frontiers in
ENVIRONMENTAL SCIENCE

REVIEW ARTICLE
published: 15 January 2015
doi: 10.3389/fenvs.2014.00069

Outdoor-indoor air pollution in urban environment: challenges and opportunity

Dennis Y. C. Leung *

Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, China

Edited by:
Chuen-yu Chan, Chinese Academy of Sciences, China

Reviewed by:
Eleni Drakaki, National Technical University of Athens, Greece
Deepak Jhajharia, North Eastern Regional Institute of Science and Technology, India

****Correspondence:***
Dennis Y. C. Leung, Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, Hong Kong
e-mail: ycleung@hku.hk

With the continual improvement in our quality of life, indoor air quality has become an important area of concern in the twenty-first century. Indoor air quality is affected by many factors including the type and running conditions of indoor pollution sources, ventilation conditions, as well as indoor activities. Studies revealed that the outdoor environment is also an important factor that cannot be neglected for indoor air quality studies. In this review, the indoor and outdoor air pollution relationships obtained from different studies are discussed in order to identify the key factors affecting the indoor air quality. As climate change is recognized as imposing impacts on the environment, how it affects the indoor air quality and the health impacts to the occupants will be evaluated in this paper. The major challenges and opportunities in indoor/outdoor air pollution studies will be highlighted.

Keywords: ventilation, infiltration, climate change, temperature rise, health impact

INTRODUCTION

With rapid development of the economy and booming population growth, an enormous amount of resources (e.g., energy, water, and food) is required in our society to sustain our activities. As a result, various kinds of pollution have been produced. Among the various pollution problems, air pollution has caused major concern over the world due to its widespread nature, damage to our environment and potential health risk to humans. Although concern has been raised regarding the emission of air pollutants from anthropogenic sources, our society still relies heavily on fossil fuels for various applications such as electricity generation, transportation, industrial and domestic heating, and so on. An obvious result of this is the deterioration of our air quality, particularly in developing countries. Air pollution has become a public concerned problem in modern metropolises. Numerous studies in physics, chemistry, geography, and other relevant areas have been conducted to investigate the cause and seriousness of the air pollution problems (Seinfeld, 1986). At the same time, the issue of indoor air pollution also piqued the interest of many scientists, as people spend most of their time (>80%) indoors (Jenkins et al., 1992). Although the time people spent indoors varies with season, age, gender, type of work, health conditions of inhabitants, and so on, good air quality can safeguard the health of the occupants and increase the productivity of workers. Apparently, indoor air quality should be better than outdoor air quality due to the shielding effect of buildings and possible installation of ventilation and air cleaning devices. However, for those combined indoor and outdoor air quality studies in literature, more than 2/3 have found indoor air pollutant concentration higher than outdoor (Chen and Zhao, 2011). This indicates the importance of conducting more studies in order to enhance our understanding on the cause of problems and associated remedial measures. Meanwhile, the number of publications related to indoor air pollution has increased tremendously in recent decades. Many studies have confirmed that indoor air quality is highly affected by outdoor air quality. Therefore, to solve our pollution problems, both indoor and outdoor environment should be considered. In this paper, various issues of indoor air quality and how it is affected by the outdoor air quality in urban environment will be discussed.

OUTDOOR ENVIRONMENT

Outdoor air pollutants mainly consist of NOx, SO_2, O_3, CO, HC, and particulate matters (PM) of different particle sizes. In urban areas, these pollutants are mainly emitted from on-road and off-road vehicles, but there are also contributions from power plants, industrial boilers, incinerators, petrochemical plants, aircrafts, ships and so on, depending on the locations and prevailing winds. Comparatively, the contribution from cross border sources is less significant in urban areas due to its increased distance from the pollution sources. However, urban air quality is highly affected by city design. Densely distributed and deep street canyons (buildings with large building height to road width ratios) can block and weaken the approaching wind, thus reducing its air dispersion capability (Cheng et al., 2009; Li et al., 2009, 2010). On the other hand, good urban design can disperse air pollutants and alleviate the problems of air pollutant accumulation (Li et al., 2005, 2009; Santamouris, 2013).

INDOOR AIR POLLUTANTS AND SOURCES

INDOOR AIR POLLUTANTS

A number of air pollutants have been recognized to exist indoors, including NOx, SO_2, O_3, CO, volatile and semi-volatile organic compounds (VOCs), PM, radon, and microorganism. Some of these pollutants (e.g., NOx, SO_2, O_3, PM) are common to both indoor and outdoor environments, and some of them may be originated from outdoors. These air pollutants can be inorganic, organic, biological or even radioactive. The effect of these air pollutants on humans depends on their toxicity, concentration and exposure time, and may vary from person to person. The most common effect is called sick building syndrome (SBS), in which people experience uncomfortable or acute health effects such as irritation of nose, eyes and throat, skin ailments, allergies, and so on. The cause may not be identified, but the syndrome may disappear after an affected person leaves the office or building. Indoor air quality can be improved and SBS can be reduced when the ventilation rate of the room is improved (Wargocki et al., 2000). The indoor air quality also affects the performance of workers and office staff. Wyon (2004) found that the performance of real office work would be significantly and substantially affected by changes in indoor environmental quality and that the work performance could be significantly enhanced by removing common indoor sources of air pollution.

SOURCES OF INDOOR AIR POLLUTANTS

Table 1 shows the source of various indoor air pollutants, and their health impacts. According to the World Health Organization (WHO), around 3 billion people in the world still cook and heat their homes using dirty solid fuels (such as waste wood, charcoal, coal, dung, crop wastes) on open fireplaces, cooking stoves or kangs, which generates a large amount of air pollutants (such as SO_2, NOx, CO, and PM). Even worse is that these air pollutants may accumulate in the indoor environment if the indoor air is not well ventilated, which seriously affects the health of the inhabitants (WHO, 2014). There are also many anthropogenic sources (such as wooden construction materials, oil based paints, fragrant decorations, and indoor plants) emitting VOCs at a variety of concentrations. These VOCs (such as formaldehyde) may be carcinogenic, while some of them (such as turpenes) may react with ozone to form secondary fine suspended indoor particles (Weschler and Shields, 1999). Wallace (1985) indicated that many indoor sources of toxic organics exist among thousands of consumer products and building materials. Radon, a colorless carcinogenic radioactive gas and the second most important cause of lung cancer in many countries (EPA, 2014a), causes problem in many houses built with stony construction materials or basements with poor ventilation. There are also biological sources including pets, dust mites and humans. The existence of these indoor air pollutants increases the risk of people with breathing problems, such as asthma sufferers, and with compromised or underdeveloped immune systems.

Many studies (He et al., 2004; Liu et al., 2006; Raunemaa et al., 1989) indicate that indoor air quality is highly related to indoor activities such as smoking, cleaning or conducting combustion processes such as cooking and using a fireplace. He et al. (2004) quantified the effect of indoor sources on indoor particulate concentrations and emission rates from different types of indoor sources and activities, and found that cooking related activities could increase PM during the process and elevate the indoor particle number concentration by 1.5 to 27 times.

EFFECTS OF OUTDOOR ENVIRONMENT ON INDOOR AIR POLLUTION

INTERACTION OF OUTDOOR AND INDOOR AIR

Many studies indicate that indoor air quality is affected by outdoor air (Baek et al., 1997; Jones et al., 2000; Kuo and Shen,

Table 1 | Indoor air pollutants, sources and health impacts.

Type of indoor air pollutant	Sources	Health impacts
PM	Cooking stoves; fireplaces; smoking; outdoor air	Respiratory and cardiovascular illnesses
SO_2	Cooking stoves; fireplaces; outdoor air	Impairment of respiratory function
NO_2	Cooking stoves; fireplaces; outdoor air	Irritate the lungs and lower resistance to respiratory infection
CO	Cooking stoves; fireplaces; water heater; outdoor air	Highly toxic and fatal at a conc. 700 ppm
Ozone	Air cleaning device with high voltage; outdoor air	Asthma and allergic triggers
VOCs (such as formaldehyde, turpenes)	Building materials including carpet, plywood (emit formaldehyde); Paint and solvents; Clothing (after dry cleaning) (emits tetrachloroethylene, or other dry cleaning fluids); air fresheners, incense, other scented items; certain plants (emit turpenes)	Some are carcinogenic; can also trigger the formation of photochemical oxidants, such as peroxyacyl nitrates (PAN) and aldehydes, which cause eye irritation
Radon	Exuded from earth and rocks such as granite and gneiss in certain locations with low ventilated air and trapped inside houses	Radioactive; leading cause of lung cancer in non-smokers
Biological air pollutants (gasses and airborne particulates)	Pets (dander), human (dust from minute skin flakes and decomposed hair), dust mites (enzymes and μm-sized fecal droppings), inhabitants (methane), wall and air-duct (mold)	Increase risk for people with breathing problems, such as asthma sufferers, and with compromised or underdeveloped immune systems

2010; Meadow et al., 2014; Fung et al., 2014). Kuo and Shen (2010) found a similar increase in concentration of PM2.5 and PM10 in both indoor and outdoor air during a dust storm event and interpreted the cause to be the extraction of outdoor air from their building's ventilation system. Baek et al. (1997) studied the I/O relationships in Korean urban areas and confirmed the importance of ambient air in determining the quality of indoor air. In their study, the majority of the VOCs measured in both indoor and outdoor environments were derived from outdoor sources. Recently, Fung et al. (2014) found evidence of diesel exhaust being extracted into a mechanically ventilated building from unloading trucks, which is a quite common phenomenon for those fresh air intakes designed at low level. Jones et al. (2000), in their study on the indoor and outdoor relationships of PM in domestic homes in different locations of Birmingham, UK, found, through the study of the chemical composition, that fine lead and sulfate particles exist in indoor indicating the penetration of air from outdoor sources to indoor environment.

Most of the literature studied the influence of outdoor environments on indoor air quality (Raunemaa et al., 1989; Freijer and Bloemen, 2000; Cyrys et al., 2004; Chen and Zhao, 2011). However, indoor air quality also affects outdoor environments. Lonc and Plewa compared the indoor and outdoor bioaerosols in poultry farms and found that the farm buildings are emitters of microbiological contaminants in the atmosphere that may affect human's health (Lonc and Plewa, 2010, 2011).

These results provide strong evidence of the existence of an interaction between indoor and outdoor air, but the relative contributions of each depends on the interaction pathways discussed in the following section.

PATHWAYS OF OUTDOOR AIR POLLUTANTS TO INDOOR ENVIRONMENT

There are three main mechanisms that allow outdoor air to enter and affect indoor environments: mechanical ventilation, natural ventilation and infiltration (**Figure 1**). Mechanical ventilation can be driven by a ventilation fan or air conditioner of a dwelling, or by a central air conditioning system of a building, all of which draws in outdoor air from their fresh air intakes. Natural ventilation is driven by prevailing wind flow and occurs whenever the doors and windows of the room/building are open. Even without these ventilations, air exchange between indoor and outdoor environments can still occur through cracks and leaks in the building envelope, a process called infiltration, which may be significant for a building with poor sealing. Due to these three mechanisms, the air pollutants from outdoor can penetrate into the indoor environment, and can either be diluted or accumulated according to the ventilation condition. Johnson et al. (2004) studied the key factors affecting air exchange rate (AER) and the relationship between indoor and outdoor concentrations of traffic-related air pollutants. They found that AER was affected by both temperature and wind speed, and tended to increase with increasing the number of opened windows and doors connected to exterior. Furthermore, both the outdoor and indoor pollutant concentrations were suggested to be the variable of choice for predicting indoor pollutant concentration.

This indicates that indoor pollution sources, ventilation conditions, and even the outdoor environment can affect indoor air pollution. In recent years, there have been an increasing number of studies on the relationship between indoor and outdoor air pollutant concentrations under different conditions. These studies and their main findings will be discussed in the subsequent sections.

I/O POLLUTANT CONCENTRATION RELATIONSHIP UNDER DIFFERENT CONDITIONS

Ventilation had a strong influence on both indoor particulate and gaseous concentrations, but the effect on each of them may be different due to the difference in the physical nature of the pollutants and source characteristics.

There is substantial interest in the study of particulate size and concentration variations in indoor and outdoor environment under different measuring and ventilation conditions (Dockery and Spengler, 1981; Baek et al., 1997; Monn et al., 1997; Abt et al., 2000; Koponen et al., 2001; Adgate et al., 2002; Chan, 2002; Cyrys et al., 2004; Cao et al., 2005; Meng et al., 2007; Diapouli et al., 2008; Hoek et al., 2008; Massey et al., 2009; Menetrez et al., 2009; Pekey et al., 2010; Gunnarsen et al., 2014; Ji and Zhao, 2014). Cyrys et al. (2004) studied the I/O ratios of particle and black smoke under different ventilation conditions and found the lowest I/O ratios under closed window conditions, whereas the highest I/O ratios were achieved under well-ventilated environments. In addition, indoor and outdoor pollutant concentrations were correlated, more than 75% of the daily indoor variations could be explained by the daily outdoor variations. Meanwhile Blondeau et al. (2005) studied the I/O relationship in eight French schools with natural and mechanical ventilation, and found that the I/O ratios of NOx vary from 0.5 to 1, but no correlation with building permeability was observed. On the other hand, the I/O ratios of O_3 vary in the range of 0 to 0.45, and low I/O ratios are strongly influenced by the building air-tightness.

Particles of different sizes may exhibit different characteristics during the interaction between indoor and outdoor air. Monn et al. (1997) studied the indoor-outdoor relationship of particulates with different particle sizes in 17 homes in Switzerland with natural ventilation. In those homes without any indoor sources and with low human activity, the PM10 I/O ratio was about 0.7. Of the indoor sources, smoking is the most dominant factor and I/O can be raised to >1.8. On the other hand, in homes not containing any apparent source, human activity is an important contributing factor to high I/O ratios. In their study of the PM I/O relationship, Jones et al. (2000) found that the I/O ratios are greater for fine than coarse particles, indicating a higher penetration of fine particles or enhanced indoor deposition of coarse particles. Diapouli et al. (2008) measured the indoor and outdoor PM at schools with ventilation and found the I/O ratios close to or above one for PM10 and PM2.5, but smaller than one for ultrafine particle. However, similar to other research findings, they also observed very high I/O ratios (>2.5) when there were intense indoor activities such as human movement, smoking, and so on. Massey et al. (2009) determined the indoor/outdoor relationship of fine particles with sizes less than 2.5 μm in residential homes located in central India, and found that the average I/O ratios for

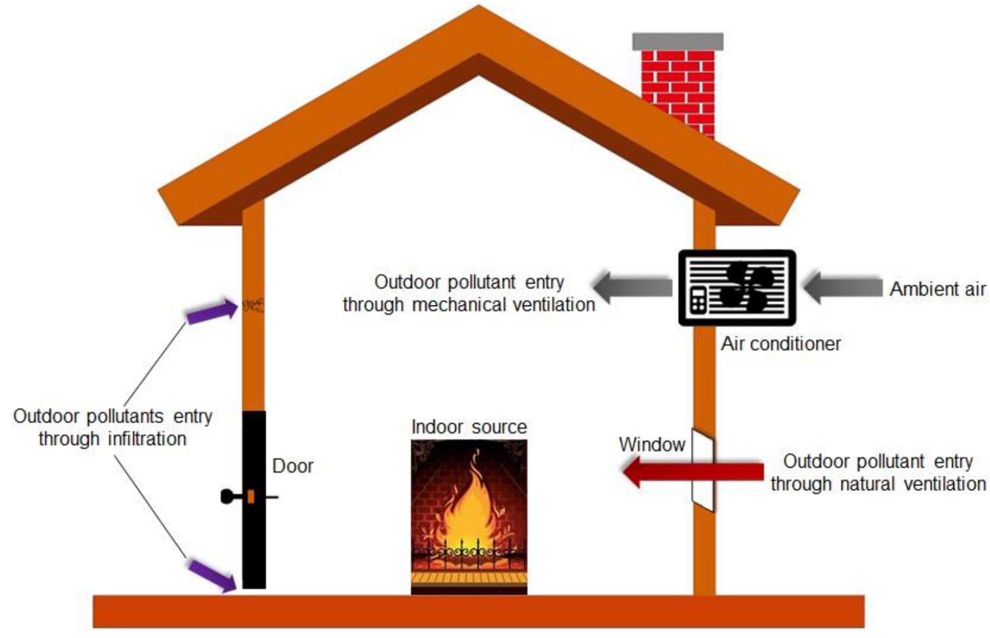

FIGURE 1 | Sources and pathways of indoor air pollutants.

PM2.5, PM1.0, PM0.5, and PM0.25 were close to or above one in roadside and in rural areas while they are less than one for urban areas. Furthermore, the I/O ratios obtained were linked to the indoor activities as recorded by the occupants.

Chen and Zhao (2011) reviewed the relationship between indoor and outdoor particles in the literature, and found that very high PM2.5 I/O ratios (i.e., >3.0) occur in the presence of indoor smoking and combustion sources such as a fireplace, while low I/O ratios (i.e., <1.0) are strongly related to fewer indoor sources, the use of air filtration devices or buildings with good seals (**Figure 2**). This latter finding is in line with the findings of Diapouli et al. (2008). They further concluded that the I/O ratios are affected by many factors and varied enormously, in many cases depending on the indoor conditions (such as the occupancy and ventilation rate) and opined that the I/O ratio is not useful in understanding the I/O relationship of particulates (Chen and Zhao, 2011). Ji and Zhao (2014) modeled the contribution of indoor PM2.5 from outdoor and found that the indoor particle level is related to both indoor and outdoor sources. They suggested that the management strategy of windows and kitchen ventilators for particulate control should be decided according to the particle levels of both indoor and outdoor environments.

Indoor air quality is affected by outdoor air quality, which in turn, is affected by ambient meteorological conditions. Chan (2002) studied the effect of meteorology on the I/O ratio of PM10 and NOx in a university student office in Hong Kong. Through statistical regression techniques, they found that temperature, humidity and solar irradiation play a vital role in the variation of the pollutant concentration's I/O ratio, which shows a convincing tendency to become more concentrated when these three weather parameters are increased. However, in the same study, pressure and wind speed were found to play a less significant role in this I/O relationship.

Compared with particulates, there are relatively fewer studies related to airborne bacteria or microorganism such as fungi. Garrett et al. (1997) studied the seasonal and I/O relationship of airborne fungal spores in 80 homes in Australia, and found that, although there is a significant seasonal variation in spore levels in both indoor and outdoor environments, outdoor spore levels influenced indoor levels significantly and were consistently higher throughout the year. Lee et al. (2006) also found that the indoor fungal and pollen levels followed the outdoor levels, and indoor levels were mostly lower. However, as compared to fungal ratios, the pollen I/O ratios were very low (medium 0.025), suggesting that only a small fraction of pollen penetrated from outdoor to indoor environments, likely due to its larger size. Takahashi (1997) found that the indoor fungi levels were significantly correlated with the indoor temperature and RH, as well as outdoor climatic factors such as temperature, RH and precipitation. Recently, Meadow et al. (2014) conducted a temporal study of indoor airborne bacterial communities in a high-traffic university building installed with a hybrid HVAC system, and found that indoor bacterial communities closely tracked outdoor communities, and human-associated bacterial genera were more than twice as concentrated indoors.

As these results demonstrate, the contribution of indoor PM from outdoor environments varies from study to study, and some of the results are even contradictory. Diapouli et al. (2013) reviewed various studies that estimate the concentration of indoor particles of outdoor origin. The review was focused on three major affection factors: air exchange rate, penetration efficiency and deposition rate, of which the latter two are

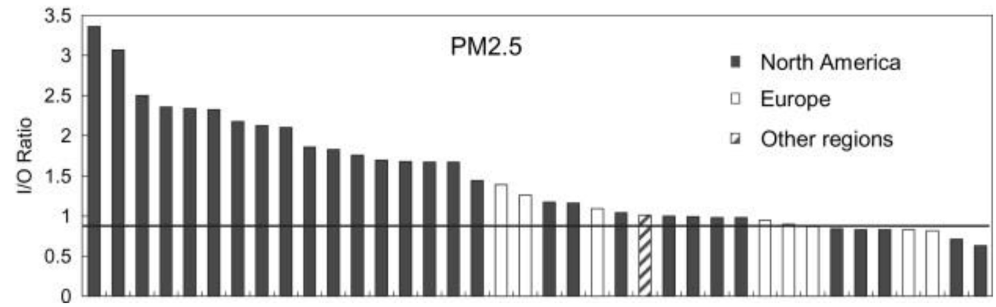

FIGURE 2 | I/O ratio of PM2.5 from different studies in literature (Reprinted from Atmos. Enviro., Vol. 45, Chun Chen, Bin Zhao, Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor, pp. 275–288. Copyright 2010, with permission from Elsevier).

considered difficult to obtain due to the difficulty in providing truly independent values for the calculation. The study on the contribution of indoor/outdoor particles to total personal exposure may be useful for studying the complex relationships between personal/ambient/indoor levels and PM-induced health effects (Diapouli et al., 2013).

IMPLICATION OF CLIMATE CHANGE ON INDOOR AIR QUALITY

Climate change is a global phenomenon caused by the excessive emission of greenhouse gasses such as carbon dioxide and methane. An importance consequence of climate change is global warming, which not only affects the outdoor environment, but also impacts building performance and occupant behavior.

The urban heat island is a well-known phenomenon that normally occurs in cities, which causes many problems to inhabitants, particularly those in tropical environment (Memon et al., 2009; Memon and Leung, 2010). Global warming worsens the heat island effect in metropolises and affects occupant behavior, such as prolonging their time indoors and extending their usage of air conditioners. Thus, possible public health consequences may arise due to increased human exposure to indoor chemical and biological pollutants. Sailor (2014) studied the risks of extreme thermal conditions in buildings in the US associated with climate change, and found that, under hot summer conditions, the interior air temperatures may rise to very uncomfortable levels in the case of an air conditioning system failure. The results of the study highlight the importance of designing buildings and their interior to account for these extreme conditions. Pakpour et al. (2014) studied the effect of climate change on airborne fungal spores and found that the total outdoor fungal spore count increased significantly due to warmer weather. Since many common indoor fungi had a likely origin outdoors, there is a high possibility of elevated indoor fungal spore abundance due to climate change.

Nazaroff (2013) explored the consequences of climate change for indoor air quality and identified three classes of factors that may have important influence on indoor air quality: pollutant attributes (increased outdoor pollutant concentrations increase indoor exposure), building features (ventilation capability due to climate change mitigation) and human behavior (human responses to climate change).

With the release of more studies, people have become more aware of the effects of climate change on indoor air quality and on our health. Vardoulakis et al. (2014) reviewed the health effects of climate change in the UK indoor environment, and indicated that climate change may potentially amplify existing health risks associated with exposure to indoor air pollutions. To counteract this, they suggested that mitigation and adaptation policies in the residential building sector could benefit the health of the occupants. The US Institute of Medicine conducted a comprehensive literature review in 2011 to investigate the effect of climate change on indoor air quality. Inadequate evidence can be found associating climate change with induced alterations in the indoor environment and any specific adverse health outcomes, but there is evidence that climate change may exacerbate existing indoor environmental problems and introduce new problems (Institute of Medicine, 2011). It further claimed that it was vital that public health be placed in the forefront of the criteria taken into account in making decisions on issues that affect indoor environments, such as applying energy conservation measures for combating climate change. The US Environmental Protection Agency also considers climate change to be an important issue for indoor air quality. In late 2013, it announced the provision of $4.5M in funding to study the effects of climate change on indoor air (EPA, 2014b) with emphases on the following aspects with potential to affect human health in indoor environments:

- Changes in pesticide use and ventilation patterns;
- Changes in VOC exposure resulting from increased thermal insulation;
- Changes in exposure to bioaerosols and VOCs resulting from decreased ventilation and increased relative humidity;
- Increases in radon exposure resulting from reduced ventilation; and
- Changes in the proportion of time spent outdoors vs. indoors.

Hopefully, a clearer picture on the different effects of climate changes on indoor air quality can be obtained through the above studies.

CHALLENGES AND OPPORTUNITY

Information about the I/O ratio of air pollutant concentrations is a crucial component in human exposure and health impact assessments of indoor environment. There are many challenges in carrying out I/O ratio study due to the presence of many influential factors, such as the outdoor weather and pollutant concentrations, indoor ventilation and infiltration rates, source strength, human activities, and so on. At present, most of the studies involving I/O ratios are experimentally oriented and the results are diverse. There are very few computational models that predict indoor air quality and its relationship to outdoor conditions (Raunemaa et al., 1989; Freijer and Bloemen, 2000). There are two approaches to evaluate this I/O relationship: a dynamic mass balance model that calculates distributions of transient I/O ratios, and the assumption of a linear relationship between indoor and outdoor pollutant concentrations. The theoretical relationship between these two approaches and the applicable conditions has not yet been fully examined in detail (Freijer and Bloemen, 2000), so this is a potential area of future study. Furthermore, as the outdoor climate may undergo significant change in this and the next century, more research efforts should be directed at how climate change will affect the indoor pollution environment and the associated health impacts.

CONCLUSION

Good indoor air quality is critically important to safeguarding our health since we spend most of our time indoors. Many sources of air pollutants exist indoors, emitting different types and amounts of air pollutants depending on the materials and fuels used, as well as the type of human activity. Air pollutants can also penetrate indoor environments through mechanical and natural ventilation, and infiltrate through gaps and leaks in doors, walls and windows. The amount of air pollutant transported in and out of dwellings depends on the ventilation and infiltration rate of the outdoor air, and the existing indoor and outdoor air quality. As the overall indoor air quality depends on the contribution of both the indoor and outdoor environments, measures and strategy to control indoor air pollution should be formulated according to the relative contribution of indoor and outdoor sources under different conditions. There are challenges in performing I/O ratio studies due to the presence of so many influential parameters. At present, most of the studies are experimentally oriented, and there is no unique model that can predict indoor air quality and its relationship with outdoor conditions.

I/O ratio is a commonly used parameter to represent the relative strength of indoor air pollutant concentration with respect to the immediate outdoor environment. Results in the literature show that large I/O ratios are normally due to the presence of intense activities such as smoking and cooking, while lower I/O ratios are the result of fewer sources and good building insulation. Although there are large variations in I/O ratios for different measurements, it is still the most commonly used parameter for various studies. On the other hand, there is growing evidence that global climate change also affects the indoor air quality and the pollutant exposure level of occupants. Additional studies are necessary to establish a more comprehensive understanding of how climate change will affect the health of residents in homes.

ACKNOWLEDGMENTS

The author wishes to acknowledge the ICEE and CRCG of the University of Hong Kong for supporting the study.

REFERENCES

Abt, E., Suh, H. H., Catalano, P., and Koutrakis, P. (2000). Relative contribution of outdoor and indoor particle sources to indoor concentrations. *Environ. Sci. Technol.* 34, 3579–3587. doi: 10.1021/es990348y

Adgate, J. L., Ramachandran, G., Pratt, G. C., Waller, L. A., and Sexton, K. (2002). Spatial and temporal variability in outdoor, indoor, and personal PM2.5 exposure. *Atmos. Environ*. 36, 3255–3265. doi: 10.1016/S1352-2310(02)00326-6

Baek, S. O., Kim, Y. S., and Perry, R. (1997). Indoor air quality in homes, offices, and restaurants in Korean urban areas – indoor/outdoor relationships. *Atmos. Environ*. 31, 529–544. doi: 10.1016/S1352-2310(96)00215-4

Blondeau, P., Lordache, V., Poupard, O., Genin, D., and Allard, F. (2005). Relationship between outdoor and indoor air quality in eight French School. *Indoor Air* 15, 2–12. doi: 10.1111/j.1600-0668.2004.00263.x

Cao, J. J., Lee, S. C., Chow, J. C. L., Cheng, Y., Ho, K. F., Fung, K., et al. (2005). Indoor/outdoor relationships for PM2.5 and associated carbonaceous pollutants at residential homes in Hong Kong e case study. *Indoor Air* 15, 197–204. doi: 10.1111/j.1600-0668.2005.00336.x

Chan, A. T. (2002). Indoor-outdoor relationships of particulate matter and nitrogen oxides under different outdoor meteorological conditions. *Atmos. Environ*. 36, 1543–1551. doi: 10.1016/S1352-2310(01)00471-X

Chen, C., and Zhao, B. (2011). Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. *Atmos. Environ*. 45, 275–288. doi: 10.1016/j.atmosenv.2010.09.048

Cheng, W. C., Liu, C. H., and Leung, D. Y. C. (2009). On the Correlation of air and pollutant exchange for street Canyons in combined wind-buoyancy-driven flow. *Atmos. Environ*. 43, 3682–3690. doi: 10.1016/j.atmosenv.2009.04.054

Cyrys, J., Pitz, M., Bischof, W., Wichmann, H. E., and Heinrich, J. (2004). Relationship between indoor and outdoor levels of fine particle mass, particle number concentrations and black smoke under different ventilation conditions. *J. Expo. Anal. Environ. Epidemiol.* 14, 275–283. doi: 10.1038/sj.jea.7500317

Diapouli, E., Chaloulakou, A., and Koutrakis, P. (2013). Estimating the concentration of indoor particles of outdoor origin: a review. *J. Air Waste Manag. Assoc.* 63, 1113–1129. doi: 10.1080/10962247.2013.791649

Diapouli, E., Chaloulakou, A., and Mihalopoulos, N. (2008). Indoor and outdoor PM mass and number concentrations at schools in the Athens area. *Environ. Monit. Assess.* 136, 13–20. doi: 10.1007/s10661-007-9724-0

Dockery, D., and Spengler, J. D. (1981). Indoor-outdoor relationships of respirable sulfates and particles. *Atmos. Environ*. 15, 335–343. doi: 10.1016/0004-6981(81)90036-6

EPA. (2014a). *The US Environmental Protection Agency Website: Exposure to Radon Causes Lung Cancer In Non-smokers and Smokers Alike.* Available online at: http://www.epa.gov/radon/healthrisks.html (Accessed 10 September, 2014).

EPA. (2014b). *The US Environmental Protection Agency Website: Funding Opportunity.* Available online at: http://www.epa.gov/ncer/rfa/2014/2014_star_indoor_air.html (Accessed 2 September, 2014).

Freijer, J. I., and Bloemen, H. J. (2000). Modeling relationships between indoor and outdoor air quality. *J. Air Waste Manag. Assoc*. 50, 292–300. doi: 10.1080/10473289.2000.10464007

Fung, C. C., Yang, P., and Zhu, Y. F. (2014). *Infiltration of Diesel Exhaust into a Mechanically Ventilated Building.* Paper#HP0626 Indoor Air 2014, Hong Kong.

Garrett, M. H., Hooper, B. M., Cole, F. M., and Hooper, M. A. (1997). Airborne fungal spores in 80 homes in the Latrobe Valley, Australia: level, seasonality and indoor-outdoor relationship. *Aerobiologia* 13, 121–126. doi: 10.1007/BF02694428

Gunnarsen, L., Witterseh, T., and Olesen, K. B. (2014). *Validation of Simple Method for Determination of Penetration of PCB in Concrete*. Paper#HP1263 Indoor Air 2014, Hong Kong.

He, C., Morawska, L., Hitchins, J., and Gilbert, D. (2004). Contribution from indoor sources to particle number and mass concentration in residential houses. *Atmos. Environ*. 38, 3405–3415. doi: 10.1016/j.atmosenv.2004.03.027

Hoek, G., Kos, G., Harrison, R., de Hartog, J., Meliefste, K., Brink, H. T., et al. (2008). Indoor–outdoor relationships of particle number and mass in four European cities. *Atmos. Environ*. 42, 156–169. doi: 10.1016/j.atmosenv.2007.09.026

Institute of Medicine. (2011). *Climate Change, the Indoor Environment, and Health*. Washington, DC: The National Academies Press.

Jenkins, P. L., Phillips, T. J., and Mulberg, J. M., Hui, S. P. (1992). Activity patterns of Californians: use of and proximity to indoor pollutant sources. *Atmos. Environ*. 26A, 2141–2148. doi: 10.1016/0960-1686(92)90402-7

Ji, W. J., and Zhao, B. (2014). *Comparison of Contribution of Outdoor Particle Between Indoor Sources to Indoor PM2.5 Concentration and Associated Exposure: A Preliminary Modeling Study*. Paper #HP0349 Indoor Air 2014, Hong Kong.

Johnson, T., Myers, J., Kelly, T., Wisbith, A., and Ollison, W. (2004). A pilot study using scripted ventilation conditions to identify key factors affecting indoor pollutant concentration and air exchange rate in a residence. *J. Expo. Anal. Environ. Epidemiol.* 14, 1–22. doi: 10.1038/sj.jea.7500294

Jones, N. C., Thornton, C. A., Mark, D., and Harrison, R. M. (2000). Indoor/outdoor relationships of particulate matter in domestic. *Atmos. Environ*. 34, 2603–2612. doi: 10.1016/S1352-2310(99)00489-6

Koponen, I. K., Asmi, A., Keronen, P., Puhto, K., and Kulmala, M. (2001). Indoor air measurement campaign in Helsinki, Finland 1999 – the effect of outdoor air pollution on indoor air. *Atmos. Environ*. 35, 1465–1477. doi: 10.1016/S1352-2310(00)00338-1

Kuo, H. W., and Shen, H. Y. (2010). Indoor and outdoor PM2.5 and PM10 concentration in the air during a dust storm. *Build. Environ*. 45, 610–614. doi: 10.1016/j.buildenv.2009.07.017

Lee, T., Grinshpun, S. A., Martuzevicius, D., Adhikari, A., Crawford, C. M., Luo, J., et al. (2006). Relationship between indoor and outdoor bioaerosols collected with a button inhalable aerosol sampler in urban homes. *Indoor Air* 16, 37–47. doi: 10.1111/j.1600-0668.2005.00396.x

Li, X. X., Britter, R. F., Koh, T. Y., Norford, L. K., Liu, C. H., Entekhabi, D., et al. (2010). Large-eddy simulation of flow and pollutant transport in urban street canyons with ground heating. *Bound. Lay. Meteorol.* 137, 187–204. doi: 10.1007/s10546-010-9534-8

Li, X. X., Liu, C. H., and Leung, D. Y. C. (2005). Development of a k-e model for the determination of air exchange rate for street canyons. *Atmos. Environ*. 39, 7285–7296. doi: 10.1016/j.atmosenv.2005.09.007

Li, X. X., Liu, C. H., and Leung, D. Y. C. (2009). Numerical investigation of pollutant transport characteristics inside deep urban street canyons. *Atmos. Environ*. 43, 2410–2418. doi: 10.1016/j.atmosenv.2009.02.022

Liu, W., Zhang, J., Zhang, L., Turpin, B. J., Weisel, C. P., Morandi, M. T., et al. (2006). Estimating contributions of indoor and outdoor sources to indoor carbonyl concentrations in three urban areas of the United States. *Atmos. Environ*. 40, 2202–2214. doi: 10.1016/j.atmosenv.2005.12.005

Lonc, E., and Plewa, K. (2010). Microbiological air contamination in poultry houses. *Pol. J. Environ. Stud*. 19, 15–19.

Lonc, E., and Plewa, K. (2011). "Comparison of indoor and outdoor bioaerosols in poultry farming," in *Advanced Topics in Environmental Health and Air Pollution Case Studies*, ed A. Moldoveanu (Rijeka: Intech). doi: 10.5772/20096

Massey, D., Masih, J., Kulshrestha, A., Habil, M., and Taneja, A. (2009). Indoor/outdoor relationship of fine particles less than 2.5 μm (PM2.5) in residential homes locations in central Indian region. *Build. Environ*. 44, 2037–2045. doi: 10.1016/j.buildenv.2009.02.010

Meadow, J. F., Altrichter, A. E., Kembel1, S. W., Kline, J., Mhuireach, G., Moriyama, M., et al. (2014). Indoor airborne bacterial communities are influenced by ventilation, occupancy, and outdoor air source. *Indoor Air* 24, 41–48. doi: 10.1111/ina.12047

Memon, R. A., and Leung, D. Y. C., (2010). Impacts of environmental factors on urban heating. *J. Environ. Sci.* 22, 1903–1909. doi: 10.1016/S1001-0742(09)60337-5

Memon, R. A., Leung, D. Y. C., and Liu, C. H. (2009). An investigation of urban heat island intensity (UHII) as an indicator of urban heating. *Atmos. Res.* 94, 491–500. doi: 10.1016/j.atmosres.2009.07.006

Menetrez, M. Y., Foarde, K. K., Esch, R. K., Schwartz, T. D., Dean, T. R., Hays, M. D., et al. (2009). An evaluation of indoor and outdoor biological particulate matter. *Atmos. Environ*. 43, 5476–5483. doi: 10.1016/j.atmosenv.2009.07.027

Meng, Q. Y., Turpin, B. J., Lee, J. H., Polidori, A., Weisel, C. P., Morandi, M., et al. (2007). How does infiltration behavior modify the composition of ambient PM2.5 in indoor spaces? An analysis of RIOPA data. *Environ. Sci. Technol*. 41, 7315–7321. doi: 10.1021/es070037k

Monn, Ch., Fuchs, A., Högger, D., Junker, M., Kogelschatz, D., Roth, N., et al. (1997). Particulate matter less than 10 μm (PM10) and fine particles less than 2.5 μm (PM2.5): relationships between indoor, outdoor and personal concentrations. *Sci. Total Environ.* 208, 15–21. doi: 10.1016/S0048-9697(97)00271-4

Nazaroff, W. W. (2013). Exploring the consequences of climate change for indoor air quality. *Environ. Res. Lett.* 8. doi: 10.1088/1748-9326/8/1/015022

Pakpour, S., Li, D.-W., and Klironomos, J. (2014). *Climatic Drivers of Airborne Fungal Spore Concentrations in Two North American Cities*. Paper #HP0115, Indoor Air 2014, Hong Kong.

Pekey, B., Bozkurt, Z. B., Pekey, H., Doğan, G., Zararsiz, A., Efe, N., et al. (2010). Indoor/outdoor concentrations and elemental composition of PM10/PM2.5 in urban/industrial areas of Kocaeli City, Turkey. *Indoor Air* 20, 112–125. doi: 10.1111/j.1600-0668.2009.00628.x

Raunemaa, T., Kulmala, M., Saari, H., Olin, M., and Kulmala, M. H. (1989). Indoor air aerosol model: transport indoors and deposition of fine and coarse particles. *Aerosol Sci. Technol*. 11, 11–25. doi: 10.1080/02786828908959296

Sailor, D. J. (2014). *Risks of Extreme Thermal Conditions in Buildings Associated with Climate Change and Exacerbation of the Urban Heat Island.* Paper#HP0794 Indoor Air 2014, Hong Kong.

Santamouris, M. (2013). "On the built environment- the urban influence," in *Energy and Climate in the Urban Environment*, ed M. Santamouris, 3–15. Available online at: http://www.google.com.hk/books?hl=zh-TW&lr=&id=_r_9lPbjxX8C&oi=fnd&pg=PP1&dq =Santamouris,+M.+On+the+built+environment&ots=4BegLwd1b1&sig=pYVwpjQwPDAMGbRqyN_Sms0Tsbw&redir_esc=y#v=onepage&q=Santamouris%2C%20M.%20On%20the%20built%20environment&f=false

Seinfeld, J. H. (1986). *Atmospheric Chemistry and Physics of Air Pollution*. New York, NY: Wiley-Interscience.

Takahashi, T. (1997). Airborne fungal colony-forming units in outdoor and indoor environments in Yokohama, Japan. *Mycopathologia* 139, 23–33. doi: 10.1023/A:1006831111595

Vardoulakis, S., Thornes, J., Lai, K. M., Dimitroulopoulou, S., Myers, I., and Heaviside, C. (2014). *Health Effects of Climate Change in the UK Indoor Environment- A Critical Review.* Paper#HP0450 Indoor Air 2014, Hong Kong.

Wallace, L. A. (1985). Personnel exposures, indoor-outdoor relationships and breath levels of toxic air pollutants measured for 355 persons in New Jersey. *Atmos. Environ*. 19, 1651–1661. doi: 10.1016/0004-6981(85)90217-3

Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G., and Ole Fanger, P. (2000). The effects of outdoor air supply rate in an office on perceived air quality, Sick Building Syndrome (SBS). *Indoor Air* 10, 222–236. doi: 10.1034/j.1600-0668.2000.010004222.x

Weschler, C. J., and Shields, H. C. (1999). Indoor ozone/terpene reactions as a source of indoor particles. *Atmos. Environ*. 33, 2301–2312. doi: 10.1016/S.1352-2310(99)00083-7

WHO. (2014). *Household (Indoor) Air Pollution*. Available online at: http://www.who.int/indoorair/en/ (Accessed 2 September, 2014).

Wyon, D. P. (2004). The effects of indoor air quality on performance and productivity. *Indoor Air* 14, 92–101. doi: 10.1111/j.1600-0668.2004.00278.x

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 22 September 2014; paper pending published: 14 November 2014; accepted: 24 December 2014; published online: 15 January 2015.

Citation: Leung DYC (2015) Outdoor-indoor air pollution in urban environment: challenges and opportunity. Front. Environ. Sci. ***2****:69. doi: 10.3389/fenvs.2014.00069*

This article was submitted to Air Pollution, a section of the journal Frontiers in Environmental Science.