014; see also references from **Papers I, II** and **IV**). Outdoor pollutants from natural (sea spray, soil dust, pollen, volcanoes, etc.) and anthropogenic sources mainly from vehicle, industrial and combustion emissions (Wark and Warner, 1981; **Paper I**) contribute significantly to concentration levels of indoor air (Franck et al, 2011) through ventilation (natural and mechanical) mechanisms (Samet et al., 1987) and infiltration systems such as window frames and fissures under the doors (**Paper**

IV). As a consequence, the air indoors tends to be more polluted than outdoors (Hulin et al., 2012, De Gennaro et al., 2014; Saad et al., 2015, see also references from **Paper IV**). In fact, it was evidenced that indoor concentrations could be 2-5 times higher and in some cases even more than 100 times higher than those found outdoors (US EPA, 2006, Saad et al., 2015; **Paper IV**).

Some of the indoor contaminants that are dangerous to human health and can be found inside houses and occupational environments settled in floor dust are polycyclic aromatic hydrocarbons (PAHs), bacteria and fungi.

In particular, PAHs are produced by the incomplete combustion of organic material such as wood, coal, oil at very high temperatures (Wenzl et al., 2006; Gevao et al., 2007; Romagnoli et al., 2014; see also references from **Papers I** and **II**). In indoor environments, PAHs are formed mainly from human activities such as tobacco smoking, cooking, domestic heating, burning of candles and incenses, gluing parquet floor (Chuang et al., 1995; US EPA, 2008; Choi et al., 2010; Kang et al. 2015; see also references from **Papers I** and **II**). People are directly exposed to PAHs through inhalation of contaminated air (Gevao et al., 2007), drinking water, having contact with soil and air, but mostly via eating contaminated food (Wenzl et al., 2006; Choi et al., 2010; Ma and Harrad, 2015, **Paper II**). However, another way of human exposure to PAHs includes ingestion (Gevao et al., 2007; Ma and Harrad, 2015), dermal contact (Wang et al., 2013) and inhalation of household dust (Maertens et al., 2004). People are also exposed to dust emanating from suspension and re-suspension of dust from activities such as cleaning, walking, vacuuming, etc. (Thatcher and Layton, 1995; Ren et al., 2006). Evidence has shown that there is a strong correlation between exposure to PAHs and adverse health effects (Szabová et al., 2008; Choi et al., 2010; see also references from **Paper II**), such as reduced lung function, damage of DNA (Farmer et al., 2003; Baird et al., 2005; Choi et al., 2010), asthma, and even cancer (Wenzl, et al., 2006; see also references from **Papers I** and **II**).

Bacteria are single-celled organisms and their sizes range from 0.3 to 10 µm (Hinds, 1999). In addition to humans, pets, solid and plants, dust perturbations are considered to be direct and indirect sources of airborne bacteria (Täubel et al., 2009; Womack et al., 2010; Bowers et al., 2011a; b; 2012). Occupants (Hospodsky et al., 2012; Kembel et al., 2012; Qian et al., 2012; Meadow et al., 2014; Barberán et al., 2015) and ventilation mechanisms (Kembel et al., 2012; Meadow et al., 2014), especially natural ventilation in the absence of human occupancy (Kembel et al., 2012), favor the composition of airborne bacteria. Exposure to bacteria and their irritants can cause serious health problems such as infectious diseases, sick building syndrome, building related illnesses, and organic dust toxic syndrome (Sanchez et al., 1987; Zhang et al., 2011), and infuriate asthma and allergies to children (Rosenstreich et al., 1997; Clark et al., 2004; Fisk et al., 2007; Jaakkola et al., 2005; Rosenbaum et al., 2010).

Fungi constitute an extraordinary group of organisms (Takahashi, 1997; Hinds, 1999) prevailing in both outdoor and indoor environments, especially in moist environments (Hinds, 1999). It should be noted that the outdoor air has a great influence on the fungal communities indoors (Amend et al., 2010; Adams et al., 2013; Barberan et al., 2015). Studies documented that inhalation of airborne fungi can cause severe respiratory diseases and allergies (Kowalski and Bahnfleth, 1998; Hinds, 1999) Moreover, exposure to fungi and their spores or their irritants could exacerbate asthma attacks and bronchial hyperactivity , whereas high concentrations of particulate matter and microbes could even lead to lung cancer (Ross et al., 2000; WHO, 2000).

Apart from exposure to PAHs, bacteria and fungi concentrations inside educational and occupational buildings, special attention has been paid lately to indoor environments where welding processes take place as it has been shown that exposure to gas and particles originating from welding activities has been associated with severe health problems such as asthma, metal fume fever, respiratory implications, even lung cancer (see references from **Paper IV**). Fumes produced during welding activities consist mainly of particles below 100 nm (ultrafine particles) and 1μm (fine particles) in diameter (Banfield and Navrotsky, 2001; Zhang et al., 2013; Lin et al., 2015, Viitanen et al., 2017). However, literature review and, thus, further knowledge concerning human exposure to coarse particles originating from welding activities is very restricted (**Paper IV**).

Moreover, even though there is a growing body of scientific research on PAHs settled in indoor dust (**Paper I**), there is no literature review on PAHs settled in floor dust in occupational environments (educational buildings, offices, etc.) and houses in Jordan (**Paper II**). Moreover, the interest on biological contamination in floor dust in the Middle East and North Africa (MENA) region is very poor.

Therefore, one of the main objectives of this thesis is to elaborate and investigate biological contamination and human exposure to PAHs in floor dust in both an educational building (**Papers I** and **III**) and dwellings (**Papers II** and **III**) within the capital city of Jordan, Amman. Moreover, another aim of this thesis is to elucidate any open questions concerning exposure to coarse particles in an educational workshop area during a combination of activities such as smoking, making coffee, iron welding, sorting/drilling, metal scrubbing, etc (**Paper IV)**. In particular, the aims of this thesis are:

- to identify the PAHs sources and their content in dust indoors and outdoors for each dwelling as well as inside an educational building (Department of Physics, University of Jordan) (**Papers I** and **II**),
- to analyze the spatial variation of the measured PAHs concentrations within the capital city Amman (**Papers I**)
- to quantify PAHs, biological and fungal concentrations in dust samples collected from eight dwellings and an educational building in Amman, Jordan. (**Papers I, II** and **III**),
- to evaluate occupational exposure to floor dust PAHs inside an educational building and inside dwellings in Amman as well as assess occupational exposure to coarse particles inside a workshop area of an educational building (**Papers II** and **IV**),
- to study and report the particle number and mass concentrations of particles in the size range between 0.3 and 10 μm, as well as estimate their emission and loss rates

during a combination of activities such as making coffee, metal scrubbing, iron welding, sorting/drilling, etc. inside an educational workshop (**Paper IV**).

Particle deposition mechanisms in the respiratory system and health effects of inhaled aerosols particles are presented in Section 2. Section 3 describes the indoor environments where the measurement campaigns were conducted, the instrumentation used and the data-analysis methods utilized. In Section 4, floor dust biological and chemical contamination inside Jordanian dwellings and an educational building as well as exposure to coarse particles inside a university workshop area are discussed based on the results presented in **Papers I-IV**. In Section 5 the review of the papers and the author's contribution are presented. As a final point, Section 6 summarizes the conclusions of this thesis.

2 Particle deposition in the respiratory system and health effects of inhaled aerosols particles

2.1 Particle deposition mechanisms in the respiratory system

The respiratory system is divided into three regions: the head airways (nasal cavity, mouth, pharynx and larynx), the tracheobronchial or lung airways (trachea and 16 airway branchings until the terminal bronchioles) and the pulmonary or alveolar region (alveolar ducts and sacs) (Figure 1) (Hinds, 1999; Cheng, 2014). In general, aerosol particles enter the head airways through the nose when people are at rest or perform light exercise or through the mouth when they perform heavy exercise. There, the inhaled air is warmed and humidified. The head airways and the tracheobronchial region serve as protectors of the alveolar region, which is the region where gas exchange takes place, against harmful particles (Hinds, 1999; Cheng, 2014).

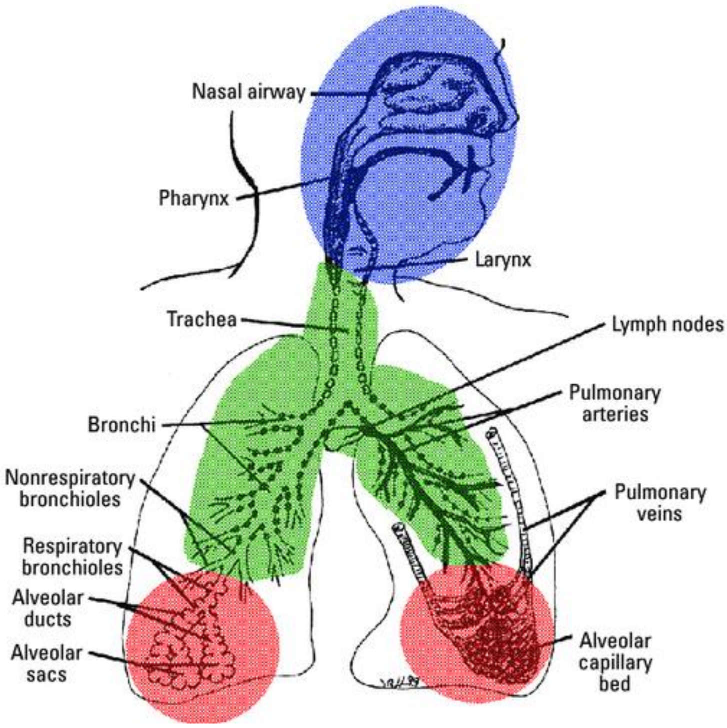

Figure 1: A schematic figure of the respiratory system and its main regions: 1) the head airways (blue color), the tracheobronchial or lung airways (green color) and the pulmonary or alveolar region (pink color), adapted from Obersdörster, 2005.

Once inhaled, aerosol particles follow a flow path through the respirator system and, eventually, they deposit in its regions depending on particles' characteristics (such as size, density and shape), the geometry of the airways and the individual's breathing pattern (Hinds, 1999; Heyder, 2004; Cheng, 2014). The primary deposition mechanisms of inhaled aerosol particles include inertial impaction, gravitational sedimentation or settling, interception, (Brownian) diffusion and electrostatic deposition. However, inertial impaction, gravitational sedimentation and (Brownian) diffusion govern the transport and the deposition of aerosol particles in the respiratory system (Hinds, 1999; Heyder, 2004).

Deposition by inertial impaction occurs when the air steam changes direction and a particle deviates from the gas streamlines, resulting in being deposited on airway walls due to its inertia. For particles larger than ~ 5 μm in diameter deposition by impaction is the most dominant deposition mechanism and its effectiveness strongly depends on particle size, density and velocity of the airflow. Particles in the size range between 0.5–5 μm in diameter deposit due to gravitational sedimentation in regions where the airflow velocity is low and the dimensions of airways are small. Deposition due to sedimentation increases with particle size, density and breathing frequency. (Brownian) diffusion deposition affects aerosol particles less than 0.5 μm in diameter and it increases with decreasing particle size and longer residence time. Diffusional deposition occurs due to Brownian (random) motion of small particles caused by gas molecule collisions (Hinds, 1999; Darquenne and Prisk 2004; Heyder, 2004). Moreover, high breathing frequencies are associated with low inhalation flow rate which leads to increase of both gravitational sedimentation and diffusion deposition and decrease of deposition due to inertial impaction, and inversely (Darquenne and Prisk, 2004, Cheng, 2014).

2.2 Total and regional deposition in the respiratory system and health effects of inhaled aerosols particles

Total deposition refers to the overall deposition of inhaled aerosol particles in all the regions of the respiratory system and it is determined by the individual’s breathing pattern, the pauses between inhalation and exhalation and the volume of air inhaled. However, regional deposition is mostly used in epidemiological studies for risk assessments of inhaled particles and it is affected by the deposition in previous regions of the respiratory system as well as by the deposition efficiency of the region (Hinds, 1999).

Originally, aerosol particles enter the respiratory system through either the nose or the mouth. The inhaled air is warmed, humidified and filtered in that region. While breathing, the air flow rate is high and undergoes a series of direction changes in the head region to the alveolar region. In general, particles with aerodynamic diameter larger than 5 μm deposit in the head airways region mainly by impaction because they fail to follow the air streamlines. Moreover, the changes in the direction of the air flow cause some particles to hit the airways and deposit, thus, by impaction and settling in the nasopharyngeal region (head region). Interestingly, ultra-fine particles (<100 nm) also deposit in this region by diffusion due to their rapid Brownian motion. Afterwards, the inhaled air reaches the lung region which consists of smaller and smaller branches (16 in total). The main purpose of this region is to further humidify and filter the inhaled air until the inhaled air reaches the alveolar region. Aerosol particles (below 5 μm in diameter) may deposit in the tracheobronchial and the alveolar region due to settling, because the air flow rate is low and the dimensions of the airways are small. Settling is even more efficient in the distal airways (Hinds, 1999;

Darquenne and Prisk, 2004, Cheng, 2014). Furthermore, in the lung airways region, hygroscopic particles grow in size due to condensation of water vapor at very high humid conditions (relative humidity in lungs is approximately 99.5% according to Ferron et al. (1988) and Anselm et al. (1990). This favors the deposition of inhaled particles due to settling and inertial impaction. Similarly, ultra-fine particles have significant deposition in the lung airways region due to diffusion caused by the rapid Brownian motion. Finally, inhaled aerosol particles smaller than 0.5 μm in diameter reach the alveolar region, due to the fact that the airways (and, thus, the distances) are even smaller and the residence time is longer. In this region, gas exchange takes place in the alveoli sacs and diffusion is the main deposition mechanism (Hinds, 1999; Heyder, 2004; Cheng, 2014).

Epidemiological studies reveal the positive correlation between exposure to aerosol particles/particulate matter (PM) and serious health implications. In fact, smaller particles (ultrafine and fine particles), and more specifically ultrafine particles, are more harmful than larger particles, because they are more inhaled and they can penetrate deeper into the human lungs causing, thus, respiratory problems (Stone et al. 2017; references from **Paper IV**). Exposure to $PM_{2.5}$ can cause serious health problems mainly to children (heart and respiratory system) and it can even lead to deaths and morbidity (WHO, 2005; Pope and Dockery, 2006; Elbayoumi et al., 2014). Studies confirmed that exposure to coarse particles is strongly associated with health effects such as asthma, problems in the respiratory system (Brunekreef and Frosberg, 2005), transmission of diseases and hosting several airborne bacterial species (Hussein et al., 2015a).

3 Materials and methods

3.1 The Hashemite Kingdom of Jordan, Amman

The experimental part was conducted in eight dwellings and an education building located in Amman, Jordan (Figure 2). The Greater Amman Municipality (31° 56′ 59″ N, 35° 55′ 58″ E) has a population of around 4 million and a land area of 777 km^2 (World's capital cities, 2018).

Figure 2: Map of Jordan, (Source: Map data © OpenStreetMap contributors, CC BY-SA, accessed 24 August 2018).

Amman is situated on seven hills (Donagan, 2009). Amman's elevation ranges from 700 to 1100 m and its variation contributes to the different weather conditions experienced in the city: warm spring, mild summer heat, pleasant winter with temperatures near or below 17 °C and occasional snow. Most of the rainfalls usually occur between October and April and on average a typical rainfall is about 300 mm a year. Based on weather data collected from 1985 until 2015, Amman has annual mean low and high temperatures of 4° C and 32°C, respectively (Time and Date AS, n.d). On average, January and August are the coolest and warmest months, respectively (Word Weather & Climate Information, n.d).

3.2 Sampling sites

3.2.1 Dwellings

Floor dust samples were collected from eight naturally ventilated dwellings: three apartments, four detached houses, and a house (see Figure 1 from **Papers I** and **III)**. In particular, we collected two dust samples from each house from floor of 1 m^2 area: one from the living room and another one from main entrance.

The occupants were asked to fill in a questionnaire in order to provide detailed information about their dwelling, cooking style and type, household appliances, heating system, type of cleaning materials and smoking activities. This information was used to correlate their answers to the results obtained from the chemical analysis in order to identify the sources of PAHs. More information on the features of each dwelling are given in Table 1 from **Paper I** and in Table S1 from **Paper III**.

3.2.2 Educational building

The measurement campaigns described in **Papers II** and **III** were conducted in the Department of Physics of the University of Jordan (Amman) (Figure 1 from **Paper II**). The building was naturally ventilated, and based on calculations made by Hussein (2014) and Hussein et al. (2015a), the ventilation rate was less than 2 h^{-1}. We collected floor dust samples from two lecture rooms, two locations of a workshop area, two corridors, and four offices (in total ten dust samples) from floor of 1 m^2 area as shown in Figure 2 from **Paper II**. A detailed description of the offices and of the lecture rooms can be found in Table 1 from **Paper II**. It should be noted that even though smoking was not allowed inside the building, workers/visitors frequently violated the law.

3.3 Settled dust collection and analysis

Papers I, II and **III** provide an extensive summary of the PAHs floor dust collection procedure. Briefly, the floor dust samples were collected by using a regular household vacuum cleaner, where a small dust bag (nylon, 25 µm-155 mm × 73/38 mm, Allied Filter Fabrics Pvt. Ltd) was placed inside the tube of the vacuum cleaner after the main façade. Each sample was collected from about 1 m^2 floor area and the vacuuming operation lasted for about 3 minutes. After the collection of settled dust, the dust samples were transferred closed inside a nylon bag which was also sealed securely. Before the conduction of the GC-MS analysis, each dust sample was saved in a glass vial, wrapped with aluminum foil and stored in the freezer.

3.3.1 PAHs analysis

The GC-MS analysis was used for the PAHs analysis. We identified 13 priority PAHs, 12 of which are listed in the 16 critical PAHs: Phenanthrene (PHE), anthracene(ANT), fluoranthene (FLA), pyrene (PYR), benz[a]anthracene (BaA), chrysene (CHR), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[j]fluoranthene (BjF), benzo(a)pyrene [BaP], indeno[1,2,3-cd]pyrene (IcdP), dibenz[a,h]anthracene (DahA), benzo[g,h,i]perylene (BghiP).

3.3.2 Biological analysis

We applied qPCR analysis (**Paper III**) by using Chemagic DNA Plant kit (PerkinElmer chemagen Technologie GmbH, Germany) on KingFisher mL magnetic bead based DNA extraction robot (Thermo Scientific, Finland). In an initial step, microbial cells were disrupted with bead-beating as described in Kärkkäinen et al. (2010), using MiniBeadBeater-16 (Biospec Products Inc). Salmon testes DNA (Sigma Aldrich, USA) was added as an internal standard to the samples prior DNA extraction (Haugland et al., 2012) to account for PCR inhibitors and variability in DNA extraction efficiency.

3.4 Aerosol size distribution measurements inside a workshop

The measurement of the particle number size distribution (0.3-10 µm) was performed by an Optical Particle Sizer (OPS 3330, TSI) inside the workshop area (Figure 1 from **Paper IV**) between 31st of March and 6th of April 2015. The workshop ($32 \times 10 \times 3$ m^3) was naturally ventilated and it was occupied from 08:00 until 16:00 during the workdays. The following events occurred: coffee brewing, smoking, having a lecture, iron welding, (exhaust) fan and welding machine on, iron welding without the use of the (exhaust) fan, iron welding (with the simultaneous use of the exhaust fan), sorting/drilling and metal turning. On average, 1 to 4 people occupied the workshop during the events, but during students' training session the number of occupants raised to 10. More information on the events, their duration and the occupancy of the workshop can be found in Table S1 from **Paper IV.**

3.5 Indoor aerosol modeling

The dynamics of indoor aerosol particles is well described by the mass-balance equation (e.g. Nazaroff, 2004; Hussein and Kulmala, 2008):

$$\frac{dI_i}{dt} = \lambda P_i O_i - (\lambda + \lambda_{d,i}) I_i + S_i \quad (3.1)$$

where I_i and O_i are the indoor and outdoor particle concentrations, respectively, P_i is the penetration factor of outdoor particles, λ is the ventilation rate, $\lambda_{d,i}$ is the deposition rate of aerosol particle onto indoor surfaces, and S_i is the emission rate of aerosol particles indoors. In this simplified model, the subscript "i" implies that the Eq. (3.1) can be used for individual size-fraction in which the properties and the dynamic behavior of aerosol particles are considered similar. The mass-balance equation is also applied to estimate some parameters such as P_i, λ, $\lambda_{d,i}$ or even S_i (Hussein et al., 2015b).

In order for the Eq. (3.1) to be valid we assume that: 1) the indoor air is well mixed, 2) indoor particles are emitted at a constant rate and 3) the penetration factor, deposition rate, ventilation rate and outdoor particle concentrations are all constant with respect to time.

The analytical solution of the Eq. (3.1) considering that there is an indoor source which produces a large amount of aerosol particle concentrations compared to the outdoor concentrations can be utilized to calculate particle losses (λ+λ_d) (Hussein, 2005):

$$\lambda + \lambda_{d,i} = \frac{1}{\Delta t} ln\left(\frac{I_i(t_0)}{I_i(t)}\right) \tag{3.2}$$

where t_0 is the time when indoor source is turned off. In other words, Eq. (3.2) is the decline rate of indoor aerosol concentrations and particle loss rate (λ+$\lambda_{d,i}$) is given in units of h^{-1} (Hussein, 2014; Hussein et al., 2015a).

Particle losses (λ+$\lambda_{d,i}$) include indoor-outdoor air exchange and dry deposition onto indoor surfaces. Particles losses of aerosol particles within the size range of 0.1−1.0 μm are equal to the air exchange rate (λ) due to the fact that the deposition rate is negligible in comparison to the air exchange rate ($\lambda_{d,i}$ << λ) (Hussein et al., 2015b).

A simplified model for the quantification of the emission rate based on the mas-balance equation (Eq. (3.1)) can be used if, in addition to the assumption made earlier (i.e. neglect outdoor sources), we also consider that there are zero particle losses:

$$\frac{dI_i}{dt} = S_i \tag{3.3}$$

There are more ways than one to estimate emissions for the purposes of modeling IAQ (Hu et al., 2012). In **Paper IV** we assumed that emission rates calculated using Eq. (3.3) took into consideration indoor sources within a well-mixed educational workshop, even though we couldn't verify that. During that measurement campaign, different activities took place, each of which had its own different way of emission or production (i.e. combustion) than another one. Therefore, without knowing the density of particles produced or emitted (such as metals) during the activities taken place inside the workshop, we couldn't estimate the corresponding mass accurately. For this reason, emission rates were expressed in terms of how much particles were emitted per time into an indoor air volume (i.e. particles/h·cm^3) instead of mg/h.

3.6 Exposure and dose assessment

Exposure assessment as explained by the International Programme on Chemical Safety (IPCS, 2004) is the "Evaluation of the exposure of an organism, system, or (sub) population to an agent (and its derivatives). Exposure assessment is the third step in the process of risk assessment". In this case, exposure denotes the concentration or the amount of a substance that gets in contact with the target organism and affects it and this can occur either directly or directly (Figure 3). (Health) risk assessment is defined as the procedure during which the risk to a certain organism (target), system, or (sub)population is estimated, after being contaminated to a specific agent, and it takes into account genetic traits of the agent of interest and of the particular target (IPCS, 2004).

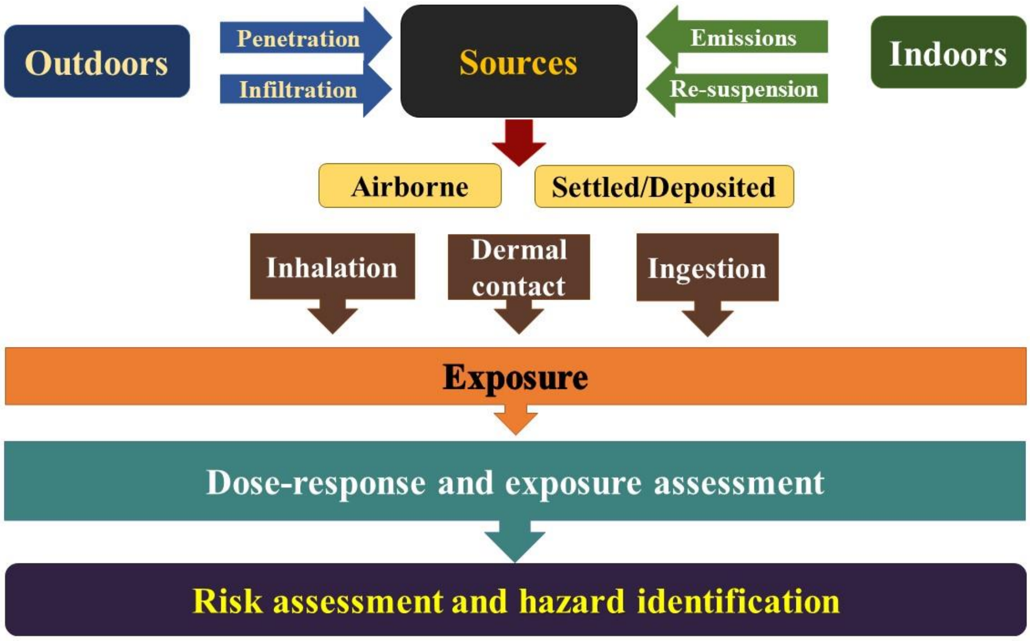

Figure 3: A schematic figure of exposure and of risk assessment procedure.

3.6.1 Ingestion of floor dust

A (health) risk assessment for the exposure to PAHs in floor dust depends on the estimation of the benzo(a)pyrene equivalent carcinogenic power (BaPE), since benzo(a)pyrene (BaP) is believed to be the most toxic PAH. BaP is also commonly used as the chemical index to estimate cancer and health risks from exposure to PAHs (US EPA, 1986; ATSDR, 1995). As shown in **Paper II**, the BaPE factor is estimated using the following equation:

$$BaPE = 0.06 \cdot BaA + 0.07 \cdot B(b+j)F + BaP + 0.6 \cdot DahA + 0.08 \cdot IcdP \qquad (3.4)$$

which takes into consideration the concentration of each PAH multiplied by its carcinogenic potency in relation to BaP (Yassaa et al., 2001; Peng et al., 2012). In Eq.(3.4), BaA, B(b + j)F, DahA and IcdP denote benz[a]anthracene, benzo[b]fluoranthene + benzo[j]fluoranthene, dibenz[a,h]anthracene and indeno[1,2,3-cd]pyrene concentrations, respectively. Since each PAH concentration is expressed in ng/g units, BaPE is also expressed in ng/g units.

As mentioned in **Paper II**, another approach to evaluate health risks from exposure to PAHs via ingestion of settled dust is by calculating BaPE as Toxic Equivalent (TEQ), as suggested by the United States Environmental Protection Agency (US EPA):

$$BaPE\ as\ TEQ = \sum C_n \cdot TEF \tag{3.5}$$

where C_n is the average concentration of an individual PAH in settled dust in ng/g and TEF is the toxic equivalence factor of that PAH (Hsu et al., 2014; Cal-EPA, 2005). TEF represents a ratio of the toxicity of a PAH congener to that of BaP and it has been applied as a useful tool for the regulation of compounds with a common mechanism of actions (Tongo et al., 2017). The TEFs of individual PAHs were taken from Nisbet and LaGoy (1992). Based on Eq. (3.5), BaPE as TEQ is expressed in units of ng/g.

An exposure assessment takes also into account both the exposure pathway (the path an agent follows from its source until it reaches the person(s) exposed) and the exposure route (how the agent enters the human body, i.e. via eating, drinking, inhaling or dermal contact). The occupants of the eight dwellings in **Papers I** and **III** were exposed to PAHs in floor dust through oral ingestion of floor dust from hand-to mouth activities. According to Maetens et al. (2004), dietary ingestion of PAHs in food and non-dietary ingestion of PAHs in settled house dust (SHD) are the most important routes of exposure to PAHs for children. In fact, ingestion of PAHs in SHD not only is more crucial than inhalation, but it is also greater for children than for adults and, hence, more hazardous. Maetens's group also pointed out that regarding exposure to SHD, (non-dietary) ingestion of SHD is the predominant exposure route of SHD for children (50-100 mg/day) than skin contact (28 mg/day) and inhalation of suspended or re-suspended house dust (0.15-0.34 mg/day). Adults are more exposed to SHD via skin absorption (51 mg/day) than through inhalation (of suspended and re- suspended dust) (0.81 mg/day) and ingestion (0.56 mg/day) of SHD.

The Estimated Daily Intake (EDI) of PAHs via hand-to-mouth ingestion of settled floor dust depends on both the individual PAHs concentration and the average ingestion of dust. Human body weight also contributes to the estimation of the EDI which is calculated as follows (see references from **Paper II**):

$$EDI = \frac{C \cdot f}{B_w} \tag{3.6}$$

where C is the average concentration of an individual PAH in ng/g, f is the daily average ingestion of the dust and, according to US-EPA (1997) and Peng et al. (2012), it is equal to 0.05 g/day for adults and B_w stands for the average body weight in kg. The average body weight of an adult in the Middle East was considered to be equal to 70 kg. EDI according to Eq. (3.6) is given in units of ng/kg-bw/day (bw: body weight).

3.6.2 Inhaled deposited dose estimation

Inhaled deposited dose has been generally defined as the amount of aerosols deposited in the respiratory system while inhaling (Löndahl et al., 2007; Hussein et al., 2015b). Generally, the inhaled deposited dose expressed in terms of particle mass can be calculated as:

$$Deposited\ dose_{PM} = \int_{t1}^{t2} \int_{D_{p1}}^{D_{p2}} V_E \cdot DF \cdot n_N^0 \cdot f \cdot dlogD_p \cdot dt \qquad (3.7)$$

where V_E ([L/min] or [m^3/h]) is the minute ventilation (known also as volume of air breathed per time), *DF* [--] is the respiratory deposition fraction of aerosol particles, $n_N^0 = \frac{dN}{dlog(D_p)}$ [particles/cm^3] is the lognormal particle number distribution and D_p is the particle diameter. *f* is a dose metric and, in our case, it denotes the particles mass. Therefore, the inhaled deposited dose based on particle mass is expressed in units of μg. It should be noted that both *DF* and n_N^0 are functions of log(D_p). The integrals are evaluated during an exposure time period $\Delta t = t_2 - t_1$ to a specific particle size-fraction (D_{p1}-D_{p2}) on any time resolution.

In this model, the values for the minute ventilation during standing and performing light exercise were adopted from Holmes (1994) for the activities of standing and walking 2.5 mph ≈ 4.0 km/h, respectively. The total and regional *DF* values were taken from Hussein et al. (2015b) for resting and exercising and they were based on the mean geometric diameter of particles between 1 and 10 μm (GMD = 2.5 μm). The regional inhaled deposited dose was estimated according to Eq. (3.3) for the head/throat, the tracheobronchial and the alveolar region. The minute ventilation or the volume of air breathed per time (V_E) and the respiratory deposition fraction (*DF*) were analyzed in depth in **Paper IV**.

In addition, **Paper IV** provides thorough information for the Eq. (3.7) that was used in order to estimate the inhaled deposited dose of coarse particles inside the educational workshop expressed in metrics of particle mass (assuming spherical particles and unit density).

4 Results and Discussion

4.1 PAHs in floor dust

4.1.1 Dwellings

GC-MS results documented the contamination level in the floor dust collected from 1 m^2 floor area in both the living room and the entrance area from each dwelling (**Paper I**). We assumed that PAHs concentrations were homogeneously distributed in both the living room, where the occupants used to spend most of their time, and the entrance area.

As shown in Figure 2 and 3a from **Paper I**, the highest total PAHs concentrations (~ 65422 ng/g) in the living room area were observed for detached house 4 (DH4) and the lowest (~ 641 ng/g) for apartment 4 (A4). Three dwellings (A3, DH3 and DH2) exhibited total PAHs concentrations between 1000 and 10 000 ng/g. Regarding individual PAHs concentrations, we observed that dwelling DH4 documented the highest concentrations for all PAHs, and more specifically for fluoranthene, pyrene, and phenanthrene followed by dwellings A3 and DH3. Fluoranthene and phenanthrene are fossil fuel combustion products and phenanthrene is also linked to tobacco smoking (Jacob et al., 1999). According to the information collected from the questionnaires (Table S1 from Supplementary information), DH4 was situated in a busy street, electric heat and kerosene were used as a heating system and gas as a kitchen appliance. Moreover, the residents stir-fried/deep-fried their food 3 times/day with the exhaust fume on, took their shoes off before entering the house and occasionally smoked indoors. Dwellings A3, DH3 and DH2 were also located close to busy streets but there were differences in the cooking activities (stir-frying/deep frying, stewing/streaming, grilling/boiling/roasting/baking every 1-2 h/day for dwellings DH2 and DH3, whereas grilling/boiling/roasting/baking 3 times /day for dwelling A3) and the smoking incidents (2-3 times/day for DH2, 1/week for DH3 and no smoking at all for A3). According to the results given by the residents, the fume exhaust was used only in apartment A3 during cooking and the occupants of dwellings A3, DH3 and DH2 didn’t use to take their shoes off before entering indoors (Table S1 from Supplementary information). Furthermore, the lowest total PAHs concentrations (~ 641 ng/g) were observed for apartment A4, which also exhibited the lowest concentrations for benzo[j]fluoranthrene and benzo[a]pyrene (Table S2 and Figure 3a from **Paper I**). These observations could be attributed to the fact that apartment A4 was located close to a quiet street and it was occupied by a nonsmoking resident, who rarely cooked at home using gas and electricity while the exhaust fume was on and occasionally used a gas heater as a heating system (Table S1 from Supplementary information).

Regarding the floor dust collected at the entrance area, the highest total PAHs concentrations (~ 9266 ng/g) were recorded for apartment A3 (Table S3 and Figure 2 from **Paper I**). Interestingly, apartment A3 recorded the highest PAHs concentrations for phenanthrene and anthracene, while dwelling DH4 recorded the highest concentrations for fluoranthene and chrysene. Both dwellings DH4 and A3 had the highest concentrations for pyrene (Table 3b from **Paper I**). In addition, the entrance area of both dwellings was inside the apartments, therefore, we believe that PAHs concentrations were affected by indoor emissions. The lowest total PAHs concentrations (~ 241 ng/g) were observed for house H which also presented the lowest (individual) PAHs concentrations for eight PAHs (Table S3 and Figure 3b from **Paper I**). Even though there is no much information for dwelling H, the results obtained for this house regarding PAHs concentrations could be attributed to the fact that it was situated in a quiet street and occupied by infrequent smokers who mainly used gas for cooking while the exhaust fume was on. The residents also used to enter the house with their shoes on. In addition, the age of the dwellings ranged from 3 to 40 years old and all the residences were naturally ventilated (Table S1 from Supplementary information).

With respect to other studies, Li et al. (2005) documented a positive correlation between house age and the observed indoor concentrations of PAHs. They also examined the association of high PAHs concentrations in indoor air with cooking activities, as well as with pollutants originated by outdoor sources (traffic, fuels, etc). Similarly, Dubowsky et al. (1999), Miguel et al. (1998), Valavanidis et al. (2006), Whitehead et al. (2013) confirmed the relationship between indoor PAHs concentrations and traffic related sources. Mannino and Orecchio (2008) reported elevated PAHs concentrations in kitchen dust content and Fromme et al. (2004) detected immense PAHs concentrations in dwellings where gas was used. In addition, Ma and Harrad (2015) pointed out the association of biomass burning, smoking, cooking and the penetration of outdoor pollutants with PAHs in indoor air. Romagnoli et al. (2014) based on numerous investigations confirmed that tobacco smoke is a significant and severe determinant of PAHs originated indoors, while Matt et al. (2004) and Whitehead et al. (2013) reported that outdoor smoking could also contribute to high indoor PAHs concentrations. Van Loy et al. (2001) and Whitehead et al. (2013) noticed that some volatile compounds such as nicotine can be easily absorbed by household surfaces (e.g. carpets and walls), resulting in having longer residence time.

The indoor to outdoor concentration ratio (I/O) is a significant parameter which enables to identify the origin (as indoors or outdoors) of the PAHs compounds. Sanderson and Farant (2004) reported that when I/O is larger than 1, the environment is enriched with indoor pollutants, whilst when I/O is less than 1, the measured pollutants originate mainly from outdoor sources. Figure 4 presents the living room-to-entrance total PAHs concentration ratios (similar to I/O ratios) for the eight dwellings. In conclusion, PAHs I/O ratio was below 0.7 for dwellings DH2 and A2, suggesting outdoor sources originated PAHs, while for dwellings DH3, DH5, A3 and A4 PAHs I/O ratios were approximately between 0.8 and 2, indicating that probably both indoor and outdoor sources contributed to the production of PAHs. This observation might be attributed to the fact that the entrance area of these dwellings was located inside the building instead of outside. Dwelling DH4, which also had the entrance area located inside the building, and house H had PAHs I/O ratios close to 9 and 3, respectively, implying that indoor sources originated PAHs.

In comparison to other studies, the I/O ratios for the majority of PAHs observed inside 24 houses in Kuwait (Gevao et al., 2007) ranged from 0.2–1.7 and they were on average less than 1, indicating that outdoor sources contributed greatly to the concentration of settled house dust. Their results were consistent with the results obtained by Sanderson and Farant (2004) for 18 residences surrounding an aluminum smelter in Canada. Although, 35% of the homes in Gevao et al.'s (2007) work exhibited I/O ratios higher than 1 for the majority of the observed PAHs, they were not able to identify the source(s) of PAHs. However, they considered that smoking, use of gas and candles burning might justify the high I/O ratios.

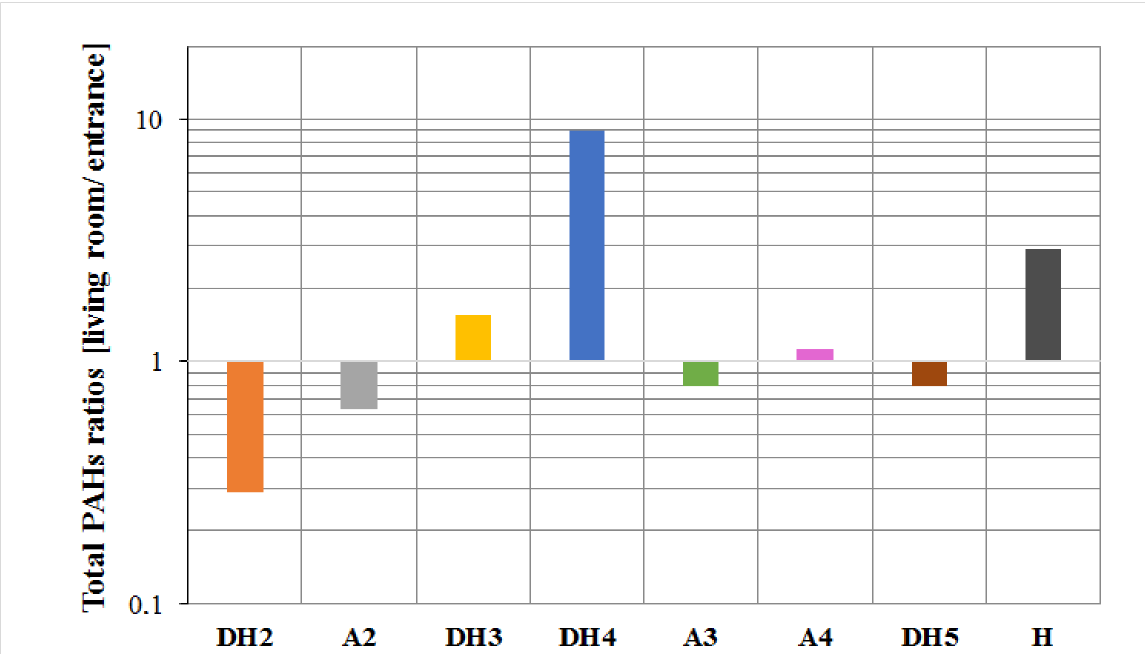

Figure 4: Total PAHs concentration ratios between living room and entrance areas.

4.1.2 Educational building

In general, inside the educational building total PAHs concentrations ranged from about 714 to 5246 ng/g. In particular, office 300 (P300) recorded the highest total PAHs concentrations due to cigarette smoking. The welding area of the workshop (WSb) exhibited the lowest total PAHs concentrations during the measurement day, despite the fact that heavy machinery activities and consumption of petroleum products took place there (Figure 3 and Table 2 from **Paper II).**

With respect to individual PAHs concentrations, and according to Table 2 from **Paper II**, office P200 recorded the highest PAHs concentrations for seven PAHs. Office P300 and corridor C1 followed by exhibiting the highest PAHs concentrations for three PAHs, separately. Moreover, amongst all PAHs compounds, fluoranthene, chrysene, pyrene and phenanthrene monitored the highest values measured in offices P300 and P200 and corridor

C1. This observation could be attributed to the frequent visits of students, professors, workers and visitors as well as to different kind of activities (re-suspension of dust resulting from walking, eating, drinking beverages) and occasional smoking. Office P300 was the office of the head of the department and most of the times occupied by students and workers. In addition to that, the building manager smoked inside every afternoon and a copy machine was operating constantly. The dissolution of benzene with toluene in office P200 for the removal of the glue from the carpet during a renovation conducted one year before the measurement campaign could justify the high concentrations of eight PAHs (Table 2 from **Paper II**).

Interestingly, it needs to be noted that although workshop area WSb was mainly used by the university staff as an area to smoke, paint and carry out welding activities, it displayed the lowest PAHs concentrations for eight compounds. This could be justified by the fact that natural ventilation (around 0.24–2.1 h^{-1} according to **Paper IV**) in the workshop area was good enough to remove pollutants from indoor sources (Table 2 from **Paper II)**.

A full analysis of the results obtained by GC-MS analysis can be also found in **Paper II.**

Figure 5 presents the rooms-to-main entrance hall total PAHs ratios (similar to I/O ratios) for the investigated areas of the educational building. Corridor BC was the main entrance hall located next to the entrance of the Department of Physics at the ground floor. Dust samples were collected near the entrance of the building and, therefore, corridor BC was used as a reference for outdoor concentrations. We assume that PAHs concentrations were homogeneously distributed in the reference area, due to the continuous movements of students, workers and the educational staff. Based on Figure 5, amongst all educational areas, only offices P200, P300 and P303 and corridor C1 demonstrated total PAHs ratios above 1, implying that indoor emissions contributed to the production of the measured PAHs, as well as to the degradation of IAQ. The rest of the studied areas displayed total PAHs ratios below 1, hence, the PAHs measured in these areas were from outdoor sources.

Compared to the results obtained for thirteen universities in Shanghai, Peng et al. (2012) observed that total PAHs concentrations from 10 lecture theatres ranged from approximately 9840– 21 440 ng/g. 2-methylnaphthalene, phenathrene and fluorene were the main contributors of PAHs in indoor dust samples. Concerning PAHs content in dust samples from 12 dining halls, total PAHs concentrations ranged from roughly 9690– 44 130 ng/g, among which 2-methylnaphthalene, phenathrene fluorene, pyrene, chrysene, benzo[b]fluoranthene-benzo[k]fluoranthene and benzo[g,h,i]perylene were the most dominant compounds. The major sources of PAHs in dust samples collected from both lecture theaters and dining halls were mainly traffic, coal and diesel combustion as well as products associated with petroleum. Interestingly, due to intense cooking activities and oil fumes, Peng et al. (2012) evidenced that PAH distribution patterns in dust samples from a commercial kitchen were in agreement with the ones from universities' dining halls.

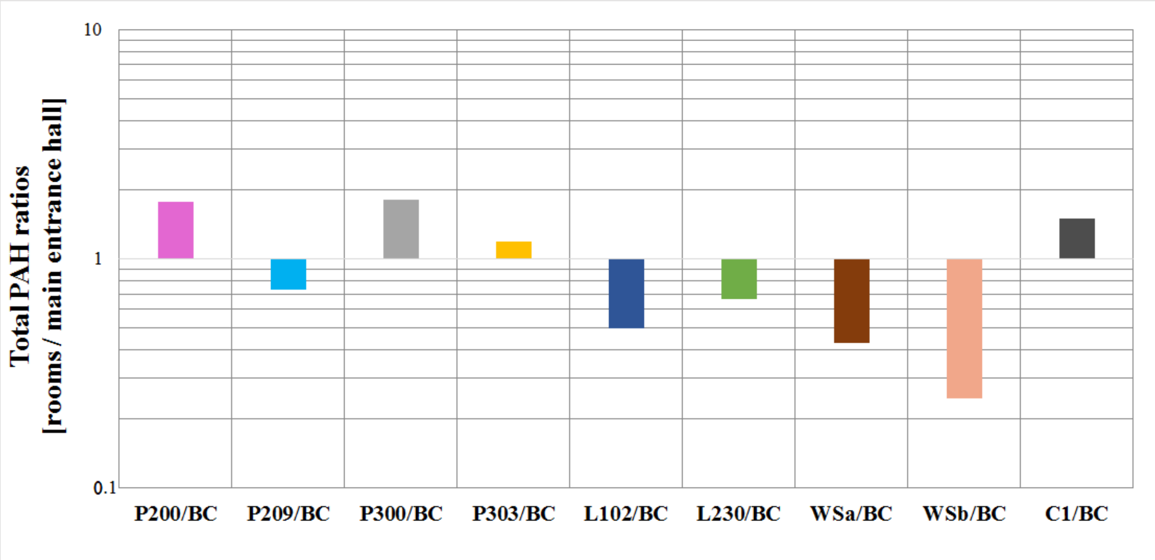

Figure 5: Total PAHs concentration ratios between rooms and main entrance hall. Corridor BC was considered as the main entrance hall.

4.1.3 Exposure, dose and risk assessment

The potential health risk due to exposure to PAHs was assessed in terms of BaP equivalent (BaPE). In general, the BaPE as TEQ values (based on Eq. (3.4)) were higher than the BaPE values (based on Eq. (3.3)); see also Tables 2 and 4. We performed a simple exposure and health risk assessment for the ingestion of PAHs present in household floor dust by estimating EDI and BaPE values of the PAHs measured in the living room and at the entrance area, since they weren't presented in **Paper I**. The EDI values are listed in Tables 1 and 3.

In particular, the total EDI values in the living room ranged between around 0.5 and 5 ng/kg-bw/day (excluding the extreme value at detached house DH4, ~ 47 ng/kg-bw/day); the lowest and the highest total EDI values were detected for the dwellings A4 and A3, respectively. The rest of the residences had total EDI values below 1 ng/kg-bw/day (Table 1). The BaPE values estimated for the living room were around 18−387 ng/g (Table 2). As expected, dwelling DH4 presented the highest BaPE values. The BaPE values in the living room of dwellings DH4, A3, DH3 and A2 were higher than the rest of the dwellings. This was expected because dwellings DH4, A3 and DH3 (apart from A2) demonstrated the highest concentrations for the majority of PAHs measured in the living room (Table 3a from **Paper I**). Surprisingly, dwelling DH2 exhibited the lowest BaPE values (Table 2).

Concerning the entrance area, the total EDI values fluctuated from about 0.2−7 ng/kg-bw/day (Table 3). The highest total EDI values were observed for dwellings A3 and DH4; they were equal to around 7 and 5 ng/kg-bw/day, respectively. Dwelling H which demonstrated the lowest PAHs concentrations measured at the entrance area had the lowest total EDI values; about 0.2 ng/kg-bw/day. Regarding the BaPE values calculated for the entrance area, they ranged from approximately 1 to 230 ng/g (Table 4). The highest and the lowest BaPE values were observed for the dwellings A3 and H, respectively. This is attributed to the fact that these dwellings exhibited the highest (A3) and the lowest (H) PAHs concentrations. (Figure 3b from **Paper I**).

Table 1: Estimated Daily Intake (EDI) [ng/kg-bw/day] for each PAH as well as the total PAHs in the living room.

EDI (ng/kg-bw/day)	DH2	A2	DH3	DH4	A3	A4	DH5	H
PHE	0.25	0.12	0.37	10.30	0.91	0.17	0.33	0.14
ANT	0.00	0.00	0.07	1.71	0.19	0.00	0.00	0.00
FLA	0.10	0.05	0.40	19.02	1.75	0.06	0.11	0.08
PYR	0.09	0.05	0.32	11.27	1.20	0.06	0.08	0.07
BaA	0.00	0.00	0.13	1.56	0.29	0.00	0.00	0.00
CHR	0.09	0.03	0.17	1.70	0.33	0.02	0.03	0.03
B(b+k)F	0.15	0.13	0.24	0.65	0.21	0.04	0.05	0.04
BjF	0.03	0.00	0.05	0.16	0.05	0.01	0.01	0.01
BaP	0.00	0.00	0.05	0.13	0.06	0.01	0.01	0.01
IcdP	0.03	0.00	0.04	0.11	0.06	0.00	0.00	0.00
DahA	0.00	0.12	0.00	0.00	0.11	0.08	0.03	0.11
BghiP	0.04	0.02	0.05	0.13	0.06	0.01	0.02	0.02
Total	0.77	0.51	1.88	46.73	5.22	0.46	0.66	0.50

Table 2: Benzo(a)pyrene equivalent carcinogenic power (BaPE) and BaPE as the Total Toxicity Equivalence (TEQ) both in units of ng/g with their corresponding Estimated Daily Intake (EDI) values [ng/kg-bw/day] for the living room.

	BaPE [ng/g] (Equation 3.4)	EDI [ng/kg-bw/day] (based on BaPE)	BaPE as TEQ [ng/g] (Equation 3.5)	EDI [ng/kg-bw/day] (based on BaPE as TEF)
DH2	17.71	0.01	31.35	0.02
A2	116.02	0.08	191.29	0.14
DH3	112.01	0.08	142.83	0.10
DH4	387.38	0.28	633.25	0.45
A3	226.84	0.16	333.57	0.24
A4	75.90	0.05	121.96	0.09
DH5	36.27	0.03	55.56	0.04
H	102.76	0.07	166.53	0.12

Table 3: Estimated Daily Intake (EDI) [ng/kg-bw/day] for each PAH as well as the total PAHs at the entrance area.

EDI (ng/kg-bw/day)	DH2	A2	DH3	DH4	A3	A4	DH5	H
PHE	0.36	0.12	0.17	0.73	3.55	0.14	0.20	0.06
ANT	0.00	0.00	0.00	0.07	0.58	0.00	0.00	0.00
FLA	1.46	0.11	0.15	2.77	1.46	0.08	0.19	0.04
PYR	0.25	0.11	0.13	0.71	0.68	0.06	0.15	0.03
BaA	0.03	0.05	0.08	0.08	0.00	0.00	0.04	0.00
CHR	0.14	0.07	0.13	0.38	0.04	0.03	0.08	0.01
B(b+k)F	0.30	0.13	0.26	0.30	0.04	0.04	0.08	0.01
BjF	0.06	0.04	0.07	0.07	0.01	0.01	0.02	0.00
BaP	0.02	0.05	0.07	0.03	0.01	0.01	0.02	0.00
IcdP	0.03	0.04	0.05	0.04	0.00	0.01	0.02	0.00
DahA	0.00	0.00	0.01	0.00	0.26	0.00	0.00	0.00
BghiP	0.04	0.08	0.08	0.04	0.01	0.02	0.04	0.01
Total	2.68	0.79	1.22	5.22	6.62	0.41	0.84	0.17

Table 4: Benzo(a)pyrene equivalent carcinogenic power (BaPE) and BaPE as the Total Toxicity Equivalence (TEQ) both in units of ng/g with their corresponding Estimated Daily Intake (EDI) values [ng/kg-bw/day] for the entrance area.

	BaPE [ng/g] (Equation 3.4)	EDI [ng/kg-bw/day] (based on BaPE)	BaPE as TEQ [ng/g] (Equation 3.5)	EDI [ng/kg-bw/day] (based on BaPE as TEF)
DH2	58.14	0.04	87.62	0.06
A2	84.99	0.06	102.02	0.07
DH3	147.37	0.11	186.03	0.13
DH4	85.49	0.06	125.97	0.09
A3	229.99	0.16	393.92	0.28
A4	17.38	0.01	22.10	0.02
DH5	46.77	0.03	58.08	0.04
H	1.41	0.00	2.99	0.00

Compared to previous studies, the total EDI values of PAHs present in household dust in Berlin and in the Netherlands (as presented in Table 4 in **Paper II**) were within the range of total EDI values reported in our case. More specifically, total EDI values were equal to around 4 ng/kg-bw/day for Berlin and 2 ng/kg-bw/day for the Netherlands. On the other hand, the total BaPE values calculated for household dust in Berlin and in the Netherlands were exceptionally higher than the ones in our research; around 467 ng/g for Berlin and 448 ng/g for the Netherlands. Therefore, our results indicated that the residents who participated in a measurement campaign taken place in houses in Berlin and in the Netherlands were at a greater risk of being exposed to carcinogenic PAHs in household dust in comparison to Jordanian residents in our research.

With respect to the EDI values of the measured PAHs in the educational building, they varied from around 0.01 to 0.7 ng/kg-bw/day (Table 4 from **Paper II**). The total EDI values varied between about 0.5 and 4 ng/kg-bw/day. The highest total EDI values were observed for the office P300 followed by offices P200, P303 and corridors C1 and BC. This was not a surprise due to tobacco smoking in these locations. Workshop areas WSa and WSb exhibited the lowest total EDI values, in spite of the activities conducted there (such as iron welding, use of petroleum products, etc.). Those two areas also documented the lowest BaPE values (~ 26 ng/g for WSa and ~ 27 ng/g for WSb), whereas corridor C1 had the highest BaPE values (~ 385 ng/g) (Table 3 from **Paper II**).

The total EDI values in lecture theatres and dining halls in Shanghai's universities as well as in six different occupational environments in Hong Kong were higher than the corresponding ones in our work. More specifically, total EDI values were equal to around 6 and 13 ng/kg-bw/day inside lecture theatres and dining halls in Shanghai's universities, respectively, and around 5 ng/kg-bw/day in different workplaces in Hong Kong. Moreover, BaPE values were about 655 and 706 ng/g for the lecture theaters and dining halls in Shanghai's universities, respectively, and around 542 ng/g for six various occupational environments in Hong Kong. This suggests that the toxic threat due to exposure to PAHs content in dust was lower for the occupants of the educational building in Amman in comparison to people in various workplaces and universities in Asia.

4.2 Bacteria and fungi contamination

The bacterial and fungal concentrations measured in the living room and at the entrance area were presented in details in Table S5 and Figure 2 (a and b) from **Paper III**. In principal, we noticed significant variations in the bacterial and fungal concentrations inside the dwellings (both in the living room and the entrance area) and the educational building. For example, concerning the Jordanian residences, apartment A4 documented the lowest fungi, Gram-negative bacteria and *Penicillium/Aspergillus* spp. concentrations both in the living room and the entrance area (Figures 2a and b from **Paper III**). This could be attributed to the fact it was the newest among the studied dwellings, located in a quiet neighborhood and the least occupied. Surprisingly, detached house DH4 demonstrated the lowest Gram-positive bacteria concentrations at the entrance area, despite the fact it was built close to a busy street, tobacco smoking occurred occasionally and the entrance area was inside the dwelling.

With respect to the bacterial and fungal concentrations determined for the educational building, the big corridor (BC) documented the highest Gram-negative bacteria and total fungal concentrations (Figure 3 and Table S6 form **Paper III**). The 1st floor corridor (C1) had the highest Gram-positive bacteria, but the lowest *Penicillium/Aspergillus* spp.

concentrations. Both students and the educational staff used to spend their time, eat and smoke cigarettes between lectures in corridors BC and C1. Surprisingly, even though in the welding area of the workshop (WSb) heavy machinery activities took place, it exhibited the lowest Gram-positive, Gram-positive bacteria and total fungal concentrations. Despite that, WSb had the highest *Penicillium/Aspergillus* spp. concentrations.

Furthermore, it needs to be stressed out that the bacteria and fungi concentrations correlated well with some PAHs observed in the floor dust collected from both the dwellings and the educational building (Table S7 from **Paper III**).

Due to the fact that bacterial and fungal concentrations varied substantially amongst the dwellings (both in the living room and the entrance area) and the different areas of the educational building, we concluded that each region within the city of Amman has its own sources of bio-contaminants. Moreover, outdoor sources have an impact on the indoor fungi and bacteria concentrations detected in indoor floor dust (Adams et al., 2014), whereas occupancy and human's activities contribute to increased concentrations of indoor bacteria, especially of Gram-positive bacteria in house dust (see references from **Paper III**). Studies conducted by Goh et al. (2000) and Grimsely et al. (2012) evidenced that environmental conditions such as relative humidity and temperature also increase significantly bacteria and fungi concentrations in indoor environments. Concerning building characteristics, Foarde and Berry (2004) showed that tiled floors increased the concentrations of airborne bio-contaminants due to resuspension of the floor dust, implying that the floor type plays an important role for their growth. In addition to that, Ali et al. (2014) pointed out that not properly cleaned carpets in mosques could pose serious health problems to people.

Nonetheless, of a great importance is also the relationship between biological contamination and PAHs due to the fact that bacteria and fungi transform PAHs into active, mutagenic and carcinogenic products (see references from **Paper III**).

4.3 Accumulation and coarse particles inside a workshop

4.3.1 Concentration during weekend and working days

According to Figure 2 from **Paper IV**, $PN_{0.3-1}$ ($PM_{0.3-1}$) were around 13-64 cm^{-3} (0.4–2 $\mu g/m^3$) and PN_{1-10} (PM_{1-10}) ranged from 0.3–0.8 cm^{-3} (1–13 $\mu g/m^3$) during the weekend (from midnight on April 3rd until 23:59 on April 4th 2015) (Figures 2 and 3 and Tables 1–4 from **Paper IV**).

During working days, $PN_{0.3–1}$ ($PM_{0.3–1}$) varied from 22–4140 cm^{-3} (0.7–152 $\mu g/m^3$) and PN_{1-10} (PM_{1-10}) ranged between 0.5 and 25 cm^{-3} (4–456 $\mu g/m^3$) (Figures 2 and 3 and Tables 1–4 from **Paper IV**).

During welding processes, and in particular, during the operation of the welding machine followed by the activity of iron welding without the use of the exhaust fan and the running of the exhaust fan afterwards (<u>Event 2</u>), the highest mean particle number and mass concentrations of particles in the diameter ranges 0.3–1 μm and 1–10 μm were recorded. Mean $PN_{0.3\text{-}1}$ ($PM_{0.3\text{-}1}$) concentrations were about 1866 cm^{-3} (55 $\mu g/m^3$) and mean $PN_{1\text{-}10}$ ($PM_{1\text{-}10}$) concentrations were about 7 cm^{-3} (103 $\mu g/m^3$) (Tables 1–4 from **Paper IV**). This finding was mainly attributed to the consumption of 1 coated rutile electrode (E 6013) in the welding area and smoking a cigarette inside the changing room of the workshop area (Figures 1–3 from **Paper IV**). In addition, $PN_{0.3\text{-}1}$ ($PM_{0.3\text{-}1}$) and $PN_{1\text{-}10}$ ($PM_{1\text{-}10}$) concentrations reached their maxima values during Event 3 (Exhaust fan on, iron welding with exhaust fan, and sorting/drilling), mainly due to the consumption of 2 coated rutile electrodes (E 6013) during iron welding. More specifically, $PN_{0.3\text{-}1}$ ($PM_{0.3\text{-}1}$) and $PN_{1\text{-}10}$ ($PM_{1\text{-}10}$) concentrations reached up to approximately 4140 cm^{-3} (152 $\mu g/m^3$) and 25 cm^{-3} (456 $\mu g/m^3$), respectively (Tables 1–4 and Figures 2 and 3 from **Paper IV**). We should bear in mind that rutile electrodes were used only during Events 2 and 3, and hence, we assume that their consumption might have been the reason for these high concentrations.

Furthermore, high mean and maxima $PN_{0.3\text{-}1}$ and $PN_{1\text{-}10}$ concentrations were detected during Event 1 (Iron welding and smoking) (in addition to Events 2 and 3) (Tables 1–4 from **Paper IV**). Interestingly, Events 4 (Coffee brewing and metal turning), 5 (Metal turning and iron welding) and 7 (Having a lecture and metal turning) demonstrated lower mean, median and maxima values of $PN_{0.3\text{-}1}$, $PM_{0.3\text{-}1}$ and $PN_{1\text{-}10}$ concentrations than Event 6 (Metal turning) (Tables 1–4 from **Paper IV**). This outcome could be justified by the fact that Event 6 occurred right after the performance of iron welding. However, due to the limited literature review on particle number and mass concentrations of aerosol particles during activities similar to the ones conducted inside the workshop area we could not confirm the above speculations.

In comparison to other studies, mean $PM_{1–10}$ concentrations observed inside the educational workshop were lower than $PM_{1–10}$ concentrations reported by Iavicoli et al. (2013), Azarmi et al. (2014), Mazzuckelli et al. (2007) (apart from Events 2 and 3), Akbar-Khanzadeh et al. (2007) and Lin et al. (2015) during welding and brazing activities, drilling and cutting of hardened concrete, cutting carbon nanofiber composite, wet grinding inside a field laboratory as well as during manual welding, automatic welding, punching holes in steel tubes and cutting steel tubes inside industrial manufacturing of fitness equipment, respectively (**Paper IV**). Particularly, as it is described in **Paper IV**, if we exclude the mean value of 60 $\mu g/m^3$ reported by Mazzuckelli et al. (2007), during these activities mean $PM_{1–10}$ concentrations fluctuated from about 110–2909 $\mu g/m^3$, whereas mean $PM_{1–10}$ concentrations during a combination of activities taken place inside the workshop ranged from around 8–103 $\mu g/m^3$. On the other hand, Buonanno et al. (2011) documented that mean $PM_{1–10}$ concentrations measured at different areas of a body shop in the vicinity of welding activities were lower (0–10 $\mu g/m^3$) than the corresponding ones inside the educational workshop (excluding mean $PM_{1–10}$ concentrations of 8 $\mu g/m^3$ during the event of coffee brewing and metal turning). Furthermore, during four welding events where a solid wire electrode (ER50-6) was used, mean $PM_{0.1–1}$ varied from 1600–3120 $\mu g/m^3$ (Zhang et al., 2013), whereas mean $PM_{0.3–1}$ during Events 2 (Exhaust fan and machine on, welding iron without exhaust fan) and 3 (Exhaust fan on, iron welding with exhaust fan and sorting/drilling) were around 55 and 44 μg/m^3, respectively.

4.3.2 Loss and emission rates

Paper IV presents a comprehensive analysis of the results obtained for the (particle) loss and emission rates of particle ranging from 0.3–1 μm and 1–10 μm in dimeter. For particles in the size range of 0.3–1 µm, the ventilation rate was determined by particle loss rates ($\lambda+\lambda_d$), since, as already pointed out in Section 3.5, the deposition of aerosol particles between 0.1 and 1 µm in diameter is considered insignificant.

Mean particle number loss rates ranged approximately 0.35–2.1 h^{-1} for coarse particles and the ventilation rate was a major particle removal process (about 0.24–2.1 h^{-1}) in the welding area of the workshop (Table 5 from **Paper IV**). Ventilation rates from previous studies as reported in **Paper IV** were smaller and/or higher than what was estimated for the educational workshop, depending on the number, type, occupancy and location of the studied indoor environment(s), and the duration of the measurement campaign(s). Furthermore, according to the literature review presented in **Paper IV,** the depositions rates of the mean geometric particle diameter of particles ranging from 1–10 μm fluctuated from 0.40–3.83 h^{-1} during cooking activities, pouring kitten litter with the fan off, and depending on other factors such as number of occupants. This remarkable observation suggests that the density of particles emitted inside the workshop area during activities such as iron welding, metal turning, coffee brewing, etc. might be almost the same with the density of particles produced during the activities described in the studies mentioned in **Paper IV**.

Regarding (particle) emission rates, in general, they were lower for coarse particles in comparison to the ones for submicron particles in the diameter range 0.3–1 µm. In particular, the emission rates of coarse particles fluctuated from 75–1008 particles/h·cm^3 and of particles in the diameter range 0.3–1 µm varied from (5.74–9.31) · 10^4 particles/h·cm^3. Emission rates of indoor sources should be investigated intensively as it can be quite a complicated subject. Special attention should be given, specifically, to emission rates of coarse particles originated by indoor sources inside occupational environments and educational building, since the majority of scientific articles have focused on reporting emission rates of ultrafine particles (**Paper IV**).

4.3.3 Exposure and inhaled deposited dose scenarios

In order to assess workers'/students' exposure to coarse particles inside the workshop area, we estimated the respiratory inhaled deposited dose based on particle mass assuming that the workers/students performed light exercise. Then we compared these values to the inhaled deposited dose values calculated for all the events occurring inside the workshop area, considering this time that the workers/students were just standing/resting (Table 6 from **Paper IV**). Sections 2.5 and 3.3 of **Paper IV** describe in details all the parameters used for our estimations. Moreover, the inhaled deposited dose rates (μg/min) presented in Table 5 derived from dividing the inhaled deposited dose (in μg units) to the duration of each event (expressed in minutes). Both the inhaled deposited dose and rates calculations were based on a healthy male adult.

Overall, the highest inhaled deposited dose of coarse particles for a male adult was observed when iron welding took place, and later the operation of the exhaust fan and the activity of iron sorting/drilling occurred (Event 3, total deposited dose ~ 205 μg). The lowest was detected during coffee brewing and metal turning (Event 4, total deposited dose ~ 12 μg) (Table 6 from **Paper IV**).

The estimated inhaled deposited dose rates of particles in the size range between 1 and 10 μm in diameter varied from 0.12–1.56 μg/min (Table 5) and the particles were mainly deposited in the alveolar region (~ 53%). The inhaled deposited doses in the tracheobronchial and the head/throat region were approximately 29% and 18%, respectively.

However, if we speculate that during all the events the workers/students were just standing/resting, then the regional deposited dose and rates will change significantly. For instance, the total inhaled deposited dose and the deposited dose in the tracheobronchial and the alveolar region will decrease remarkably, whereas the deposited dose in the head/throat region will increase. Particularly, the calculated inhaled deposited dose rate would range from 0.07–0.94 μg/min (Table 5), of which around 64% would deposit in the head/throat region, 30% in the alveolar and about 6% in the tracheobronchial region (Table 6 from **Paper IV**).

Hussein et al. (2013) estimated the total and regional deposited dose of submicron particles for three groups older than 12 years old (teens, adults and elderly), whereas in another study Hussein group (Hussein et al., 2015b) studied the exposure and calculated the inhaled deposited dose of a healthy male adult during his daily routine based on two scenarios (including and excluding indoor sources). Moreover, Koivisto et al. (2012a, b; 2014; 2017; 2018) reported (regional) inhalation exposure levels of nanoparticles during activities such as nanoparticle synthesis, packing of pigment and nanoscale TiO_2 material without the use of respirators, handling and sieving of ND powder, removal painting form wood boards by sanding and application of ceramic honeycomb cells on photoactive suspension based on nanoscale TiO_2. However, none of these studies included any welding activities. Therefore, this work could be used in risk assessments and epidemiological studies investigating inhalation exposure levels during welding or similar processes inside a laboratory or a workshop.

More attention should be given to exposure to fumes emitted from welding processes as it has been reported that welding fumes are responsible for severe health and pulmonary problems such as asthma, respiratory and heart problems, metal fume and even lung cancer (see references from **Paper IV**). One way to reduce workers' and students' exposure and, thus, potential health risks is to improve exhaust ventilation and ventilation mechanisms both near the sources and during different activities or operations. Education of occupants on safety measures and health risk as well as application of respiratory, eye and hearing protectors should be also encouraged (**Paper IV)**.

Table 5: Inhaled deposited dose rates [µg/min] of coarse particles based on particle mass calculated for a health male adult during all events (apart from undefined events)

	Event 1 (Iron welding & smoking)		Event 2 (Fan & machine on, welding iron without fan)		Event 3 (Fan on, welding & sorting/drilling iron)		Event 4 (Making coffee & metal scrubbing)		Event 5 (Metal scrubbing & iron welding)		Event 6 (Metal turning)		Event 7 (Lecture & metal scrubbing)	
	Standing/ Resting	Light exercise	Standing/ Resting	Light exercise	Standing/ Resting	Light exercise	Standing/ Resting	Light exercise	Standing/ Resting	Light exercise	Standing /Resting	Light exercise	Standing /Resting	Light exercise
Head	0.31	0.15	0.60	0.28	0.54	0.26	0.05	0.02	0.25	0.12	0.21	0.10	0.14	0.06
Tracheobronchial	0.03	0.23	0.06	0.45	0.05	0.41	0.00	0.04	0.02	0.19	0.02	0.16	0.01	0.10
Alveolar	0.15	0.43	0.28	0.83	0.26	0.75	0.02	0.06	0.12	0.35	0.10	0.30	0.06	0.19
Total	0.49	0.80	0.94	1.56	0.85	1.41	0.07	0.12	0.40	0.66	0.34	0.56	0.22	0.36

5 Review of papers and author's contribution

Paper I assesses the indoor air quality of eight Jordanian dwellings by chemically characterizing the levels of 13 priority PAHs (phenanthrene (PHE), anthracene(ANT), fluoranthene (FLA), pyrene (PYR), benz[a]anthracene (BaA), chrysene (CHR), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[j]fluoranthene (BjF), benzo(a)pyrene [BaP], indeno[1,2,3-cd]pyrene (IcdP), dibenz[a,h]anthracene (DahA), benzo[g,h,i]perylene (BghiP)) from dust inside and outside of Jordanian dwellings and an attempt was made in order to identifying the source origin (indoor or outdoor) of the PAHs. To do that, two samples were taken from each house from floor at 1 m^2 area: (1) living room area and (2) main entrance. Moreover, it investigates the spatial variation of the PAHs within the capital city Amman. Results from the GC-MS (chemical) analysis are reported. The author was responsible for the collection of the majority of the floor dust samples, the data analysis and the manuscript writing under the supervision of K. Hämeri and T. Hussein. This study is the first of its own in Jordan.

Paper II describes a study, the first of its own in Jordan as well, which focuses on investigating the indoor air quality of an educational building (Department of Physics, the University of Jordan). In particular, it presents the concentrations of 13 priority PAHs (same PAHs as **Paper I**) contained in floor dust. In order to evaluate the hand-to-mouth exposure of people at the Department of Physics of the University of Jordan a simple exposure and health risk assessment for the ingested dust was made by calculating total Estimated Daily Intake (EDI) and benzo(a)pyrene toxic equivalent (BaPE). The author was responsible for the exposure and health risk assessment for the ingested dust in conjunction with S. Arar under the supervision of T. Hussein. Furthermore, the author was responsible for the floor dust collection procedure, the data analysis and the manuscript writing under the supervision of K. Hämeri and T. Hussein.

Paper III studies, illustrates and quantifies fungal and bacterial concentrations inside floor dust samples collected from dwellings (**Paper I**) and an educational building (**Paper II**) in Amman, Jordan. Simple statistical tests between the tested microbe concentrations and the PAHs concentrations were applied in order to examine correlations between bacteria, fungi and PAHs concentrations. The author was responsible for collecting the majority of the floor dust samples from the Jordanian dwellings and from the educational building as well as for providing the data for the PAHs concentrations. Moreover, the author contributed to the writing of the article.

In **Paper IV** particle number (PN) and mass (PM) concentrations of accumulation and coarse particles inside a workshop area of the Department of Physics of the University of Jordan, Amman were measured, reported and illustrated over a seven day period from March 31st until April 6th 2015. **Paper IV** also investigates the effect of some indoor activities (such as having lecture, smoking, making coffee, iron welding, turning and sorting/drilling) occurring inside the workshop area on the particle number (PN) and mass (PM) concentration as well as it assesses the exposure to coarse particles. In addition, it presents particle concentrations in the air when the same workshop was unoccupied during the weekend. A simple indoor aerosol model was used to estimate the emission and loss rate of aerosol particles within the measured size range (300 nm -10 μm) inside the workshop area. The author was responsible for performing aerosol measurements using an Optical Particle Sizer (TSI OPS 3330, 13 size-bins) and recording the events of indoor activities (such as having lecture, smoking, making coffee, iron welding, turning and sorting/drilling) under the supervision of T. Hussein and in collaboration with O. Jaghbeir. Moreover, the author was in charge of analyzing the data and writing the manuscript under the supervision of K. Hämeri and T. Hussein.

6 Conclusions

This thesis investigated biological contamination and human exposure to PAHs in floor dust in both an educational building (**Papers II, III** and **IV**) and eight dwellings (**Paper I, Paper III**) within the capital city of Jordan, Amman. Exposure to coarse particles inside an educational workshop area during a combination of activities such as smoking, making coffee, iron welding, sorting/drilling, metal scrubbing, etc. was assessed as well. In particular, we focused on the following aspects:

- identification of the source origin of the PAHs and their content in dust inside and outdoors for each dwelling as well as inside an educational building (Department of Physics, University of Jordan),
- analysis of the spatial variation of the measured PAHs concentrations within the capital city Amman.
- quantification of PAHs, biological and fungal concentrations in dust samples collected from eight dwellings and an educational building in Amman, Jordan
- exposure to, dose and health risk assessment of floor dust PAHs inside an educational building and inside dwellings in Amman as well as assessment of occupational exposure to coarse particles inside a workshop area of an educational building.
- study and report of the particle number and mass concentrations of particles in the diameter ranges 0.3–1 μm and 1–10 μm and estimation of their emission and loss rates during a combination of activities such as making coffee, metal scrubbing, iron welding, sorting/drilling, etc. inside an educational workshop.

Total PAHs concentrations at the living room area were lower than that at the entrance area for four out of eight dwellings. Evidence showed that both indoor and outdoor sources were responsible for the production of the observed PAHs, as different environmental conditions occurred in each house. Therefore, it was not possible to reach a firm conclusion concerning the specific source of different PAHs.

However, according to the questionnaires filled in by the residents of the dwellings, the main sources of PAHs in settled dust included traffic, heating system, cooking activities and indoor smoking.

With respect to the educational building, the highest total PAHs concentrations were observed inside some offices, where smoking incidents occurred, suggesting that exposure to tobacco smoking inside small and poorly ventilated indoor environments could have adverse health implications. A further and a more detailed study including more dust samples from the university area is needed in order to have a better picture of the source origin of each PAH.

Keeping in mind that the university staff as well as the residents of the Jordanian dwellings were exposed to PAHs via dust ingestion, we calculated Estimated Daily Intake (EDI) and benzo[a]pyrene equivalent carcinogenic power (BaPE). Consequently, our results indicated that the health risk of being exposed to carcinogenic and toxic PAHs via dust ingestion inside Jordanian residences and inside an educational building was lower in comparison to European residences and Asian occupational environments, respectively.

The differences in bacterial and fungal concentrations indicate that indoor and outdoor sources of bio-contaminants differ depending on the locations of the city of Amman. Our findings showed that apart from occupancy, human's activities and outdoor sources, environmental conditions and the floor type play a significant role in the growth of bacterial and fungal concentrations indoors.

Moreover, we observed that the bacterial and fungal concentrations of the studied indoor environments in Jordan clearly correlated with PAHs, suggesting that the occupants could be at high risk of being contaminated to PAHs carcinogenic and mutagenic products.

Regarding the indoor air measurement campaign taken place in the workshop area at the Department of Physics of the University of Jordan (Amman), we noticed that during workdays, the highest mean PN_{1-10} (PM_{1-10}) and $PN_{0.3-1}$ ($PM_{0.3-1}$) concentrations were observed during welding operations. Moreover, the emission rates were generally lower for coarse particles compared to the ones for particles in the size range between 0.3 and 1 µm.

We trust that variations in the PM and PN concentration between particles with diameters 0.3–1 µm and 1–10 µm particles during the occurrence of the activities could be attributed to the type of the activity (i.e. source specific) and the particle loss rate. Nonetheless, we believe that further study is required in order to confirm these speculations.

Moreover, during an 8-hour exposure and assuming that the workers/students carried out light exercise, the estimated inhaled deposited dose would be less than 750 µg, where approximately 53% of the particles would be deposited in the alveolar region.

Overall, the first reports of PAHs concentrations and content in floor dust inside Jordanian indoor environments were presented. Residential and occupational health risk and dose assessments of PAHs were conducted for the first time in Jordan as well (**Paper I** and **II**). We also reported fungal and bacterial concentrations observed in floor dust and investigated their correlation with PAHs, since there has been little awareness on exposure to bio-contaminants in floor dust in the MENA region (**Paper III**). This dissertation demonstrates that there is a significant variation between sites and a considerable influence of both indoor and outdoor sources. Exposure and risk assessment are highly important to ensure the health of the population and workforce, and our study shows that further research would be highly valuable and fundamental. In addition, this dissertation and, in particular, **Paper IV** are hoped to bring additional insights on inhaled deposited dose and emission rates of coarse particles during welding activities, since the literature review on these two topics is limited. The work presented in **Paper IV** is considered innovative as it joins together conduction of measurements, use of indoor aerosol model and performance of exposure assessment, as opposed to other studies.

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Supplementary Information

Table S1: Detailed information (type and age of each dwelling, ventilation type, cooking style and type, household appliances, heating system, type of cleaning materials, smoking activities inside the dwelling, etc.) on each dwelling based on the questionnaires filled in by the occupants.

Type of dwelling	**Age of the dwelling**	**Quality of the street**	**Heating system**	**Monthballs**	**Ground pavement**	**Take off shoes when entering the home**	**Cooking appliance**	**Fume exhaust**	**Smoke inside the dwelling**	**Boiler**	**Cooking activities**	**Ventilation**	**Drying of clothes**	**Chemicals**
DH2	10	Busy sometimes	Kerosene	No	Brick	No	Gas	No	Often(2-3/day)	Outside the house	Stir-frying/deep frying, Stewing/streaming, grilling/boiling/roasting/baking, 1-2 h/day	Natural, 2 h/day	Use hangers and leave them to dry	Detergents-storage room
A2	5	Busy sometimes	Kerosene	No	Ceramic	No	Gas	No	Occasionaly(1/3months	Basement	Stir-frying/deep frying, Stewing/streaming, grilling/boiling/roasting/baking, 1-2 h/day	Natural, 2 h/day	Dryer machine, use hangers, put close to radiators	Detergents- kitchen
DH3	30	Busy sometimes	Kerosene	No	Cement	No	Gas	No	Occasionaly(1/week)	Kitchen	Stir-frying/deep frying, Stewing/streaming, grilling/boiling/roasting/baking, 1-2 h/day	Natural, 2 h/day	Use hangers and leave them to dry	Detergents- kitchen

DH4	15	Busy sometimes	Kerosene and electric heat	No	Cement	Yes	Gas	Yes	Occasionally(every two months)	Basement	Stir-frying/deep frying, 3/day	Natural, 2 h/day	Dryer machine,	Not mentioned
A3	4	Busy sometimes	Electric heat	Yes, bathrooms	Cement	No(take off shoes in the living room	Gas	Yes	No	No boiler	Grilling/boiling/roasting/baking, 3/day	Natural,	Dryer machine	Not mentioned
A4	3	quiet	Gas heat (including fireplace)	Not mentioned	Not mentioned	Yes but not always	Gas and electricity	Yes	No	Kitchen	Grilling/boiling/roasting/baking	Natural, 1 h/day	Use hangers and leave them to dry	Detergents,drugs in kitchen
DH5	40	Busy sometimes	Kerosene and gas heat (including fireplace)	No	Cement	Yes	Gas	No	Occasionally	Kitchen	Stir-frying/deep frying, Stewing/streaming, grilling/boiling/roasting/baking, 2-3 h/day	Natural	Use hangers and leave them to dry	Not mentioned
H	10	quiet	Gas heat (including fireplace)	No	Not mentioned	No	Gas	Yes	Occasionally	Kitchen	Not mentioned	Natural, 1 h/day	Put close to radiators	Not mentioned