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Review article

Indoor air pollution and exposure assessment of the gulf cooperation council countries: A critical review

Patrick Amoatey, Hamid Omidvarborna, Mahad Said Baawain*, Abdullah Al-Mamun

Department of Civil and Architectural Engineering, College of Engineering, Sultan Qaboos University, P.O. Box 33, Al-Khoudh 123, Muscat, Oman

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ABSTRACT

Indoor air pollution is one of the human health threat problems in the Gulf Cooperation Council (GCC) countries. In these countries, due to unfavorable meteorological conditions, such as elevated ambient temperature, high relative humidity, and natural events such as dust storms, people spend a substantial amount of their time in indoor environments. In addition, production of physical and biological aerosols from air conditioners, cooking activities, burning of Arabian incense, and overcrowding due to pilgrimage programs are common causes of low quality indoor air in this region. Thus, due to infiltration of outdoor sources as well as various indoor sources, people living in the GCC countries are highly exposed to indoor air pollutants. Inhalation of indoor air pollutants causes mortalities and morbidities attributed to cardiorespiratory, pulmonary, and lung cancer diseases. Hence, the aim of this review study is to provide a summary of the major findings of indoor air pollution studies in different microenvironments in six GCC countries. These include characterization of detected indoor air pollutants, exposure concentration levels, source identifications, sustainable building designs and ventilation systems, and the mitigation strategies. To do so, > 130 relevant indoor air pollution studies across the GCC countries were critically reviewed. Particulate matters (PM_{10} and $PM_{2.5}$), total volatile organic compounds (TVOCs), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and heavy metals were identified as the reported indoor air pollutants. Apart from them, indoor Radon and bioaerosols were studied only in specific GCC countries. Thus, future studies should also focus on the investigation of emerging indoor air pollutants, such as ultrafine and nanoparticles and their associated health effects. Furthermore, studies on the mitigation of indoor air pollution through the development of advanced air purification and ventilation systems could improve the indoor air quality (IAQ) in the GCC region.

1. Introduction

Indoor air pollution is a serious health problem as it causes about 4.5 million annual deaths globally resulting from pneumonia (12%), stroke (34%), ischemic heart diseases (IHD) (26%), chronic obstructive pulmonary diseases (COPD) (22%), and lung cancer (LC) (6%) (Amoatey et al., 2017; Tageldin et al., 2012; Thurston et al., 2016; WHO, 2018). Indoor air pollution has been extensively studied in homes (Morawska et al., 2017; Rohra and Taneja, 2016), schools (Cai et al., 2015; Forns et al., 2017), hospitals (Cabo Verde et al., 2015; Wang et al., 2015b), offices (Azuma et al., 2018; Song et al., 2015), restaurants (Dai et al., 2018; Fazlzadeh et al., 2015), and subway metros (Kim et al., 2015; Xu and Hao, 2017). However, indoor air pollution continues to be a global problem, especially in developing countries. Research studies have shown that about 90% of time is being spent in the aforementioned indoor environments (Andrade and Dominski, 2018). This is about 5 times higher than that of average time spent in outdoor environments, which indicates the enormity of human health risk posed by the indoor air pollutants (Andrade and Dominski, 2018; Boor et al., 2017; Cincinelli and Martellini, 2017; Du et al., 2018). These indoor air pollutants generally originate from the ambient environment. However, in cities with high ambient air pollutant levels, indoor air pollutants may be of greater concern (Morawska et al., 2017).

Higher ambient temperature and humidity in the Gulf Cooperation Council (GCC) countries has increased the time duration, which is being spent at homes, offices, cafés, shopping malls, and similar indoor places (Ali et al., 2016b). Further, the GCC countries are categorized as developing countries and they are well-known as the hub for the majority of global oil reserves and crude oil production plants. Hence, with the recent increase in industrial activities, infrastructural developments, and population growth, which are coupled with unfavorable outdoor

* Corresponding author.
E-mail address: msab@squ.edu.om (M.S. Baawain).

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weather conditions, indoor air quality (IAQ) can be counted as a great concern for human health. This affirms that there can be a high risk of exposure to indoor air pollutants compared to the countries with favorable weather conditions, where people spend much of their time in outdoor environments.

Since external and internal air pollutant sources and activities may vary significantly among the GCC countries, the review provides an in-depth analysis of indoor air pollution, according to different geographic locations (Bahrain, Kingdom of Saudi Arabia (KSA), Kuwait, Oman, Qatar, and United Arab Emirates (UAE)). For all of these countries, most indoor air pollution studies have been focused on measuring the concentration levels and characterization of chemical species. Previous reviews have shown that particulate matters (PMs), carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen dioxide (NO_2) and heavy metals were the major indoor air pollutants in the GCC countries (Abdul-Wahab and Yaghi, 2004; Al-Rehaili, 1999; Al Mulla et al., 2015; Argyropoulos et al., 2016; Elkilani and Bouhamra, 2001; Elsayed et al., 2016; Farahat, 2016; Omidvarborna et al., 2018; Saraga et al., 2017). Recent studies in KSA have identified Radon (^{222}Rn) gas as another indoor air pollutant (Abo-Elmagd et al., 2018; Alghamdi and Aleissa, 2014). Moreover, it has been reported that indoor air pollution in most cities in the GCC region is due to the infiltration of ambient air pollutants into residential buildings, poor ventilations, burning of biomasses (Arabian incense), and overcrowding (Argyropoulos et al., 2016; Fadeyi et al., 2014; Jomehzadeh et al., 2017; Weitzman et al., 2016; Yaghi and Abdul-Wahab, 2003). For example, incomplete burning of Arabian incense emits CO, PM_{10}, $PM_{2.5}$, polycyclic aromatic hydrocarbons (PAHs), and black carbon (BC), which cause deleterious health effects for the exposed population (Du et al., 2018). To critically assess the current state of indoor air pollution in the GCC countries, this structured review was conducted to characterize emission of indoor air pollutants, identify the sources, discuss the possible mitigation strategies, identify knowledge gaps, and recommend future research works. For this purpose, > 130 research articles were selected and reviewed.

2. Methods

Based on the state-of-the-art scientific literature guidelines, a search was conducted in Web of Science and PubMed for original and review English papers published after 2010 and a few papers published after 1986. The terms employed during the search were (“indoor air pollution in GCC” or “indoor air quality in GCC”), (“indoor air quality in < *name of the GCC country* > ” or “indoor Radon in GCC” or “Building ventilation in GCC” or “sustainable buildings in GCC”), and also “indoor < *name of the pollutants* > ”. For the respective countries, “ambient” or “outdoor” research studies were excluded. Since many published peer reviewed articles were not indexed in the above scientific electronic databases, gray search procedures in Google search engine were carried out based on the similar terminologies. In addition, published documents found on the national and international organization websites, such as the World Health Organization (WHO), were also considered.

The order of the countries in this review study is based on the top-to-bottom approach, which represents how detailed an IAQ study has been conducted by a particular country. Thus, countries with detailed studies came to the top list, followed by less detailed ones. This approach will help the readers to follow the trend of indoor air pollution in the GCC countries.

3. UAE

Environmental issues, including air pollution, have been one of the top policy agendas in UAE, following rapid industrialization and expansion of many commercial cities in the region. As the population growth and infrastructure developments continued to increase, indoor air pollution is deemed as one of the public health problems in UAE (Loney et al., 2013).

Table 1
Population and the economics activities in the GCC countries.

Country	~Population ($\times 10^3$)				[g]GDP ($\times 10^6$ USD)	
	Total	Males	Females	Children (0–4 yrs.)	Per capita	Real estate developments
[a]UAE	9120	6298	2822	N/A	44,808	49,140
[b]KSA	32,612	18,746	13,866	2734	20,912	48,410
[c]Qatar	2617	1975	642	138	67,537	15,819
[d]Kuwait	4500	2838	1662	311	28,710	11,230
[e]Oman	4414	2887	1527	393	16,790	3313
[f]Bahrain	1424	889	535	11.4	22,714	1775

[a] FCSA (2017).
[b] GASTAT (2018).
[c] MDPS (2018).
[d] PACI (2018).
[e] NCSI (2017).
[f] IEGA (2018).
[g] GCC-STAT (2018).

The population, economic growth, and real estate data of UAE are summarized in Table 1. Comparatively, UAE has a smaller population than that of KSA, but it is ranked as the second highest gross domestic product (GDP) per capita after Qatar with the highest investment in real estate developments among the GCC countries. Currently, UAE is undergoing massive economic and infrastructural growth with lack of country-specific local IAQ guidelines. Thus, indoor air pollution is going to be a serious public health issue of the residential population.

Environmental agencies in Abu Dhabi and Dubai Municipalities have embarked on various environmental health projects aimed at characterizing indoor air pollutants in various residential buildings in UAE. Despite these interventions, indoor air pollutions continue to be a health threat to UAE populations as it has been estimated to cause 290 deaths and about 89,000 hospital emergency visits annually (Funk et al., 2014). To date, about 30 articles on IAQ in UAE were published, while they focused mostly on characterization of trace gases and PMs with excessive attention to IAQ measurements within similar indoor environments (e.g., residential homes). Most of these studies were conducted in cities, while very limited studies in rural and per-urban locations have been carried out. The details of available local and international guidelines and indoor air pollutants and concentration levels in UAE are summarized in Tables 2 and 3, respectively.

3.1. Air pollutants in UAE

Measurement of indoor pollutions from different human living environments (homes, offices, and restaurants) is known to give rise to different concentration levels, chemical species, and human exposure levels (Xu and Hao, 2017). Different types of air pollutants were found in UAE indoor environments, where these pollutants were emitted from household materials, kitchen activities, infiltration from ambient sources, burning of incense, secondhand smoke, and overcrowding (Cohen et al., 2013; Meier et al., 2015; Vanker et al., 2015) (Table 4). Further, infiltration of PMs from outdoor sources is the major contributor to indoor PM levels in UAE; because, SO_2 can be converted to sulfate PMs as a result of high ambient temperature, which favors photochemical reactions (Hamdan et al., 2018).

Few studies identified that burning of Arabian incense in various homes, restaurants, and offices is the main source of indoor air pollution in UAE, as it can emit a wide amount of air pollutants (Balasubramanian et al., 2017; Jetter et al., 2002). Elsayed et al. (2016) characterized a complete profiling of Bakhour (an Arabian incense), as a commonly burnt indoor household biomass used in UAE (commonly produced in Sharjah). It was found that Bakhour emitted trace metals such as Pb, Zn, Cd, Al, Fe, Co, and other known or suspected

Table 2
Selected Indoor air quality guidelines of GCC (Kuwait) in comparison with international standards and the world (Abdul-Wahab et al. (2015b); Canada Government (2018); WHO (2010)).

Pollutant	WHO				Canada				Kuwait					USA				
	1-h	8-h	24-h	1-yr	1-h	8-h	24-h	1-yr	30-min	1-h	8-h	24-h	1-yr	15-min	1-h	8-h	24-h	1-yr
CH_2O [μg/m^3]	N/A	N/A	N/A	N/A	132	52.9	N/A	N/A	120[b]	N/A	52.9	N/A	N/A	2645	100	107	N/A	N/A
CO [mg/m^3]	35	10.6	4	N/A	30.8	13.6	12.3	N/A	60	30	10	N/A	N/A	N/A	40	10	N/A	N/A
CO_2 [mg/m^3]	1938	N/A	N/A	N/A	N/A	N/A	N/A	6,782[d]	N/A	9689	N/A	2713	581	58,130	N/A	9689	N/A	N/A
NO_2 [μg/m^3]	203	N/A	N/A	40.5	182	101	22.3	N/A	660	200	N/A	100	N/A	2026	203	N/A	N/A	107
O_3 [μg/m^3]	10,570[b]	135	N/A	N/A	254	106	N/A	N/A	N/A	235	200	120	60	N/A	254	148	N/A	N/A
[a]PAHs [ppm]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5000	N/A	1400	N/A	30,000	N/A	5000	N/A	N/A
$PM_{2.5}$ [μg/m^3]	N/A	N/A	25	10	100	40	N/A	N/A	N/A	N/A	40	N/A	N/A	N/A	N/A	5000	35	15
PM_{10} [μg/m^3]	N/A	N/A	50	25	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10,000	150	50
Radon [Bq/m^3]	N/A	N/A	100[c]	N/A	N/A	N/A	200[c]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SO_2 [μg/m^3]	375	N/A	135	N/A	N/A	50	N/A	N/A	N/A	N/A	50	N/A	N/A	14,100	212	N/A	395*	84.6
TSP [μg/m^3]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	230	75	N/A	N/A	15	N/A	N/A
VOCs [ppm]	0.133 mg/m^3	N/A	0.048 mg/m^3	N/A	N/A	N/A	N/A	N/A	3[d]					5	0.14	5	N/A	N/A

[a] All indoor exposures levels could affect human health.
[b] Maximum level.
[c] No time limits.
[d] Long-term exposure, taken as 1 year.
* Not to be exceeded more than once per year.

carcinogenic compounds of acetic acid phenylmethyl ester, benzoic acid hydrazide, ethylbenzene, 1,2-dimethoxy-4-(1-propenyl)-benzene, 9-dodecyl-tetradecahydro-anthracene, and α-methyl-benzenemethanol. About 859 chemical compounds (e.g., p-xylene, styrene, β-myrcene, acetic acid, furfural, 1,4-dibenzehaxanoic acid, azulene, diethyl phthalates) are known to be emitted from the smokes and fine ashes of Bakhour (Dalibalta et al., 2015). Hookah cigarette is another major source of indoor air pollution problem in UAE. Weitzman et al. (2016) measured that there is a wide variability of exposure levels between non-hookah $PM_{2.5}$ concentration level (210.8 μg/m^3 (95% CI: 78.4–343.2)) and hookah smoking $PM_{2.5}$ concentration level (428.6 μg/m^3 (95% CI: 50.2–806.9)) rooms. Additionally, large amounts of Zn, Cu, V, Ni, Pb, Mn and Cr elements were found to exist as ultrafine particles ($PM_{0.1}$) and fine particles ($PM_{2.5}$) in UAE indoors (Hamdan et al., 2018), where the majority of dwellers spend 85% of their times indoors, especially during summer seasons.

Analysis of indoor air compositions in 638 homes in Abu Dhabi, Dubai, Fujaira, Sharjah, and Ajman revealed that the median concentrations of formaldehyde (HCHO) (13.2 μg/m^3), $PM_{2.5}$ (6.06 μg/m^3), and PM_{10} (41.3 μg/m^3) were higher than the recorded urban exposure levels of HCHO (66.1 μg/m^3), $PM_{2.5}$ (6.0 μg/m^3), and PM_{10} (38.5 μg/m^3) in many cases (Funk et al., 2014). The sources of the pollutants were attributed to smoking, air conditioners, and kitchen activities. A one year IAQ measurement campaign was conducted in 16 elementary schools within Dubai and Fujairah in UAE. Average indoor O_3 concentration (106 μg/m^3) in classrooms was found to be low compared to average CO (1.43 mg/m^3) and CO_2 (3110 mg/m^3) levels. However, the large amount of average inhalable PM concentration levels (316 to 9828 μg/m^3) were found to be a major concern, especially to children in the classrooms (Fadeyi et al., 2014). This is due to greater susceptibility to indoor air pollution by children as they could breathe larger volume of air contained respirable pollutants compared to adults (Cai et al., 2015).

A study concluded that several indoor gaseous air pollutants (CO_2, CO, total volatile organic compound (TVOC), total particulate matter (TPM), and HCHO) were found in 3 classrooms in UAE at their elevated levels during class hours (9:36 AM and 2:00 PM). TPM and TVOC were ranged from 102–157 μg/m^3 and 1202–2340 μg/m^3, respectively; while, HCHO concentration level (13.2 mg/m^3) was low (Behzadi and Fadeyi, 2012). Considering the diverse sources of indoor air pollutants in residential buildings, an occupant exposure assessment to TVOC and CO_2 was carried out in an office building in the megacity of Dubai prior to undertaking interior design decorations. The TVOC and CO_2 concentration levels were found to be 6319 μg/m^3 and 2885 mg/m^3, respectively. The sources of the TVOC were identified as: paints, sealants, finishes, cleaning agents, and personal care products, while the presence of CO_2 was due to the respiration of the occupants (Fadeyi and Taha, 2013).

Bioaerosols are tiny microscopic bacteria, fungi, and viruses in the size of 0.003–20 μm that can thrive in the ambient environments. Bioaerosols are another important indoor air pollutants, which pose serious health risk to humans due to their ease of contamination and difficulties of prevention among humans (Ghosh et al., 2015). In Al-Ain city, different species of bacteria were unraveled as indoor bioaerosols within the residential building (bedrooms and living rooms), which mainly included *Staphylococci* sp. (1963 CFU/m^3), *Bacillus* sp. (2600 CFU/m^3), *Streptomyces* sp. (606 CFU/m^3), and *Micrococcus* sp. (1215 CFU/m^3) (Jaffal et al., 1997a). Also, these airborne bioaerosols were identified in hospitals to be higher in intensive care units (687 CFU/m^3) compared to the operating theatre rooms (473 CFU/m^3) (Jaffal et al., 1997b). The high indoor bacterial exposure concentrations were attributed to overcrowding (Memish et al., 2014).

4. KSA

Population of KSA is about four times higher than each country in the GCC region (Table 1). In addition, KSA has higher GDP due to economic growth and massive investments in real estate developments. These might have led to initiate early scientific research on indoor air pollution in KSA in 1990s. To date, the number of published articles on IAQ in KSA is > 40, which is higher than UAE. Compared to UAE, majority of indoor air pollution studies in KSA were based on the determination of pollutant concentrations and characterizations rather than the designing mitigation measures due to exposures.

Although various indoor air pollutants and indoor environments were explored well in KSA, most of the studies were focused on urban areas compared to rural areas. Similarly to UAE, KSA does not currently have IAQ guidelines and current standards have been adapted from other developed countries and international organizations (Abdul-Wahab et al., 2015b). The characterizations, concentrations and measurement techniques of indoor air pollutants in KSA are summarized in Table 3.

4.1. Air pollutants in KSA

As one of the earliest studies in this region, IAQ of thirty buildings

Table 3
Summary of exposed indoor air pollutant emission measurements and characterizations in the GCC countries.

Countries	Study environment	Number of buildings	Duration of measurement	Measurement techniques	Pollutant species	Average concentration	References
UAE							
Dubai and Fujairah	Schools	16	10 months	Direct sense IAQ probe, particle analyzer, formaldehyde gas monitor	TVOC, CO_2, O_3, CO, PM	815 μg/m^3, 3110 mg/m^3, 106 μg/m^3, 1.43 mg/m^3, 1730 μg/m^3	Fadeyi et al. (2014)
Urban areas	Home	1	3 h.	Portable monitors	PM, CO, NO_X, HCHO, $C_5H_{10}O$, $C_2H_2O_2$	1420 μg/m^3, 150 mg/m^3, 0.3 ppm, 111 μg/m^3, 37.9 μg/m^3, 84.8 μg/m^3	Cohen et al. (2013)
Urban areas	Homes	33	0.9–2 h.	Personal environmental monitors	$PM_{2.5}$, BC, CO	206 μg/m^3, 3.68 μg/m^3, 5.48 mg/m^3	Weitzman et al. (2016)
Urban areas	Residential homes	268	7 days	Passive samplers	$^aPM_{10}$, $^aPM_{2.5}$, ^{b}CO, ^{b}HCHO, ^bH_2S, $^bNO_2$, $^bSO_2$	35.2 μg/m^3, 5.73 μg/m^3, 1.91 mg/m^3, 66.1 μg/m^3, 180 μg/m^3, 20.3 μg/m^3, 141 μg/m^3	Funk et al. (2014)
KSA							
Al-Olaya and Al-Manfouha	Homes	N/A	1 yr.	MDCO dust collector, ICP-AES	Pb (in dust)	2.4×10^2 μg/g	El-Desoky et al. (2014)
Jazan city	Homes	> 12	9 months	Radon detectors	^{222}Rn	22 ± 15 Bq/m^3	Al-Jarallah and Fazal Ur (2005)
Jeddah	Homes	15	1 yr.	Vacuum cleaners, GC-MS	^{a}PAHs (in dust)	2650 ppb	Ali et al. (2016b)
Riyadh	Homes	786	19–20 days	Electric passive radon monitor	^{222}Rn	24.68 Bq/m^3	Alghamdi and Aleissa (2014)
Riyadh	Homes	N/A	8 months	Dosimeters, NTDs	Gamma Rays, ^{222}Rn	318.57 ± 31 μSv/y, 18.4 Bq/m^3	Al-Saleh (2007)
Riyadh	Homes	30	4 days	Passive monitors	TSP, Pb, CO	6–478 μg/m^3, 0.01–2.13 μg/m^3, 143 mg/m^3	Al-Rehaili (1999)
Riyadh	Buildings (offices, schools, hospitals, library)	30	2 weeks	Semi-portable drager, interscan analyzers	SO_2, NH_3, HCHO	1.3 mg/m^3, 1.09 mg/m^3, 29.1 μg/m^3	Al-Rehaili (2002)
Riyadh	Hospitals, research centers, colleges	6	3 months	Radon dosimeters	^{222}Rn	16.1–44.3 Bq/m^3	Al-Khateeb et al. (2017)
Al-Khobar	Hospital	1	1 week	Passive monitor, air sampler	PM_{10}, TSP, CO, SO_2, O_3	255 μg/m^3, 1845 μg/m^3, 0.68 mg/m^3, 254 μg/m^3, 42.3 μg/m^3	El-Sharkawy and Noweir (2014)
Dammam, Al-Khobar	Restaurants	44	11 months	Passive monitor, air sampler	PM_{10}, $PM_{2.5}$, CO, CO_2, VOC, NO_2, SO_2	78.2 μg/m^3, 38.1 μg/m^3, 5.43 mg/m^3, 2360 mg/m^3, 0.4 ppm, 608 μg/m^3, 0.2 mg/m^3	El-Sharkawy and Javed (2018)
Dammam	Elementary schools	16	2 h./day	Personal air samplers	TSP, CO, NO_2, SO_2, C_6H_6	4 ppm, 3.95 mg/m^3, 40.5 μg/m^3, 169 μg/m^3, 1.38 mg/m^3	El-Sharkawy (2014)
Mekkah city	Mosque	5	5 h./day/month	Portable airport gelatin sampler	Bioaerosols: gram + bacillus, micrococcus (bacteria), aspergillus niger (Fungi)	Mean colony = ~10^2–10^5 CFU/m^3 for bacteria and fungi	Mashat (2015)
Dammam	Slaughter house	1	2 h./day	Staplex air sampler	PM_{10}, PM_1, $PM_{2.5}$, CO, VOCs	384 μg/m^3, 206 μg/m^3, 162 μg/m^3, 654 μg/m^3, 0.87 ppm	Salama and Berekaa (2016)
Riyadh	Hospital theatre	1	3 weeks	Diffusive air samplers	HCHO	965 μg/m^3	Vohra (2011)
Qatar							

(continued on next page)

Table 3 (*continued*)

Countries	Study environment	Number of buildings	Duration of measurement	Measurement techniques	Pollutant species	Average concentration	References
Doha, Al Wakra, Al Rayyan	Elementary schools	16	3 months	Q-Track monitors, PM Environmental monitors	PM_{10}, $PM_{2.5}$, CO, CO_2	93.2 ± 42.4 μg/m³, 60.1 ± 28.1 μg/m³, 370 μg/m³, 3445 ± 1720 mg/m³	Abdel-Salam (2017)
Doha	Waterpipe cafes	40	3 months	Personal aerosol monitors	$PM_{2.5}$	476 μg/m³	Al Mulla et al. (2015)
Doha	University buildings	2	1 week	Gas sensor nodes	CO_2, CO, O_3, Cl_2	1938 mg/m³, 1.23 mg/m³, 423 μg/m³, 156 μg/m³	Benammar et al. (2018)
Doha	Public offices	3	10 days	Aerosol samplers	$PM_{2.5}$	180 μg/m³	Argyropoulos et al. (2016)
Doha	Public offices	N/A	2 months	Passive samplers	PM_{10}, $PM_{2.5}$, EC	3.49 μg/m³, 3.29 μg/m³, 0.98 μg/m³	Saraga et al. (2017)
Kuwait							
Jahra, Kuwait city, Hawalli, Farwaniya, Al-Kabeer, Ahmedi	Homes	N/A	2 yrs.	Hazdust air monitoring system	$PM_{2.5}$	34.4–94.86 μg/m³ (bed rooms), 16.08–71.84 μg/m³ (living rooms)	Bu-Olayan and Thomas (2010)
Kuwait city	Homes	15	1 yr.	Vacuum cleaners, GC-MS	[a]PAHs (in dust)	1675 ppb	Ali et al. (2016b)
Kuwait city	Homes	15	N/A	Vacuum cleaners, GC-MS	Organophosphates	16.9 ppm	Ali et al. (2013)
Kuwait city	Homes, offices	46, 24	6 weeks	Passive samplers	PBDEs	2–385 pg/m³	Gevao et al. (2006)
Kuwait city	Residential buildings	10	N/A	Diffusive passive sampler	VOCs	16.3 mg/m³	Elkilani and Bouhamra (2001)
Kuwait city	Residential buildings	300	9 months	Radon detectors	^{222}Rn	32.8 Bq/m³	Al-Azmi et al. (2008)
Kuwait city	Residential buildings	200	2 yrs.	NaI dosimeter	^{40}K, ^{214}Bi, ^{208}Ti	39.3–103.3 nSv/h	Al-Azmi (2016)
Kuwait governorates	Homes	10	24 h.	Dust-track samplers	$PM_{2.5}$	44 μg/m³	Yassin et al. (2012)
Jahra, Kuwait city, Hawalli, Farwaniya	Parking lots	N/A	2 yrs.	RAD7 radon detector	^{222}Rn	63.15–41.73 Bq/m³	Bu-Olayan and Thomas (2016)
Al-mansouriya, Al-Dasma, Al-Badiya, Al-Shuiba	Elementary schools	7	1 yr.	Passive samplers	SO_2, NO_2, H_2S, CH_2O	7.7 mg/m³, 29.8 mg/m³, 6.3 mg/m³, 66.56 mg/m³	Al-Hemoud et al. (2017)
Kuwait city	Elementary schools	25	6 months	Passive radon detectors	^{222}Rn	35 ± 8.8 Bq/m³	Maged (2006)
Kuwait city	Secondary schools	46	7 months	Environmental monitors	PM_{10}, NO_2, VOCs	244.1 μg/m³, 405 μg/m³, 1.1 ppm	Al-Hubail and Al-Temeemi (2015)
Kuwait city	Office buildings	8	17 months	Passive canisters, GC-MS	VOCs	8.07 ppm	Al-Mudhaf et al. (2013)
Oman							
Al-Suwayq	Residential homes	3	24 h.	High volume sampler	Al, Si, Na, Mg	11%, 34.35%, 4.02%, 9.55%	Abdul-Wahab et al. (2005)
Bait	Residential homes	3	15 mins./location	Air quality probe, Airborn particle counter probe	O_3, NO_2, CO_2, CO, VOCs	159 μg/m³, 20.3 μg/m³, 1170 mg/m³, 321 μg/m³, 689 ppm	Abdul-Wahab et al. (2013)
Sohar	Residential homes	12	24 h.	High volume sampler	TSP, Cu, Ni, Pb, Cr	171.5 μg/m³, 0.3 ng/m³, 4.9 ng/m³, 3.2 ng/m³, 3.0 ng/m³	Abdul-Wahab and Yaghi (2004)
Bait	Museum	3	15 mins./location	Air quality probe, Airborn particle counter probe	SO_2, O_3, CO_2, TSP	2.82 μg/m³, 90.9 μg/m³, 953 mg/m³, 67.5 μg/m³	Abdul-Wahab et al. (2013)

(*continued on next page*)

Table 3 (*continued*)

Countries	Study environment	Number of buildings	Duration of measurement	Measurement techniques	Pollutant species	Average concentration	References
Al-Rusayl	Industrial buildings	23	24 h.	Portable large volume sampler	TSP, Pb, Cu, Ni, Cr, Zn	1802 μg/m^3, 1293 ng/m^3, 131 ng/m^3, 17 ng/m^3, 23 ng/m^3, 464 ng/m^3	Yaghi and Abdul-Wahab (2003)
Bahrain							
Urban areas	Homes	N/A	N/A	Vacuum cleaner/ICP-OES	Zn, Cd, Cr, Ni, Pb	202 ppm, 1.9 ppm, 11 ppm, 10 ppm, 517 ppm	Madany (1994)
Urban areas	Homes	N/A	2 months	Vacuum cleaner/AAS	Pb, Zn, Cd, Ni, Cr	360 ppm, 64.4 ppm, 37 ppm, 110.2 ppm, 144.7 ppm	Akhter (1993)
Urban areas	Homes	32	14 days	Diffusive tubes	NO_2	29.8 μg/m^3	Madany (1992)

located in urban and per-urban areas of Riyadh were investigated between 1992 and 1994. The study revealed that Pb, CO and TSP concentration levels were far more than the threshold limits, whereas the emission sources were found in outdoor environments as indicated by the statistical correlations with the indoor levels (Al-Rehaili, 1999). In the same city, three most abundant trace gases were measured with average concentration levels of 1300, 1095 and 26.4 μg/m^3 for SO_2, NH_3, and HCHO, respectively (Al-Rehaili, 2002). Although the average concentration values were reported low, the concentration levels in most sampling locations (e.g., hospitals and schools) exceeded the US EPA's 24-h standards of 395 μg/m^3, for example for SO_2 (Al-Rehaili, 2002).

The measurements of IAQ continued in other cities as well. In Dammam city, lower concentration levels of CO (3.95 mg/m^3), NO_2 (40.5 μg/m^3), SO_2 (169 μg/m^3), and VOCs (e.g., C_6H_6) (0.4 ppm) were detected among the elementary schools. It was reported that high proximity of the school buildings to the traffic was the reason to detect such pollutants indoors (El-Sharkawy, 2014). In another study, a slight increase in the concentration levels of CO (5.43 mg/m^3), NO_2 (608 μg/m^3), SO_2 (197 μg/m^3), and VOCs (0.4 ppm) with the exception of PM_{10} (78 μg/m^3) and $PM_{2.5}$ (38 μg/m^3) was observed in restaurants, where PM concentration values exceeded the international standards as listed in Table 2 (El-Sharkawy and Javed, 2018). The main cause of high PM levels was found as poor ventilation in the restaurants. The concentration levels of indoor CO_2 in university buildings were assessed in Jeddah city, KSA. A significant association among indoor temperature, humidity and high CO_2 concentration levels was reported (Jaber et al., 2017).

Exposure assessments to PM_{10} and TSP were compared with three trace gases (SO_2, NO_2, and O_3) in hospitals in the Al Khobar city. Activities such as emissions from nearby industries, traffic, and poor ventilation systems were the main causes of high indoor concentrations of PM_{10} (225 μg/m^3) and TSP (1845 μg/m^3); while, the trace gases were found to be within the acceptable limits (El-Sharkawy and Noweir, 2014). Exposures to indoor air pollutants were also characterized in waiting rooms of bus terminal stations in the Eastern Province of KSA. The measured VOCs, SO_2, NO_2, PM (PM_{10}, PM_4, $PM_{2.5}$ and PM_1), and BETEX (benzene, toluene, ethyl benzene, and xylene) all exceeded the permissible limits among the stations (Dammam, Al-Hasa, and Hafar Al-Batin). The bus idling operations, combustion of diesel fuel, and close proximity to refueling stations might have contributed to high level of emissions in the waiting rooms (Salama et al., 2017).

Due to high usage of cars and air conditioners, analysis of human exposure to PAHs in specific indoor microenvironments (air-conditioner filters, cars, and households) was conducted in Jeddah (Ali et al., 2016b). The median level of indoor PAHs in air-conditioner filters, cars, and households was revealed to be 3450, 2200 and 2650 ppb, respectively (Ali et al., 2016b). The main sources were low-molecular weight PAHs from incomplete combustion of petrochemical products, which were characterized by 2–3 and 4–6 rings referred to as petrogenic and pyrogenic sources, respectively.

In recent years, there have been increasing concerns about emerging flame retardants (FRs) and polybrominated diphenyl ethers (PBDEs) due to their recalcitrant persistence and bioaccumulation behaviors in

Table 4
Indoor air pollution apportionment studies in the GCC countries.

Location	Sources	Reference
Sharjah, UAE	Evidence from source apportionment reveals that Bakhour (Arabian incense) is the main sources of PM in indoor environment consisting of carbon (27.5%), calcium (23.9%), silicon (1.48%), Sulfur (0.42%), Lead (0.07%) by weight.	Elsayed et al. (2016)
Dubai, UAE	Indoor air pollution were very in smoking rooms and hookahs producing fine $PM_{2.5}$ containing elemental carbon (66%) and organic carbon (88%).	Weitzman et al. (2016)
Dubai, UAE	Close proximity of buildings to dusty hilly environments especially during windstorm and sandstorm are potential sources of indoor PM levels. Parking of vehicles close to buildings increases indoor CO levels.	Fadeyi et al. (2014)
Riyadh, KSA	Indoor radon concentrations were high in rooms with no ventilations.	Alghamdi and Aleissa (2014)
Qatif, KSA	Cracks and joints of underground concrete floors are the main sources of Radon.	Al-Jarallah and Fazal Ur (2005)
Doha, Qatar	Outdoor-Indoor PM infiltration and entry via windows and building cracks are the main sources of $PM_{2.5}$ composing of crystal matter(31.5%), nitrates (17.7%), sulfates (16.5%), organic carbon (7.6%).	Saraga et al. (2017)
Kuwait	*Nargyla* smoking are significant contributor to NO_2 (50%) emissions in residential buildings.	Freeman et al. (2018)
Kuwait	Emissions from Kitchen accounted for about 50% of $PM_{2.5}$ concentrations.	Yassin et al. (2012)
Oman	Housing materials, carpets, computers and cleaning materials are the sources of SO_2, NO_2,CO_2, VOCs and TSP.	Abdul-Wahab et al. (2013)

the air (He et al., 2018). According to Ali et al. (2016a), average exposure levels to organophosphate FRs in indoor cars, air conditioning filters, and household floors in Jeddah were recorded to be 10,500, 15,400, and 3750 ppb, respectively. From the study, penta-PBDEs, decabromodiphenylethane (DBDPE), and chlorinated alkyl phosphate were identified as the most common indoor chemicals within the three indoor microenvironments. In another study, indoor HCHO in a medical science laboratory room was investigated in King Saud University. The sources of HCHO exposure levels (~0.93–1.2 mg/m^3) were attributed to poor ventilations. However, HCHO concentrations were higher at the center of the dissecting rooms compared to the corners, where instructors and students might experience higher exposure levels (Vohra, 2011). In addition, several studies have identified the presence of other non-conventional organic pollutants (including siloxanes, phenolic antioxidants, and tetrabromobisphenol A) in indoor dust in KSA, which were emitted from household products (Tran et al., 2015; Wang et al., 2015a; Wang et al., 2016).

Besides the trace gases (FR and PBDEs) and PMs, which are primary pollutants in indoor environments of KSA, an extensive study on a radioactive contaminant (Radon gas) has been carried out in KSA, while lacking in UAE. Radon is known to be colorless and odorless gas. Due to its carcinogenic health effects, Radon has been widely monitored in many developed countries (Al-Jarallah and Fazal Ur, 2005). A measuring campaign of indoor Radon gas in 786 dwellings in Riyadh showed an average emission of 24.6 Bq/m^3, which was below the WHO standard limit (100 Bq/m^3). Radon levels were high (1–195 Bq/m^3) in rooms with low ventilation rates compared to central air conditioning rooms (Alghamdi and Aleissa, 2014). Similarly, about 651 dosimeters were deployed to measure indoor Radon levels in 60 rooms, including kitchen, bed rooms, and living rooms over a continuous period of 8 months in Riyadh. The overall average (18.4 Bq/m^3), minimum (2.0 Bq/m^3), and maximum (69 Bq/m^3) concentration levels were below WHO standard limit (Al-Saleh, 2007). In King Abdulaziz Medical City in Riyadh, Radon concentrations in buildings with basement during winter and summer seasons were 44.3 and 26.1 Bq/m^3, and buildings without basement were 16.1 and 16.7 Bq/m^3, respectively. Thus, seasonal variations were critical factors affecting Radon concentration levels in KSA. Exposures to Radon gas in residential buildings were carried out in different parts of Al-Madinah Al-Munawarah in the Western province of KSA over a 6 months period. The concentration levels of Radon (Bq/m^3), which could be exposed to the residents of the Northern, Eastern, Western and Southern parts of the city were 42 ± 1.6, 21 ± 2.5, 27 ± 3.2, and 37 ± 2.6, respectively (Mohamed et al., 2014).

Bioaerosols have been widely investigated in KSA compared to UAE. This could be due to the fact that KSA serves as the global hub for a large number of pilgrims annually. Large overcrowding at worshiping places (Mosques), pilgrimage centers, and airports are the important causes of airborne bioaerosols. Al-Madinah Al-Munawarah is a province in KSA, where there could be high concentration levels of indoor bioaerosols might happen due to overcrowding of pilgrims. A survey study measured pilgrim's exposure to bacterial and fungi aerosols over four consecutive weeks using sedimentation procedures in Al-Haram and Al-Nabawi cities. The most common identified bacterial aerosols were *Staphylococcus* sp. (32.47%), *Mircrococus* sp. (18.8%), *Baccilus* sp. (12.85%), and *Dermacoccus* (11.23%); while, *Aspergigillus* sp. (78%) was the highest among identified fungi species. The main causes were poor ventilation and overcrowding. However, the degree of infection depends on the immunity of the exposed population (Alananbeh et al., 2017). Human adenovirus (42.8%), human coronavirus (42.8%), *Haemophilus influenza* (14.2%), and *Moraxella catarrhalis* (14.2%) were the dominant respiratory pathogens that identified in King Abdul Aziz International Airport during Hajj season (Memish et al., 2014). Another study on concentration and characterization of bioaerosols using Airport MD gelatin filter sampler was conducted in mosque buildings in Makkah, KSA. Bacterial and fungal concentrations were found to be 10–50 CFU/m^3 and 10 CFU/m^3, respectively. *Bacillus* sp., *Microccoccus* sp., and *Aspergillus niger* were the most abundant species of airborne microbes found within the mosques (Mashat, 2015). Later, a study focused on bioaerosols among the schools in KSA. Bacteria aerosols of 252 samples in 25 middle schools in Riyadh were isolated over one month period. It was found that the highest airborne bacteria were *Pseudomona stutzeri*, *Francisella tularensis*, *Ralstonia mannitolillytica*, *Staphylococcus aureus*, and *Kocuria kristinae*. The highest bioaerosol concentrations were occurred during class hours (overcrowding); therefore, immediate mitigation action was required (Al Mijalli, 2017).

5. Qatar

Compared to UAE and KSA, there is an increased economic diversification in Qatar. Although Qatar is the second least populated country in GCC, it has the highest GDP per capita (Table 1). Due to the large abundance of proven reservoirs, the economy of the country chiefly depends on oil and gas extraction, which have led to serious concerns about air pollution and associated health effects. Qatar was recently rated as the second among the top globally air polluters (especially PM) caused by both anthropogenic (e.g., oil industries) and natural (e.g., dust storms) sources (Alfoldy, 2018). In addition, massive construction activities in the country are happened similar to UAE. These construction activities, which count as the important sources of air pollution, have increased steadily as Qatar is preparing to host the FIFA World Cup in 2022 (Sofotasiou et al., 2015). Literature review revealed that infiltration of ambient air caused a serious health issues in Qatar (Al-Rehaili, 2002; El-Sharkawy, 2014; Radaideh and Shatnawi, 2015; Soleimani et al., 2016). > 20 indoor air pollution articles were published about Qatar, which were lower than that of UAE and KSA. Some of the current indoor air pollution studies in Qatar are summarized in Table 3.

5.1. Air pollutants in Qatar

About 16 randomly selected schools, consisting of 32 classrooms, in Al Wakra and Rayyan Municipalities were sampled for indoor CO_2, PM_{10}, and $PM_{2.5}$ levels. High indoor concentrations of 3442 ± 1710 mg/m^3, 93.2 ± 42.4 μg/m^3, and 60.1 ± 28.8 μg/m^3 were observed for CO_2, PM_{10}, and $PM_{2.5}$, respectively. These exposure levels exceeded the international threshold limits (Table 2) as Qatar currently does not have IAQ standards (Abdel-Salam, 2017). In 2018, 24-h measurements of pupil's exposure to $PM_{2.5}$, VOC, PAHs, and aldehydes were conducted in three classrooms, pupils' homes, and outdoor environments in Doha. It was revealed that the indoor exposure levels to VOC, PAHs, and aldehydes exceeded the ambient concentration levels with exception of $PM_{2.5}$, which showed higher values compared to classrooms. In homes, the emission sources were identified to be from furniture, decorations, air fresheners, cooking, and smoking activities, including Bakhour (Alfoldy, 2018).

A computational fluid dynamic (CFD) and Multi-Zone models were applied to simulate the infiltration of outdoor $PM_{2.5}$ emissions during dusty storms in Doha. Airflow and transportation of ambient pollutants into the residential buildings were well predicted by the models, while the maximum predicted and measured concentration levels of infiltrated $PM_{2.5}$ were 220 and 180 μg/m^3, respectively (Argyropoulos et al., 2016). Sampling of the hydrocarbon aerosols was carried out because air conditioner filters were among the main sources of indoor air pollutants in the residential and office buildings. The median carcinogenic PAHs (by GC-MS analysis) for the residential and office buildings were 129.2 ppb and 137.9 ppb, respectively. While, benzo[*b*]fluoranthene (BbF) and Benzo[*a*]pyrene (BaP) accounted for 18.8 and 16.9% of all PAHs identified in residential and workplace environments, respectively (Kotb et al., 2016).

In air-tight public building (Supreme Council of Health Building) in Doha, a 2-month measurement campaign during summer season showed the existence of Ni, Cr, Pb, Al, Cu, and Fe in the samples. The most dominated elemental species were Zn, Ba, and Pb, including high levels of xylene and limonene (Eman et al., 2016). The presence of these elemental-PM based aerosols suggested infiltration and penetration of PMs via ventilation systems, windows, and building cracks, which were the main causes of indoor air pollution in the buildings in Doha (Saraga et al., 2017).

Although public smoking has been banned in Qatar since 2002, this legislation exempted indoor smoking of the tobacco water pipes. A study in 40 water pipe café and 16 smoke-free buildings showed that $PM_{2.5}$ exposure level was significantly higher ($p < 0.001$) in café buildings (476 μg/m^3) than that of the smoke-free buildings (17 μg/m^3). The emissions in the café building far exceeded the 24-h average (25 μg/m^3) WHO standard by about 19 times (Abdul-Wahab et al., 2015b). Hence, indoor air pollution poses a health threat to Qatari residents even in a building, where no major activities occur (e.g., smoke-free) (Al Mulla et al., 2015). This implies that infiltration from outdoor sources, mostly from dust storms, heavy traffic emissions, and industrial activities are the principal sources of indoor air pollution in Qatar (Abdel-Salam, 2017; Alfoldy, 2018).

Very few indoor Radon studies have been carried out in Qatar. In 1992, the charcoal canister based procedure was used to measure indoor Radon exposure in new residential houses over one year period. Radon concentrations were ranged from 11 to 23 Bq/m^3, which were within the acceptable limits of 100 Bq/m^3 (Arafa and El-Karadawi, 1997). However, most recent studies should be carried out to precisely measure Radon exposure levels in different environments.

Bioaerosols have not been studied extensively in Qatar. An Anderson Six-Staged Impactor was implemented to sample a temporal (summer and autumn seasons) respirable bacterium within the buildings of German International School in Southern Doha. The maximum exposed bacterial aerosols before classes for summer and winter periods were 204 and 35 CFU/m^3, respectively. After classes, the maximum exposed bacterial aerosols for summer and winter periods were increased to 348 and 543 CFU/m^3, respectively. It was revealed that high concentrations of airborne bacteria were due to human sources compared to infiltration from the outdoor environment (Obbard, 2018).

6. Kuwait

IAQ is one of the biggest environmental problems in Kuwait due to massive ever-increasing growth in constructional and petrochemical activates. These major activities, irrespective of the small population size of the country, have translated Kuwait as the third GCC country with the highest per capita GDP and fourth real estate investment after UAE, KSA, and Qatar (Table 1).

Although industrial revolution and urbanization have begun in Kuwait many years ago, most studies on indoor air pollution have initiated a decade ago. In addition to the anthropogenic sources from these major activities, frequent natural dust storms are of concerns contributing to indoor air pollution in Kuwait. Thus, IAQ research interests in Kuwait have been focused mostly on VOCs, PAHs, PM, and Radon with limited studies related to respirable bioaerosols similar to UAE and Qatar. Currently, > 30 research papers on IAQ were published in Kuwait. Selected IAQ studies in different indoor environments are summarized in Table 3.

6.1. Air pollutants in Kuwait

Exposure to TVOC was measured in 10 residential homes in Kuwait city and compared to the outdoor TVOC level. It was found that the average indoor TVOC level (16.3 mg/m^3) was worse compared to the ambient concentration level (7 mg/m^3), where infiltration from outdoor sources were attributed to the high indoor TVOC concentration level (Elkilani and Bouhamra, 2001). In another study, about 78 VOC species (~8 ppm) were identified from 800 air samples using Entech grab samplers in a complex office building, where the indoor environment was free from smoking and industrial emissions (open windows). Alcohols and carbonyls were the most abundant compounds measured in the office complex. The presence of chlorofluorocarbons (CFC) could be due to leakage from the heating, ventilation, and air conditioning (HVAC) systems (Al-Mudhaf et al., 2013).

FRs have been investigated in few microenvironments such as cars ($N = 15$) and households (N = 15) in Kuwait city. The exposure levels to organophosphate FRs in Kuwaiti houses and cars were measured to be 475 and 16,900 ppb, respectively (Ali et al., 2013). Similarly, exposure assessment to total PAHs in dust aerosols collected from the cars and houses in Kuwait city showed median concentration levels of 1675 and 950 ppb, respectively (Ali et al., 2016b). The impact of door opening/closure on three main indoor air pollutants (VOCs, HCHO, and NO_2) was investigated in a modern office complex in Kuwait city. When the doors were closed, significant amount of VOCs (81.5 ppb), HCHO (29.14 μg/m^3), and NO_2 (32.6 μg/m^3) were detected at $p = 0.027$, 0.018 and 0.002 (95% CI) levels, respectively (Al-Hemoud et al., 2018). Likewise, indoor classroom VOCs were ranged from 100 to 1000 ppb within four elementary schools in Kuwait (Al-Awadi, 2018). The results confirmed the presence of about 87% halogenated and 12% oxygenated functional groups in the measured VOCs.

Measurement campaign of indoor $PM_{2.5}$ was carried out in residential homes of three distinct governorates of Jahra (industrial area), Hawalii (business area), and Farwaniya (densely populated area) in Kuwait. The overall results indicated that $PM_{2.5}$ concentrations were higher in bedrooms followed by the kitchen and living rooms of all three governorates. The sequence of higher $PM_{2.5}$ concentrations was Hawalii > Farwaniya > Jahra. Furthermore, the characterization of the respirable $PM_{2.5}$ (ppb) revealed that Al (156.3), Fe (167.9), Zn (32.8), Cu (13.8), Ni (13.5), Cd (7.6), and Pb (5.7) were the most abundant metals bound to $PM_{2.5}$ (Bu-Olayan and Thomas, 2010). These elements could be also emitted from air conditioner filters apart from the infiltration from the ambient sources (Azuma et al., 2018). A personal exposure to $PM_{2.5}$ with a dust-track aerosol monitor in 10 selected residential homes located in Kuwait city (Hawalli, Aljahra, Alahmedi) showed a total inhalable average concentration of 44.1 μg/m^3. $PM_{2.5}$ concentrations in kitchens (63 μg/m^3) were higher compared to the living rooms (44.2 μg/m^3) and bedrooms (25.9 μg/m^3) (Yassin et al., 2012).

In 2008, the indoor dusts of several residential homes in Jahra residential area in Kuwait were sampled for Hg exposures. The average concentration of Hg observed in the samples was about 2.28 ng/m^3 (Al-Awadi et al., 2008). Analysis of indoor dust emissions from air conditioners was carried out in 11–15 years old newly renovated elementary schools ($N = 7$) in Kuwait city. The results showed the maximum concentration (in ppb) of PAH (1667), PBDE (645.5), Pb (74.3), V (74.3), and As (13.7) from the air conditioners over one year period (2011 − 2012). Most of the indoor PBDE were predominantly BDE-209 congeners in school buildings located close to urban and residential zones. They were emitted from electrical wiring installations and electronic appliances, while the presence of high concentration levels of BaP showed an indication of PAHs biomarkers (Al-Hemoud et al., 2017).

In 2017, the pollutant emissions from a 60-seater water pipe café equipped with a brand new HVAC system were carried out for six days in Kuwait city. Hourly maximum concentration levels of PM_1 (27 μg/m^3), $PM_{2.5}$ (92 μg/m^3), CO (49.5 mg/m^3), and CO_2 (3244 mg/m^3) were obtained, especially during the late hours operation of the café (Al-Dabbous et al., 2018). Due to the importance of the topic, Freeman et al. (2018) estimated the annual emissions of indoor "Sheesha" and "Nargila" water pipes in the selected restaurants and cafés in Kuwait city via Monte Carlo simulation. The yearly emission levels (kg) were 744.3, 233.7, 225.7, and 1.34 for NOx, N_2O, NH_3, and PAH, respectively. Further, CO, which is one of the hazardous indoor air pollutants, was determined to be 80.33 tons. In other words, the yearly emissions of NOx, N_2O, NH_3, PAHs and CO could be converted into 85, 26.7, 25.8, 0.15 and 9170 g per hour, respectively. These concentration levels were extremely high and could dangerously affect human health. However, measured emission data were important to be compared with the modeled data.

There is a hypothesis that indoor Radon exposure is associated with incidence of cancer and it is the second risk factor for lung cancer after cigarette smoking (Abo-Elmagd et al., 2018; Al-Khateeb et al., 2017). This naturally occurring radioactive pollutant has been fairly studied in Kuwait. In 2003, a measurement campaign was conducted in 271 bedrooms and 268 living rooms in Kuwait city by using Pico-Rad detectors. The mean indoor Radon exposure levels ranged from 4.0–241 Bq/m^3, where few homes had Radon concentrations above the threshold limit of 100 Bq/m^3 (Al-Azmi et al., 2008). In educational institutions, Radon testing was carried out in 25 school buildings with similar building designs and HVAC systems over a period of 6 months with Track-Etch detectors. The results showed a mean Radon level of 16 ± 4 Bq/m^3 and alpha dose equivalent rate of 0.97 ± 0.25 mSv/yr (Maged, 2006). Another 2-year comparative indoor Radon gas assessment among a total of 150 schools and residential buildings was conducted in Kuwait by Al-Awadi and Khan (2018). The minimum and maximum Radon concentrations in school buildings were 7 ± 1 and 405 ± 21 Bq/m^3, respectively. The Radon levels increased in residential homes, where the minimum and maximum concentrations were 13 ± 1 and 595 ± 30 Bq/m^3, respectively. The exposure level was attributed to the basement of the buildings, where poor ventilations could be an important factor for high Radon concentration levels.

Respirable bioaerosol studies have not been investigated well in Kuwait. *Aspergillus fumigatus* was isolated in Mubarak Al-Kabeer Hospital rooms in Jabriya with Anderson 6-stage air impactor, where 7 out of 92 collected samples were tested positive for *A. fumigatus*. Airborne bacteria and fungi aerosol measurements in residential buildings in Al-Qurain area resulted in 14 CFU/m^3 of bioaerosols, consisting of *Staphylococcus gallinaium*, *Streptococcus sanguinis*, and *Asprigllus niger*. Higher CFU counts were attributed to homes with low environmental hygienic standards (Yassin and Almouqatea, 2010).

7. Oman

Environmental performances, including IAQ, are very important in Oman since the country has massively invested in real estate developments of the emerging tourism industry. Oman has the least per capita GDP among all of the GCC countries and the investment in real estate development is higher compared to Bahrain (Table 1). Oman has similar unfavorable climatic conditions, including extreme and longer summer temperature with very low precipitation and dust storms from the Northern part of the country.

Due to industrial development and massive construction activities, which are similar to other GCC countries, infiltration of ambient pollutants is one of the main sources of indoor air pollution in Oman. IAQ studies have started in Oman more than a decade ago, whereas they focused mainly on the residential buildings in close proximity to industrial zones (Baawain et al., 2017). Very few studies have been conducted with reference to conventional air pollutants in Oman (i.e., PM, CO_2, VOC, SO_2, and NO_2). Currently, there are no indoor FR, Radon, and bioaerosol exposure assessment studies in Oman, covering different microenvironments (e.g., homes, schools, cars, mosques, airports, and hospitals). Only around 12 IAQ research articles were published in the literature about Oman. While most of these studies were focused commonly on characterization of indoor air pollutants as indicated in Table 3.

7.1. Air pollutants in Oman

Satellite observations and air quality monitoring stations have shown that Middle East (including Oman) dust storms are one of the natural sources of ambient PMs in the region (Farahat, 2016). Mineralogical analysis of indoor PM samples in residential homes of Al-Suwayq in the Northern Oman showed large amounts of calcite, quartz, dolomite, and goethite PMs. Likewise, the microanalysis of the indoor particles showed the presence of K, Fe, Zn, Si, Cl, Na, and Al elements (Abdul-Wahab et al., 2005). Occupational exposure to indoor air pollutants was conducted at Al-Rusayl industrial estates in Muscat. The concentration levels of indoor TSP in the workplace were averaged to be 1802 $\mu g/m^3$. Also, the average respirable heavy metal PMs (Pb, Cu, Ni, and Cr) was measured to be 1293, 131, 17 ng/m^3, respectively (Yaghi and Abdul-Wahab, 2003). In 2003, assessment of indoor dust aerosols in residential houses located in close proximity to industries revealed high amounts (ppm) of Pb (108 ± 65), Cr (34 ± 14), Cu (108 ± 91), and Ni (130 ± 125). Correlation analysis showed that indoor Cu and Pb were generated internally, while Ni and Cr were entered from the ambient environment (Yaghi and Abdul-Wahab, 2004). High amounts of TSP (171.5 $\mu g/m^3$) and heavy metals (ng/m^3), including Cr (3), Zn (748), Ni (4.9), and Pb (3.2) were detected in 12 houses in Sohar industrial estate (Abdul-Wahab and Yaghi, 2004).

Limited studies have been conducted in terms of indoor gaseous air pollutants in Oman. Museums in Bait Al Zubair, which attract about 1000 visitors daily, had CO_2, SO_2, and TSP concentration levels of 953 mg/m^3, 2.8 $\mu g/m^3$, and 67.5 $\mu g/m^3$, respectively. The pollutants were emitted from the artifact collections and decorations (Abdul-Wahab et al., 2013). Comparative assessment of IAQ in two residential apartments in Muscat (built in 1986 and 1991) showed that indoor TVOC concentrations were 330 and 1250 $\mu g/m^3$, respectively. Thus, the exposure levels to TVOC in the relatively new building far exceeded the acceptable standards compared to the old building (Abdul-Wahab, 2017). An ultra-modern library complex in Muscat with > 1000 seater-capacity was examined for sick building syndrome. The short-term (15 min sampling) study results disclosed that the library occupants were exposed to high levels of CO_2 (2073 mg/m^3), TVOC (510 $\mu g/m^3$), and PM_{10} (71 $\mu g/m^3$) (Abdul-Wahab et al., 2015a).

Indoor smoking habit in most public locations and residential homes in the GCC countries is not different in Oman. The amount of $PM_{2.5}$ emissions from indoor second-hand smoke in 30 different public places in Muscat (about 562 $\mu g/m^3$) was higher than that of the highest average concentration of $PM_{2.5}$ occurred in cafés (256 $\mu g/m^3$) with water pipe smoking services, offices (11 $\mu g/m^3$), and transport passengers' waiting rooms (43 $\mu g/m^3$) (Al-Lawati et al., 2015). The health effects from the exposure to these $PM_{2.5}$ emissions might even be severe because of the long durations of time that people spend at café, especially during the nighttime. Hence, future building designs in public buildings could help to reduce harmful pollutants by diluting the indoor pollution levels. No studies have been reported on the assessment of Radon and bioaerosol pollution in Oman.

8. Bahrain

Bahrain is a GCC member with the least population and real estate investments as evidenced by being the second lowest per capita GDP among the other countries in the region (Table 1). Although Bahrain has recognized the importance of IAQ since 1980s, it has the least number of indoor air pollution studies in the region. The few and early studies on indoor air pollution in Bahrain concentrated mainly on the characterization of heavy metals on household dust aerosols and NO_2. To date, only about four published articles on indoor air pollution are available in Bahrain. Most of the few studies were conducted in homes compared with other GCC countries with diversified microenvironments. Table 3 summarizes few selected indoor air pollution findings in Bahrain.

8.1. Air pollutants in Bahrain

All indoor air pollution studies in Bahrain have been focused mostly on exposure assessment of heavy metals. Pb coated paints had been commonly used in indoor households in Bahrain since 1930s. In 1986, atomic absorption spectrometry (AAS) analysis of fine paint PMs sampled from household buildings showed that Pb concentrations were deemed within the US limits (200–5700 ppm). However, they were considered hazardous to human health, especially the vulnerable populations such as children and the aged population (Madany et al., 1987). Indoor dusts, the main source of inhalable fine PMs, were collected from households and hospitals and analyzed to determine their chemical constituents. The results showed that the average indoor Pb, Cd, and Cr were 360, 29.2, and 154.5 ppm in homes and 697, 72, and 144.4 ppm in hospitals, respectively. The study attributed the high concentration of heavy metals to outdoor traffic emissions (Akhter, 1993). Similarly, in-home assessment of indoor heavy metals from traffic related emissions was investigated. The probable concentrations of human exposure for Pb, Zn, Cd, Cr, and Ni were reported to be 517, 202, 1.9, 11, and 10 ppm, respectively (Madany, 1994). All the conducted studies in Bahrain supported the presence of Pb in indoor environments.

Passive diffusive samplers were employed to determine NO_2 exposure in 32 homes with relatively similar designs and ventilation systems in Bahrain. The average concentrations of NO_2 within the kitchens, living rooms, and bedrooms were about 52.3, 22.1, and 15.2 $\mu g/m^3$, respectively. Moreover, a positive correlation between NO_2 concentration levels in the kitchen and the frequency of cooking were reported (Madany, 1992). Air pollution studies in Bahrain are different compared to the rest of the GCC countries, where indoor air pollution measurements and characterizations involve PM_{10}, $PM_{2.5}$, Radon, VOC, PAHs, and bioaerosols.

9. Ventilations and building designs

The exposure levels to air pollutants in indoor environments are greatly influenced by ventilation systems as they provide a mechanism for dilution of the pollutants. An efficient ventilation system (i.e., either natural or mechanical) should reduce the concentration of indoor air pollutants and prevent the entry of ambient air pollutants (Cabo Verde et al., 2015; Jovanović et al., 2014; Vanker et al., 2015; Xu and Hao, 2017). In addition, the unfavorable climatic conditions, such as high temperature and humidity, and low precipitation have increased the ambient concentration levels of these recalcitrant pollutants (Table 5) (Farahat, 2016; Omidvarborna et al., 2018). This situation is different in UAE, where ambient air pollutant levels, especially PMs from dust storms and trace gases from petroleum industries, are very high. Such conditions have led to high usage of air conditioners in UAE (Azar and Al Ansari, 2017; Bekhet et al., 2017; Giusti and Almoosawi, 2017; Krarti and Dubey, 2018). According to Azuma et al. (2018), air conditioners are one of the main sources of indoor PMs (mostly $PM_{0.1}$) as those fine PMs are emitted via medium efficiency particulate air filters (normally used in residential building air conditioners).

The effects of ventilation performance on IAQ for 4 elementary schools were investigated in Dubai (Behzadi and Fadeyi, 2012). The results showed that the ventilation rate per person (3.7 l/s) failed to meet the American society of heating, refrigerating and air-conditioning engineers (ASHRAE) threshold standard (8 l/s). It was reported that factors such as proper building orientations and efficient natural ventilations in UAE, which were depended on the building type, could reduce energy consumption by 30–79%, while improving indoor environmental quality (Friess and Rakhshan, 2017). Fadeyi et al. (2014) reported a strong correlation (r = 0.88) of CO_2 concentration levels and ventilation systems in school buildings in Dubai. They concluded that the levels of indoor air pollutants were greatly reduced by proper ventilation systems, but at the same time, it could increase pollutant concentrations by taking infiltrated air from the outdoor environment. Although many environmentally sustainable building designs have been introduced in UAE, they have focused only on CO_2 reductions from indoor pollution other than improving ventilation systems. Therefore, since adequate ventilation mechanisms to prevent entry of outdoor pollutants have not been incorporated in the current buildings in UAE, infiltration of ambient air pollutants is now a big challenge that should be addressed (Table 6).

Similar to UAE, ventilations and building designs have not been well explored in KSA due to harsh environmental conditions (Table 5 and Table 6). For example, in one case, IAQ modeling approach called TAS was employed to simulate environmentally sustainable school building design capable of adapting the unfavorable microclimate conditions in Makkah and Abha cities. The results showed that for a better environmental performance, including IAQ, the modeled buildings in the hot climate of Makkah natural ventilations were required, while in Abha city with moderate climate cross natural ventilations were required (Alwetaishi and Balabel, 2017). However, El-Sharkawy and Javed (2018) argued that the major source of indoor pollution was infiltration of outdoor sources, which might be as a result of natural ventilations. In another study, CFD simulation system was employed to assess the optimum reduction of IAQ of Al-Haram mosque in Makkah. The model output revealed that indoor CO_2 levels were reduced by increasing the ventilation rate (Jaafar et al., 2017). Hence, a study concluded that the residents of KSA would prefer of purchasing houses with improved ventilation systems to reduce indoor air pollution (Opoku and Abdul-Muhmin, 2010). This implies environmentally sustainable building design that prevents penetration of ambient air into buildings that should be implemented in KSA (El-Sharkawy, 2014).

Unfavorable weather conditions of Qatar (Table 5) could result in a maximum daily temperature of about 45 °C and dust loading of about 200 mg/m^3 (second highest global) through atmospheric deposition (Yigiterhan et al., 2018). The same as other GCC countries, there are no building designs in Qatar that incorporate advanced ventilation efficiency to improve IAQ. Green building rating study based on Global sustainability assessment system (GSAS) procedure was conducted in some selected buildings in Qatar. According to the results, 50% of the occupants felt that controlling indoor trace gases (use of low emitting VOCs building materials and improvement of natural and mechanical ventilations in building designs) would ensure occupants productivity and health (Al Horr et al., 2017). Additionally, analysis of indoor air velocity in office buildings in Qatar, which is a critical factor in reducing build-up indoor air pollutants, showed that the indoor air velocity (0.0–0.05 m/s) in the current buildings did not meet the limits set by ASHRAE (0.18–0.25 m/s) (Indraganti and Boussaa, 2017). Further, the

Table 5
Average environmental meteorology variations in the GCC countries (1991–2015).

Parameter	KSA	UAE	Qatar	Oman	Kuwait	Bahrain
[abc]Humidity (%)	N/A	10–90	N/A	32–78	N/A	20–79
[d]Temperature (°C)	15.8–33.2	19.36–34.78	17.49–37.29	21.53–30.38	13.24–38.13	17.07–36.21
[d]Precipitation (mm)	0–23.96	0–14.26	0–18.55	0–95.3	0–27.38	0–25.26

[a] NCM (2018).
[b] NCSI (2017).
[c] Meteorological Directorate (2018).
[d] World Bank (2018).

Table 6
The environmentally sustainable building designs in the GCC countries in terms of IAQ.

Location	Name of the building	Assessment tool (s)	Observations	Reference
KSA	Non-residential building	BREEAM, LEED, green star, estidama	IAQ accounted for 27% of all environmental factors (72% by weight) as important criteria for sustainable buildings.	Banani et al. (2016)
Oman	Residential-SQU ecohouse	Energy simulation	About 40% of energy will be saved which may improve IAQ emissions.	Alalouch et al. (2016)
Qatar	Residential-baytna, villa	Passive house institute standards	50% annual CO_2 (including indoor) emissions could be achieved including water and energy consumptions.	Alalouch et al. (2016)
UAE	Residential	Simulation and energy analysis	Net CO_2 (including indoor) emissions could be increased by 5.4% from residential buildings.	Radhi (2009)
UAE	Residential villas	Design builder/energy plus models	Insulation of residential walls could reduce CO_2 emissions of 7.6 tons per household.	Friess et al. (2012)

degree of indoor air pollution also could be affected by building envelopes, air tightness, and ventilation systems as mentioned by Alfoldy (2018).

Designing sustainable buildings to suit the unique weather conditions is important in controlling built-up indoor air pollutants. Kuwait ambient temperature in summer season could reach about 45 °C and the lowest temperature during the winter season (November to January) could reach −2 °C with average annual precipitation below 127 mm (Yassin and Almouqatea, 2010). Thus, this climatic system may affect the ambient air pollution levels and subsequently IAQ, which depend primarily on the meteorological factors (Alenezi and Aldaihan, 2018). Hence, to improve IAQ, various new green building design projects have been examined (Table 6). Some studies improved ventilation systems of the existing local buildings. A compartment building modeling system was applied to a typical Kuwaiti building to determine the indoor VOC levels. The results showed that an efficient indoor VOC reduction could be achieved if the ratio of makeup air to the recirculation air could fall within the range of $0.7-1.3$ (Elkilani and Bouhamra, 2001). According to Al-Hemoud et al. (2018), application of conventional ventilation systems such as opening of doors compared to door closures in an office building did not result in a significant reduction in indoor VOC concentrations. In their study, both door opening and closure maintained VOC concentration levels of 10 ppb. Hence, new technologies should be implemented to further improve the IAQ.

Oman has similar weather conditions as other GCC countries (Table 5). Therefore, infiltrations of outdoor air pollutants from both natural and anthropogenic sources are important factors in determining the IAQ (Baawain and Al-Serihi, 2014). Abdul-Wahab et al. (2005) reported the presence of high-level earth metals (Zn, Mg, Fe, and Cu) in homes due to natural dust storms, while limestone borne-aerosols were attributed to nearby cement industries.

Few studies in Oman explored the efficiency of sustainable buildings in improving IAQ (Table 6). According to Abdul-Wahab et al. (2015a), increasing in humidity levels coupled with low ventilation in a library complex in Muscat were the major causes of high indoor levels of CO_2 and VOCs. The improvement of IAQ in the future buildings was the first priority in Oman, followed by improving energy efficiency and water resource managements (Al-Jebouri et al., 2017). Another study showed that the green building concept should adhere while using building materials for constructions (Safinia et al., 2017).

In Bahrain, poor meteorological conditions are not different from the rest of the GCC countries (Table 5). Ambient pollution levels in Bahrain were within unacceptable limits and they might penetrate to the indoor environments (Khamdan et al., 2009). According to Jassim et al. (2018), ambient PM_{10} and $PM_{2.5}$ concentration levels based on measurement from 5 monitoring stations were ranged from 101–336 and 46–74.6 μg/m^3, respectively; thereby, making it a causative factor for indoor air pollution.

Currently, there are no sustainable architectural building designs in Bahrain compared to other GCC countries, where mitigations of indoor air pollution have been fairly investigated (Table 6). Most sustainable building design studies targeted CO_2 emission reduction technologies and performance of mechanical ventilation systems (Alnaser et al., 2008; Radhi et al., 2009). Thus, IAQ will continue to remain uncertain unless sustainable green building projects are adopted in Bahrain.

10. Mitigation strategies

Currently there is no study in the literature, focusing on the science based mitigation measurements of indoor air pollution in UAE. In limited studies, a study showed that installation of air purifiers on the ceilings of metro trains could reduce PM_{10} levels by 15.5–26% (Xu and Hao, 2017). Also in UAE, applying highly efficient particulate air filters was suggested as an urgent solution to reduce the emission of indoor submicron PMs (Azuma et al., 2018). Table 7 summarizes strategies of reducing indoor air pollution in UAE and other GCC countries. The proved strategies were based on researchers' recommendations and lack of scientific evidences; however, they might be useful as precautionary approaches.

Current studies in UAE have recommended natural ventilations as a means of reducing indoor air pollutant levels. But this approach was not efficient as it could lead to infiltration of ambient air pollutants (Funk et al., 2014; Hamdan et al., 2018). However, the mechanism that could filter out ambient pollutants via natural ventilation was recommended by Behzadi and Fadeyi (2012). Replacing charcoal burning stoves with electronic heating plates had a greater potential of reducing concentration levels of CO emitted from hookah smoking locations (Weitzman et al., 2016). Since indoor air pollution is one of the public health issues in UAE schools, UAE government has instituted Emirates coalition for green schools. The main objective was optimizing environmental performance of various schools starting from K-12 to the university level. This policy requires buildings that would significantly reduce indoor VOC emissions to acceptable limits by controlling/reducing the consumption of sealants, adhesives, and paints (Jason and Sheena, 2018).

Similar to UAE, no study has provided scientific or technological findings about mitigation of indoor air pollution in response to microclimatic conditions peculiar to KSA. However, recommendations from individual indoor air pollution studies and KSA government environmental sustainability policies will be crucial in ameliorating the effects of indoor air pollution. KSA government has promoted green building practices in the region. Although this policy intends to reduce energy consumption and CO_2 emission from buildings, it will also reduce indoor air pollution. Moreover, the policy accounts for efficient ventilation systems, which is an important factor of energy reduction plans (Al-Tamimi, 2017).

Some of the KSA mitigation-based studies are summarized here. Alghamdi and Aleissa (2014) proposed that indoor Radon emissions in KSA could be reduced by assessing building materials via gamma spectroscopy analysis prior to selecting for construction. Also, cross ventilation in buildings has been recommended recently as the most

Table 7
Mitigation measurement of indoor air pollution exposures in the GCC countries by various studies.

Reference	Pollutants	Recommended mitigation measure
Cohen et al. (2013), UAE	Incense smoke	Proper ventilations while burning incense, application of low smoke-producing charcoal when burning incense greatly reduces CO and CO_2.
Weitzman et al. (2016), UAE	Hooker, Cigarette-smoke	Public health education and regulations will be important to reduce PM and trace gas emissions in indoor smoking.
Al Mijalli (2017), KSA	Airborne bacteria	Reducing overcrowding of students in classrooms and frequent cleaning of air conditioners filters could reduce bacteria growth and exposure.
Alghamdi and Aleissa (2014) KSA	Radon	Adequate ventilations in red brick buildings with water air conditioners reduces Radon concentrations in dwellings.
Al-Saleh (2007), KSA	Radon	Natural and forced ventilations could reduce Radon levels.
El-Sharkawy (2014), KSA	TSP, CO_2, SO_2, NO_2	Improving both mechanical and air conditioning systems in classrooms could better improve indoor air pollutants exposures.
Memish et al. (2014), KSA	Airborne bacteria	Wearing of certified respirators, hand hygiene, and frequent cleaning and disinfection could reduce bioaerosols contaminations in busy airports.
Salama and Berekaa (2016), KSA	Airborne bacteria	Environmentally controlled slaughter houses with efficient ventilation systems could reduce the production and exposure of indoor bioaerosols.
Bu-Olayan and Thomas (2010), Kuwait	$PM_{2.5}$, trace metals	There should be a proper storage for household materials and chemicals to reduce emissions.
Al-Hubail and Al-Temeemi (2015), Kuwait	PM_{10}, CO_2	There should be proper ventilations systems.
Abdel-Salam (2017), Qatar	PM_{10}, $PM_{2.5}$, CO, CO_2	Frequent cleaning and renovation of old classroom buildings could reduce infiltration of outdoor pollutants into indoor environment.
Al Mulla et al. (2015), Qatar	$PM_{2.5}$	Indoor smoking policies should be implemented to safeguard human health.
Al-Rawas et al. (2009), Oman	Incense smoke	Proper ventilations and avoidance of smoking emissions from children could reduce the health effects of indoor air pollution.

effective way of reducing indoor air pollution compared to natural ventilation (Alwetaishi and Balabel, 2017). Wearing recommended respirators with improvement in sanitation practices, such as disinfections, is a potential remedy of reducing contaminations from airborne harmful microbes during Hajj (Memish et al., 2014). Further, in order to reduce human exposure levels to bioaerosols, frequent cleaning of air conditioning filters and efficient ventilations were recommended in school buildings (Al Mijalli, 2017).

There are no studies on strategies for indoor air pollution control in Qatar. However, there are several indoor studies, where the performance of platform screen doors (PSD) and magnetic filters to remove indoor PMs have been studied (Xu and Hao, 2017). The situation in Qatar involves very few indoor air pollution control recommendations based on specific IAQ characterization studies (Table 7). For example, a study recommended thorough cleaning of playgrounds in all schools to avoid transportation of outdoor pollutants (PMs) to school buildings. Likewise, installation of air cleaners and frequent renovation of buildings could improve the IAQ (Abdel-Salam, 2017). Currently, there is a ban on public smoking in Qatar but the legislation exempts indoor water pipes. Al Mulla et al. (2015) suggested a ban on indoor tobacco smoking, which is one of the main causes of indoor air pollution. Finally, advanced ventilation systems could be incorporated by the current and future green buildings to reduce indoor pollutants in Qatar (Sergio et al., 2017).

Studies on the mitigation strategies in Kuwait were limited too. In addition to the mitigation measures summarized in Table 7, Al-Awadi (2018) recommended that installation of activated carbon coated with calcium and magnesium oxides might help to reduce indoor CO_2 levels of school buildings. According to Al-Awadi and Khan (2018), in order to safeguard the health of the dwellers buildings constructed in Kuwait in the 1990s should be regularly monitored for Radon levels and equipped with Radon exhalation systems. In case of modeling studies, CFD modeling of indoor $PM_{2.5}$ in a test house showed that air purifier was not an efficient tool of reducing indoor $PM_{2.5}$ levels (Al-sarraf et al., 2013). The micrometric adsorption analyzer was used to simulate the absorption rates of VOC in a living room in Kuwait. The result revealed that the adsorbed weight of 1,2-dichlorobenzene ranged $0.077-0.639\ mg/m^2$, while the simulated value was 0.066–0.652 mg/m^2, which showed a good consistency and agreement (Elkilani et al., 2001).

To improve IAQ, several mitigation measures have been suggested by many GCC countries (Table 7). However, no study has been carried out on mitigation measures of indoor air pollution in Oman except few recommendations. According to Al-Lawati et al. (2015), the government of Oman should ensure that the indoor second-hand tobacco smoke, especially in public places, should be complied to protect human health from $PM_{2.5}$ exposures.

Neither mitigation strategies nor recommended measures of reducing indoor air pollution were available in Bahrain. In other GCC countries, several attempts were made to provide mitigation or precautionary measures of reducing the exposure to the indoor air pollutants (Table 7). However, the stringent abatement measures of ambient air pollution on industries and transportation sectors suggested by Jassim and Coskuner (2017) and Jassim et al. (2018) might be beneficial in IAQ.

11. Knowledge gaps and future study

GCC countries are massively undergoing infrastructural developments as the member countries are diversifying their economies through manufacturing, urbanization, construction, tourism, aviation, and sports in addition to the already existing oil and petrochemical industries. Due to such aforementioned economic activities, the assessment and mitigation of indoor air pollution are not optional, but rather a serious health threat to the exposed populations that require important considerations.

Indoor air pollution is one of the main causes of cancer, cardiorespiratory, and pulmonary diseases, including morbidities globally. To better understand and mitigate indoor air pollution problems in the GCC countries, the following knowledge gaps and research limitations must to be addressed:

- There is lack of indoor air pollution mitigation studies in the GCC region, future studies should be focused on advance indoor air purification systems.
- There is inadequate IAQ modeling studies. Evaluating model results with measured values will provide a better understanding about the uncertainties of the pollutant estimations.
- There is a lack of studies on indoor asbestos, ozone, and noise in all GCC countries. Also, indoor Radon assessment is poorly conducted in most GCC countries except KSA and Kuwait. Besides, some conventional indoor air pollutants (trace gases, PMs, PAHs, and

bioearosols, including molds) studies are greatly lacking in Oman and Bahrain.

- To identify the actual causes of Radon emissions, the emission levels of Radon from soil and building materials in comparison with the indoor Radon levels should be adequately investigated.
- Future IAQ studies in the GCC countries should focus on ultrafine and nanoparticles as they may cause serious human health problems compared to PM_{10} and $PM_{2.5}$.
- There are inadequate health assessment studies on most of the common indoor air pollutants and Radon levels in the region. Thus, future epidemiological studies should link indoor air pollution to human health.
- Future studies should be able to explore indoor multi-pollutant effects on human health compared to the effects of single pollutants. In addition, further studies should be carried out to clearly differentiate health effects between exposure to indoor and outdoor pollutants.
- Most current indoor air pollution studies in the GCC countries were conducted in urban areas. Future studies should be focused on per-urban and rural indoor microenvironments as indoor building architectures and activities may differ from buildings in urban centers.
- There should be local and regional IAQ guidelines available in the GCC countries.

12. Concluding remarks

The study focused on indoor air pollution in the GCC region with its unique emission sources (e.g., infiltration from ambient environment (mainly dust storms), indoor smoking, and incense burning) and ambient climatic conditions. Salient findings of IAQ based scholarly peer reviewed articles on several microenvironments in the GCC countries were summarized in this review. These encompass the major sources, characterization, measurement, and mitigation measures of different indoor air pollutants. In addition, the effects of building and ventilation designs on the quality of air based on the GCC microclimatic conditions were explored. The review of previous studies showed minor differences of indoor air pollutants in each GCC country. Throughout the entire GCC region, VOCs, NO_2, SO_2, PM_{10}, $PM_{2.5}$, heavy metals, and CO_2 were the most dominant indoor air pollutants found in homes, schools, cafés, and office buildings. The main sources of these pollutants were infiltration of ambient air, burning of Arabian incense, and smoking. Other pollutants such as PAHs, Radon, bacteria, and fungi bioaerosols were well investigated in very few GCC countries, which were originated primary from overcrowding and poor ventilation systems. There was a lack of science based mitigation studies that could reduce the emission and the exposure of these pollutants in the GCC countries. However, several recommendations and precautionary measures were provided to minimize the levels of exposure. Above all, future studies should focus on 1) the advanced methods of modeling human health effects from the exposure to indoor air pollutants, and 2) further development of air purification systems.

Nomenclature

^{222}Rn	Radon
A	measured in median
AAS	Atomic absorption spectrometry
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
B	measured in 90th percentiles
BaP	benzo[*a*]pyrene
BbF	Benzo[*b*]fluoranthene
BC	Black carbon
BDE	Brominated diphenyl ether
BETEX	Benzene, toluene, ethyl benzene, and xylene
$C_2H_2O_2$	Glyoxal
$C_5H_{10}O$	2-pentanone
CFC	Chlorofluorocarbons
CFD	computational fluid dynamic
CFU/m^3	Colony forming unit per cubic meter of air
Cl_2	Chlorine gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COPD	Chronic obstructive pulmonary diseases
DDT	Dichlorodiphenyltrichloroethane
EC	Elemental carbon
EPA	Environmental Protection Agency
FIFA	The Fédération Internationale de Football Association
FR	Flame retardant
GCC	Gulf Cooperation Council
GC-MS	Gas chromatography-Mass Spectrometer
GDP	gross domestic product
GSAS	Global sustainability assessment system
H_2S	Hydrogen sulfide
HCHO	Formaldehyde
HVAC	heating, ventilation and air conditioning
IAQ	Indoor Air Quality
IARC	International Agency for Research on Cancer
ICP-OES	Inductively coupled plasma optical emission spectrometry
IHD	Ischemic heart diseases
KSA	Kingdom of Saudi Arabia
LC	Lung cancer
NH_3	Ammonia
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
NTP	National Toxicological program
O_3	Ozone
OR	Odd ratios
PAHs	Polyaromatic hydrocarbons
PBDEs	Polybrominated diphenyl ethers
PSD	Platform screen doors
PM	Particulate matter
PM_1	Particulate matter with aerodynamic diameter $< 1\,\mu m$
$PM_{2.5}$	Particulate matter with aerodynamic diameter $< 2.5\,\mu m$
PM_{10}	Particulate matter with aerodynamic diameter $< 10\,\mu m$
SO_2	Sulfur dioxide
TPM	total particulates
TSP	Total suspended particulate matter
TVOC	Total volatile organic compound
UAE	United Arab Emirates
VOCs	Volatile organic compounds
WHO	World Health Organization
ΣOCs	Organochlorines
ΣPCBs	Polychlorinated biphenyls

Declaration of conflict of interest

The authors declared no potential conflict of interest of this article.

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