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Review Article

A Review of Scientific Evidence on Indoor Air of School Building: Pollutants, Sources, Health Effects and Management

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ABSTRACT

Schools are one of the critical social infrastructures in a society, the first place for social activity and the most important indoor environment for children besides the home. Poor IAQ in classrooms can increase the chance of long-term and short-term health problems for students and staffs; affects productivity of teachers; and degrade the student learning environment and comfort levels. The primary objective of this paper is to review and summarize available scientific evidence on indoor air quality of schools and related health effects in children. It was found that the indoor air pollutant levels in school buildings varied over a wide range in different parts of the world depending on site characteristics, climatic conditions, outdoor pollution levels, occupant activities, ventilation type and building practices. Among the indoor air pollutants, particulate matter concentrations were found to be very high in many schools. Outdoor pollutant sources also play a major role in affecting the IAQ of the school building. Hence, scientific knowledge on sources of indoor pollutants, quantification of emissions, temporal and spatial dispersion of pollutants, toxicological properties, chemical and morphological characteristics of the pollutants and associated health risk among children in the school buildings are essential to evaluate the adequacy and cost effectiveness of control strategies for mitigating the IAQ issues.

Key words: Indoor Air Quality, Schools, Health effects, Pollutants, Children

1. INTRODUCTION

Over the years, changes in building design to improve energy efficiency have made modern homes, schools and workplaces more airtight than the older buildings. These improvements have led to more energy efficient buildings with less operational costs. The increased use of synthetic materials in the buildings has contributed to increase of a large number of harmful compounds indoors. In addition, outdoor air pollutants can also enter into the building through ventilation intakes, open doors and windows, and leaks in the building envelope. In general, the concentration of a pollutant in the indoor environment depends on the relationship between the volume of air contained in the indoor space, the rate of production or release of the pollutant, the rate of removal of the pollutants (reaction or settling), the rate of air exchange with the outside atmosphere, and the outdoor pollutant concentration (Maroni *et al*., 1995).

The Indoor Air Quality (IAQ) of schools is gaining much attention in recent years. Children spend almost 25-30% of their time, inside classrooms and worldwide, the length of the education expectancy of children over the age of five increased from 10.1 years in 1999 to 11.0 years in 2007 (UNESCO, 2009). School environments differ from adult work environments because children have special habits such as unprotected coughs and sneezes, less likely to wash their hands, and more likely to share the "tools of the trade" such as pencils, that encourage the spread of infectious disease (Oliver and Shackleton, 1998). Moreover, children are more sensitive to air pollutants. Since their organs are in developing stage they breathe more air relative to their body size than adults (WHO, 2006a; Mendell and Health, 2005; Faustman *et al*., 2000). Poor IAQ can increase the chance of long-term and short-term health problems for students and staff; reduce productivity of teachers; and degrade the student learning environment and comfort levels. The National Center for Education Statistics of the Department of Education reported that approximately one in five U.S. public schools had unsatisfactory IAQ (U.S. EPA, 2012).

This paper presents a state of the art analysis of rese-

Table 1. Indoor air pollutants and their sources in schools.

Pollutants	Sources	
	Indoor	Outdoor
Particulate Matter (PM)	Chalk dust, soil dust, new furniture, cleaning activities, resuspension of particles due to children's movements, combustion sources such as heaters, gas- and woodstoves and smoking	Traffic and industrial emissions
Carbon monoxide (CO)	Heaters, gas and woodstoves and smoking	Traffic and industrial emissions
Nitrogen dioxide (NO_2)	Gas appliances, heaters and smoking	Traffic and industrial emissions
Sulpher dioxide (SO_2)	–	Burning of coal and other fuels
Ozone (O_3)	Ozone generators, electrostatic air cleaners, photocopiers and laser printers	Secondary photochemical reactions
Volatile organic compounds (VOCs)	Furnishings such as desks and shelves, resins of wood products, adhesives, glues, paints, fibre board, plywood, cleaning products and carpets	Traffic emissions
Bioaerosols	Human occupants and heating, ventilation and air-conditioning system	Pollens

arch in the area of health and wellbeing of children and their relationship to IAQ in school buildings. The focus of this paper is to review and summarize available scientific evidence on the various sources, types and level of indoor air pollutants in classrooms and further to establish a link between these IAQ parameters with the health and wellbeing of students. The paper also discusses the indoor air quality management practices across the world. This may help researchers of the future to establish a robust foundation for research in this area. In this study, quite an extensive range of literature was reviewed. The literature included refereed journals, books, refereed conference proceedings and reports available on the internet.

2. INDOOR AIR POLLUTANTS AND THEIR SOURCES

The composition of indoor pollutants is quite complex and their concentration levels and sources exhibit large variability among different microenvironments. The IAQ issues in schools may be very different from those observed in residential and commercial buildings. In residential and commercial buildings, pollutants can arise from a range of sources, such as environmental tobacco smoke, cooking, domestic chemicals and furnishings. Classrooms normally lack of typical indoor sources such as smoking and cooking. Yet, several studies reported that the pollutant concentrations measured inside classrooms were higher than the concentrations measured in residences and commercial buildings (Oeder *et al*., 2012; Lee *et al*., 2002). In general, schools have their own particular sources of pollutants: chalk dust; fungi, bacteria, and viruses brought to the school environment by children and adults; and vapors and fumes from laboratories, and art classes. Indoor air pollutants can originate within the building or be drawn in from outdoors. The pollutants present in the indoor air is classified into three major types namely, particulate matter (PM), gaseous pollutants and bioaerosols. The major indoor and outdoor sources of air pollutants in schools are summarized in Table 1.

2.1 Particulate Matter

The PM is a mixture of solid particles and liquid droplets found in the air. Atmospheric particles possess a range of morphological, chemical, physical and thermodynamic properties and its constituents typically vary in size, composition and origin. The distribution of particles with respect to size is an important physical parameter governing their behaviour. Particle diameters span more than four orders of magnitude, from a few nanometers to one hundred micrometers. They often are not spherical and have a range of densities. Therefore, their diameters are often described by an 'equivalent' diameter called aerodynamic diameter. It is defined as the diameter of a spherical particle with a density of 1 g/cm^3 but with a settling velocity equal to that of the particle in question. Particles are generally classified as 'coarse' and 'fine' particles according to the aerodynamic diameter. The most commonly used PM size fractions in air quality research are as follows.

- Total suspended particulate matter (TSPM): Comprises all airborne particles up to 100 μm.
- PM_{10}: Particles with an aerodynamic diameter <10

μm with a 50% efficiency cut-off.
- $PM_{2.5}$: Particles with an aerodynamic diameter <2.5 μm with a 50% efficiency cut-off.

The size of the particles also determines the time they spend in the air. While sedimentation removes PM_{10} from the air within few hours of emission, $PM_{2.5}$ may remain there for days or even a few weeks. Consequently, these particles can be transported over long distances (Krzyzanowski *et al*., 2005). Finer particles are of great concern to human health since they can penetrate deep into the respiratory system, take longer time to remove from the body (Miller, 2000) and associated with many respiratory and cardiovascular diseases (Mate *et al*., 2010; Wallenborn *et al*., 2009; Medina *et al*., 2004; Mohanraj and Azeez, 2004; Neuberger *et al*., 2004; Pope *et al*., 2004, 2002; WHO, 2003; Morris, 2001; Pearce and Crowards, 1996; Schwartz *et al*., 1996).

PM pollution has been identified to be a major indoor air pollution (IAP) problem in many schools. Particulate pollutants are emitted from a broader range of sources including chalk dust, soil dust, new furniture, cleaning activities, resuspension of particles due to children's movements, combustion sources such as heaters, gas and wood stoves, smoking when allowed, outdoor traffic and industrial emissions. Traffic emissions are found to be one of the most important sources of indoor and outdoor air pollution in schools (Mazaheri *et al*., 2016; van der Zee *et al*., 2016; Demirel *et al*., 2014; Buonanno *et al*., 2013; Habil *et al*., 2013; Raysoni *et al*., 2013; Zwozdziak *et al*., 2013; Tran *et al*., 2012; Guo *et al*., 2010; Goyal and Khare, 2009; Yang *et al*., 2009; Stranger *et al*., 2008; Branis *et al*., 2005; Lee and Chang, 2000). Another main reason for elevated coarse PM concentrations in classrooms is due to intense occupant activities (Agarwal and Nagendra, 2016; Chithra and Nagendra, 2012; Diapouli, 2008; Fromme *et al*., 2008; Stranger *et al*., 2008; Branis *et al*., 2005; Poupard *et al*., 2005; Janssen *et al*., 1999, 1997). Human activities could act as an important indoor source for particulate generation in classrooms considering that the occupant density in the schools was several times higher than that in other buildings. Elevated indoor PM concentrations were predominantly generated by the activities of occupants such as movement of students and teachers inside the classroom, black board writing using chalk, cleaning/sweeping etc. Major movement of occupants occurs at the start of the school day, breaks, and at the end of the school day. Thatcher and Layton (1995) reported that even low activity would have a significant impact on the concentration of airborne particles with diameters greater than 5 μm. Just walking into and out of the room can increase the mass of coarse suspended particles by almost 100%. From experiments, they concluded that the particles larger than 5 μm were subjected to resuspension, particles smaller than 5 μm were not readily resuspended, and particles smaller than 1 μm showed almost no resuspension, even with vigorous activity.

Many researchers analysed the effect of PM sources in the immediate vicinity of schools (Rufo *et al*., 2016; Fromme *et al*., 2007; John *et al*., 2007; Poupard *et al*., 2005) by monitoring PM in more than one school located in different sites like urban, rural, near traffic and industrial areas. Lee and Chang (2000) investigated the indoor and outdoor air quality at five schools in Hong Kong and found that high level of PM_{10} was due to vehicle exhaust emissions followed by emissions from industrial processes or construction activities. Janssen *et al*. (2001) also observed that $PM_{2.5}$ and soot concentrations in both indoor and outdoor air of schools in the Netherland were significantly increased with increasing truck traffic. Gadkari (2010) studied the indoor fine PM among school communities in mixed urban-industrial environment in India and reported that school located near the steel plant have shown 5 to 6 times higher PM values compared to the National Ambient Air Quality Standards (NAAQS). Several investigators compared the PM concentration in different indoor environments in the school building like classrooms, library, administrative office, laboratory etc. (Gaidajis and Angelakoglou, 2009; Diapouli *et al*., 2008; Sawant *et al*., 2004) and concluded that the resuspension of particles due to occupants' activities plays an important role in indoor coarse particle concentration. A study by Triantafyllou *et al*. (2008) reported that tobacco smoking was a major source of fine particles in schools. Location of the classroom inside school also plays an important role in the IAQ level. PM mass and number concentrations were measured in multilevel classrooms by Agarwal and Nagendra (2016). Result showed highest PM_{10} mass concentration in ground floor classroom and showed decreasing trend with increase in floor height. The highest particle number concentration (PNC) for particles of size 0.3-1 μm were observed in first floor classroom followed by second floor classroom and then ground floor classroom. Similarly, El-Sharkawy (2014) also found that the average levels of pollutants inside the classrooms of the first floor were higher than that of the second floor.

Most of the previous studies conducted at school buildings were focused on PM_{10} and $PM_{2.5}$ mass concentration. Few measurements were also reported on ultrafine particles (Mazaheri *et al*., 2016; Rufo *et al*., 2016; Dorizas *et al*., 2015; Rivas *et al*., 2015; Viana *et al*., 2015; Zhang and Zhu, 2012; Mullen *et al*., 2011; Morawska *et al*., 2009; Diapouli *et al*., 2008), which

represent a significant fraction of the particulate emitted from combustion sources. It can remain suspended in the air for a long time and can easily penetrate deep portion of the lungs where the gas exchange occurs between the air and blood stream. The health effects of PM strongly depend on its composition, which consists of inorganic ions, organic carbon (OC), elemental carbon (EC), crustal elements and toxic metals. Recently, few attempts were also made to chemically characterize the particles in the school building. John *et al*. (2007) analysed trace elements and ions in the ambient fine PM at three elementary schools in Ohio and observed strong seasonal and regional variations in indoor PM. Most of the researchers observed that sulphate and calcium (caused by the use of chalk) were the major components of indoor PM in the school building (Rivas *et al*., 2015; Amato *et al*., 2014; Canha *et al*., 2014; Chithra and Nagendra, 2013; Pegas *et al*., 2012; Tran *et al*., 2012; Diapouli, 2008; Fromme *et al*., 2008; Stranger *et al*., 2008; John *et al*., 2007). Organic and elemental carbon was also found in indoor PM (Rivas *et al*., 2015; Alves *et al*., 2014; Chithra and Nagendra, 2013; Pegas *et al*., 2012). The influence of traffic at roadside is reflected in higher EC mass fractions. Tran *et al*. (2014) reported lower concentrations of carcinogen elements such as As, Cd, Cr, and Ni in French classrooms.

2.2 Gaseous Pollutants

Gaseous pollutants include both VOCs and inorganic gases. The major gaseous pollutants found in the school buildings are carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ozone (O_3) and VOCs.

2.2.1 Carbon Dioxide

It is a colourless, odourless gas exhaled by humans continuously due to the metabolic processes. Although CO_2 is produced by the combustion of fossil fuels, it is not classified as an air pollutant. At low concentrations typically occurring indoors, CO_2 is harmless and is not perceived by humans. Exhaled air is usually the largest source of CO_2 in classrooms. CO_2 concentrations are often used as a surrogate of the rate of outside supply air per occupant. Indoor CO_2 concentrations above 1,000 ppm are generally regarded as indicative of ventilation rates that are unacceptable with respect to body odours. Norback *et al*. (1990) studied the incidence of sick building syndrome (SBS) in six primary schools. This study showed that the average CO_2 concentrations in all sites were greater than 800 ppm and indicated inadequate ventilation. Similarly, Lee and Chang (2000) investigated IAQ of five classrooms in Hong Kong and reported that the CO_2 concentrations often exceeded 1,000 ppm in classrooms. In most of the classrooms the CO_2 concentrations were found to be exceeding 1,000 ppm (Buonanno *et al*., 2013; Pegas *et al*., 2012; Yang *et al*., 2009; Fromme *et al*., 2007; Godwin and Batterman, 2007), indicating inadequate ventilation. However, Kim *et al*. (2007, 2005), Smedje and Norback (2000) and Chithra and Nagendra (2012) reported CO_2 concentrations below this limit value.

Most of the available information on CO_2 concentration in schools comes from measurements performed in mechanically ventilated classrooms. In order to evaluate the existing knowledge on CO_2 concentration in schools, Santamouris *et al*. (2008) conducted a comprehensive review on CO_2 concentration in naturally (287 classrooms of 182 schools) and mechanically ventilated (900 classrooms of 220 schools) buildings. A higher average CO_2 concentration was observed in naturally ventilated schools (median = 1,420 ppm) than the mechanically ventilated ones (median = 910 ppm). Only 25% of the naturally ventilated schools present concentrations lower than 1,000 ppm, while for the mechanically ventilated schools the figure increases to 52%. Available information on the CO_2 concentrations in naturally ventilated schools comes mainly from measurements under closed windows conditions, or measurements under static conditions where the area of the opened windows remains constant (Santamouris *et al*., 2008).

2.2.2 Carbon Monoxide

CO is a colourless, odourless toxic gas formed by incomplete combustion of fuel. It is a nonreactive species in the air, does not react rapidly with surfaces and has low water solubility. Once it is released to the atmosphere, its main fate is oxidation, by reaction with $OH\cdot$ to CO_2. In school buildings, CO mainly derives from combustion sources such as heaters, gas and wood stoves, and smoking when allowed (Triantafyllou *et al*., 2008). Main outdoor sources of CO in urban schools are vehicular emissions (Chithra and Nagendra, 2012; Yang *et al*., 2009; Chaloulakoua and Mavroidis, 2002). Yang *et al*. (2009) measured the indoor and outdoor CO concentrations at 55 different schools from six metropolitan areas in Korea. The indoor/outdoor (I/O) CO concentration ratios in the classrooms, laboratories and computer rooms were 0.71, 0.20 and 0.14, respectively. The CO concentrations in the school buildings were found to be very low in most of the studies, since they are mainly originated from outdoor vehicular emissions. Tran *et al*. (2014) reported that cigarette smoking also contribute indoor CO concentrations.

2.2.3 Nitrogen Dioxide

It is a corrosive gas with a pungent odour and it has low water solubility. The sources of NO_2 emissions in

the indoor environment are gas appliances, heaters, and smoking of cigarettes. The presence of these sources is very limited in most of the schools. Hence, outdoor air can act as an important source for indoor NO_2 pollution in school buildings. NO_2 is generally considered as a marker for traffic emissions. In the absence of indoor emission sources, levels of NO_2 in classrooms generally correlate well with those observed outdoors (Stranger *et al*., 2008; Lee and Chang, 2000). Also, the indoor concentrations of NO_2 were higher than outdoor concentrations. In most of the previous studies in schools reported very low NO_2 concentrations (Rivas *et al*., 2015; Demirel *et al*., 2014; Raysoni *et al*., 2013; Poupard *et al*., 2005; Lee and Chang, 2000) expect in Antwerp, Belgium where the maximum concentration reached up to 159 $\mu g/m^3$ (Stranger *et al*., 2008). The increased values for NO_2 concentrations in schools of Belgium were related to elevated O_3 levels in the warmer season, promoting increased nitric oxide (NO) to NO_2 conversion and with the consequent O_3 formation in the presence of VOCs and sunlight.

2. 2. 4 Ozone

O_3 is a secondary air pollutant that forms at ground level when hydrocarbons and oxides of nitrogen react with ultraviolet radiation in sunlight to produce photochemical smog. In general, indoor O_3 concentrations are substantially lower than outdoor concentrations unless there is an important O_3 source such as ozone generators, electrostatic air cleaners, photocopiers and laser printers exist (Stranger *et al*., 2008). In general, O_3 concentrations in schools were higher in outdoors than indoors (Demirel *et al*., 2014; Jovanovic *et al*., 2014; Mi *et al*., 2006; Poupard *et al*., 2005). There is evidence to suggest that a lower I/O ratio for O_3 in the classroom was resulted from deposition on various solid surfaces, and chemical reactions in the indoor air, rather than the filtering of the ventilation air when entering the building (Demirel *et al*., 2014; Poupard *et al*., 2005). Absence of the major sources at classrooms such as photocopy machines or ozone generators may also result in lower indoor O_3 concentrations (Stranger *et al*., 2008).

2. 2. 5 Sulphur Dioxide

It is a colourless gas with a strong pungent odour. It is readily soluble in water and can be oxidised within airborne water droplets. SO_2 is a precursor to sulphates, which is one of the main components of respirable particles in the atmosphere. SO_2 is produced by the oxidation of sulphur present in the coal and other fuels. SO_2 levels were generally lower in indoors than outdoors. Only very few studies have been reported on SO_2 concentration in school buildings (Stranger *et al*., 2008; Lee and Chang, 2000). Lee and Chang (2000) investigated IAQ of five classrooms in Hong Kong and observed that the SO_2 levels ranged from 5 to 16 $\mu g/m^3$. Stranger *et al*. (2008) measured SO_2 concentrations in 27 primary schools located in Antwerp, Belgium and reported that the indoor SO_2 concentrations were on average 70% lower than the corresponding outdoor levels, with a very low average I/O ratio of 0.3 ± 0.1, confirming the outdoor origins of indoor SO_2.

2. 2. 6 Volatile Organic Compounds

According to U.S. EPA, volatile organic compounds means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions. VOCs are organic chemical compounds whose compositions make it possible for them to evaporate under normal indoor atmospheric conditions of temperature and pressure. This general definition of VOCs is used in the scientific literature, and is consistent with the definition used for IAQ. The European Union uses the boiling point, rather than its volatility in its definition of VOCs. A VOC is any organic compound having an initial boiling point less than or equal to 250°C measured at a standard atmospheric pressure of 101.3 kPa. VOCs are sometimes categorized by the ease they will be emitted. For example, WHO categorizes indoor organic pollutants as very volatile, volatile, and semi-volatile. Very volatile organic compounds (VVOCs) are so volatile that they are difficult to measure and are found almost entirely as gases in the air rather than in materials or on surfaces. The least volatile compounds (SVOCs) found in air constitute a far smaller fraction of the total present indoors.

VOCs include a variety of chemicals and the concentrations of many VOCs are consistently higher indoors (up to ten times higher) than outdoors. VOCs are emitted by a wide array of products which includes paints and lacquers, paint strippers, cleaning supplies, pesticides, building materials and furnishings, office equipment such as copiers and printers, correction fluids and carbonless copy paper, graphics and craft materials including glues and adhesives, permanent markers, and photographic solutions (U.S. EPA, 2014). VOCs have low boiling points which means that they readily offgas vapours into indoor air. In any given environment, the concentration of individual VOCs will be very variable and depend upon the presence or absence of an extremely wide range of potential emission sources.

The known emission sources of VOCs in schools are construction materials, furnishings such as desks and shelves, resins of wood products, adhesives, glues, paints, cleaning products and carpets (Alves *et al*., 2016; Jovanovic *et al*., 2014; Yang *et al*., 2009; Godwin and

Batterman, 2007). The levels of VOCs found in schools indoor can be much higher than those found outdoor. VOC concentration may be much higher than typical ambient levels in newly constructed school buildings, or those in which decorations have recently taken place. VOCs in schools can also contribute from outdoor air (traffic emissions). Measurements of total and speciated VOCs in schools were reported in the literature (Demirel *et al*., 2014; Jovanovic *et al*., 2014; Raysoni *et al*., 2013; Pegas *et al*., 2012; Yang *et al*., 2009; Stranger *et al*., 2008; Godwin and Batterman, 2007). The most common species of VOCs found were benzene, toluene, ethylbenzene and xylene (BTEX). Among BTEX, toluene concentrations were found to be higher in classrooms than other compounds (Madureira *et al*., 2015; Demirel *et al*., 2014; Jovanovic *et al*., 2014; Raysoni *et al*., 2013). Formaldehyde is another VOC present in the classrooms, which is used widely to manufacture building materials and numerous other products. In school buildings, it is emitted via glues, fibre board, pressed board, plywood, insulating materials, carpet backing, fabrics, paints, cleaning and other consumer products (Madureira *et al*., 2015; Yang *et al*., 2009). Formaldehyde concentrations in the classrooms were also found to be very low and sometimes even below detectable limit (Yang *et al*., 2009; Lee and Chang, 2000). However, a study reported by Jovanovic *et al*. (2014) in Serbian schools indicated that the average value of formaldehyde in all classrooms was significantly higher than recommended value.

2. 3 Bioaerosols

Bioaerosols refers to a diverse variety of agents from biological sources found in indoor environments, which include: viruses; bacteria, endotoxins released from bacteria; allergens; and fungi. This definition includes all airborne microorganisms regardless of viability or ability to be recovered by culture; it comprises whole microorganisms as well as fractions, biopolymers and products from all varieties of living things (ACGIH, 1999). Major indoor sources of bioaerosols at schools include human occupants, as well as the heating, ventilation and air-conditioning (HVAC) system. The air-conditioning system controls the air humidity, temperature and particulate content, etc. by means of various components such as filters, humidifiers, fresh air supply, cooling and heating systems. At the same time, the system may induce a serious indoor microbial contamination problem. Water spray humidifiers containing stagnant water, filters packed with organic dust, cooling coils covered with condensation, condensate pans being undrained and any excessively humid interior might all offer suitable environments for microbial proliferation. Airborne Bacteria Count (ABC) in an indoor environment is a good indicator of the cleanliness of the HVAC system and one of the important parameters to evaluate IAQ (Mui *et al*., 2008). Human bodies can generate bioaerosols through activities like talking, sneezing, and coughing. Qian *et al*. (2012) estimated size-resolved emission rates of airborne bacteria and fungi in an occupied classroom. Particle size distributions of total airborne PM, bacterial genomes, and fungal genomes were measured under occupied and vacant conditions, and a material balance model was applied to determine the per person emission rates of bacterial and fungal size-fractionated particles attributable to occupancy.

The bioaerosols levels in the school buildings were found to be very high with maximum bacterial concentration of 5,525 CFU/m^3 was found in Korean schools (Yang *et al*., 2009). They observed a significant correlation between CO_2 and bacterial concentrations and indicated that low ventilation may be the cause of increased bacteria. Another study conducted in Korea also reported higher concentrations of bacterial and fungal aerosols (Jo and Seo, 2005). In contrast, Lee and Chang (2000) observed lower concentrations of bioaerosols ($<$1,000 CFU/m^3) in Hong Kong schools. Deng *et al*. (2016) reported the presence of both gram-positive and gram-negative bacteria in the kindergartens of Hong Kong. Gram-positive bacilli were the most dominant genus. Other gram-positive bacteria, including Staphylococcus, *Coprococcus, Ruminococcus, Micrococcus*, and *Corynebacterium*, were found in all the samples. Gram-negative bacteria, including *Bacteroidetes, Escherichia, Rhizobium*, and *Enterobacter*, also made up a large proportion. The most commonly found fungal species in the classroom are *Cladosporium, Penicillium, Aspergillus*, and *Alternaria*. The indoor bioaerosols concentrations in classrooms were found to be higher than outdoors in all the studies.

The indoor air pollutants and their levels in schools in different regions of the world during the last two decades were summarized in Table 2. Among the indoor air pollutants, PM concentrations were found to be very high in many schools. The maximum PM_{10} concentrations (1,181 μg/m^3) were observed in Delhi, India (Goyal and Khare, 2009) and the minimum PM_{10} (3 μg/m^3) levels were observed in Porto, Portugal (Branco *et al*., 2014). PM concentrations in urban schools of India were much higher than those measured in European countries and elsewhere. Indoor air pollutant levels in school buildings varied over a wide range in different parts of the world depending on site characteristics, climatic conditions, outdoor pollution levels, occupant activities, ventilation type and building practices. Hence, while considering the student exposure to pollutants at school, one need to take into account both

Table 2. Indoor air pollutants and their concentration levels in schools across the world.

Location	Site characteristics	Pollutants concentrations	References
Amsterdam, Netherlands	Urban, non-industrial	PM_{10} = 45.9-74.4 μg/m^3	Janssen *et al*., 1997
Hong Kong	Urban, residential, industrial, rural, natural and mechanical ventilation	PM_{10} = 21-617 μg/m^3; SO_2 = 5-16 μg/m^3; NO = 18-115 μg/m^3; NO_2 = 31-67 μg/m^3; HCHO = < MDL*-27 μg/m^3; Bioaersols = < 1,000 CFU/m^3; CO_2 > 1,000 ppm	Lee and Chang, 2000
Athens, Greece	Urban, naturally ventilated	CO = 1.17-3.96 ppm	Chaloulakoua and Mavroidis, 2002
California, USA	Semi-rural, mechanically ventilated	$PM_{2.5}$ = 16.3 μg/m^3; Carbonyl = 38-105 μg/m^3	Sawant *et al*., 2004
Prague, Czech Republic	Urban, naturally ventilated	PM_{10} = 42.3 μg/m^3; $PM_{2.5}$ = 21.9 μg/m^3; PM_1 = 13.7 μg/m^3	Branis *et al*., 2005
Daegu, Korea	Urban, mechanically ventilated	Bacteria = 269-1,621 CFU/m^3; Fungi = 28-616 CFU/m^3	Jo and Seo, 2005
La Rochelle, France	Urban, traffic, industrial, residential, rural, seaside, natural and mechanical ventilation	O_3 = 15-41 ppb; NO = 1-52 ppb; NO_2 = 1-27 ppb; $PM_{0.3\text{-}0.4}$ = 17,026-117,690/L; $PM_{1.6\text{-}2}$ = 67,365-504,540/L	Poupard *et al*., 2005
Munich, Germany	Urban residential, naturally ventilated	CO_2 = 480-4,172 ppm; PM_{10} = 105 μg/m^3; $PM_{2.5}$ = 23 μg/m^3	Fromme *et al*., 2007
Michigan, USA	Suburban, mechanically ventilated	Total VOCs = 58 μg/m^3; Bioaerosols = 505 CFU/m^3; CO_2 > 1,000 ppm	Godwin and Batterman, 2007
Ohio, USA	Urban, suburban, rural, industrial	$PM_{2.5}$ = 15.56-17.3 μg/m^3	John *et al*., 2007
Montana, USA	Urban	$PM_{2.5}$ = 4.6-54 μg/m^3	Ward *et al*., 2007
Athens, Greece	Urban, naturally ventilated	PM_{10} = 229 ± 182 μg/m^3; $PM_{2.5}$ = 82 ± 56 μg/m^3; Ultrafine PM = 24,000/cm^3	Diapouli *et al*., 2008
Munich, Germany	Urban residential, naturally ventilated	PM_{10} = 118.2 μg/m^3; $PM_{2.5}$ = 37.4 μg/m^3	Fromme *et al*., 2008
Antwerp, Belgium	Urban, naturally ventilated	$PM_{2.5}$ = 57 ± 10 μg/m^3; SO_2 = < MDL*-3.5 μg/m^3; O_3 = < MDL*-9.9 μg/m^3; NO_2 = 14-159 μg/m^3; BTEX = 0.12-10.6 μg/m^3	Stranger *et al*., 2008
Kozani, Greece	Suburban, naturally ventilated	PM_{10} = 107 μg/m^3; O_3 = 1-10 ppb; CO = 0-1 ppm	Triantafyllou *et al*., 2008
Delhi, India	Urban roadside, naturally ventilated	PM_{10} = 133.5-1,181.1 μg/m^3; $PM_{2.5}$ = 54.6-366.1 μg/m^3; PM_1 = 27.8-221.7 μg/m^3	Goyal and Khare, 2009
Brisbane, Australia	Urban, mechanically ventilated	Max ultrafine PM = 1.4×10^5 cm^{-3}	Morawska, 2009
Chiang Mai, Thailand	Urban, naturally ventilated	$PM_{0.3\text{-}0.5} = 1.6 \times 10^8$ m^{-3}; $PM_{0.5\text{-}1.0} = 1.7 \times 10^7$ m^{-3}; $PM_{1.0\text{-}2.5} = 1.2 \times 10^6$ m^{-3}; $PM_{2.5\text{-}5.0} = 4.1 \times 10^5$ m^{-3}	Tippayawong, 2009
Korea	Urban	PM_{10} = 8-403 μg/m^3; CO = 0.1-5.4 ppm; TVOCs = 20-1,501 μg/m^3; HCHO = 0.01-0.8 ppm; TBC = 97-5,525 CFU/m^3; CO_2 = 268-3,000 ppm	Yang *et al*., 2009
Chhattisgarh, India	Suburban, industrial, residential, traffic, naturally ventilated	RPM = 188.8 ± 43.9 μg/m^3	Gadkari, 2010

Table 2. Continued.

Location	Site characteristics	Pollutants concentrations	References
Brisbane, Australia	Urban, mechanically ventilated	$PM_{0.015-0.79} = 3.19 \times 10^3$ cm^{-3}; $PM_{2.5} = 6.7 \pm 0.2$ μg/m^3	Guo *et al*., 2010
California, USA	Urban, residential, traffic, natural and mechanical ventilation	Ultrafine PM = 10,800 cm^{-3}	Mullen *et al*., 2011
Lisbon, Portugal	Urban, residential, traffic, naturally ventilated	PM_{10} = 30-146 μg/m^3; $PM_{2.5}$ = 10 μg/m^3; $PM_{2.5-10}$ = 73 μg/m^3	Almeida *et al*., 2011
Porto, Portugal	Urban, residential, traffic, naturally ventilated	PM_{10} = 140 μg/m^3; $PM_{2.5}$ = 95 μg/m^3; PM_1 = 91 μg/m^3	Madureira *et al*., 2012
Munich, Germany	Urban, naturally ventilated	$PM_{10} = 117 \pm 48$ μg/m^3	Oeder *et al*., 2012
Aveiro, Portugal	Urban, suburban, naturally ventilated	CO_2 = 833-2,540 mg/m^3; NO_2 = 10.63-20.93 μg/m^3; PM_{10} = 9.7-108.6 μg/m^3; TVOC = 145-175 μg/m^3	Pegas *et al*., 2012
Nord-Pasde-Calais, France	Urban, rural, industrial, naturally ventilated	PM_{10} = 72.7-85.3 μg/m^3	Tran *et al*., 2012
Texas, USA	Urban, rural, mechanical ventilation	Ultrafine PM = 0.6×10^3-29.3×10^3 cm^{-3}	Zhang and Zhu, 2012
Chennai, India	Urban, naturally ventilated	PM_{10} = 95-149 μg/m^3; $PM_{2.5}$ = 32-61 μg/m^3; PM_1 = 18-43 μg/m^3; CO = 0.1-0.11ppm	Chithra and Nagendra, 2012
Cassino, Italy	Urban, suburban, naturally ventilated	PM = 2.0×10^4-3.5×10^4 cm^{-3}; CO_2 = 3,000 ppm	Buonanno *et al*., 2013
Gaza strip, Palestine	Urban, suburban, naturally ventilated	$PM_{10} = 349.49 \pm 196.57$ μg/m^3; $PM_{2.5} = 103.96 \pm 84.96$ μg/m^3	Elbayoumi *et al*., 2013
Agra, India	Urban, residential, roadside, naturally ventilated	PM_{10} = 215.99-324.32 μg/m^3; $PM_{2.5}$ = 70.42-106.41 μg/m^3; PM_1 = 40.16-73.96 μg/m^3	Habil *et al*., 2013
Lublin, Poland	Urban, naturally ventilated	PM_{10} = 39-263 μg/m^3; $PM_{2.5}$ = 19-167 μg/m^3; PM_1 = 18-166 μg/m^3; TSP = 73-740 μg/m^3	Polednik, 2013
Texas, USA	Urban, mechanically ventilated	PM_{10} = 6.5-100 μg/m^3; $PM_{2.5}$ = 3.4-37 μg/m^3; BC = 0-0.96 μg/m^3; NO_2 = 1.38-14.13 ppb; Benzene = 0.2-1.67 μg/m^3; Toluene = 0.36-17.06 μg/m^3; Ethyl benzene = 0.09-2.11 μg/m^3; m,p-xylene = 0.12-2.67 μg/m^3; o-xylene = 0.08-1.05 μg/m^3	Raysoni *et al*., 2013
Wrocław, Poland	Urban, naturally ventilated	PM_{10} = 12.6-93.1 μg/m^3; $PM_{2.5}$ = 8.9-86.6 μg/m^3; PM_1 = 4.2-33.4 μg/m^3	Zwozdziak *et al*., 2013
Aveiro, Portugal	Urban, naturally ventilated	PM_{10} = 37-399 μg/m^3	Alves *et al*., 2014
Barcelona, Spain	Urban	$PM_{2.5}$ = 1-192 μg/m^3	Amato *et al*., 2014
Porto, Portugal	Urban, naturally and mechanically ventilated	PM_{10} = 3.25-197.25 μg/m^3; $PM_{2.5}$ = 3.25-158 μg/m^3; PM_1 = 2.75-145 μg/m^3; PM_{total} = 3.25-605 μg/m^3	Branco *et al*., 2014
Eskişehir, Turkey	Urban, suburban	Benzene = 0.83-0.92 μg/m^3; Toluene = 10.63-42.01 μg/m^3; Ethyl benzene = 0.32-0.39 μg/m^3; m,p-xylene = 0.67-0.74 μg/m^3; o-xylene = 0.46-0.51 μg/m^3; NO_2 = 8.42-27.06 μg/m^3; O_3 = 16.93-23.76 μg/m^3	Demirel *et al*., 2014

Table 2. Continued.

Location	Site characteristics	Pollutants concentrations	References
Zajecar, Serbia	Urban, naturally ventilated	PM_{10} = 37-103 μg/m^3; $PM_{2.5}$ = 26-63 μg/m^3; PAHs = 10-198 μg/m^3; VOC = 39-61 μg/m^3; HCHO = 42-88 μg/m^3; O_3 = 8-15 μg/m^3; NO_2 = 7-22 μg/m^3; CO_2 = 1-1.1 μg/m^3	Jovanovic *et al*., 2014
Attika, Greece	Urban, naturally ventilated	CO = 0-13.9 ppm; CO_2 = 538-5,049 ppm; VOC = 0-39.7 ppm, TPM = 41-1,867 μg/m^3; PM_{10} = 21-1,618 μg/m^3; PM_5 = 11-709 μg/m^3; $PM_{2.5}$ = 2-68 μg/m^3; PM_1 = 0.82-28 μg/m^3; $PM_{0.5}$ = 0.39-19.57 μg/m^3; UFP = 751-36,641	Dorizas *et al*., 2015
Porto, Portugal	Urban, naturally ventilated	PM_{10} = 139 μg/m^3; $PM_{2.5}$ = 94 μg/m^3; VOC = 172 μg/m^3; HCHO = 19.8 μg/m^3; CO = 0.48 mg/m^3; CO_2 = 1,669 ppm; Bacteria = 3,600 CFU/m^3; Fungi = 300 CFU/m^3	Madureira *et al*., 2015
Sant Cugat del Valles, Spain	Urban, naturally and mechanically ventilated	NO_2 = 5-69 μg/m^3; $PM_{2.5}$ = 8-95 μg/m^3; UFP = 3,233-41,407 cm^{-3}	Rivas *et al*., 2015
Chennai, India	Urban, naturally ventilated	PM_{10} = 942 ± 248 μg/m^3; $PM_{2.5}$ = 61 ± 17 μg/m^3; PM_1 = 16 ± 3 μg/m^3; CO = 0.93 ± 0.43 ppm; CO_2 = 458 ± 58 ppm	Agarwal and Nagendra, 2016
Brisbane, Australia and Barcelona, Spain	Urban, naturally ventilated	PNC = 8.35×10^3-8.5×10^3 cm^{-3} (Brisbane); PNC = 9.29×10^3-1.37×10^4 cm^{-3} (Barcelona)	Mazaheri *et al*., 2016
Porto and Trofa, Portugal	Urban and rural, naturally ventilated	UFP = 5.7×10^3-10.4×10^3 cm^{-3}	Rufo *et al*., 2016
Amsterdam, Netherlands	Urban, mechanically ventilated	PM_{10} = 5.8 ± 35.6 μg/m^3; $PM_{2.5}$ = 5.5 ± 21.8 μg/m^3; Black Carbon = 0.49-2.03 μg/m^3	van der Zee *et al*., 2016

*MDL = Minimum Detection Limit

the outdoor and the indoor sources. In case of outdoor sources their type, location in terms of the distance from the school as well as their intensity and frequency of emission are important. The various factors that affect the IAQ of school buildings are presented in the subsequent sections.

3. FACTORS AFFECTING IAQ

The factors namely ventilation rate, temperature and relative humidity (RH), outdoor air pollution levels and outdoor meteorological conditions affect the IAQ of school building.

3.1 Comfort Parameters

The comfort parameters that affect IAQ are ventilation rate, temperature and relative humidity. Ventilation is one of the most important factors for maintaining acceptable IAQ in buildings. Ventilation is used to remove unpleasant smells/odours and moisture, introduce outside air, to keep interior building air circulating, and to prevent stagnation of the interior air. Buildings are typically ventilated using three mechanisms: natural ventilation, mechanical ventilation and infiltration. Natural ventilation is the flow of air through open windows, doors, grilles, and other planned building envelope penetrations, and it is driven by natural and/or artificially produced pressure differences. Mechanical (or forced) ventilation is the intentional movement of air into and out of a building using fans, air conditioners and intake and exhaust vents. Infiltration is the flow of outdoor air into a building through cracks and other unintentional openings and through the normal use of exterior doors for entrance and egress (ASHRAE, 2009).

Inadequate ventilation is the major issue in many of the classrooms in developed countries. It is expressed in terms of CO_2 concentrations. Although inadequate ventilation is often suspected to be an important condition leading to reported health symptoms, only few studies have reported on ventilation rates in schools (Toyinbo *et al*., 2016; Dorizas *et al*., 2015; Elbayoumi *et al*.,

2013; Habil *et al*., 2013; Mullen *et al*., 2011; Goyal and Khare, 2009). Daisey *et al*. (2003) compiled the average ventilation rates and ranges reported in the scientific literature for US and European schools (Casey *et al*., 1995; Turk *et al*., 1987; Nielsen *et al*., 1984). In poorly ventilated classrooms, students are likely to be less attentive on instructions given by teachers. Low ventilation rates in classrooms significantly reduce pupils' attention and vigilance, and negatively affect memory and concentration (Bakó-Biró *et al*., 2012). Inadequate ventilation was mostly observed in air-conditioned buildings than naturally ventilated buildings.

According to ASHRAE "Thermal comfort is that condition of the mind that expresses satisfaction with the thermal environment" (ASHRAE, 1992). The ASHRAE's standard-55 (ASHRAE, 1992) recommends indoor temperatures in the winter and summer are between (20 and 23.8°C) and (22.7 and 26.1°C), respectively with a relative humidity level between 30 and 60%. The temperature and humidity above or below this range in the building may affect the comfort and productivity of the occupants, as well as the emission of chemicals from building materials. Elevated relative humidity can promote the growth of mold, bacteria, and dust mites, which can aggravate allergies and asthma. Many previous IAQ studies in school buildings reported that the temperature and humidity were not in the acceptable limits (Almeida and de Freitas, 2014; Montazami *et al*., 2012; Twardella *et al*., 2012; Yang *et al*., 2009; Geelen *et al*., 2008; Santamouris *et al*., 2008; Theodosiou and Ordoumpozanis, 2008; Grimsrud *et al*., 2006; Jo and Seo, 2005; Kim *et al*., 2005; Lee and Chang, 2000).

3.2 Meteorological Parameters

Outdoor meteorological parameters are the main factor, which affects the IAQ of naturally ventilated buildings. The substantial difference in the climatic environment between indoors and outdoors could bring vastly different pollutant levels and dispersion characteristics. Recently, U.S. EPA (2011) reported that local climate change also has the potential to affect the IAQ. Climate change increases the frequency of heat waves and hot weather in many urban environments. As a result, building envelopes can become hotter during heat waves, adding to thermal stress and adverse health consequences in vulnerable populations (White-Newsome *et al*., 2012). It is now appreciated that climate change will impact ambient air pollution through increased emission rates and faster chemical reaction rates associated with higher temperatures. PM and O_3 levels are projected to increase in the ambient environment, which can penetrate indoors and subjected further reactions (Spengler, 2012; IOM, 2011).

The important meteorological parameters that affect IAQ of naturally ventilated building are wind speed and direction, temperature, relative humidity, precipitation, atmospheric pressure and solar radiation. In the past, few studies have been carried out to examine the relationship between air pollution and meteorological processes in different indoor environments. It was found that the correlation between indoor and outdoor pollutant concentrations varied over a wide range in different areas with different emission rate and meteorological characteristics. Chan (2002) studied the indoor-outdoor relationships of the PM and NO_2 under different ambient meteorological conditions. It is found that temperature, humidity and solar radiation played a vital role in the variation of the I/O ratio. On the other hand, both pressure and wind speed seems to have relatively little effect on the I/O ratio. Similarly, Gupta and Cheong (2007) reported that the temperature ($R^2 = 0.543$) plays the most significant role in affecting the I/O ratio of PM followed by the relative humidity ($R^2 = 0.539$) and wind speed ($R^2 = 0.379$). It was observed that with an increase in ambient temperature enhances more particle migration to indoors. This may be attributed to the temperature gradient that is established between the indoor and outdoor locations, which favours the motion of the particles. Tippayawong*et al*. (2009) observed a significant negative correlation ($R^2 = 0.195$-0.679) between temperatures and indoor $PM_{2.5}$ concentrations during daytime and positive correlation ($R^2 = 0.187$-0.675) at night. Among all the meteorological variables, wind speed has been the most closely analyzed since it influences the dispersion and dilution of pollutants. Cheng and Li (2010) and Chithra and Nagendra (2014) reported that low wind speeds and low mixing-layer heights lead to high indoor PM_{10} and $PM_{2.5}$ levels. Massey *et al*. (2012) observed that I/O PM ratios decrease with increasing temperature and wind speed, whereas a good relationship was not found between PM ratios and humidity. Riain *et al*. (2003) found that wind direction has considerable impact on fine PM and CO concentration levels in naturally ventilated buildings. For a constant wind speed, the I/O ratios of CO and PM varied by 50-60% and 20-30%, respectively for varied wind direction.

The indoor air pollutant concentrations at school also exhibit seasonal variations. Fromme *et al*. (2007) evaluated IAQ in 64 schools in the city of Munich and surrounding area and reported that the median indoor CO_2 concentration in a classroom was 1,603 ppm in winter and 405 ppm in summer. A median $PM_{2.5} = 19.8$ μg/m^3 and $PM_{10} = 91.5$ μg/m^3 were observed during winter period. In summer, a reduced PM concentration were reported (median $PM_{2.5} = 12.7$ μg/m^3 and median $PM_{10} = 64.9$ μg/m^3). Few other researchers were also found that the pollutant concentrations in classrooms were

higher during winter when compared to summer (Rivas *et al*., 2015; Chithra and Nagendra, 2014; Elbayoumi *et al*., 2014; Goyal and Khare, 2009; Chaloulakou and Mavroidis, 2002). However, Yang *et al*. (2009) observed that the indoor bacterial concentrations in classrooms were significantly higher during summer and autumn than during winter. This means that students' exposure is subjected to these variations according to the season of the year. Therefore, studies covering longer periods and a broader range of rooms are required in order to compare the exposure-effect of indoor and outdoor associations between the seasons.

3. 3 Outdoor Air Pollution Levels

Many studies reported that outdoor air pollution is having a significant effect of IAQ of naturally ventilated buildings (Chithra and Nagendra, 2014; Pegas *et al*., 2012; Tran *et al*., 2012; Lawson *et al*., 2011; Lim *et al*., 2011; Riain *et al*., 2003; Chao and Wong, 2002; Koponen *et al*., 2001; Kingham *et al*., 2000). Especially, in buildings close to industrial areas or roadways, outdoor pollutants can migrate to the indoor environment through open doors and windows. Therefore, understanding the relationship between indoor and outdoor pollutant concentrations is quite important. The I/O ratio directly represents the relationship between indoor and outdoor pollutant concentrations, which is very easy to understand and widely used. The measurement method for I/O ratio is relatively simple. The most common method is installing two monitors inside and outside the building, and then the I/O ratio can be obtained. I/O ratio >1 implies the major sources of pollutants are indoor and I/O <1 means the predominance of outdoor sources.

In school building, the IAQ is mostly discussed in terms of I/O ratios. The I/O ratios vary considerably due to the difference in indoor emission rates, cracks in building envelopes, and the air exchange rates. Chaloulakou and Mavroidis (2002) carried out a study to investigate the indoor and outdoor CO concentration at a public school building in Athens, Greece. The mean daily I/O CO concentration ratios ranged between 0.49 and 0.79 and 0.53 and 0.89 in the summer and winter periods, respectively. Triantafyllou *et al*. (2008) reported that the average indoor PM_{10} values in the school building were found to be lower than the respective outdoor values when building was unoccupied and I/O ratio ranged between 0.2 and 1.6. When it was occupied, this ratio ranged between 0.7 and 11.4. Diapouli *et al*. (2008) also observed that variation of mean I/O ratios depending on the indoor activities and the outdoor concentration levels. The I/O ratios for PM_{10} and $PM_{2.5}$ were ranged between 0.54 and 2.46 and 0.67 and 2.77, respectively. The corresponding ratio for ultrafine particles was smaller than 1, because vehicular traffic was presumed to be the main source. Similar observations were made by Goyal and Khare (2009) and Chithra and Nagendra (2012).

4. IMPACT OF IAQ ON HEALTH, COMFORT AND PRODUCTIVITY OF SCHOOL CHILDREN

Better IAQ in schools is important to provide a safe, healthy, productive, and comfortable environment for students, teachers, and staffs. It is very important for children because early childhood is also a critical period for the continued development and maturation of several biological systems such as the brain, lung, and immune system and air toxics can impair lung function and neurodevelopment, or exacerbate existing conditions, such as asthma. Since children's organs are in developing stage they breathe more air relative to their body size than adults (WHO, 2006a; Mendell and Health, 2005; Faustman *et al*., 2000). They also spent a significant part of their school hours doing physical activity, especially during recess and physical education, therefore, their air pollutant intake is generally higher during these times.

The assessment of the health effects from air pollution exposure at school is faced with a number of challenges: seasonal variability, pollutant interactions, heterogeneity, effects of daily variations in physical activity on air pollutant inhalation rates, and the contribution of non-school based exposures (Mejía *et al*., 2011). Few studies have assessed relationships of various health outcomes among students with indoor environmental factors in schools (Table 3). Most studies considered respiratory health such as asthma, current asthma, wheezing, or allergies as assessed by standardized self-administered questionnaires. Fewer studies considered lung function, nasal patency, or acoustic rhinometry (Altuğ *et al*., 2013; Simoni *et al*., 2010; Shendell *et al*., 2004). Significant association between formaldehyde concentrations and health outcomes were observed by Zhao *et al*. (2008) and Annesi-Maesano *et al*. (2012). Formaldehyde has been related to the nocturnal attack of breathlessness and cumulative asthma overall in non-allergic children (Zhao *et al*., 2008) and related to an increased risk of rhinitis (Annesi-Maesano *et al*., 2012). Mi *et al*. (2006) reported that 10 $\mu g/m^3$ increase in the indoor concentration of NO_2 was associated with current asthma, asthma attacks, and asthma medication. Zhao *et al*. (2008) reported an increased risk of 1.27 for the nocturnal attack of breathlessness for each rise of 100 $\mu g/m^3$ of SO_2 concentration. Protective effects of

Table 3. Children exposures to environmental pollutants in schools and associated health symptoms.

IAQ parameters	Health symptoms	References
CO_2, air exchange rates, particle counts	Nasal congestion, sore throat, headache	Kinshella *et al*., 2001
Bioaerosols	Asthma, allergic rhinitis, atopic eczema	Meklin *et al*., 2002
VOCs, bioaerosols	Respiratory irritation, asthmatic symptoms, common viral respiratory infection	Putus *et al*., 2004
CO_2, allergens	Wheeze, asthma, respiratory symptoms	Kim *et al*., 2005
CO_2, NO_2, O_3	Asthma, wheeze, breathlessness	Mi *et al*., 2006
SO_2, NO_2, O_3, HCHO	Asthma, wheezing, breathlessness	Zhao *et al*., 2008
CO_2, PM_{10}	Dry cough, rhinitis, nasal patency	Simoni *et al*., 2010
PM	Rhinitis, asthma	Canha *et al*., 2011
PM_{10}, $PM_{2.5}$, PM_1	Allergies, dry flaking skin, dizziness	Habil and Taneja, 2011
$PM_{2.5}$, NO_2, acrolein, HCHO, acetaldehyde	Rhinoconjunctivitis, Asthma	Annesi-Maesano *et al*., 2012
SO_2, NO_2, O_3	Impaired lung function	Altuğ *et al*., 2013
CO_2, Temperature	Fatigue, stuffy nose, headache, wheezing, cough with wheezing, fever	Turunen *et al*., 2014
CO_2, PM_{10}, $PM_{2.5}$	Difficulties in focusing, heavy headed and dizziness, feeling thirsty, feeling uncomfortable, heavy sweating, muscle pain	Elbayoumi *et al*., 2015
CO_2, Temperature, Relative humidity, Bacteria	Respiratory symptoms, Gastrointestinal symptoms	Haverinen-Shaughnessy *et al*., 2015

O_3 on daytime breathlessness were recorded inside and outside schools by Mi *et al*. (2006), while Zhao *et al*. (2008) found that O_3 was linked to an increase in nocturnal attacks of breathlessness.

The presence bioaerosols were linked to adverse health outcomes such as respiratory irritation, asthmatic symptoms, and increased occurrence of common viral respiratory infections in school children (Putus *et al*., 2004; Meklin *et al*., 2002). Some studies of health symptoms and pollutant exposures in classrooms have used surrogates of exposure (e.g. presence of molds on walls) (Simons *et al*., 2010). Even though the exposure of PM concentration in school building was very high, only few studies attempted it to relate with children's health. It was well documented that the exposure to PM has been linked to adverse health effects, including acute and chronic respiratory disorders, lung cancer, morbidity and mortality in children (Maté *et al*., 2010; Wallenborn *et al*., 2009; Neuberger *et al*., 2004; WHO, 2003; Pope *et al*., 2002; Pearce and Crowards, 1996). Canha *et al*. (2011) reported the presence of rhinitis and asthma in school children exposed to higher PM levels. Additionally, Annesi-Maesano *et al*. (2012) observed an increased prevalence of past year asthma was found in the classrooms with high levels of $PM_{2.5}$ in France.

There are concerns that health problems caused by poor IAQ may impair performance and reduce attendance of students. Some studies incorporated children's performance and absenteeism because of exposure to poor air quality in schools (Simons *et al*., 2010; Shendell *et al*., 2004). Shendell *et al*. (2004) explored student attendance in relation to dCO_2 (the difference between simultaneously measured indoor and outdoor CO_2 level) in 434 classrooms in the states of Washington and Idaho, USA. A 1,000 ppm increase in dCO_2 was associated with a 0.5-0.9% decrease in annual average attendance after controlling for many other factors known or suspected to be associated with absence. Mendell and Heath (2005) reviewed the existing evidence for direct associations between indoor environmental quality and performance or attendance of school children. Persuasive evidence links higher indoor concentrations of NO_2 to reduced school attendance, and suggestive evidence links low ventilation rates to reduced performance. These evidences suggest that poor IAQ in schools is adversely affecting the performance and attendance of students, primarily through health effects

from indoor pollutants. Most of the scientific literature providing evidence for the health impacts of IAP comes from studies conducted in developed country settings within North America and Western Europe, which was used for exposure and risk assessment. However, the differences between developed and developing countries in exposure concentrations, the nature of pollutants, baseline health, and determinants of susceptibility add uncertainties while extrapolating exposure-response relationships across countries.

5. SOURCE APPORTIONMENT OF INDOOR AIR POLLUTANTS

The relative contributions from indoor and outdoor sources are needed to evaluate the adequacy and cost effectiveness of control strategies for mitigating the IAQ issues. Resource allocation to control air pollution depend on adequate information about important emission sources (i.e. source identification), chemical and physical properties of emissions (i.e. emissions characterization), the effects of important source categories on air quality (i.e. source apportionment), as well as the health effects resulting from exposures. While the major indoor sources have been identified, comparatively little is known about the chemical nature of associated airborne emissions, especially particle-phase and vapor-phase organic compounds. Furthermore, the relative impact of indoor and outdoor emissions on exposures has not been addressed in a systematic and comprehensive manner (Abt *et al*., 2000; Sexton and Hayward, 1987). Source apportionment of indoor air pollution has its challenge because indoor air pollution is controlled by both indoor and outdoor sources, ventilation, outdoor meteorology and long-range transport pollutants (Uhde and Salthammer, 2007).

Passive sampling is more suitable for in-situ measurements of emissions. The estimation of the emission rate of organic compounds released from various types of indoor materials can be performed using the flux sampler. The formaldehyde emission rates from building and furniture materials in 24 student rooms were measured using a passive sampling method by Blondel and Plaisance (2011). Data analysis revealed that the emissions released from furniture and building materials are the main contributions to the indoor formaldehyde concentrations with 45 and 43% on average. Similarly, Poulhet *et al*. (2014) investigated formaldehyde sources in French schools using a passive flux sampler. More than 29 sources of formaldehyde were characterized in each investigated classroom, with higher emissions from building materials compared to furnishing materials.

A wide variety source oriented and receptor oriented models were applied to outdoor air, to apportion the sources of PM and VOCs. Among this, receptor-based apportionment method is most commonly used for the source apportionment purpose. The fundamental principle of receptor modelling is the mass and species conservation in the atmosphere. An overview of the wide range of statistical models and modelling approaches that is currently available in the literature. One of the main differences between the models is the degree of knowledge required about the pollution sources prior to the application of receptor models. The two main receptor models widely used in source apportionment are chemical mass balance (CMB) and multivariate models (Viana *et al*., 2008).

Relatively few attempts were made to use receptor-oriented methods like Positive Matrix Factorization (PMF) (Amato *et al*., 2014; Minguillón *et al*., 2012; Larson *et al*., 2004), Cluster Analysis (CA) (Tran *et al*., 2012), Factor analysis (Krugly *et al*., 2014), Principal Component Analysis (PCA) (Madureira *et al*., 2016; Guo, 2011; Lim *et al*., 2011) and CMB (Pervez *et al*., 2012; Arhami *et al*., 2010) to apportion the sources of indoor air pollutants. Most of the source apportionment studies have reported on PM concentrations in residential buildings. Sources and properties of indoor aerosols exhibit large variability among different microenvironments. The composition and toxicity of indoor particles are very complex, as it is a mixture of particles emitted indoors, ambient particles that have infiltrated indoors, and particles formed through the reactions of gas phase precursors. The major sources identified in these studies were outdoor traffic emissions and soil dust for PM, while the VOCs were mainly originated from building materials and household products. John *et al*. (2007) conducted a study at elementary schools in Ohio indicated that the primary sources at the study region were industrial, fossil fuel combustion and geological sources. A study conducted in French classrooms reported that resuspension dust, traffic and marine aerosols were the major sources of PM in classrooms (Tran *et al*., 2012). Another source apportionment study using PMF model was conducted by Amato *et al*. (2014) in 39 primary schools of Barcelona. Results indicated that on average 47% of indoor $PM_{2.5}$ measured concentrations was found to be generated indoors due to continuous resuspension of soil particles (13%) and a mixed source (34%) comprising organic (skin flakes, clothes fibers, possible condensation of VOCs) and Ca-rich particles (from chalk and building deterioration). Madureira *et al*. (2016) reported that the influence of activities or building features as major sources of indoor CO_2, PM_{10} and VOCs levels in schools of Portugal. A critical review of receptor modelling for particulate matter in India

suggest CMB model for source apportionment for PM rather than other multivariate receptor models (Pant and Harrison, 2012). But its application on source contribution of indoor PM is very limited. Gadkari and Pervez (2008) analysed the elemental composition of indoor PM among school communities in central India. Source apportionment of personal exposure shows that industrial emissions and road traffic dust are the major sources of personal exposure of fine particulates.

6. INDOOR AIR QUALITY STANDARDS AND GUIDELINES

As the importance of the human exposure to IAP are increasingly recognized, national and international organizations proposed IAQ standards and guidelines for improving air quality in indoor environments. IAQ standards suggested by Occupational Safety & Health Administration (OSHA), ASHRAE, NIOSH and WHO are mostly used in many countries for assessing the IAQ. The American Conference of Industrial Hygienists (ACGIH) TLVs (Threshold Limit Values) are often applied in industrial environments. Industrial workers are generally exposed to larger concentrations of contaminants, and worker exposure is controlled by using personal protective equipment and other protective methods. In non-industrial settings such as offices, homes and schools, occupants are more commonly exposed to low levels of many contaminants. However, only few such standards or guidelines apply to nonindustrial indoor settings. For example, the ASHRAE has established guidelines for ventilation rates (ASHRAE, 1999) and thermal comfort (ASHRAE, 1992) for a variety of indoor settings. ASHRAE recommends a minimum ventilation rate of 8 L/s-person (15 cfm/person) for classrooms. For typical occupant density of 33 per 90 m^2 (1,000 ft^2) and a ceiling height of 3 m (10 ft), the current ASHRAE standard would require 3 air changes per hour (ACH) for a classroom (Daisey *et al*., 2003). Table 4 summarizes the standards and guidelines international agencies for pollutants commonly found in-

Table 4. Indoor air quality standards and guidelines.

Pollutants	NAAQS/U.S. EPA	OSHA	NIOSH	ACGIH	WHO
CO_2	–	5,000 ppm (8 h) 30,000 ppm (15 min)	5,000 ppm (8 h) 30,000 ppm (15 min)	5,000 ppm (8 h) 30,000 ppm (15 min)	–
CO	9 ppm (8 h) 35 ppm (1 h)	35 ppm (8 h)	35 ppm (8 h)	25 ppm (8 h)	90 (15 min) 50 (30 min) 25 (1 h) 10 (8 h)
NO_2	100 ppb (1 h) 53 ppb (Annual)	1 ppm (15 min)	1 ppm (15 min)	3 ppm (8 h) 5 ppm (1 min)	200 μg/m^3 (1 h) 40 μg/m^3 (Annual)
SO_2	75 ppb (1 h, Primary) 0.5 ppm (3 h, Secondary)	2 ppm (8 h) 5 ppm (15 min)	2 ppm (8 h) 5 ppm (15 min)	2 ppm (8 h) 5 ppm (15 min)	500 μg/m^3 (10 min) 20 μg/m^3 (24 h)
O_3	0.075 ppm (8 h)	0.1 ppm (8 h) 0.3 ppm (15 min)	0.1 ppm (8 h)	–	100 μg/m^3 (8 h)
$PM_{2.5}$	35 μg/m^3 (24 h) 12 μg/m^3 (Annual, Primary) 15 μg/m^3 (Annual, Secondary)	5 mg/m^3 (8 h, respirable fraction)	–	3 mg/m^3 (8 h)	25 μg/m^3 (24 h) 10 μg/m^3 (Annual)
PM_{10}	150 μg/m^3 (24 h)	–	–	10 mg/m^3 (8 h)	50 μg/m^3 (24 h) 20 μg/m^3 (Annual)
HCHO	–	0.75 ppm (8 h) 2 ppm (15 min)	0.016 ppm (8 h) 0.1 ppm (15 min)	0.3 ppm (8 h)	–
Lead	0.15 μg/m^3 (3 months)	0.05 mg/m^3 (8 h)	0.1 mg/m^3 (10 h)	0.05 mg/m^3 (8 h)	0.5 μg/m^3 (Annual)
Bioaerosol	–	–	1,000 CFU/m^3 (total bioaerosol)	1,000 CFU/m^3 (total bioaerosol) 500 CFU/m^3 (total bacteria)	–

doors.

The NAAQS were developed by the U.S. EPA for outdoor air quality, but they are also applicable for indoor environment. The WHO air Quality Guidelines (WHO, 2006b) for PM, O_3, NO_2, and SO_2 specified that they can be applied in all non-occupational environments, including indoors in households, schools, vehicles, etc. They are intended for application to both indoor and outdoor exposures. But, these are guidelines rather than an enforceable standard. There are also standards and guidelines for other organic and inorganic compound present in the indoor air. The WHO has also provided health-based guidelines for 55 airborne inorganic and organic compounds for carcinogenic and non-carcinogenic health endpoints. ACGIH has published TLVs for more than 700 chemical substances and physical agents. Permissible exposure limits (PELs) are set by OSHA to protect workers against the health effects of exposure to 500 hazardous substances (Charles *et al*., 2005). In some countries, including Australia (Worksafe Australia, 2013), Canada (Health Canada, 1989), China (AQSIQ, 2002), Finland (FiSIAQ, 2001), Germany (Federal Republic of Germany, 2000), Hong Kong (HKEPD, 1999), Japan (MHLW, 2009), Malaysia (DOSH, 2010) and Singapore (Institute of Environmental Epidemiology, 1996) air quality guidelines have been developed or suggested also for indoor air.

7. INDOOR AIR QUALITY MANAGEMENT

The indoor air pollutants include wide variety of compounds with varying concentrations and are emitted from several sources. Several instruments and techniques are available for measuring air pollutants in the ambient environment. But, the physical size, noise, airflow rates, power consumption, difficulty in installation etc. of these instruments restricts their applicability in the indoor environment (U.S. EPA, 1990). Therefore, it is important to know the sampling and measurement techniques that can be used in indoor environments. Many governmental agencies and research organizations have developed indoor air monitoring protocols for industrial workplaces. However, the instrumentation requirements for non-industrial microenvironments (residential, commercial and institutional buildings) differ from those of ambient or industrial applications. At present, developed countries have set up guidelines for IAQ Assessment (CPCB, 2014; ASTM, 2012; HKEPD, 2003; U.S. EPA, 2003, 1990; Macher, 1999; U.S. EPA and NIOSH, 1991), which may not be suitable for developing nations, because of the difference in climatic and socioeconomic conditions and building design and construction practices.

There are many programs exists in developed countries to improve IAQ in schools. The U.S. EPA has developed useful documents to assist building operators and managers. These documents provide guidance on how to prevent IAQ problems and how to establish an organizational structure to manage IAQ events (U.S. EPA and NIOSH, 1991). U.S. EPA has developed an IAQ Tools for Schools Action Kit, which provides best practices, industry guidelines, sample policies and a sample IAQ management plan to improve IAQ in schools at little or no cost (U.S. EPA, 2013). In the US, 42% of schools were having an IAQ management program and each year new schools are added to this program. Nearly half of these schools use the U.S. EPA's IAQ Tools for Schools program (Moglia *et al*., 2006). The SINPHONIE (Schools Indoor Pollution and Health Observatory Network in Europe) project is a complex research project funded by the European Union (EU), intended to improve air quality in schools and kindergartens, to reduce respiratory disease due to outdoor and indoor air pollution in children and teachers, and to define policy recommendations on remedial measures in the school environment. Twenty-three countries from all of Europe are involved in this project (SINPHONIE, 2013). In other countries, the state of knowledge on IAQ is schools are very limited. There are no programmes or guidelines currently exist for IAQ assessment and monitoring in different indoor environments (i.e. commercial, institutional, residential and sensitive buildings) in most of developing and undeveloped countries.

8. CONCLUSIONS

Over the last years, public attention on IAQ and indoor comfort has been increased. One of the main reasons is the fact that people usually spend most of their time in indoor environments, such as home, workplace, in transit, educational and recreational facilities. In developed countries, many studies were conducted during the past decade with the aim of understanding IAQ of the school environment. Many researchers have widely investigated the composition of indoor pollutants, sources, physical and chemical characteristics, and effects on human health. The composition of indoor pollutants is quite complex and their concentrations are greatly different. It was reported that particulate matter plays a major role in affecting the IAQ of the school building. If the ambient PM concentrations are already high, that could further deteriorate the IAQ of the building. This is particularly true for developing countries like India and China where the world's highest levels of PM have been reported.

In many countries, there are no programs in place at the national or state level to improve the indoor environmental quality in schools. Also, there is no standard protocol available for IAQ assessment for developing countries. Considering the public concern and limited knowledge in IAQ in schools, there is a need to determine the extent of IAQ problems in schools located in urban areas. Scientific knowledge on sources of indoor air pollutants, quantification of emissions, temporal and spatial dispersion of pollutants, toxicological properties of the pollutants, chemical and morphological characteristics and associated health risk among children in the school buildings are essential to evaluate the adequacy and cost effectiveness of control strategies for mitigating the IAQ issues. Hence, there is a need for high quality research to investigate the characteristics of IAQ and associated health risk in school buildings. The knowledge established as part of this paper would be helpful for designers, engineers, facilities maintenance managers and researchers who endeavour to undertake research in this area.

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