

Chapter 32

Indoor Air Quality in Chemical Laboratories

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List of Abbreviations

ACH Air change per hour	HVAC Heating, ventilating and air conditioning
BBP Butyl benzyl phthalate	IAQ Indoor air quality
ChE Chemical Engineering Department	OCP Organochlorine pesticides
d_p Particle diameter	PAH Polycyclic aromatic hydrocarbons
DBP Dibutyl phthalate	PBDE Polybrominated diphenyl ethers
DEHP Di (2-ethylhexyl) phthalate	PCB Polychlorinated biphenyls
DIBP Diisobutyl phthalate	PCDD Polychlorinated dibenzo- <i>p</i> -dioxins
DIDP Diisodecyl phthalate	PCDF Polychlorinated dibenzo- <i>p</i> -furans
DINP Diisononyl phthalate	POP Persistent organic pollutants
DnOP Di- <i>n</i> -octyl phthalate	PVC Polyvinyl chloride
DnPP Di- <i>n</i> -pentyl phthalate	

PM Particulate matter	SVOC Semivolatile organic compounds
UFP Ultrafine particles	VOC Volatile organic compounds
R_a Minimum outdoor airflow rate required per area	WBGT Wet bulb globe temperature
R_p Minimum outdoor airflow rate required per person	T Temperature
RH Relative humidity	TSP Total suspended solids
	TVOC Total volatile organic compounds

1. PERTINENT POLLUTANTS, SOURCES AND HEALTH EFFECTS

Indoor air pollutants important for laboratories can be listed as particulate matter (PM), trace elements, inorganic gases, bioaerosols and volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs).

1.1 Particulate Matter

PM can be regarded as one of the most important and frequently encountered indoor air pollutants. PM is classified into three groups based on their sizes: coarse particles (particles with diameter $2.5 < d_p \leq 10 \mu\text{m}$), fine particles ($0.1 < d_p \leq 2.5 \mu\text{m}$) and ultrafine particles (UFP, $d_p \leq 0.1 \mu\text{m}$). Fine particles are more potent when inhaled compared to the coarse fraction because they can penetrate deeper into the respiratory system [1–3]. UFP can penetrate to alveoli, and transfer to blood, which can be considered as the most impacting group [4]. Although the contribution of ultrafine and fine particles are very low and low, respectively, to the PM in mass basis, they have the highest contribution based on the particle number concentration [5].

Possible sources of PM in the laboratories, that determine their concentrations, are combustion sources such as Bunsen burners, used and produced powders in the experiments, human skin scales, insect parts, chipped pieces from walls and other construction materials and generally the main source that is outdoor air. Hence, ventilation plays a major role because it may act as a highway for their transport from outdoors to indoors. Additionally, occupant behaviour in the laboratories can cause resuspension of the settled particles affecting indoor air PM concentrations considerably, along with type of cleaning and its frequency, similar to reports from other indoor microenvironments such as by Abt et al. and Ocak et al. [6,7].

PM is an irritant and a Group-1 carcinogen [8]. The level of toxicity changes depending on the trace element and organic substance content which may be incorporated during the formation of particles and/or sorbed later on from anthropogenic sources. Exposure to PM may lead to effects on respiratory system, such as inflammation, asthma and lung diseases, and

cardiovascular system such as variability in the heart rate [9–11]. Although health effects of PM have been shown by epidemiological studies, there is not a significant evidence for the effects of particles with different sizes mechanistically [12]. Therefore, the standards set for PM_{2.5} and PM₁₀ are used to determine the level of health effects.

1.2 Trace Elements

Common potentially toxic trace elements associated with PM are Al, Fe, Mg, Zn, As, Cd, Co, Cr, Cu, Mn, Ni and Pb. Trace elements such as Al, Fe and Mg are mostly released from the crustal sources like parent rocks, metallic minerals, seas and oceans [13]. Fossil fuel combustion, wood and biomass burning and metal processing can be given as examples of anthropogenic sources releasing many trace elements such as As, Cd, Co, Cr, Cu, Ni, Pb, etc. [14,15]. Consequently, ambient air PM-bound trace elements can be carried into the laboratories from outdoors by ventilation and infiltration. In addition, transport on the shoes and clothing of individuals may be a source. Indoor sources may be chipped paint, re-entrainment of the dust settled onto the floors and other horizontal surfaces. However, the main trace element source may be some specific operations and procedures carried out in the laboratories involving processing of solid materials, powders, chemicals, samples, etc., that are rich in trace element content. Chronic exposure to some trace elements may cause various human health effects ranging from irritation of the mucosa and coughing to cardiovascular diseases and cancer [16].

1.3 Inorganic Gases

CO₂ is one of the minor components of the atmosphere emitted by humans, animals and plants as a result of biological processes. Beside metabolic processes, CO₂ is also released to the environment as the major combustion product from vehicles, industries, electricity production and residential heating. Number of workers and students in the laboratory, operation of fume hoods during experiments, presence of combustion sources and ventilation rate are the main factors influencing CO₂ levels in laboratories. Types of experiments conducted in the laboratories are also important. For example, if animals and plants are used for different purposes, extra CO₂ emissions occur or leakage from the use of CO₂ cylinders may occur. If 600 ppm is taken as reference point, decrease in decision-making performance of people was found to be statistically significant at concentrations >1000 ppm, whereas the decrease was more pronounced at concentrations >2500 ppm [17].

CO is mainly produced as a result of incomplete combustion in such sources as unvented kerosene heaters and gas appliances [18]. Its indoor concentrations rise above outdoor levels when there are strong indoor sources. Otherwise, ambient air is the main source. CO gas cylinders are available in

chemical laboratories and leakages during usage may be a significant source. Additionally, it can also be used as a reducing agent and produced as a result of some chemical reactions (such as reaction of sulphuric acid and formic acid, dehydration of formic acid in the medium of concentrated sulphuric acid, etc.). Exposure to CO at high levels leads to acute neurological and cardiovascular health effects. CO exposure may also be a cause of cardiovascular mortality and cardiovascular disease hospitalisation even at the ambient CO concentrations from 0 to 11 ppm [19].

NO is formed by reaction of nitrogen and oxygen at high temperatures followed by oxidation to NO₂. NO₂ formation is directly related to heating appliances, tobacco smoke, fireplaces, wood-burning stoves, motor vehicles, industrial boilers and electric utilities [18,20]. Beside the infiltration of outdoor NO₂, indoor combustion sources that use LPG and natural gas are the main indoor sources of NO₂. In corrosion studies on different surfaces such as zinc, copper and aluminium, NO₂ can leak to the indoor air [21]. NO₂ is also used as an oxidant for transformation of polycyclic aromatic hydrocarbons (PAHs) to nitro-PAHs [22]. Exposure to NO₂ can cause lower respiratory diseases and damages to the lungs [23,24]. Additionally, considerable effects were recorded on the children and asthmatics [25].

SO₂ is also considered as one of the important inorganic gases released from combustion processes (kerosene heaters and gas stoves) and industrial sources. Not only gas form of SO₂ but also formation of aerosols from SO₂ is a big concern in the atmosphere due to acid deposition potential. However, indoor levels are generally found to be lower than those of outdoors [1]. SO₂ is used as a reducing agent for bleaching, preservation of foods and disinfection. Respiratory effects, higher pulse rate, nausea and vomiting are possible adverse health effects of SO₂ exposure [26–29].

Sources of O₃ may be air cleaners, UV lighting, laser printers, photocopiers and photochemical reactions [20,30]. O₃ can be used in the organic chemistry laboratories for ozonolysis of compounds, such as eugenol, to obtain carbonyl compounds from alkynes and alkenes, and to investigate air pollution and climate change resulted from stratospheric ozone depletion, while its main source is the outdoor air [31]. Ozone is an important component of indoor air chemistry both consumed and produced depending on other factors including the outdoor O₃ concentration, air exchange rates, indoor emission rates, surface removal rates and reactions between O₃ and other chemicals in the air [32]. Ozone exposure can lead to headaches; irritation on eyes, nose and throat; difficulty in breathing; increase in the bronchial reactivity and further narrowing of airway for people with asthma [33,34].

1.4 Bioaerosols

Bioaerosols are either naturally generated particles or contamination-generated particles from biological origins, and may stay suspended in air because their

small sizes that can vary from 20 nm to $>100\ \mu\text{m}$ [35]. Beside the organisms (viruses, bacteria and fungi), associated attributes such as spores, toxins, microbial VOCs and antigens are also important to the human health [36].

Indoor air of laboratories can face with the bioaerosol contamination if indoor temperature and relative humidity are suitable for the growth of those organisms. Air conditioners or ventilation systems, outdoor pollution, water baths, ultrasonic baths, sample drying in ovens operating at moderate temperatures (35–40°C) with moisture content, uncleaned sinks, benches, pumps for water transportation in the laboratory devices, building and furnishing materials, number of people and their activities (sneezing, coughing and talking), organic wastes, water leakages from devices such as climate-controlled chambers, deionised or ultrapure water systems may be the sources of contamination in chemical laboratories. Exposure to bioaerosols has been related to asthma, humidifier fever, allergic rhinitis, hypersensitivity pneumonitis, pontiac fever, Legionnaire's disease, hypersensitivity pneumonitis and atopic dermatitis [20,37,38].

1.5 Volatile and Semivolatile Organic Compounds

VOCs, which are more than 220 compounds, have typically a boiling point range from 50–100°C to 240–260°C, excluding pesticides [39]. These compounds can be classified as aliphatic (methane, hexane, heptane, etc.), aromatic (benzene, toluene, xylene, etc.), oxygenated (aldehydes, alcohols, etc.) and halogenated hydrocarbons (chloroform, methyl chloride, chloromethane, etc.). Hydrocarbons are generally used in the laboratories as solvents (for extraction or purification), cleaning agents for glassware, chemical intermediates for reactions and for instrumental analysis such as the use of ethyl alcohol as mobile phase in chromatography. Leakages from the bottles, spillage while pouring, evaporation from the left open sources, mixing into air from ovens (if solvent containing material is dried) may be the main sources of VOC emissions in the laboratories. Exposure to these pollutants causes adverse health effects such as irritation, impairment of concentration, fatigue, headache and impacts on kidney, lung and nervous system [40–42].

SVOCs are organic compounds with vapour pressures between 10^{-14} and 10^{-4} atm, and boiling points from 240–260°C to 380–400°C [39,43]. They can either be in the gas form or adsorbed to available surfaces such as house dust and airborne particles, materials like polyurethane foam, etc. The main groups of SVOCs can be listed as phthalates, polychlorinated biphenyls (PCBs), organochlorine pesticides (OCPs), polychlorinated dibenzo-*p*-dioxins and-furans (PCDD/PCDFs), PAHs, sulfanates, polybrominated diphenyl ethers (PBDEs) and other brominated flame retardants. Phthalates are used as plasticisers to make products (building materials, polyvinyl chloride (PVC) flooring, toys, cosmetics, etc.) softer and elastic, eg, in PVC [44]. Some of the commercially used phthalates are dibutyl phthalate (DBP), diisobutyl

phthalate (DIBP), butyl benzyl phthalate (BBP), di-n-pentyl phthalate (DnPP), di (2-ethylhexyl) phthalate (DEHP), di-n-octyl phthalate (DnOP), diisononyl phthalate (DINP) and diisodecyl phthalate (DIDP). Because of having low vapour pressure, they evaporate making the material brittle in time. Phthalates are mostly investigated in chemical laboratories in plastics, toys, foods and cosmetics. Exposure to phthalates can lead to health effects such as impacts on liver, respiratory system and metabolism and development disorders in the reproductive organs [45–48].

SVOCs are categorised as persistent organic pollutants (POPs) because they are resistant to degradation in the environment, can be transported over long distances and bioaccumulate [49]. These compounds are mostly used for industrial or agricultural applications rather than commercially available laboratory products as VOCs. However, some of them, that are currently in use, such as PBDEs and other types of flame retardants, can be emitted from electric/electronic devices and building/furnishing materials. SVOC levels are investigated in different media such as air, soil, water, milk and living organism tissues because they partition between the gaseous phase and organic matter in solid/particle phase. Processing and analysis of samples are carried out in the environmental monitoring laboratories. Depuration chemicals, internal and surrogate standards for instrumental analysis are available in these laboratories. Furthermore, evaporation from the brought in samples is also possible. SVOCs may leak into indoor air of laboratory during extraction, concentration and instrumental analysis of SVOC-containing samples. Possible health effects related to POPs exposure are impacts on immune, endocrine, nervous and reproductive systems; developmental problems; thyroid dysfunction and cancer [50,51].

Finally, building construction materials, caulking, furnishing materials in the laboratory, cleaning products, outdoor air, improper working or not using fume hoods, ventilation rate can be considered as important sources and factors for both VOCs and SVOCs.

2. FACTORS THAT DETERMINE THE CONCENTRATIONS OF INDOOR AIR POLLUTANTS IN LABORATORIES

Pollutant source strength and ventilation rate are the two main factors that determine indoor air quality (IAQ) in chemical laboratories. The other factors that may have an effect are building characteristics such as moisture damage, building and furnishing materials, and cleaning products. Indoor air chemistry may also be of importance as a source of secondary pollutants.

2.1 Source Strength

One of the main determinants that affect the IAQ is the strength of indoor emissions. The factors that lead to the presence of contaminants in the indoor

environment are exemplified by indoor sources (combustion sources, construction materials, etc.), outdoor sources, indoor conditions and occupant activities. In other words, source strength depends on the intensity of indoor sources and the factors such as moisture content, temperature, etc. that allow release of pollutants from these types of sources at different rates. For example, the concentrations of volatile organics usually increase linearly with increase in ambient temperature, depending on their volatility properties. Unlike most indoor microenvironments, various types of chemicals are stored in laboratories, and they are used for experiments and analyses. Therefore, exposures to various agents are likely during experiments, and to volatiles during storage in laboratories. People in laboratories can be directly exposed to the chemicals by inhalation and dermal routes, at large quantities making this specific type of indoor microenvironment special to its both types of occupants: staff and students in educational and research laboratories.

2.2 Ventilation

Air exchange between outdoor and indoor environments, ie, ventilation, is used to prevent accumulation of pollutants that have strong indoor sources by exchanging indoor and outdoor air, assuming the concentrations are lower in the latter (making it fresh) compared to indoor air. So, ventilation works in two ways: dilution and exhausting. The types of ventilation are classified into two main groups: natural and mechanical ventilation. The air exchange process in natural ventilation depends on the pressure difference associated mainly with air temperature and winds. It occurs by flow of air from the region of higher pressure toward lower pressure, which requires opening the windows to increase the flow. Although it is economical and it has environmental benefits, this method is almost always inadequate for laboratories. Mechanical ventilation is needed because emission strengths and hazardous potencies of laboratory indoor air pollutants are high. HVAC (heating, ventilating and air conditioning) systems are installed to obtain thermal comfort and acceptable IAQ. HVAC systems, operating even at high air change per hour (ACH) values, are generally not sufficient for some experimental procedures with high emission strength. Therefore, fume hoods are also required for exhausting to outdoors directly preventing entrainment into the laboratory air.

2.3 Building Characteristics

In addition to ventilation type, the other building characteristics that may affect IAQ in chemical laboratories may be moisture damage, building and furnishing materials, and cleaning products. Moisture damage can occur due to leak or high humidity, and affect building materials and components. The colonisation of building materials and HVAC systems by moulds, bacteria and insect pests is an example that occurs as a result of moisture damage in

buildings [52]. Building and furnishing materials can emit different types of chemicals (eg, VOCs and SVOCs) which affect IAQ adversely. Cleaning products are another group of emission sources for VOCs. The use of low-emitting products in building, furnishing materials and for cleaning would lead to healthier buildings.

3. INDOOR ENVIRONMENTAL COMFORT

Along with IAQ, indoor environmental comfort is the second component of indoor environmental quality. Indoor environmental comfort consists of thermal comfort, noise, lighting, vibration and odours, all of which may affect wellbeing and performance of the occupants. In an environment with lack of comfort, occupants may lose their motivation and may need to make an extra effort not to lose concentration on work [53]. Comfort varies from person to person because of differences in age, gender, nationality, health status, etc.; however, the majority of the occupants should feel comfortable in healthy indoors.

3.1 Thermal Comfort

Thermal comfort indicates satisfaction of the occupant from thermal conditions of indoor environment. Therefore, indoor air of laboratories should be neither cooler nor warmer than an optimum temperature range. Thermal comfort is affected from both environmental factors, such as air temperature, relative humidity, air velocity and mean radiant temperature and personal factors (clothing and activity level of people) [54]. Outside air temperature, time of the day and year, heating and cooling capacity of the building, existence of insulation, number of windows and doors and ventilation type are some parameters that can influence the temperature in a laboratory. Oven, muffle furnace, burners, heaters of soxhlet, reactors, separation columns, hotplates and running computers can increase temperature in the laboratories. Changes in the temperature can adversely affect the occupant performance. It was found that 1°C increase in temperature decreases the performance in offices by 2% in the temperature range of 25–32°C whereas no observed effect in 21–25°C [55]. Additionally, warmer air temperature can lead to dissatisfaction and increased heart rate variation [53]. Comfort ranges are variable according to geographic/climatic regions.

Relative humidity is another important comfort variable that depends on various factors such as temperature, air conditioning, human activities and water content in the laboratory; geographic location of building; existence of humidifiers and experimental conditions. Nasal dryness, nasal congestion and skin dryness can be observed at low humidity conditions [56] whereas mould formation and water damages can occur with elevated humidity because of condensation of excess water on the surfaces.

3.2 Noise

Since chemical laboratories are host to various types of laboratory devices, noise pollution is generally inevitable. Location of the laboratory, noise of outside, poor acoustic design of building, existence of insulation in the windows, air conditioners, fume hoods, compressors, gas generators such as N₂, ultrasonic bath and cleaners, stirrers, centrifuge, pumps, refrigerators and most of the other working devices are potential sources of the noise in chemical laboratories. Effect of 2.6 dB change in noise level was found to be same as 1°C change in temperature, and it was shown that the higher the noise level, the higher the thermal unpleasantness [57]. High level and frequency of noise can lead to difficulty in communication. Hearing loss and impairment, cardiovascular diseases, increase in the levels of adrenalin and noradrenalin, headache and nausea are some of the potential health risks of noise pollution [58–62]. Necessary precautions such as insulation, suitable windows and construction materials must be taken for newly constructed buildings. Additionally, equipment minimising noise generation should be chosen if available, for example, the use of lower noise compressors can lower the noise generation by about 10 dBA.

3.3 Lighting

Lighting is the effective parameter for visual comfort of occupants' wellbeing. It is important in chemical laboratories due to the fact that researchers, laboratory technicians or students spend long hours in these environments, and proper preparation to experiments is very crucial. Colour of lamps, illumination and its uniformity, amount of daylight entering to laboratory, types of lamps (fluorescent light, daylight, etc.) and number of windows determine the quality of lighting of the indoor environment. Low illumination intensity causes decrease in concentration on work while high intensity makes participants feel discomfort [63]. Additionally, insufficient lighting can give rise to decrease in working efficiency, fatigue and nervousity [64,65]. Not only light properties but also the incidence direction of the light to the benches (parallel, perpendicular, from one source or more, etc.) affects the workers comfort in a laboratory. The standard for lighting power density of laboratories is 19.5 W/m² (converted from 1.81 W/ft²) [66].

3.4 Vibration

Sources of vibration in indoor environments can be categorised into two groups as internal and external sources. External sources can be listed as traffic (if building is close to a road or railway), motors of ventilators, winds and building construction, whereas vibration caused by internal sources may be walking of occupants, air conditioners and laboratory equipment such as ultrasonic baths,

stirrers, fume hoods, centrifuging, pumps, etc. Hand-transmitted vibration contributes to occurrence of hand-arm vibration syndrome, summation of vascular, neurological and musculoskeletal disorders [67]. Furthermore, whole body-transmitted vibration is related to low back pain, sciatic pain and degeneration in spine [68]. Vibration is a problem for the sensitive measurements as in the case of receiving distorted images from a microscope.

3.5 Odour

Since chemical laboratories involve a wide diversity of chemicals (acids, VOCs, SVOCs, etc.) or samples for investigation (sludge, wastewater, animal tissues, etc.), odour may be an important issue for the indoor environmental quality. Formation of bioaerosols as a result of water damage and their secretions, furnishing materials and paints (if new building), cleaning products, body odour and most importantly inadequate ventilation are the other sources of odour. Degree of influence of odour varies depending on the intensity, frequency, exposure duration, location and offensiveness [69]. Exposure of chemical workers to odour causes loss of sense of smell, nausea, vomiting, gagging, dizziness, lightheadedness and headaches [69–71].

4. REVIEW OF THE LITERATURE ON LABORATORY INDOOR AIR QUALITY

Investigations of IAQ in laboratories have been reported in a very limited number of studies in the international literature [72–76]. These studies are summarised in Table 1 and described in the following paragraphs.

Rumchev et al. [72] conducted a study to assess IAQ in 15 laboratories including five chemistry, six biology, three engineering and computing, and one geology laboratories during the semester and semester break in Curtin University of Technology, Perth, Australia. During sampling periods, laboratories were ventilated naturally or mechanically. After the measurements, a survey was applied to the participants to associate symptoms such as asthma, allergy and fever to the laboratory working hours. The highest median levels of TVOC, UFP, T and RH were measured in chemistry laboratories with the levels of $29.9 \mu\text{g}/\text{m}^3$, $21,694 \text{ particles}/\text{cm}^3$, 23.5°C and 52.5% , respectively. PM_{10} ($27 \mu\text{g}/\text{m}^3$, engineering laboratory) and $\text{PM}_{2.5}$ ($10 \mu\text{g}/\text{m}^3$, biology laboratory) levels were slightly higher than those measured in the chemistry laboratory. It was concluded that levels of pollutants and comfort variables were significantly higher in the semester compared to the break. Additionally, PM_{10} , TVOC and T values were higher in the laboratories without an air conditioner. The results of the survey showed that exposure to higher levels of PM_{10} and TVOC were related to asthma, cough, wheeze, eczema, trouble breathing and itchy eyes.

Valavanidis and Vatista [73] measured IAQ in the undergraduate and research laboratories, lecture halls, classrooms, offices, libraries and cafeterias

TABLE 1 Summary of Studies About the IAQ of Laboratories in the Literature

Reference	Sampling Location	Sampling Period	Laboratory Number and Type	Ventilation Type	Measured Variables	Measurement Location
Rumchev et al. [72]	Curtin University of Technology, Perth, Australia	During semester time and break, 2002 (using a 4 h period)	Five chemistry, six biology, three engineering and computing, one geology laboratories	Mechanical (10 lab) Natural (5 lab)	VOCs, PM ₁₀ , PM _{2.5} , UFPs, T and RH	Lab indoor air
Valavanidis and Vatista [73]	Chemistry Department Building of the University of Athens, Greece	October–June in 2002–2003, 2003–2004 and 2004–2005	Undergraduate experimental and research laboratories	Natural	CO ₂ , CO, NO ₂ , SO ₂ , O ₃ , HCHO, VOCs, TSP, T, RH, noise and WBGT	Lab indoor air
Yau et al. [74]	Malaysia	–	Four pharmaceutical laboratories	Mechanical	PM ₁₀ , CO, CO ₂ , VOCs, HCHO, T, RH and air velocity	Lab indoor air
Park et al. [75]	University Campus in Seoul, South Korea	Using two 8 h period for each sampling area	Four laboratory buildings, two nonlaboratory buildings	–	VOCs	At the stacks of lab fume hoods
Ugranli et al. [76]	Izmir Institute of Technology, Izmir, Turkey	Three weekday measurements with 8 h a day	Three research laboratories in chemistry department and three in chemical engineering department	Mechanical in chemical engineering labs Natural in chemistry labs	PM _{2.5} , PM ₁₀ , VOC, CO ₂ , CO, T and RH	Lab indoor air

IAQ, indoor air quality; VOCs, volatile organic compounds; UFPs, ultrafine particles; PM, particulate matter; RH, relative humidity; TSP, total suspended particles; WBGT, wet bulb globe temperature.

of chemistry department at the University of Athens in Greece for 3 years. Mean levels of CO₂, CO, NO₂, SO₂, O₃, HCHO, TVOCs and TSP in undergraduate laboratories were 980, 3.2, 0.3, 0.2, 0.02, 0.025 ppm, 7.5 mg/m³ and 0.2 mg/m³ for autumn + winter, and 840, 2.8, 0.3, 0.24, 0.02, 0.32 ppm, 8.5 mg/m³ and 0.7 mg/m³ for spring + summer, respectively. These values were found to be 780, 2.6, 0.3, 0.22, 0.02, 0.20 ppm, 6.2 mg/m³ and 0.2 mg/m³ for autumn + winter, and 570, 2.3, 0.24, 0.20, 0.02, 0.25 ppm, 6.8 mg/m³ and 0.5 mg/m³ for spring + summer in research laboratories. Noise, temperature, and RH and wet bulb globe temperature in the undergraduate laboratories were in the range of 68–72 dB, 16–18°C, 65–70% and 16–17°C for autumn + winter, and 56–69 dB, 23–27°C, 48–52% and 18–19°C for spring + summer, respectively, while those were measured as 55–66 dB, 15–18°C, 65–72% and 16–17°C for autumn + winter, and 54–67 dB, 24–26°C, 45–50% and 18–20°C for spring and summer in research laboratories, respectively. High number of students leads to CO₂ concentrations >1000 ppm in the undergraduate laboratories. Concentrations of NO₂ and SO₂ were not considerable and not associated to the experimental studies and number of people. Measured O₃ levels were similar to those measured outdoors. Elevated levels of TVOC and HCHO in the laboratories were related to volatilisation from sources and applied experimental procedures. It was concluded that higher temperatures led to higher volatilisation rates from solvents, thus more contamination in summer. It was found that concentrations of CO₂, CO and TSP were highly affected from ventilation because natural ventilation was restricted in winter.

Comfort variables and indoor air pollutants in pharmaceutical laboratories were studied in Malaysia [74]. Air temperature and RH in the laboratories were ranged 19.5–23.0°C and 49.1–63.5%, respectively. Temperature and RH values were below the standard of ASHRAE except for one laboratory. It was claimed that cooling level of air conditioner in the laboratories could be decreased for satisfactory thermal conditions. Average concentrations of PM₁₀, CO, CO₂, TVOC and HCHO were in the range of 2310–5390 particles/m³, 0.73–2.5, 475–511, 0.5–2.6 and 0.0323–0.0465 ppm, respectively. PM_{0.1}, PM_{0.5}, PM₁, PM₃ and PM₅ were also measured in the study. Except for TVOC concentrations in two microenvironments (chemical and washing rooms), pollutants were not exceeding the standards, so it was recommended that ventilation rate in those laboratories should be increased.

Park et al. [75] investigated VOC concentrations at the stacks of laboratory fume hoods in a university campus in Seoul, South Korea. Building average Σ₁₁VOC concentrations were significantly higher in the four laboratory buildings (range: 85–393 µg/m³) than the two nonlaboratory buildings with values of 9.30 and 18.32 µg/m³ due to utilisation of large amount of chemicals and improperly working purification systems. The differences among the laboratory buildings were considered as the indication of effects caused by experimental conditions.

IAQ and environmental comfort variables were investigated by Ugranli et al. [76] in research laboratories of Departments of Chemistry and Chemical Engineering at Izmir Institute of Technology in Izmir, Turkey. Average values of measured parameters, $PM_{2.5}$, PM_{10} , TVOC, CO_2 , CO, T and RH, were in the range of 9.30–26.2 $\mu\text{g}/\text{m}^3$, 26.1–63.0 $\mu\text{g}/\text{m}^3$, 33.3–43.1 ppb, 413–514 ppm, below detection limit, 23.0–25.0°C and 35.3–44.8%, respectively, in the laboratories of chemistry department. The respective concentrations were measured as 7.64–19.4 $\mu\text{g}/\text{m}^3$, 12.5–48.3 $\mu\text{g}/\text{m}^3$, 13.8–182 ppb, 0.08–0.99 ppm, 402–413 ppm, 26.0–30.0°C and 39.0–46.0% in the laboratories of the Department of Chemical Engineering (ChE). Levels of $PM_{2.5}$ and PM_{10} were found to be related to occupant behaviour, number of people in the laboratory, and outdoor sources thus ventilation. In general, pollutant concentrations and comfort variables were in compliance with the standards (except for TVOC and temperature in one laboratory), hence ventilation systems were sufficient to keep indoor air healthy and comfortable. Therefore, it was recommended to install air conditioner to keep temperature values in the comfort zone. Descriptive statistics for the measured variables reported in the five studies are summarised in Table 2.

The project, in which the study by Ugranli et al. was a part of, also included investigation of the indoor environmental comfort of laboratory staff in ChE [77]. All 19 research laboratories in ChE were visited for observation/assessment of risk factors regarding safety and hygiene. Almost all of the staff of the 19 laboratories (90.2%, $n = 38$) were administered a questionnaire regarding their use of/exposure to physical, chemical, biological and ergonomic risk factors. The observations and the occupant responses were classified according to a four-level scheme. The staff of ChE research laboratories who participated in the study was consisted of 29 females (76%) and 9 males (24%) who were research assistants, specialists and technicians. Majority (79%) of the laboratories had records of the chemicals used while the remaining had partial records. Majority of the laboratories were found to be not satisfactory by the occupants in terms of ventilation and thermal comfort (Table 3). The highest uses of chemicals, therefore probable exposures, were of inorganic gases (80%) and the least to metals (58%). Preventive measures regarding the use of chemicals were in place in all laboratories; however, they were considered as not sufficient by the occupants against direct exposure to solvents and acids in 48% of the laboratories (Table 3). The majority of the laboratories were classified as sufficient in terms of cleanliness and tidiness (53%); however, the majority were classified as not sufficient (21%) or somewhat sufficient (47%) regarding compliance to the university's laboratory safety and hygiene rules.

5. INDOOR ENVIRONMENTAL QUALITY MANAGEMENT

IAQ and occupational safety guidelines/standards can be used to evaluate laboratories, in order to consider management measures to obtain acceptable

TABLE 2 Descriptive Statistics [Mean/Median (Range)] of Indoor Air Quality and Environmental Comfort Variables Measured in Laboratories

	Rumchev et al. [72]			Valavanidis and Vatasta [73]				Yau et al. [74]				Park et al. [75]		Ugranli et al. [76]					
	Chemistry Labs	Biology Labs	Eng. Labs	Undergraduate Labs		Research Labs		Lab. 1	Lab. 2	Lab. 3	Lab. 4	Lab. Buildings	Non-lab. Buildings	Chemistry Department			Chemical Engineering Department		
				winter+ autumn	spring+ summer	winter+ autumn	spring+ summer							Lab. 1	Lab. 2	Lab. 3	Lab. 1	Lab. 2	Lab. 3
Concentrations of Pollutants																			
TVOC	-29.9 (3.4-83.4) µg/m ³	-22.3 (6.3-85.1) µg/m ³	-13.9 (12.7-31.3) µg/m ³	7.5/- (3.0-7.0) mg/m ³	8.5/- (6.8-9.5) mg/m ³	6.2/- (4.2-6.7) mg/m ³	6.8/- (4.5-7.8) mg/m ³	2.6/- ppm	1.3/- ppm	3.5/- ppm	0.5/- ppm	184.74/- µg/m ³	12.1/- µg/m ³	33.3/22.6 (0.00-78.5) ppb	34.5/29.8 (0.00-82.2) ppb	43.1/24.5 (0-938) ppb	13.8/14.1 (2.80-63.5) ppb	20.3-13.8 (6.40-76.6) ppb	182-103 (3.70-2379) ppb
PM _{2.5}	-9.00 (4.2-25.1) µg/m ³	-10.0 (5.2-43.3) µg/m ³	-8.1 (4.1-14.2) µg/m ³											9.30/9.56 (5.31-13.0) µg/m ³	18.7/18.3 (17.6-20.2) µg/m ³	26.2/23.8 (16.8-38.1) µg/m ³	7.64/4.17 (1.04-17.7) µg/m ³	10.4/9.38 (6.30-15.6) µg/m ³	19.4/17.7 (15.6-25.0) µg/m ³
PM ₁₀	-17.0 (8.2-46.1) µg/m ³	-19.5 (13.1-47.3) µg/m ³	-27.0 (10.1-29.2) µg/m ³					3860/- (0-10600) particle/m ³	5390/- (0-15200) particle/m ³	4020/- (0-10600) particle/m ³	2310/- (0-10500) particle/m ³			30.6/31.2 (8.70-79.5) µg/m ³	26.1/30.4 (5.00-62.4) µg/m ³	63.0/41.8 (14.6-328) µg/m ³	12.5/9.43 (2.35-39.0) µg/m ³	14.4/14.6 (1.35-47.1) µg/m ³	48.3/32.2 (6.10-206) µg/m ³
UFP	-721694.5 (6029.2-33998.1) (n/cm ³)	-5637 (5485.1-21740.2) (n/cm ³)	-9245 (5634.1-12019.2) (n/cm ³)																
TSP				0.2/- (0.10-0.30) mg/m ³	0.7/- (0.4-0.80) mg/m ³	0.2/- (0.10-0.30) mg/m ³	0.5/- (0.25-0.70) mg/m ³												
CO ₂				980/- (770-1100) ppm	840/- (700-870) ppm	780/- (450-850) ppm	570/- (460-640) ppm	504.11/- ppm	511.35/- ppm	475.15/- ppm	488.41/- ppm			514/503 (401-725) ppm	463/462 (409-544) ppm	413/415 (364-471) ppm	413/398 (356-608) ppm	402/406 (316-622) ppm	410/411 (343-536) ppm
CO				3.2/- (2.3-4.8) ppm	2.8/- (2.2-3.1) ppm	2.6/- (2.1-3.0) ppm	2.3/- (1.8-2.7) ppm	2.5/- ppm	0.9/- ppm	1.5/- ppm	0.73/- ppm						0.99/1.00 (0.60-1.05) ppm	0.65/0.95 (0.00-1.95) ppm	0.08/0.00 (0.00-1.00) ppm
NO ₂				0.3/- (0.30-0.32) ppm	0.3/- (0.20-0.30) ppm	0.3/- (0.12-0.30) ppm	0.24/- (0.20-0.28) ppm												
SO ₂				0.2/- (0.18-0.20) ppm	0.24/- (0.20-0.30) ppm	0.22/- (0.20-0.25) ppm	0.20/- (0.18-0.20) ppm												
O ₃				0.02/- (0.01-0.02) ppm	0.02/- (0.01-0.03) ppm	0.02/- (0.01-0.28) ppm	0.02/- (0.02-0.1) ppm												
HCHO (ppm)				0.025/- (0.20-0.28) ppm	0.32/- (0.20-0.45) ppm	0.20/- (0.10-0.25) ppm	0.25/- (0.10-0.30) ppm	0.0465/- ppm	0.0428/- ppm	0.0323/- ppm	0.0386/- ppm								
Settled Dust				-/- (360-450) mg/m ²	-/- (400-480) mg/m ²	-/- (350-400) mg/m ²	-/- (340-380) mg/m ²												
Physical Measurements																			
T (°C)	-23.5 (20.0-29.1)	-23.1 (21.5-26)	-23.1 (22.8-26.1)	-/- (16-18)	-/- (23-27)	-/- (15-18)	-/- (24-26)	22.38/-	22.97/-	20.53/-	19.50/-			23.0/22.9 (21.5-24.6)	23.8/25.2 (22.8-26.3)	25.0/25.2 (22.7-27.1)	28.0/28.0 (24.0-30.0)	30.0/30.0 (27.0-32.0)	26.0/26.0 (21.0-28.0)
RH (%)	-52.5 (41.0-75.1)	-44.1 (32.5-52.1)	-45.9 (37.3-53.3)	-/- (65-70)	-/- (48-52)	-/- (65-72)	-/- (45-50)	50.76/-	49.10/-	59.92/-	63.50/-			35.3/35.6 (34.1-46.1)	39.1/40.4 (36.0-46.1)	44.8/45.6 (37.7-51.5)	40.0/40.0 (37.0-47.0)	39.0/39.0 (30.0-49.0)	46.0/48.0 (35.0-53.0)
Noise (dB)				-/- (68-72)	-/- (56-69)	-/- (55-66)	-/- (54-67)												
WBGT (°C)				-/- (16-17)	-/- (18-19)	-/- (16-17)	-/- (18-20)												
Air Velocity (m/s)								0.16/- (0.08-0.23)	0.08/- (0.08/0.11)	0.09/- (0.03-0.16)	0.09/- (0.03-0.19)								

TVOC, Total volatile organic compounds; PM, particulate matter; UFPs, ultrafine particles; TSP, total suspended particles; RH, relative humidity; WBGT, wet bulb globe temperature.

*geometric mean

TABLE 3 Physical and Chemical Risk Factors Assessed by Staff in ChE Laboratories (%)

<i>Physical</i>		Absolutely Sufficient	Sufficient	Not Sufficient	Absolutely Not Sufficient
Ventilation		0.00	10.5	68.4	21.1
Thermal comfort		15.8	10.5	73.7	0.00
Noise		36.8	15.8	36.8	15.8
<i>Chemical</i>	No Danger	Danger—Sufficient Preventive Measures	Danger—not Sufficient Preventive Measures	Danger—no Preventive Measures	
Metals	57.9	26.3	15.8	0.0	
Solvents	15.8	36.8	47.4	0.0	
Acids—bases	15.8	36.8	47.4	0.0	
Gases	20.0	68.0	12.0	0.0	

TABLE 4 Indoor Environmental Quality/Occupational Safety Standards

Indoor Environmental Factor	Limit	AT	Reference
PM _{2.5} (µg/m ³)	<i>Indoor air</i>		
	35	24 h	USEPA [81]
	100	1 h	Health Canada [82]
PM ₁₀ (µg/m ³)	<i>Indoor air</i>		
	150	24 h	USEPA [81]
TVOC (µg/m ³)	<i>Indoor air</i>		
	300	8 h	Seifert et al. [87]
NO ₂ (ppm)	<i>Indoor air</i>		
	0.053	1 year	USEPA [81]
	0.25	1 h	Health Canada [82]
	0.02	1 year	WHO [83]
	0.11	1 h	
	<i>Occupational</i>		
	5	8 h	MAK [84]
CO (ppm)	<i>Indoor air</i>		
	9	8 h	USEPA [81]
	11	8 h	Health Canada [82]
	8.7	8 h	WHO [83]
	<i>Occupational</i>		
	30	8 h	MAK [84]
CO ₂ (ppm)	<i>Occupational</i>		
	5000	8 h	NIOSH [85]
	10 000	1 h	MAK [84]
T (°C)	<i>Indoor air</i>		
	23.5–28	Summer	ASHRAE [86]
	19–26.5	Winter	
	<i>Occupational</i>		
	23–26	Summer	CSA [88]
20–23.5	Winter		
RH (%)	30–80	Summer	Health Canada [82]
	30–55	Winter	

AT, averaging time; TVOC, total volatile organic compounds; PM, particulate matter; RH, relative humidity.

IAQ. Some IAQ and occupational safety standards are tabulated in Table 4, adapted from Toprak et al. [77]. In comparison to the common sources of pollutant emissions, release of contaminants to indoor air during storage, experimental and analytical procedures play a major role for laboratory IAQ. The storage areas should be away from sunlight and should be well ventilated with an exclusive exhaust. Temperature should be kept stable. Chemicals should be kept in sealed containers both to reduce the exposure level and to avoid interaction with other chemicals. The same precautions are also valid for chemical wastes. Containers, in which chemical wastes are accumulated, must be resistant to chemical effects, sealed and should be kept in well-ventilated spaces.

In addition to source control, ventilating at rates according to occupant density and potential contaminant sources is the other major management tool for acceptable IAQ. The minimum outdoor airflow rates required per person (R_p) and per unit area (R_a) were recommended as 5 L/s.person and 0.9 L/s.m², respectively for both science and university/college laboratories [78]. The ACH in laboratories was also recommended in the range of 6–12 ACH [79]. However, it was also stated that the ventilation rates in this range may not be appropriate for all types of laboratories. The hazard level of materials expected to be used in the laboratories and the operation and procedures to be performed should also be considered, then minimum ventilation rates should be determined on a laboratory-by-laboratory basis [80]. In addition, fume hoods as local exhaust ventilation devices should be used for especially potential exposure experiments. Their use helps preventing instantaneous large variations in IAQ. Conducting experiments under fume hoods allows chemicals to be removed without dispersion into the indoor environment. Another important issue about mechanical ventilation systems is that contaminants may accumulate in ventilation ducts creating additional sources of pollution with potential for adverse health effects. Re-entrainment of pollutants emitted from laboratory and fume hood exhausts back into supply air would result in risen exposure in the laboratories and in the other microenvironments in the building spread by the ventilation system. Components of HVAC systems may become fertile grounds for microbial growth, one of the most important sources of risk, resulting in infection of scores of people. Because of these reasons, application of regular care/maintenance and cleaning procedures on the HVAC systems have very important roles for keeping the IAQ at acceptable levels.

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