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Indoor air quality in day-care centres: a global review

Winifred U. Anake[1] · **Esther A. Nnamani**[1]

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Abstract

A healthy indoor environment is critical for children due to the severe effect of poor indoor air quality (IAQ) on their overall well-being. Day-care centres (DCCs) are important indoor microenvironments for children apart from their homes. Therefore, monitoring IAQ in this microenvironment is vital because of the vulnerability of the occupants. This review gives a global overview of the predominant indoor chemical pollutant levels monitored in DCCs, compares their concentration with available regulations for IAQ, evaluates the sources and health risk effects of chemical pollutants and proposes strategies for enhancing IAQ in DCCs. Thirty-seven (37) articles were used based on specific stated inclusion and exclusion criteria. Continents like Europe and Asia have the most published studies in indoor DCCs. The decreasing trend of pollutants examined in most studies include particulate matter > carbon dioxide > formaldehyde > carbon monoxide > total volatile organic compounds > volatile organic compounds > nitrogen dioxide > ozone > benzene > sulphur dioxide = radon. Particulate matter in the size and mass concentration range of PM_{10} (0.116–1920.71 μg/m^3) > $PM_{2.5}$ (0.279.2–260.74 μg/m^3) was the most investigated pollutant. While nitrogen dioxide, radon and carbon monoxide were consistent with the existing national and international reference values for IAQ across the continents, exceedances occurred in other pollutants. The limited number of indoor chemical pollutant studies suggests the need for more comprehensive studies on IAQ in DCC globally. Further studies should highlight the availability of low-cost sensors and mobile analytical equipment that will promote affordable ground-level data accessibility.

Keywords Chemical pollutants · Day-care centres · Indoor air quality · Health effects · Particulate matter · SDGs

Introduction

A healthy environment is vital for efficient and impactful learning, especially for children vulnerable to air pollution (Masekela and Vanker 2020). Over time, it has been proven that a clean-air environment increases a child's attention rate and leads to better and improved participation in the learning and development process of the child (Clark et al. 2020; Adaji et al. 2020; Michelot et al. 2013; Agbo et al. 2021). Therefore, it is vital to always ensure that the environment is clean and health-promoting. The environment is categorized into two divisions: indoor and outdoor environments. There have been numerous studies on ambient air pollution/quality. Still, very few studies have been conducted on indoor air quality (IAQ), particularly in children's public spaces such as day-care centres (DCCs), preschools, nurseries and kindergartens (Annesi-Maesano et al. 2013; Zhang et al. 2021; Manuel et al. 2021). There are many definitions for IAQ (Cincinelli and Martellini 2017); for this context, IAQ has been defined as the air quality within and around a building, which can affect the general well-being of its occupants (Soreanu 2016; USEPA 2022). Two major parameters are used in assessing IAQ, namely, infiltration of outdoor contaminants and thermal conditions such as temperature, relative humidity and airflow (Cincinelli and Martellini 2017; WHO 2021a). Indoor air pollution in children's learning spaces is associated with types of indoor activities, infiltration of outdoor pollutants into the indoor environment, nature of building structures, interior decorations, emission of pollutants from building materials, cleaning chemicals, geographical conditions and the nature of ventilation system in use (natural, mechanical or a combination of the two) (Branco et al. 2014; Mannan and Al-Ghamdi 2021; Oliveira et al. 2019; Salthammer et al. 2016; Valderrama-Ulloa et al. 2020; WHO 2021b).

Air quality in an indoor environment is critical because it has been scientifically proven that we spend approximately

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✉ Winifred U. Anake
winifred.anake@covenantuniversity.edu.ng

[1] Department of Chemistry, College of Science & Technology, Covenant University, Km10 Idiroko Road, Ota, Nigeria

70–90% of our time indoors (UNICEF 2019). According to WHO, about five hundred thousand (500,000) children under the age of 5 died in 2016 due to respiratory tract diseases induced by indoor air pollution (IAP) (WHO 2017). Given the health relevance of IAQ, unhealthy IAQ has been assessed as the eighth (8th) most critical environmental risk factor and is responsible for 2.7% of death cases globally. Based on the foregoing, the United Nations Sustainable Development Goal (UNSDG) 3.9 focuses on drastically reducing deaths and illnesses caused by air pollution. As a result, there is an urgent need to navigate research interests to this area.

Some of the indoor chemical pollutants that thrive in children learning environments include particulate matter (PMs) (Guak et al. 2021; Sara et al. 2020; Kalimeri et al. 2016), carbon monoxide (CO) (Masekela and Vanker 2020), nitrogen dioxide (NO_2) (Holgate et al. 2021; Nunes et al. 2016), (ozone (O_3) (Vu et al. 2019; WHO 2021b), sulphur dioxide (SO_2) (Kotzias 2021), phthalate esters (PAEs) (Li et al. 2021, Anake and Nnamani 2022), polycyclic aromatic hydrocarbons (Vardoulakis et al. 2020; Wang et al. 2021), benzene (C_6H_6) (Siwarom et al. 2017; Vu et al. 2019), formaldehyde (HCHO) and volatile organic compounds (VOCs) (Almeida et al. 2011; Zhang et al. 2021). In order to protect public health from the adverse effects of exposure to these indoor chemical pollutants, standards and guidelines values have been provided by governments in different countries and worldwide organisations. Table 1 outlines the criteria for chemical pollutant set limits by the two internationally recognized regulatory bodies across the globe: the United States Environmental and Protection Agency (USEPA) and World Health Organization (WHO).

Previous study report shows that the effect of elevated levels of these indoor chemical pollutants on a child is more than that of an average adult (Olaoye et al. 2021; Canha et al. 2016). A review conducted by Zhang et al. (2021) on indoor air pollution levels and its associated environmental and behavioural factors in nurseries was able to highlight the thermal comfort, ventilation rate and exposure of children to measured pollutants (biological and chemical) in nursery environments. Their study examined work done between 1992 and 2018 in nurseries of children in the age bracket of 3 months to 10 years in Europe, Asia and North America except for Africa. Overall, inadequate ventilation evidenced in the increased levels of CO_2 above recommended standards was observed. Also, IAQ in nurseries often exceeded current guidelines; as such, the IAQ performance was declared unacceptable. In this article, we have provided a global overview of the predominant indoor chemical pollutant levels monitored in DCCs from reported studies, compare their concentration with available regulations for IAQ and health protection, evaluate the sources and health risk effects of chemical pollutants on children's health and propose strategies for enhancing IAQ in DCCs. Furthermore, to the best of the authors' knowledge, this review is the first to provide information on monitored indoor chemical pollutants in DCCs on the African continent.

Materials and methods

Selection of research method

In this study, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach was used to identify eligible studies for inclusion in the review. All English –language reported work on chemical pollutants done globally on IAQ in DCCs from January 2008 to June 2021 was considered. Databases such as Science Direct, Google Scholar, Scopus, SCIVAL and Journal Storage (JSTOR) were used to generate the relevant materials.

Table 1 Air quality standards for criteria air pollutants by the USEPA and WHO

Air pollutants	WHO AQG	USEPA AQG
PM_{10}	45 µg/m^3 (24 h mean) 15 µg/m^3 (annual mean)	48 µg/m^3 (24 h mean) 15 µg/m^3 (annual mean)
$PM_{2.5}$	5 µg/m^3(annual mean) 15 µg/m^3 (24 h mean)	12 µg/m^3 (annual mean) 35 µg/m^3 (24 h mean)
O_3	100 µg/m^3(8 h daily maximum) 60 µg/m3(peak season 8 h mean)	0.07 ppm (8 h daily mean)
NO_2	10 µg/m^3(annual-mean) 25 µg/m^3 (24 h mean)	53 ppb (annual mean) 100 ppb (1 h)
SO_2	40 µg/m^3 (24 h mean)	75 ppb (1 h) 0.5 ppm (3 h)
CO	4 mg/m^3 (24 h mean)	9 ppm (10 mg/m^3) (8 h) 35 ppm (40 mg/m^3) (1 h)

Source: (WHO 2021a; USEPA 2021)

PM particulate matter, O_3 ozone, NO_2 nitrogen dioxide, SO_2 sulphur dioxide, *CO* carbon monoxide

The keywords used for the search were day-care centres, preschools, kindergartens, indoor air quality, air pollution, criteria pollutants, chemical pollutants, health effects of chemical pollutants, sources of chemical pollutants and SDGs. The search yielded two hundred and seven (207) peer-reviewed journal articles and conference papers. The exclusion criteria defined for this review include microbial pollutants, measurements in settled dust, studies published before January 2008 and after June 2021, studies conducted in other indoor microenvironments (homes, vehicles, offices, laboratories and universities), non-English articles and when sufficient data were not made available or only plots given without figure descriptions. The inclusion criteria focused solely on indoor chemical pollutant(s), studies published between January 2008 and June 2021, indoor studies conducted in preschools, day-care centres, kindergartens and nursery schools, English articles and articles with results indicating at least one of the following measurement values: minimum, maximum, arithmetic mean or median. The studies' titles and abstracts were screened using the inclusion and exclusion criteria. Based on the appropriate selection criteria, thirty-seven (37) out of two hundred and seven (207) articles were suitable for inclusion, as shown in Fig. 1.

Results and discussion

Indoor chemical pollutants monitored in children's DCCs across the continents

Figure 2 represents the geographical distribution of the 37 articles summarized in the current study. Slovenia, Spain, Greece, France, Poland and Portugal are among the European nations that have published research work on IAQ in DCCs. The continent of Asia with published work on IAQ in DCCs includes South Korea, Malaysia, Iran, Singapore and Thailand. North America has two published research works in Canada and the United States of America (USA) while in Africa, Nigeria is the only country with two published research articles. The USEPA and other environmental regulatory bodies in the USA, such as California health care

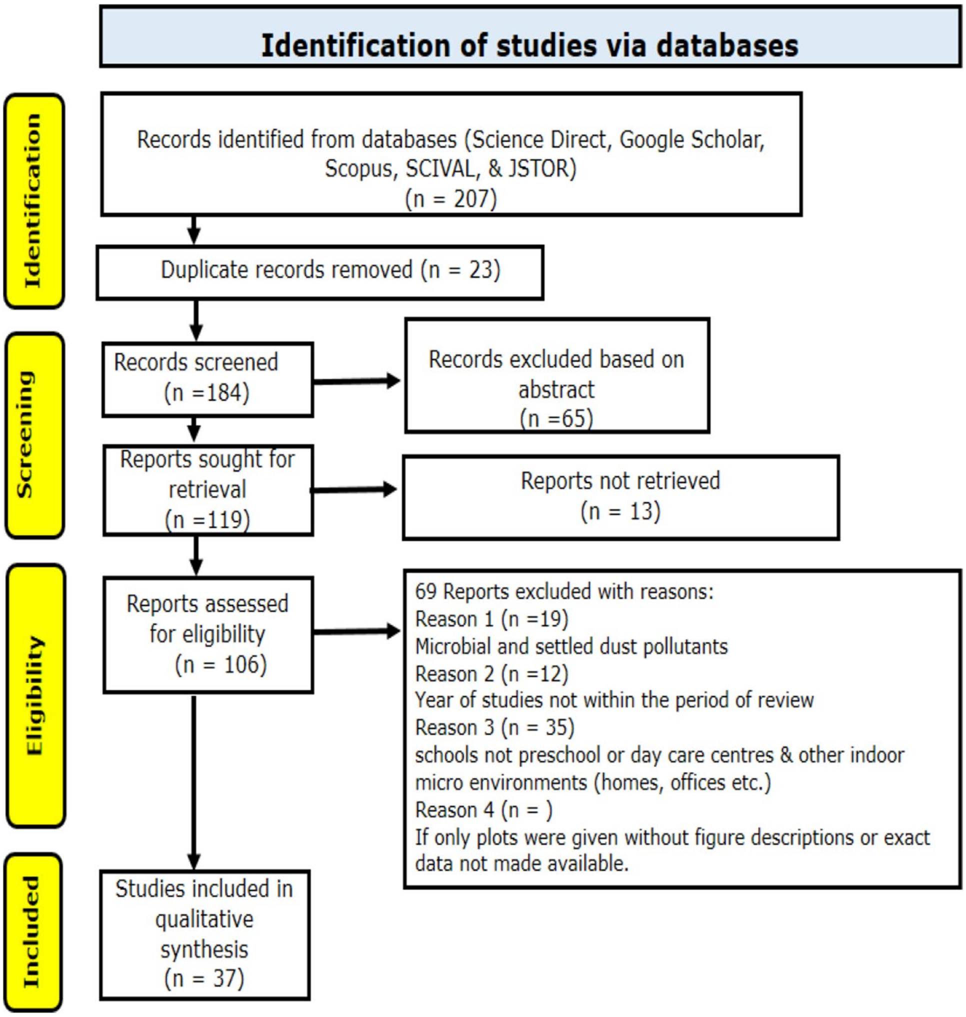

Fig. 1 PRISMA study flow diagram of IAQ in DCCs

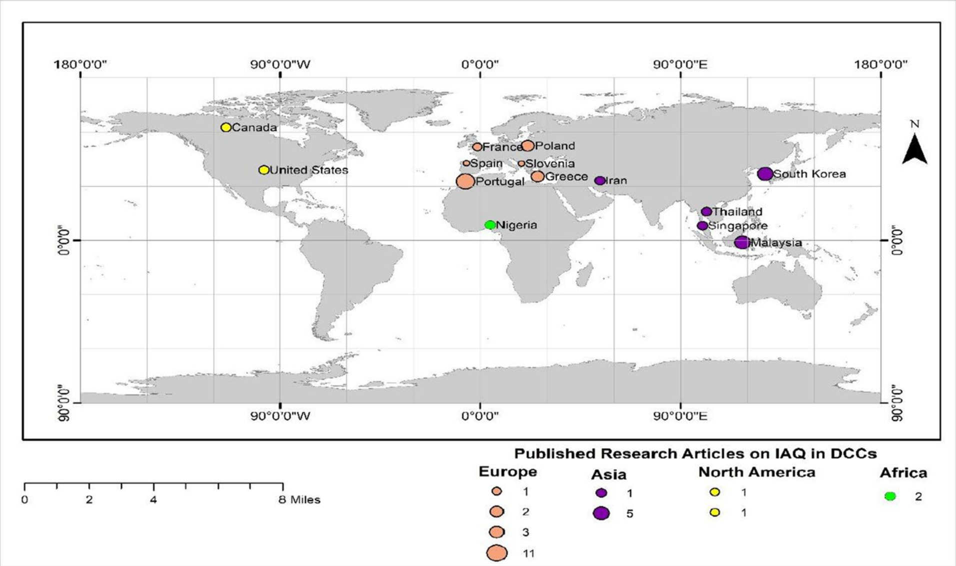

Fig. 2 Continental map depicting the paucity of data on IAQ in day-care centres

programs, frequently publish articles on indoor air quality in day-care centres. Australia and South America have no published research work on IAQ in DCCs. However, relevant governmental agencies frequently update their websites with information on IAQ in DCCs. To the best of the authors' knowledge, no information has been viewed or obtained for Antarctica as of the time this review was being written.

An overview of the 37 reviewed papers' results for IAQ in day-care centres with locations, chemical pollutants, age of children in the class, measurement device and the number of centres monitored is shown in Table 2. Also, Table 3 shows a glimpse of the concentration of indoor chemical pollutants in DCCs endemic in specific countries and continents reported from 37 studies. As shown in Tables 2 and 3, only a few studies investigated above five parameters of indoor chemical pollutants, and these studies were mostly from the European continent. A breakdown of the studies based on their pollutants of interest includes 10 studies (I indoor pollutant), 1 study (2 indoor pollutants) 5 studies (3 indoor pollutants), 10 studies (4 indoor pollutants), 6 studies (5 indoor pollutants), 2 studies (6 indoor pollutants), 2 studies (7 indoor pollutants) and 1 study (9 indoor pollutants). However, there were variations in the measurement devices used for measuring specific pollutants across the study.

From the studies of indoor air quality in preschools, kindergartens and day-care centres conducted across the globe between January 2008 and June 2021, the investigated indoor chemical pollutants identified were particulate matter (total suspended particulate matter (TSP), coarse particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$) and ultrafine particulate matter (PM_1, $PM_{0.1}$)) carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO), volatile organic compounds (VOCs), total volatile organic compounds (TVOCs), nitrogen dioxide (NO_2), ozone (O_3), benzene (C_6H_6.), sulphur dioxide (SO_2) and radon (Rn). The predominant indoor chemical pollutant was PM (TSP: 3 studies; PM_{10}: 19 studies, $PM_{2.5}$: 14 studies, PM_1: 5 studies and $PM_{0.1}$: 2 studies). This was followed by CO_2 (23 studies), HCHO (14 studies), CO (12 studies), TVOCs (10 studies), VOCs (8 studies), NO_2 (8 studies), O_3 (7 studies), C_6H_6 (4 studies), SO_2 (2 studies) and Rn (2 studies). In total, 15 pollutants were considered (see Table 3). The decreasing trend among the investigated indoor chemical pollutants globally is as shown: PM ($PM_{10} > PM_{2.5}$) > CO_2 > HCHO> CO > TVOCs > VOCs = NO_2 > O_3 > C_6H_6 > SO_2 = Rn.

Particulate matter was the most investigated indoor chemical pollutants in day-care centres in this review. Particulate matter is used as a surrogate indicator of air pollution on a broad scale (Almeida et al. 2011). It has been reported as one of the most researched contaminants because of its effects on a child's growing brain (Jelili et al. 2020). The concentration ranges for the different classes of particulate matter results shown in Table 3 are coarse particulate matter (PM_{10}) (0.116–1920.71 $\mu g/m^3$), fine particulate matter ($PM_{2.5}$) (0.279.2–260.74 $\mu g/m^3$), ultrafine particulate matter (PM_1 and $PM_{0.1}$) (8.99–78.13 and 30.50–90.50 $\mu g/m^3$) and total suspended particulate matter (TSP) (15.04–217.33 $\mu g/m^3$). There are three main categories of particulate matter: PM_{10}, $PM_{2.5}$ and $PM_{0.1}$. PM_{10} particles have a diameter of less than 10 µm, $PM_{2.5}$ particles are smaller than 2.5 µm, and $PM_{0.1}$ particles are smaller than 0.1 µm (Anake et al. 2017; Mukherjee and Agrawal 2017). However, the two most frequently investigated categories of particulate matter across the globe in descending order were PM_{10} (19 studies) > $PM_{2.5}$ (14 studies). From the result presented, it was observed that the continent of Asia (Iran) had the highest levels of PM_{10} (1920.71 $\mu g/m^3$) and $PM_{2.5}$ (260.74 $\mu g/m^3$) which was attributed to the occurrence of the Middle

Table 2 A summary of reviewed paper results for indoor air pollutants in day-care centres

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Africa (Nigeria)	PM_{10}	0–3 years	Digital PM counter	10 DCCs	PM_{10} concentration was 19 μg/m^3 to 536.8 μg/m^3 and 23 μg/m^3 to 677 μg/m^3 in the morning and afternoon, respectively. The highest value was recorded in the dry season and exceeded WHO guidelines.	Ana and Umar (2013)
Africa (Nigeria)	NO_2, SO_2, CO and PM_{10}	0–2 years	Portable air monitors (Multi-Gas Analyzer MRU-Model 2002)	6 preschools	The results showed NO_2 > 88 μg/m^3, SO_2 > 50 μg/m^3 and PM_{10} > 70 μg/m^3, especially in industrial sites with high concentrations for short periods. CO annual averages were 1.3 to 1.83 μg/m^3. SO_2 was largely responsible for cough and cold, all through the examined period. For both seasons, NO_2 and SO_2 increased the cases of bronchitis.	Nkwocha and Egejuru (2008)
Asia (Singapore)	CO_2, CO, O_3 and $PM_{2.5}$	NP	CO (three T15v Langan CO Measurers) $PM_{2.5}$ (DustTrak aerosol monitors). O_3 (a pair of UV-absorbance ozone analysers)	104 DCCs	The pollutants' concentration includes CO_2 (357–3344 ppm), CO (0–3.7 ppm), $PM_{2.5}$ (20.1–177.2 μg/m^3) and O_3 (2.2–80.2 ppb). 25 classrooms had higher levels of CO_2 than the stipulated limit of 1000 ppm.	Zuraimi and Tham (2008)
Asia (South Korea)	PM_{10}, $PM_{2.5}$ and CO_2	5 years	A real-time multiple monitoring sensor	1 childcare centre	The operation of energy recovery ventilation (ERV) system showed that the highest CO_2 (2257 ppm) and PM_{10} (52.8 μg/m^3) levels were reduced by 51.4% and 29.5%, respectively, during the occupied hours.	Oh and Song (2021)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Asia (South Korea)	PM_{10}	0–5 years	Real-time monitor (Air Guard K)	87 preschools	Annual indoor PM_{10} level was between 20.9 and 147.5 µg/m^3 in DCCs and 18.7–39.7 µg/m^3 in the kindergartens' schools. The indoor PM_{10} level in DCCs was the highest. It was above the Korean PM_{10} IAQ standard of 75 µg/m^3 annual limit.	Guak et al. (2021)
Asia (South Korea)	CO, CO_2, PM_{10}, TVOCs and HCHO.	NP	CO and CO_2 (non-dispersive infrared analyser), PM_{10} (pall flex membrane filter), TVOCs (Tenax-TA tube) and HCHO (DNPH-coated silica gel)	5 kindergartens	The study was done during summer, autumn and winter season. The range of results for all seasons for CO was 0.01–1.40 ppm; CO_2 (555.00–1675.00 ppm); PM_{10} (26–216 µg/m^3); TVOCs (264–1024 µg/m^3); and HCHO (0.03–0.46 ppm). PM_{10}, CO_2 and TVOCs exceeded the Korean recommended levels of 75 µg/m^3 with a 24 h average, 1000 ppm and 400 µg/m^3.	Yang et al. (2009)
Asia (South Korea)	$PM_{2.5}$, PM_{10}, Radon, CO_2 and VOCs.	0–5 years	Integrated IAQ Sensor (model: CESCO EM)	1 DCC	$PM_{2.5}$, PM_{10} and CO_2 conformed to the national guideline.	Kim et al. (2021)
Asia (Malaysia)	CO, O_3 and TVOCs	1–5 years	Real-Time Monitoring Aeroqual series 500	2 DCCs	Minimum and maximum values for O_3, TVOCs and CO were 0 ppm and 0.012 ppm, 0.20 ppm and 1.38 ppm and 0 ppm and 0.80 ppm. They were all below the Department of Occupational Safety and Health Industry Code of Practice (ICOP) in indoor air quality 2010 set limit of 0.05 ppm, 3 ppm and 10 ppm, respectively	Chinathamby et al. (2020)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Asia (Malaysia)	$PM_{0.1}$, PM $_{2.5}$, PM_{10} and VOCs	5–6 years	Ultrafine Particle Counter ($PM_{0.1}$), TSI Dust-TRAK DRX Aerosol Monitor ($PM_{2.5}$ and PM_{10}); ppbRAE (VOCs)	6 preschools	The median concentration for $PM_{0.1}$ was 90.50 µg/m^3 (36.73), $PM_{2.5}$ 83.10 µg/m^3 (254.6), PM_{10} 86.23 µg/m^3 (299.0) and VOC 53.83 ppb (2.85). Exposure to $PM_{0.1}$, PM $_{2.5}$ and PM_{10} showed increased occurrences of respiratory inflammation and symptoms among children.	Zainudin et al. (2019)
Asia (Malaysia)	PM_{10}	NP	An optical PM_{10} sensor	1 preschool	PM_{10} daily average indoor concentration on weekdays was 11.2 ± 0.45–13.4 ± 1.05 µg m^{-3} and complied with the WHO set limit.	Othman et al. (2019)
Asia (Thailand)	PM_{10}, SO_2, NO_2, CO, O_3 and C_6H_6	< 6 years	Not documented	11 DCCs	Three out of eleven DCCs had PM_{10} higher than the set limit in all the seasons. The mean level of PM_{10} was 70 µg/m^3. O_3 levels exceeded WHO standards by 80%. The mean level of SO_2 was 16 µg/m^3. Benzene (C_6H_6) in two DCCs exceeded the WHO limit during the rainy season (0.105 and 0.054 mg/m^3). NO_2 and CO were below WHO standards for all seasons.	Siwarom et al. (2017)
Asia (South Korea)	CO_2, CO, HCHO and TVOCs (benzene, toluene, ethylbenzene, xylene and styrene	NP	CO_2, CO (multi-gas monitor), HCHO (SIBATA A_MP-Σ100) TVOCs (SIBATA A_MP-Σ30)	25 DCCs	CO and HCHO were within the Korean IAQ guide of 10 ppm and 100 µg/m^3, respectively. CO_2 was within the range except for 2 DCCs. Also, TVOCs were within the limit except for 4 DCCs.	Hwang et al. (2017)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Asia (Iran)	PM_1, $PM_{2.5}$ and PM_{10}	NP	Dust monitoring spectrometer	6 DCCs	The highest concentrations of PM_1 (53.78 μg/m^3), $PM_{2.5}$ (260.74 μg/m^3) and PM_{10} 1920.71 μg/m^3) were reported and attributed to the Middle Eastern Dust (MED) storm.	Harbizadeh et al. (2019)
Malaysia (Asia)	PM_{10}	NP	*Dust Mate Environmental Dust Detector*	4 nurseries and kindergartens were child care Institutions	PM_{10} levels ranged from 4 to 30 μg/m^3 All the studied areas met the stipulated limit of 150 μg/m^3 by the Industrial Code of Practice on indoor air quality.	Nazri et al. (2017)
Asia (Malaysia)	CO_2 HCHO, NO_2 and VOCs	NP	MultiRAE meter and formaldehyde meter	2 preschools	The concentration of VOCs, CO_2, NO_2 and HCHO at the selected kindergartens was between 0.08 and 0.54 mg/m^3, 961.3 and 1005.9 ppm, 0 and 0 ppm and 0.00 and 0.01 ppm, respectively. CO_2 exceeded the Malaysia department of safety and health's set limit of 1000 ppm.	Kamaruzzaman and Razak (2011)
Europe (Poland)	CO_2	NP	NP	4 kindergartens	The lowest CO_2 concentrations, 420 ppm to 549 ppm, were recorded at night and early in the morning. The levels rose very quickly during the day, often exceeding 4200 ppm.	Telejkoa and Zender-Świercza (2016)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Europe (Greece)	CO_2	NP	Telaire 7001 sensor (0–4000 ppm with _50 ppm measuring accuracy) connected to a Hobo Energy data logger	11 nurseries	Average concentrations of CO_2 range between 480 and 2500 ppm and were above the maximum recommended CO_2 concentration of 800 ppm above the outdoor concentration according to prEn 13779 in some nurseries.	Theodosiou and Ordoumpozanis (2008)
Europe (Spain)	TVOCs, HCOH, C_6H_6 and NO_2	3–12 years	VOCs (RAD 130, activated charcoal), C=O (DNPH coated florisil) and NO_2 (RAD 166 TEA)	18 kindergartens	Average concentrations of TVOCs, C_6H_6, HCHO and NO_2 were 13–130 μg/m^3, 0.2–2.1 μg/m^3, 13.2–52.7 μg/m^3 and 8.1–25.2 μg/m^3. All values were below the stipulated threshold limits of the current European Union and WHO annual guidelines for indoor air quality.	Villanueva et al. (2018)
Europe (Portugal)	$PM_{2.5}$ and PM_{10}, CO, O_3, CO_2, HCHO and TVOCs	3–5 years	Multipara metric probe (model TG 502)	1 preschool (two classrooms)	The highest concentration of PM_{10} (35.7 μg/m^3), $PM_{2.5}$ (26.6 μg/m^3), CO (2.73 mg/m^3), CO_2 (3605 mg/m^3) and HCHO (61.4 μg/m^3) was within the statutory guideline established for air quality of Portuguese public buildings with exception of TVOCs (3.91 mg/m^3). Regarding O_3 (230 μg/m^3), there is no limit value in indoor air based on Portuguese 2013 legislation (Decreto Lei 118/2013).	Oliveira et al. (2016)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Europe (Slovenia)	CO_2,	NP	Data logger rotatronic CL 11	1 kindergarten	The average concentration of CO_2 (ppm) exceeds the limit value of 1000 ppm every day. On average, the children were exposed to the carbon dioxide concentration over 1000 ppm for more than half the time spent in school. Intensive natural ventilation/additional mechanical systems for ventilation was advised	Lovec et al. (2020)
Europe (Greece)	CO_2, Radon, $PM_{2.5}$, PM_{10}, CO, HCHO, C_6H_6, NO_2 and O_3	NP	HCHO, NO_2 and O_3 were measured with diffusive samplers. Radon (radon detector). $PM_{2.5}$ and PM_{10} (optical light scattering techniques	2 primary school and 1 kindergarten	Indoor air pollution concentrations were within the set limits, with indicative ranges for benzene, formaldehyde, NO_2 and ozone being 1.5 to 9.4 µg/m^3, 2.3 to 28.5 µg/m^3, 4.6 to 43 µg/m^3 and 0.1 to 15.6 µg/m^3 respectively.	Kalimeri et al. (2016)
Europe (Portugal)	PM_{10}, TVOC, HCHO, CO_2 and CO	3 months –5 years	PM_{10} was sampled using polytetrafluoroethylene (PTFE) filters, TVOC was collected using a stainless steel tube with Tenax TA while CO_2 and CO were measured using photoacoustic multi gas monitor	9DCCs (52 classrooms in two locations (Lisbon and Porto)	PM_{10} levels were higher than the national reference levels; TVOC kindergarten peak values were high and may raise some concern; CO_2 was present at high maximum levels both by classroom type and by season. This can affect the general well-being and daily performance of the children.	Mendes et al. (2014)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Europe (Portugal)	PM_1, $PM_{2.5}$ and $PM_{10;}$ TSP	0–5 years	TSI Dust Trak DRX 8534 Aerosol Monitor.	1 urban and 3 rural nursery schools	$PM_{2.5}$ (9.03–31.72 µg/m^3) and PM_{10} (12.09–58.28 µg/m^3) concentrations in the urban nursery were higher than rural nursery schools and exceeded the WHO guidelines and Portuguese legislation.	Nunes et al. (2016)
Europe (Poland)	PM_1, $PM_{2.5}$, PM_{10}, TSP, VOCs, CO_2	3–6 years	Air sampling pump, model 224-PCMTX8 – SKC(PM_1, $PM_{2.5}$, PM_{10}, TSP), CO_2 automatic portable monitor	2 urban nursery and 1 rural nursery school	The maximum indoor levels of PM_1, $PM_{2.5}$, PM_{10} and TSP in the rural area were higher than in the urban area due to the proximity to a busy road. CO_2 concentration was higher than 1000 ppm.	Mainka et al. (2015)
Europe (Portugal)	CO, HCHO, NO_2, O_3 and TVOCs	1–5 years	Haz-Scanner IEMS Indoor Environmental Monitoring Station.	4 nursery schools	CO_2, NO_2 and O_3 were less than the IAQ set limit for both local and international standards. Exceedance occurred for HCHO and TVOCs with peak concentrations of 204 and 2320 mg/m^3, respectively.	Branco et al. (2015)
Europe (Portugal)	PM_{10}, $PM_{2.5}$, TVOCs, CO_2 , CO, NO_2, O_3 and HCHO	3–5 years	Haz-Scanner IEMS Indoor Environmental Monitoring Station. TSI Dust-Trak DRX 8534 particle monitor	648 pre-schoolers	This work showed significant associations between inhaled doses of indoor air pollutants in nursery schools and other respiratory health issues in early childhood. Also, reported wheezing (due to NO_2 exposure) and reduced FEV_{1V}, which indicates abnormal lung function (due to $PM_{2.5}$ and O_3 exposure). Even though NO_2 (51.2–54.2 µg/m^3) and O_3 (8.6–13.6 µg/m^3) were always below 200 µg m–3 threshold from WHO and National Portuguese legislation, respectively.	Branco et al. (2020)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Europe (Poland)	PM_{10}, $PM_{2.5}$, PM_1, TSP and CO_2	3–6 years	Three-stage impactor (TSP, PM_{10} and $PM_{2.5}$)	4 DCCs	Indoor CO_2 was more than 1000 ppm pointing to poor ventilation systems. PM_1, $PM_{2.5}$ and PM_{10} were above the WHO set limit. This finding revealed elevated indoor PM contributions due to high occupancy, poor ventilation and the intensive activities of children resulting in the particle resuspension.	Mainka and Zajusz-Zubek (2015)
Europe (Portugal)	PM_{10}, $PM_{2.5}$, PM_1 and $PM_{0.1}$	1–5 years	TSI DustTrak DRX 8534 particle monitor	3 nursery schools	PMs level was high, especially for $PM_{2.5}$.The maximum hourly average was 145 µg/m^3 and 158 µg/m^3 for PM_{10} and $PM_{2.5}$, respectively. This exceeds the threshold recommended by WHO up to 80% for $PM_{2.5}$. This is of concern due to exposure effects on children's health.	Branco et al. (2014)
Europe (Portugal)	CO_2	5–6 years	CO_2 (photoacoustic multi-gas monitor) activated carbon)	45 DCCs in phase 1 and 20 DCCs in phase 2	The mean CO_2 levels were 2137 ± 368 ppm in phase 1 and 1233 ± 170 ppm in phase 2. CO_2 exceeded the limit of 1000 ppm. CO_2 level is a surrogate of ventilation therefore improving ventilation will positively impact on air borne contaminants.	Araújo-Martins et al. (2014)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Europe (France)	$PM_{2.5}$, VOCs CO_2 and HCOH	3–5 years	Gravimetric Micro Vol Samplers; CO_2 sensors; and passive samplers	7 nursery schools (3 classroom per school)	The concentration of $PM_{2.5}$ (21 ± 9 µg/m^3), VOCs (15.6 ± 7.7 µg/m^3) and HCHO (28 ± 17 µg/m^3) was within the statutory guideline established for air quality. Except for CO_2 (1200 ± 400 mg/m^3). Overall, the studied classrooms presented CO_2 concentrations above 1000, 1300 and 1500 ppm during 65%, 46% and 35% of the occupied period, respectively.	Canha et al. (2016)
Europe (Portugal)	PM_{10}, TVOCs, CO_2, CO and HCHO	3 months–6 years	Formaldehyde (personal pumps GilAir 5). PM_{10} (PM_{10} collectors (PEM, SKC), TENAX Tubes using SKC personal pumps for TVOCs. CO and CO_2 (photoacoustic multi-gas monitor	19 DCCs (125 classrooms)	1850–2541 mg/m^3 median CO_2 concentrations levels were above the set limit of 1800 mg/m^3. Concentrations of CO, TVOCs and HCHO in most rooms were acceptable.	Cano et al. (2012)
Europe (France)	VOCs, NO_2, CO_2 and HCHO	NP	Passive samplers, Radiello for aldehydes and VOCs. Palmes tubes for NO_2	28 DCCs	Indoor chemical pollutants levels were: NO_2 30.2 mg/m^3 in playroom and 29.5 mg/m^3 in restrooms. HCHO (4.8 to 40.1 µg/m^3), CO_2 (447 to 2037 ppm), VOCs (0.2–44.54 µg/m^3), higher NO_2 levels were attributed to the proximity of child daycare centres to roadways with heavy traffic.	Roda et al. (2011)
Europe (Portugal)	CO_2	Mean age (3.1±1.5)	CO_2 (non-dispersive infrared absorption detector)	64 DCCs	90% of the CO_2 concentration exceeded the recommended limit of 1000 ppm. The results suggest that the inability of reducing CO_2 to acceptable levels is associated with poor ventilation in DCCs and may be related to wheezing in children.	Carreiro-Martins et al. (2014)

Table 2 (continued)

Continents (country)	Chemical pollutants	Age of children	Measurement device	Number of centres monitored	Significant findings	Reference
Europe (Portugal)	TVOC, CO_2 and HCHO	NP	Gent samplers with a stacked filter unit	3 preschools	The CO_2 and TVOC concentrations were above the protection threshold. Organizational recommendations include intensifying ventilation when using teaching materials (glues and paints) and avoiding the use of ammonia cleaners, organic solvents and chemicals that affect IAQ.	Manuel et al. (2021)
Europe (Portugal)	TVOCs,	2	Research grade instruments – HazScanner Model IEMS and GrayWolf AndvanceSence BE	1 nursery school	TVOC concentration range and average mean were 348–1570 mg/m^3 and 647 µg/m^3. The monitored hourly mean data before and during the COVID-19 pandemic indicated an exceedance of 1,200 µg/m^3 reference Portuguese legislated limit value for TVOC. This occurred only during the occupancy period.	Sa et al. (2021)
North America (Kanas City, USA)	VOCs and C_6H_6	0–3 years	Active Sampling Onto Sorbent Tubes	10 classrooms in a school	The VOC concentrations varied between groundfloor and the basement classrooms, as well as between fall and winter.	Vu et al. (2019)
North America (Canada)	CO_2, VOCs and HCHO	1–5 years	YES-206LH Falcon monitor	21 DCCs	About 85% of the DCCs had average CO_2 concentrations higher than 1000 ppm. DCCs with mechanical ventilation system and a large surface of play area per child recorded lower CO_2 level.	St-Jean et al. (2012)

PM particulate matter, *O_3* ozone, *NO_2* nitrogen dioxide, *SO_2* sulphur dioxide, *CO* carbon monoxide, *VOC* volatile organic compound, *CO_2* carbon dioxide, *HCHO* formaldehyde, *TSP* total suspended particles, *TVOC* total volatile organic compounds, *NP* Not provided, *DNPH* dinitophenylhydrazyne, *TEA* triethanolamine

Table 3 Concentration of common chemical pollutants reported across the continents

Location	PM_{10}	$PM_{2.5}$	PM_1	$PM_{0.1}$	TSP	VOCs	TVOCs	CO_2	CO	NO_2	O_3	SO_2	HCHO	Rn	C_6H_6	Reference
Nigeria, Africa	19–677 μg/m^3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Ana and Umar 2013
Nigeria, Africa	> 70 μg/m^3	–	–	–	–	–	–	–	1.3–1.83 μg/m^3	> 88 μg/m^3	–	> 50 μg/m^3	–	–	–	Nkwocha and Egejuru 2008
Singapore, Asia	–	70.6 μg/m^3	–	–	–	–	–	486 ppm	1.1 ppm	–	35.6 ppb`	–	–	–	–	Zuraimi and Tham 2008
South Korea, Asia	52.8 μg/m^3	15.2 μg/m^3	–	–	–	–	–	2257 ppm	–	–	–	–	–	–	–	Oh and Song (2021)
South Korea, Asia	18.7–147.5 μg/m^3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Guak et al. (2021)
South Korea, Asia	26.00–216.00 μg/m^3	–	–	–	–	–	264.00–1024.00 μg/m^3	555.00–1675.00 ppm	0.01–1.40 ppm	–	–	–	0.03–0.46 ppm	–	–	Yang et al. (2009)
South Korea, Asia	0–754.7 μg/m^3	0–279.2 μg/m^3	–	–	–	125–513 μg/m^3	–	381–3623 ppm	–	–	–	–	–	0–7.8 Bq/m^3	–	Kim et al. (2021)
Malaysia, Asia	–	–	–	–	–	–	0.20–1.38 ppm	–	0.00–0.80 ppm	–	0.000–0.012 ppm	–	–	–	–	Chinathamby et al. (2020)
Malaysia, Asia	^{b}34.77–86.23 μg/m^3	^{b}37.90–83.10 μg/m^3	–	^{b}30.50–90.50 μg/m^3	–	^{b}53.83–67.17 ppb	–	–	–	–	–	–	–	–	–	Zainudin et al. (2019)
Malaysia, Asia	–	11.2 ± 0.45–13.4 ± 1.05 μg/m^3	–	–	–	–	–	–	–	–	–	–	–	–	–	Othman et al. (2019)
Thailand, Asia	70 μg/m^3	–	–	–	–	–	–	–	ND	ND	123 μg/m^3	16 μg/m^3	–	–	0.105 mg/m^3	Siwarom et al. (2017)
–South Korea, Asia	–	–	–	–	–	–	133.0–512.9 μg/m^3	502.7–1261.4 ppm	0.1–1.3 ppm	–	–	–	19.9-89.1 μg/m^3	–	–	Hwang et al. (2017)
Iran, Asia	1920.71μg/m^3	260.74 μg/m^3	53.78 μg/m^3	–	–	–	–	–	–	–	–	–	–	–	–	Harbizadeh et al. (2019)
Malaysia, Asia	4–30 μg/m^3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	Nazri et al. (2017)
Malaysia, Asia	–	–	–	–	–	0.08–0.54 mg/m^3	–	961.3–1005.9 ppm	–	0–0 ppm	–	–	0.00–0.01 ppm	–	–	Kamaruzzaman and Razak 2011
Poland, Europe	–	–	–	–	–	–		420–4207 ppm	–	–	–	–	–	–	–	Telejkoa and Zender-Świercza (2016)
Spain, Europe	–	–	–	–	–	–	13–130 μg/m^3	–	–	8.1–25.2 μg/m^3	–	–	13.2–52.7 μg/m^3	–	0.2–2.1 μg/m^3	Villanueva et al. (2018)
Portugal, Europe	15.9–35.7 μg/m^3	11.3–26.6 μg/m^3	–	–	–	–	nd–3.91 mg/m^3	796–3605 mg/m^3	0.23–2.73 mg/m^3	–	20.0–230 μg/m^3	–	nd–61.4 μg/m^3	–	–	Oliveira et al. (2016)
Slovenia, Europe	–	–	–	–	–	–	–	410–2452 ppm	–	–	–	–	–	–	–	Lovec et al. (2020)
Greece, Europe	> 50 ppm	72–83 μg/m^3	–	–	–	–	–	> 1000 ppm	4.2 ppm	4.6–43 μg/m^3	0.1–15.6 μg/m^3	–	4 2.3–28.5 μg/m^3	11–84 Bq/m^3	1.5–9.4 μg/m^3	Kalimeri et al. (2016)
Portugal, Europe	10–421 μg/m^3	–	–	–	–	–	17–3899 μg/m^3	351–3087 ppm	0.0–2.0 ppm	–	–	–	< 17 μg/m^3	–	–	Mendes et al. (2014)

Table 3 (continued)

Location	PM$_{10}$	PM$_{2.5}$	PM$_1$	PM$_{0.1}$	TSP	VOCs	TVOCs	CO$_2$	CO	NO$_2$	O$_3$	SO$_2$	HCHO	Rn	C$_6$H$_6$	Reference
Portugal, Europe	[a]12.09–58.28 µg/m^3	[a]9.03–31.72 µg/m^3	[a]8.99–31.00 µg/m^3	–	[a]15.85–101.75 µg/m^3	–	–	–	–	–	–	–	–	–	–	Nunes et al. (2016)
Poland, Europe	117.57–149.81 µg/m^3	70.53–106.06 µg/m^3	51.21–78.89 µg/m^3	–	134.43–163.81 µg/m^3	11.91–58.80 µg/m^3	–	< 1000–3700 ppm	–	–	–	–	–	–	–	Mainka et al. (2015)
Portugal, Europe	–	–	–	–	–	–	0–2320 µg/m^3	–	0–4956 µg/m^3	0–189 µg/m^3	0–61 µg/m^3	–	0–204 µg/m^3	–	–	Branco et al. (2015)
Greece, Europe	–	–	–	–	–	–	–	480–2500 ppm	–	–	–	–	–	–	–	Theodosiou and Ordoumpozanis (2008)
Poland, Europe	68.26–104.90 µg/m^3	41.17–80.94 µg/m^3	25.97–78.13 µg/m^3	–	73.05–124.24 µg/m^3	–	–	> 1000 ppm	–	–	–	–	–	–	–	Mainka and Zajusz-Zubek (2015)
Portugal, Europe	[a]22.31–56.77 µg/m^3	[a]18.17–48.94 µg/m^3	[a]16.79–47.85 µg/m^3	[a]32.61–85.8185 µg/m^3	–	–	–	–	–	–	–	–	–	–	–	Branco et al. (2014)
Portugal, Europe	–	–	–	–	–	–	–	1233 ± 170–2137 ± 386 ppm	–	–	–	–	–	–	–	Araújo-Martins et al. (2014)
France, Europe	–	21 ± 9 µg/m^3	–	–	–	15.6 ± 7.7 µg/m^3	–	1200 ± 400 ppm	–	–	–	–	28 ± 17 µg/m^3	–	–	Canha et al. (2016)
Portugal, Europe	[a]70.8–88.0 µg/m^3	[a]49.0–54.7 µg/m^3	–	–	–	–	[a]78.6–149.8 µg/m^3	[a]1949–2335 mg/m^3	[a]1887–2257 µg/m^3	[a]51.2–54.2 µg/m^3	[a]8.6–13.6 µg/m^3	–	[a]37.5–39.8 µg/m^3	–	–	Branco et al. (2020)
Portugal, Europe	–	–	–	–	–	–	0.19–0.62 ppm	841–2518 ppm	–	–	–	–	0.02–0.08 ppm	–	–	Manuel et al. (2021)
Portugal, Europe	0.007–9.01 mg/m^3	–	–	–	–	–	0.036–6.44 mg/m^3	642–5647 mg/m^3	0.036–7.5 mg/m^3	–	–	–	<0.02 mg/m^3	–	–	Cano et al. (2012)
France, Europe	–	–	–	–	–	0.2–44.54 µg/m^3	–	447–2037 ppm	–	9.5–53.5 µg/m^3	–	–	4.8–40.1 µg/m^3	–	–	Roda et al. (2011)
Portugal, Europe	–	–	–	–	–	–	–	1440 ppm	–	–	–	–	–	–	-	Carreiro-Martins et al. (2014)
Portugal, Europe	–	–	–	–	–	–	348–1570 mg/m^3	–	–	–	–	–	–	–	–	Sa et al. (2021)
USA, North America	–	–	–	–	–	*1.19–29.39 µg/m^3	–	–	–	–	–	–	–	–	nd–2.27 µg/m^3	Vu et al. (2019)
Canada	–	–	–	–	–	*8.1–163.2 µg/m^3	–	723–2252 ppm	–	–	–	–	11.8–44.8 µg/m^3	–	–	St-Jean et al. (2012)

ND not documented, *nd* not detected

*Concentrations of VOCs is sum of the measured chemical family (toluene, ethylbenzene, o-xylene, m, p-xylene, naphthalene and alpha-pinene)

[a]Mean concentration

[b]Median concentration

Eastern Dust (MED) storm in February 2017 (Harbizadeh et al. 2019). In order of decreasing trend, PM concentrations in Asian children's day-care centres were Iran > South Korea > Malaysia > Thailand. The second highest continent with respect to PM_{10} was Africa (Nigeria: 677 μg/m^3) and Europe (Poland: 80.94 μg/m^3), respectively. The second and third most measured indoor chemical pollutants were CO_2 and HCHO, with the highest concentration of 5647 mg/m^3 and 204 μg/m^3 documented in Europe and Asia, respectively (Table 3). Portuguese nurseries from the European continent recorded the highest concentration of CO (4956 μg/m^3) and TVOCs (3899 μg/m^3), respectively. In addition, the highest concentration of O_3 (123 μg/m^3) was recorded in Asia while Europe had the highest levels of NO_2 (189 μg/m^3), C_6H_6 (9.4 μg/m^3) and Rn (84 Bq/m^3).

However, the intercontinental comparison indicates that Iran in Asia recorded indoor mean PM_{10} concentrations of 1920.71 μg/m^3 in day-care centres which exceeded the acceptable Korean PM_{10} IAQ standard limits of 75 μg/m^3 with a 24-h average (Harbizadeh et al. 2019). In South Korea, indoor PM_{10} levels of range 0–754.7 μg/m^3, 21–216 μg/m^3 and 20.9–147.5 μg/m^3 by Kim et al. (2021), Yang et al. (2009) and Guak et al. (2021) in the day-care centres, nursery and kindergartens, respectively exceeded the Korean PM_{10} IAQ standard of 75 μg/m^3 with a 24-h average. Also, Thailand's results showed that three out of eleven DCCs had mean PM_{10} levels of 70 μg/m^3 higher than the set limit in all the seasons (Siwarom et al. 2017). Similarly in Africa (Nigeria), some of the PM_{10} levels monitored in the morning and afternoon (536.8 μg/m^3 and 677 μg/m^3) exceeded the WHO PM_{10} guideline limit of 50 μg/m^3 with a 24-h average (Ana and Umar 2013). European children educative facilities in Portugal equally indicated elevated PM_{10} levels across different years as follows: 421 μg/m^3 (Mendes et al. 2014), 88.0 μg/m^3 (Branco et al. 2020), 58.28 μg/m^3 (Nunes et al. 2016) and 56.77 μg/m^3 (Branco et al. 2014) showing consistently the exceeded threshold of 50 μg/m^3 established by national regulations for air quality of public buildings in Portugal. Also, in Poland, Mainka and Zajusz-Zubek (2015) and Mainka et al. (2015) reported PM_{10} indoor concentration range of 68.26–104.90 μg/m^3 and 117.57–149.81 μg/m^3 in the day-care centres and the urban and rural nurseries, respectively. This finding revealed indoor PM_{10} contributions above the 24-h mean concentration of 50 μg/m^3 limit set by WHO and the Polish legislation.

Furthermore, for $PM_{2.5}$, South Korea and Singapore in Asia recorded the highest concentration of 260.74 and 279.2 μg/m^3 by Harbizadeh et al. (2019) and Kim et al. (2021) respectively, above the Korean $PM_{2.5}$ IAQ threshold of 35 μg/m^3 with a 24-h average. In the European continent, reports from Poland by Mainka and Zajusz-Zubek (2015) (range: 41.17–80.94 μg/m^3) and Mainka et al. (2015) (range: 70.53–106.06 μg/m^3) clearly indicated elevated concentrations of some indoor fine particulate in the day-care centres for the urban and rural nurseries, respectively. Also, some indoor $PM_{2.5}$ concentration from Greece and Portugal exceeded the threshold of a 24-h average standard of 25 μg/m^3 established by national regulations for air quality of public buildings in Portugal as shown: 72–83 μg/m^3 (Kalimeri et al. 2016), 49.0–54.7 μg/m^3 (Branco et al. 2020) and 18.17–48.94 μg/m^3 (Branco et al. 2014). Overall, the levels of PMs in most studies exceeded the various regulatory limits set by both local and international bodies. It is worth noting that regulatory bodies such as the USEPA and WHO have identified PM as a priority pollutant with a high probability of causing pulmonary diseases, shortness of breath, asthma, allergic reactions and several other respiratory-related disorders such as coughing, sneezing and wheezing. To lower the concentration of particulate matter, an adequate ventilation strategy is critical. This was verified in a study by Lee et al. (2020), where it was noted that day-care facilities practising good hygiene procedures experienced a considerable decrease in particulate matter concentration. It is worth noting that the indoor air pollutants above the established threshold were usually observed during the occupancy period implying that control ventilation and indoor activity can assist in obtaining better indoor air quality. Continents and countries with evidenced exceedance in the concentrations of CO_2 above the regulatory limits set by both local and international bodies include Asia, North America and Europe. In Asia, South Korea indoor CO_2 levels of range; 381–3623 ppm, 895–2257 ppm, 555.00–1675.00 ppm and 502.7–1261.40 ppm by Kim et al. (2021), Oh and Song (2021), Yang et al. (2009) and Hwang et al. (2017) in some of the day-care centres and kindergartens exceeded the Korean IAQ recommended levels of 1000 ppm. Also, Malaysia with highest CO_2 levels of 1005.9 ppm (Kamaruzzaman and Razak 2011) exceeded the Malaysia Department of Safety and Health set limit of 1000 ppm given by the American Society for Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). Furthermore, in North America, St-Jean et al. (2012)'s report indicated that about 85% of the DCCs had CO_2 concentrations (range: 723–2252 ppm and mean 1333) higher than Canada's Residential IAQ Guideline of 1000 ppm. Similarly, European nurseries confirmed non-compliance to set regulatory limits indoor CO_2 concentration range of 420–4207 ppm (Telejkoa and Zender-Świercza 2016) which were far above the < 1000–3700 ppm CO_2 concentration range recorded by Mainka et al. (2015) in Poland. Both CO_2 values were well above the recommended levels of 1000 ppm. From Greece, Theodosiou and Ordoumpozanis (2008) observed that some of the monitored values (range: 480–2500 ppm) exceeded the maximum recommended CO_2 concentration in a classroom of 800 ppm above that of outdoors. Also, in Slovenia, Lovec et al. (2020) with CO_2 levels of 410–2452 ppm exceeded the national required value of 1667 ppm in some locations (Dovjak et al. 2020) while Portuguese highest CO_2 levels above the stipulated regulatory limits were observed by Cano et al. (2012) (5647 mg/m^3), Mendes et al. (2014) (3087 ppm), Manuel et al. (2021) (2518 ppm), Branco et al. (2020) (2335 mg/m^3), (Araújo-Martins et al. (2014) (2137 ± 368 ppm) and Carreiro-Martins et al. (2014) (1440 ppm). Similarly, Roda et al. (2011) and Canha et al. (2016) with CO_2 concentration of 2037 ppm and 1200±400 mg/m^3, respectively, exceeded the 1000 ppm regulatory limit in France. From the foregoing, CO_2 level exceeding the specified threshold was commonly reported in most DCCs across the globe, a pointer to inadequate ventilation systems. However, many of the studies reviewed suggest that the presence of an effective mechanical ventilation system and a large surface of play area per child was significantly associated with lower CO_2 level.

Exceedance in the concentration of VOCs above the standard value set by both local and international bodies was equally reported in Asia and Europe. From Asia, Kamaruzzaman and Razak (2011) in Malaysia noted that from the indoor VOC concentration range of 0.08–0.54 mg/m^3, only the VOC rate of 0.54 mg/m^3 was above the Malaysian Department of Safety and Health set limit of 0.1 mg/m^3, given by ASHRAE. The concentrations of TVOCs above the standard value set by both local and international bodies were equally reported in Asia and Europe. From Asia, Yang et al. (2009) reported TVOC concentration range of 264.00–1024.00 μg/m^3 in four (4) DCCs which was far above Hwang et al. (2017)'s TVOC concentration range of 133.0–512.9 μg/m^3 in South Korea. However, both TVOCs were higher than the Korean recommended level of 400 μg/m^3. Also in Europe, Oliveira et al. (2016) reported the highest TVOC levels of 3.91 mg/m^3 (3910 μg/m^3) which was slightly above Mendes et al. (2014)'s TVOC concentration of 3899 μg/m^3 and far above Branco et al. (2015)'s TVOC levels of 2330 μg/m^3. All the authors confirm TVOC levels to be well above the Portuguese legislation (Portaria n° 353-A/2013) indoor concentration limit value of 600 μg/m^3. Recently, Sa et al. (2021) reported indoor TVOC concentration range of 348–1570 μg/m^3 above the reference Portuguese legislated limit value of (1,200 μg/m^3) in a nursery classroom during the COVID-19 pandemic. Furthermore, in Asia, a single measured SO_2 level exceeded the WHO standard level of 20 μg/m^3 for 24 h of indoor exposure to SO_2 in three DCCs while O_3 levels of 123 μg/m^3 exceeded the WHO standards level of 100 μg/m^3 (8 h) for short-term indoor exposure in 80% of DCCs during the winter season (Siwarom et al. 2017). Based on our findings from the studies included in this review, only the levels of NO_2, Rn and CO were consistent with the existing national and international reference values for IAQ and health protection across the continents.

Review on indoor air quality in Asia, Europe and North America day-care centres

As shown in Fig. 1, thirteen (13) papers within the scope of this review have been published from Asian countries. Eleven (11) pollutants were observed in the following decreasing trend: PM > CO_2 > CO > VOCs = TVOCs = HCHO = O_3 > NO_2 > C_6H_6 = SO_2 = Rn. Iran had the highest concentration of PMs, while South Korea had the highest concentration of VOCs, TVOCs and CO_2. Underlying factors, such as rapid economic development and urbanization, accounted for the decline in IAQ in most Asian indoor microenvironments. Despite significant improvement according to the Clean Air Initiatives for Asian Cities (CIA-Asia, 2010), PMs and VOCs still exceeded the WHO threshold limits. Furthermore, European cities with twenty papers recorded the highest number of reported studies within the context of this review. The distribution according to countries was Portugal (11 studies), Poland (3 studies), Greece (2 studies) France (2 studies), Spain (1 study) and Slovenia (1 study). The investigated pollutants are as shown: PM > CO_2 > HCHO > TVOCs > CO> NO_2 > VOC = O_3 > C_6H_6 > Rn. However, in most European studies, very high concentrations of CO_2 were recorded in children daycare centres, with Portugal (5647 mg/m^3) taking the lead. Portugal also had the highest concentration of PM_{10} (421 μg/m^3), TVOCs (3899 μg/m^3) and HCHO (204 μg/m^3) in Europe (Table 3). Only two (2) papers within the scope of this review were published in North America. The pollutants investigated in North America include VOCs, CO_2, HCHO and C_6H_6. Only VOC was present in both studies, with the highest concentration of 163.2 μg/m^3 recorded in Canada. Although not considered among the common indoor chemical pollutants in this review, it is worth noting that 2-(2-methoxyethoxy) ethanol which has never been observed and documented in any research, was detected in one of the classrooms in the USA study (Vu et al. 2019).

Review on indoor air quality in Africa day-care centres

According to a United Nations Children's Fund (UNICEF) report, indoor air pollution in Africa is said to be the highest in the world due to inadequate modern energy access in rural areas (UNICEF 2019). The continent of Africa consists of 54 countries, with Nigeria being the most populous, yet there is no sufficient information on this sensitive research focus. Figure 3 shows the scarcity of work on IAQ in DCCs in Africa. At the time of this review, only two (2) published studies, Ana and Umar (2013) and Nkwocha and Egejuru (2008), both in Nigeria, had been recorded, as shown in Table 2. However, minimal parameters such as particulate matter (PM), nitrogen dioxide (NO_2), sulphur dioxide (SO_2)

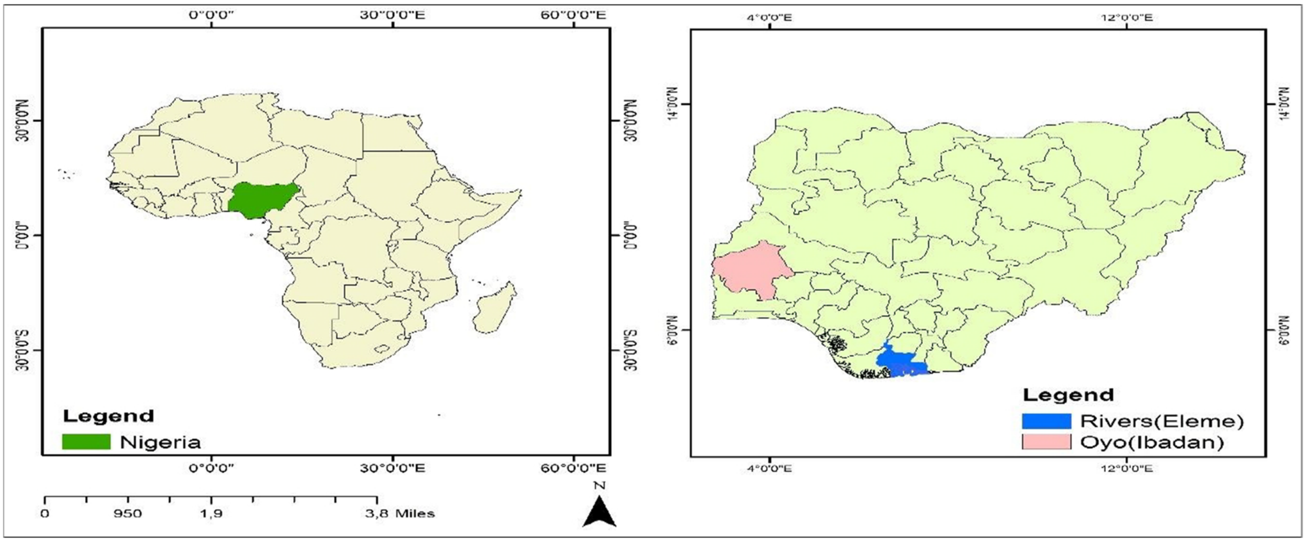

Fig. 3 Map of Africa depicting the paucity of data on indoor air quality in DCCs

and carbon monoxide (CO) were investigated in these studies. The findings showed that the concentration of particulate matter exceeded the WHO set limit. The results obtained from the Nigeria studies are in agreement with the research works carried out in Malaysia (Sara et al. 2020), Portugal (Branco et al. 2020), Iran (Harbizadeh et al. 2019), Thailand (Siwarom et al. 2017), Portugal (Nunes et al. 2016), Greece (Oliveira et al. 2016), Poland (Mainka et al. 2015) and a review study conducted by Zhang et al. (2021).

Another vital reason for unhealthy IAQ in Africa is the unavailability of real-time air monitoring stations in most parts of the continent. Although knowledge about air pollution on the African continent is growing, the severe health effects and epidemiological studies are still unknown (Agbo et al. 2021). Compared to other continents, such as North America and Europe, only about 6% of children on the African continent live within a 50-km radius of online real-time air monitoring stations. Approximately seven African countries, including Zambia, Zimbabwe, Madagascar, Ethiopia, Ghana, Botswana and Tanzania, have adequate and dependable real-time air pollution monitors. These shortcomings and differences necessitate a serious and timely intervention (UNICEF 2019; WHO 2021a, 2021b; Jafta et al. 2017; Kouao et al. 2019; Manisalidis et al. 2020; da Rocha Silva et al. 2018; Makoni 2020; Anake et al. 2020; Nicholl 2019).

Comparing the results of the indoor chemical pollutant (PM_{10}, NO_2, CO and SO_2) studies carried out in African nurseries with those obtained in other global areas, as given in Tables 2 and 3 and outlined in section A, our findings show that the highest PM_{10} concentration range of 677 μg/m^3 from African DCCs was lower than those reported in Asian countries except South Korea and Thailand (Guak et al. 2021; Yang et al. 2009; Siwarom et al. 2017), but significantly higher than those in Europe (Mendes et al. 2014; Branco et al. 2020): 58.28 μg/m^3 (Nunes et al. 2016). Table 3 indicates that NO_2 levels were reported only in Europe (Portugal: 6–136 and 51.2–54.2 μg/m^3; France: 9.5–53.5 μg/m^3; Greece: 4.6–43 μg/m^3; Spain: 8.1-25.2 μg/m^3) and Africa (Nigeria > 88 μg/m^3). The highest mean level of NO_2 in European preschool (136 μg/m^3) was significantly higher than that in Africa (88 μg/m^3). However, both values were within the WHO 1-h indoor nitrogen dioxide guideline of 200 μg/m^3. Previous preschool studies have shown that indoor NO_2 levels are usually indicators of outdoor levels, in the absence of an indoor source (Villanueva et al. 2018; Sadrizadeh et al. 2022). From Table 3, it is shown that the indoor CO concentration range of 1.83 μg/m^3 recorded in Africa was significantly lower than the 4956 μg/m^3 levels reported in Europe but higher than those reported in Asia (1.4 μg/m^3). From the reports, indoor studies with observed CO were attributed mainly to traffic-related pollutants from outdoor-related sources (Nunes et al. 2016; Zhang et al. 2021). Only a fewer studies monitored indoor SO_2 concentration in DCCs. The mean level of indoor SO_2 recorded in Africa (> 50 μg/m^3) was higher than that in Asia (16 μg/m^3). However, as shown in Table 3, North American studies did not monitor PM_{10}, NO_2, CO and SO_2 and as such not included in the comparison.

It is worth mentioning that several studies in other environments, such as residential homes, bakeries and school buildings, have been conducted in Africa (Jafta et al. 2017). Highlights of the studies are documented in Table S1, including Uganda (villages) (Nakora et al. 2020), Malawi (households) (Rylance et al. 2019), Côte d'Ivoire (homes) (Kouao et al. 2019), Ethiopia (homes) (Downward et al. 2018), South Africa (homes) (Jafta et al. 2017), Botswana (national review) (Wiston 2017), Kenya (homes) (Yip et al. 2017), Nigeria (homes) (Mbanya and Sridhar 2017), Nepal, Kenya and Sudan (homes) (Bikram et al. 2011). In comparison with Nigerian studies, a study carried out in six villages in Uganda showed that PM exceeded the WHO limit (Nakora et al. 2020), and CO was above the threshold in forty-five households in Kenya (Yip et al. 2017) and Uganda (Nakora et al. 2020). Furthermore, NO_2 exceeded the set limit in a Bostwana national study while SO_2 was within the WHO limit in Bostwana but higher than the threshold in South Africa.

Sources of indoor chemical pollutants and health risk effect

Indoor air can be contaminated by two major types of indoor air pollutants namely biological and chemical pollutants (Abaje et al. 2020). Chemical pollutants occur naturally or are caused by human activities. Poor aeration also encourages indoor chemical pollutants (Kim et al. 2021). Therefore, indoor CO_2 concentration is always used as an indoor air quality evaluator and not necessarily considered a pollutant (Telejkoa and Zender-Świercza 2016; Salthammer et al. 2016; Schibuola and Tambani 2020; Branco et al. 2020; Zhang et al. 2021). Table 4 outlines some significant indoor chemical pollutants, their sources and their health effects. Exposure to these chemicals has been associated with several health issues such as minor to acute respiratory-related illnesses, including cough, cold, bronchitis, cardiovascular diseases, headaches, eye irritation, dizziness, fatigue, delayed child development and lifetime illnesses like chronic asthma, even in families without a history of the condition (Simwela et al. 2018; Siwarom et al. 2017; Guak et al. 2021; Manuel et al. 2021; Persson et al. 2019; Rees et al. 2019; Stamatelopoulou et al. 2019). When children breathe in high amounts of chemical contaminants from the environment, it can hinder their growth and have negative effects on their immunological and respiratory systems (WHO 2018). Excessive indoor air pollution can impair lung growth and function and increase the likelihood of metabolic disorders in human physiology. It also inhibits brain maturation and the development of cognitive function in schoolchildren. Lee et al. (2020) and Jafta et al. (2017) reported that the IAQ has significant effects on the intelligence quotient (IQ) of a child. Another study discovered that infants exposed to polluted air in the womb could have a four-point drop in their intelligence quotient (IQ) at age 5 (Perera et al. 2019).

Similarities and differences have been observed in the sources of indoor chemical pollutants affecting DCCs across different countries and global areas. Similar sources have been associated with vehicular activities, infiltration from the outdoor environment, improper ventilation, inadequate floor spacing and proximity to busy roads and industrial activities (Guak et al. 2021; Harbizadeh et al. 2019; Kim et al. 2021; Othman et al. 2019; St-Jean et al. 2012; Vu et al. 2019). Underlying reasons for variation in the sources of indoor chemical pollutants in different countries and continents have been attributed to geographical, climatic and seasonal differences; indoor activities and the nature of the building and interior decoration materials (Vardoulakis et al. 2020; Yoon et al. 2011; Roda et al. 2011; Vu et al. 2019). For example, low- and medium-income continents like Africa and Asia, which rely heavily on solid fuel, have a higher concentration of particulate matter compared to European and North American continents. Also, a very high concentration of VOCs and TVOCs attributed to the innovation of new chemical substances was observed in Europe.

Indoor air quality remediation methods in day-care centres

- Addressing indoor air quality in a day-care environment through source identification and eradication is a cost-effective and time-efficient method (Stamatelopoulou et al. 2019; Siwarom et al. 2017; Rylance et al. 2019; Gola et al. 2019).
- Appropriate ventilation and adequate floor spacing should be employed. Proper aeration regulates room temperature and dilutes indoor airborne pollutants (Yip et al. 2017; Bukina 2018; Namvar et al. 2020; Langer et al. 2020; Agarwal et al. 2021; Wolkoff 2018; Kedare et al. 2020).
- Heating, ventilation and air conditioning systems (HVACs) should be serviced and inspected regularly to avoid the accumulation of indoor pollutants (Canha et al. 2016; Chen et al. 2020; Lucattini et al. 2018)
- Frequent cleaning of classrooms using microfiber mops and a vacuum with a clean high-efficiency particulate air (HEPA) filter (Rosário Filho et al. 2021; Zainudin et al. 2019).
- Low-emission materials should be used rather than general building finishing materials in childcare facilities (Arar and Jung 2021).
- Educating preschool administrators about indoor air quality management (Sadrizadeh et al. 2022).
- Growing an indoor air pollution tolerance plant is critical because it absorbs toxic substances from the air and purifies the air in that environment (Anake et al., 2018; Brilli et al., 2018).
- Air purifiers can deactivate suspended particles in the atmosphere by trapping a high proportion of airborne dust particles, allergens and odours, thereby improving indoor air quality (IAQ) in a room. However, it must be maintained optimally to prevent ozone emissions (Agarwal et al. 2021; Wolkoff 2018; Kedare et al. 2020; Chen et al. 2020; Lucattini et al. 2018. Nicholl 2019; Yoda et al. 2020).

Table 4 Sources and health risk effect of the most probable indoor chemical pollutants in DCCs

Significant indoor pollutants	Sources	Health effects	Reference
Asbestos	Construction materials in and around the house.	Childhood cancer, mesothelioma and asbestosis	Yoon et al. (2011); Cho et al. (2019)
Carbon monoxide	Vehicular activities and slow combustion stove	Headache, dizziness, nausea and vomiting, loss of consciousness and death	Ana and Umar (2013); Chinathamby et al. (2020)
Ozone	Mostly from outdoor air infiltration, solvent-related emission, electronic air cleaners	respiratory symptoms (cough, throat irritation, chest tightness or discomfort, wheezing, shortness of breath), decreased peak expiratory flow (PEF) in children	Hubbard et al. (2005); Kalimeri et al. (2016); Oliveira et al. (2016); Siwarom et al. (2017)
Volatile organic compounds(VOCs) Formaldehyde (HCHO)	Foam insulation, particle boards, pressed wood products, glues, clothing cabinets and furniture, paints, aerosol sprays, dry-cleaned clothing, wallpaper, textile curtain and disinfectants	Irritation and burn to the eye, throat, nose and skin; liver and kidney damage; tumour of the upper airways; central nervous system; fatigue; shortness of breath; nasal cancer and leukaemia	Van Tran et al. (2020); WHO (2018); WHO (2021b)
Lead	Lead-based paint, lead dust, toys, lead-contaminated soil from an outdoor playground	Impaired growth and development in children, chronic learning deficits, hyperactivity and reduced attention span	UNICEF (2020); Van Tran et al. (2020)
Benzene	Infiltration from outdoor emission from solvents, furniture and building materials that off-gas benzene, paints	Childhood leukaemia, toxic to the bone marrow, associated with various haematological cancers	Siwarom et al. (2017); WHO (2021b)
Sulphur dioxide	Infiltration from outdoor activities such as the burning of fossil fuels or gas flaring activities	Eye irritation, wheezing, chest tightness, aggravation of asthma and chronic bronchitis, inflammation of the respiratory tract (coughing, mucus secretion)	Abaje et al. (2020); Chinathamby et al. (2020)
Nitrogen dioxide	Pipes, gas stoves and furnaces; the inflow of outdoor pollutant gases from industries	Childhood asthma, lung infection, wheezing, coughing, flu and bronchitis	Rosário Filho et al. (2021); Kim et al. (2021); Choo and Jalaludin (2015); Nkwocha and Egejuru (2008)
Particulate matter	Road traffic dust, automobile exhaust, carpeted floor, soft plastic toys, textile curtains or blinds, chalk crayons, outdoor infiltration from construction site activity etc.	Neurodevelopmental disorder, respiratory symptoms reduced lung function, lung cancer and cognitive impairment	Anake et al. (2020); Guak et al. (2021); Oliveira et al. (2016); Zhang et al. (2021);WHO (2021b)
Phthalate esters	Plastic wares, PVC floors, child care articles, electronic devices, soft plastic toys and foam mattresses	Asthma, hyperactivity disorder, breast cancer and neurodevelopmental issues	Balck (2015); Larsson et al. (2017); Anake and Nnamani (2022)
Radon	Gas infiltration from the outdoor, water system, through the earth below buildings (cracks and drain openings in foundations) and building materials containing granite	Lung cancer or other lung dysfunction	Kalimeri et al. (2016); WHO (2010)

Important findings from the study

- A limited number of chemical pollutants were investigated by different researchers across different study locations. This makes it difficult to provide an in-depth assessment of the IAQ in the studied areas.
- The top 5 predominant pollutants examined in most studies were particulate matter, carbon dioxide, formaldehyde, carbon monoxide and total volatile organic compounds while benzene, sulphur dioxide and radon were the least monitored indoor chemical pollutants.
- Poor IAQ characterizes most of the DCCs, as evident in the high concentrations of the investigated pollutants exceeding the WHO and available regulations.
- Only the levels of nitrogen dioxide, radon and carbon monoxide were consistent with the existing national and international reference values for IAQ and health protection across the continents.
- African studies were evaluated in this global review, which had never been reported in any global review on IAQ in DCCs.
- The studies with good indoor air quality were due to adequate floor ventilation, consistent cleaning habits and an appropriate heating and ventilation system.

Research priorities

The global state and health consequences of IAQ in DCCs were examined in this review. PRISMA approach was adopted for identifying eligible studies suitable for inclusion in the review. The day-care location, toxic building materials and external air contaminant infiltration all play a significant role in the decline of indoor air quality in the majority of day-care centres. Consequently, this has led to various respiratory symptoms and diseases in children, including acute lower respiratory infection, asthma and impairment of cognitive conditions. Particulate matter was projected as the most investigated pollutant among other predominant indoor pollutants due to its unique characteristic and severe health challenges. The following are additional important information gaps, recommendations and suggestions for future studies.

- A comprehensive evaluation of chemical pollutants in a single research study across the continents is required and should be done on a periodic basis.
- Integrating processes such as the cultivation of indoor air tolerance plants, adequate HVACs systems, continuous equipping and training of school administrators and staff are highly recommended to improve IAQ in these sensitive environments.
- The design of affordable and mobile analytical equipment will aid in affordable ground-level data accessibility, especially in low- and medium-income countries.
- Concentration on the relationship between respiratory-related diseases in children and indoor chemical pollutants should be prioritized especially in continents with paucity of data.
- Finally, there is a dire need to increase research focus in day-care centres for both criteria and emerging indoor chemical pollutants.

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Declarations

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