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Indoor air quality index for preoccupancy assessment

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Abstract

The purpose of this study is to document the potential impacts on indoor air quality associated with different types of building materials (wall and floor finishes) through the development of an Indoor Air Quality index. The study first identifies pollutant sources and their corresponding health impacts due to short-term and long-term exposures. The study also quantifies levels of certain pollutants within a steady-state controlled environment, comparing the results of this study with previous studies conducted in different regions. It also proposes an IAQ index as an assessment tool which can be utilized preoccupancy. The field studies were conducted in residential buildings during January and February in Cairo to monitor volatile organic compounds (VOCs), formaldehyde (HCHO), ammonia (NH_3), radon gas, and particulate matter (PM). The indoor air was monitored in nine locations: four during the construction process and five following completion of construction. For this investigation, three rooms under construction within a Cairene building site were utilized to test the finishing materials. Chemical analysis and direct reading devices were used for air sampling and monitoring. The results revealed that the concentration of some pollutants decreased within the first year of construction, while others remained above target limits. The results of this study offer recommendations for engineers regarding the selection of appropriate materials through the implementation of source control strategies and an IAQ index which can be used as an assessment tool to ensure that the Indoor Air Quality meets recommended standards. Based on the conclusions and limitations of this study, recommendations for future work are documented such as the screening of materials and monitoring of Indoor Air Quality.

Keywords Indoor · Air pollution · IAQ · VOC · PM · Residential

Introduction

Design decisions, material selection, and construction practices are all factors that influence the performance of buildings. To increase the user's health and well-being, it is essential to monitor factors which may unintentionally pose health risks to occupants. With the introduction of chemicals in the building industry, the coexistence of materials in the indoor environment exposes individuals to complex compositions of air pollutants. Therefore, the investigation of the cumulative impacts of these contaminants is necessary. In developed countries, there has been increasing concern regarding contaminants in building environments and the potential exposure risks to occupants (Godish 2001). Shettler (2010), keynote speaker in a workshop hosted by the US Green Building Council, states that many components used have not been tested and their safety profile is unknown. This is problematic because standards are available for only certain pollutants, while humans are typically exposed to many components in the air simultaneously. The reaction of compounds in air pollutants can generate new secondary pollutants, which are not yet fully investigated. Studying the built environment in real time can give a better understanding of the sources of indoor air pollutants and can lead to the development of feasible solutions.

Since residential buildings host occupants of varying age and health, the users demonstrated different levels of tolerance to the same level of pollutant exposure. Consequently, resultant health symptoms due to exposure to indoor air pollutants vary in severity and are highly dependent on the individual's vulnerability as well as the type and concentration of the pollutant in air. The effect of the emissions can be realized due to short-term exposure or on a long-term basis due to cumulative exposure that results in chronic symptoms. The failure to

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identify and quantify the problem can lead to the continuous use of chemicals and the introduction of new chemicals within the construction industry. Table 1 presents a list of pollutants that are commonly found in indoor environments, as well as their sources and possible health effects (Hansen 1991; Kim et al. 2008; WHO 2010).

This paper reports the findings of field studies that were performed to quantify the levels of six different pollutants (particulate matter (PM), VOCs, formaldehyde, ammonia, and radon) after the application of selected finishing materials. The effects of these pollutants on human health are summarized below.

Particulate matter

The size, distribution, and chemical and biological properties of PM in indoor spaces vary and are dependent on several variables. Airborne particles are 10 μm (referred to as PM10) or less in size. The smaller the size of PM, the higher the risk on human health because smaller particles are easily respired and can bypass respiratory defense mechanisms. Airborne particles are carriers of other contaminants and thus deliver harmful substances into the respiratory system. PM in concentrations from 250 to 350 $\mu g/m^3$ has been found to increase respiratory symptoms in susceptible individuals (Hansen 1991).

Volatile organic compounds

Organic compounds include a large group of hydrocarbons and VOCs, which are released from some building materials and consumer products. VOCs are common constituents of the manufacturing or installation processes associated with renovations or new construction projects. Building materials release a wide range of VOCs including toluene, *n*-butanol, *n*-hexane, *p*-xylene, and styrene. For this reason, to evaluate the level of VOCs in interior spaces, the combined total VOC (TVOC) exposure should be recorded. Because of the large number of VOCs existing, there is still a lack of proper indices to quantify the overall VOC levels. There is also a lack of recognized indoor air standard on VOCs.

Formaldehyde

Aldehydes are a group of VOCs that belong to a larger group of compounds called carbonyls. This group of compounds is soluble in water and can be absorbed rapidly by the respiratory tract once inhaled. This, in turn, triggers sensory irritation and can irritate the mucous membrane at low concentrations when present in indoor environments. Formaldehyde (HCHO) is a colorless gas with a pungent odor. It is found in urea-formaldehyde resins that are commonly used as wood adhesives in the manufacture of pressed wood products as well as some finish coatings. The chemical instability of urea-formaldehyde leads to decomposition and emission of formaldehyde into the air, increasing its concentration in indoor environments. The US Environmental Protection Agency (EPA), Occupational Safety and Health Administration (OSHA), and International Agency for Research on Cancer (IARC) have listed formaldehyde as a class 2A suspected human carcinogen. The concentration of HCHO and associated

Table 1 Indoor air pollutants, sources, and health effects

Pollutant	Source	Health effect
Radon	Soil and building materials	Lung cancer
Nitrogen oxides	Incomplete combustion	ENT irritation
Ozone	Electronics	Asthma
Lead and asbestos	Building materials	Lung cancer
Ammonia (NH_3)	Concrete and floor structures	ENT irritation
PM10	Building materials	Allergic symptoms
PM2.5	Building materials	Cancer
Volatile organic compounds (VOCs)	Building materials	Respiratory irritations
Carbon monoxide (CO)	Incomplete combustion	Acute exposure: reduction of exercise tolerance High exposure: ischemic heart disease and nausea
Carbon dioxide (CO_2)	Human emissions Burning of fossil fuels	Headaches and nausea

symptoms are affected by the change in temperature and humidity (Hansen 1991).

Ammonia

Ammonia is added to some water-based paints (latex) and coatings to maintain the desired pH. Low concentrations of ammonia can cause eye and skin irritation. Higher concentrations can cause respiratory distress in the long term. Children are more vulnerable to these symptoms than adults at the same levels of exposure.

Radon

Radon is measured in becquerels per cubic meter (Bq/m^3) or in picocuries per liter (pCi/l). Due to its long half-life, radon release remains constant over an extended period. Radon is the number one cause of lung cancer among non-smokers (US EPA 2015). Its fast rate of decay releases radioactive particles that, if inhaled, can cause damage to lung cells (National Cancer Institute).

This paper investigates both pollutants which are released during the construction and installation process and those emitted by building materials in the long term. The "Literature review" section starts by reviewing previous studies conducted on indoor air quality in different regions, as well as a review of studies which have focused on developing rating schemes or indexes for indoor air and environmental quality. The "Standards and exposure limits" section presents the standards and benchmarks and outlines the method used to identify the benchmark values which were used in this study. The "Materials and method" section describes the studies which were conducted in residential units (old and new) during the months of January and February in Cairo, Egypt. The Indoor Air Quality (IAQ) index explains how the results were aggregated and demonstrates the implementation of the index using the readings obtained from the field studies. The measurements are then compared to previous studies conducted in Sweden, Finland, Japan, Korea, China, and Egypt.

This study aims to encourage the implementation of healthier finishing materials, ultimately improving indoor air quality and minimizing health risks in occupants, through the achievement of the following:

1. Investigating the impact of mainstream building materials on the indoor air quality within structures built using synthetic products (namely wall and floor finishing materials) in Cairo.
2. Developing an IAQ index as an assessment tool which can be used to assist designers and contractors in selecting materials and evaluating the quality of the interior space prior to occupancy.

Literature review

The selection of materials is considered key to source control, which has been evaluated as the most effective mitigation strategy towards minimizing IAQ problems as specified by the US EPA and Consumer Product Safety Commission (CPSC).

Previous research conducted to measure levels of pollutants in real-life settings has each used different air sampling and monitoring devices. Devices used for field tests vary in size, and new technologies are being developed to achieve more accurate measurements and to include a wider range of pollutants. Winegar and Keith (1993) states that field techniques yield better results than lab techniques when considering sample quality since it is difficult to assure that the sample being analyzed in the lab is a representative sample. Previous studies have been reviewed and can be presented in two groups. The first group includes field studies and the second group comprises Indoor Air Quality indexes. The methods used and results of these studies are discussed in further detail.

Field studies

Field studies investigate and quantify the levels of one or more different pollutants. Some studies have focused on measuring indoor pollutants during occupancy, while others have particularly tested the contribution of materials to specific emissions in chamber tests. From previous studies, building materials have been found to contribute to the radon levels among other parameters (Ivanova et al. 2017).

The field studies conducted were mostly in occupied buildings and are often associated with surveys to correlate health symptoms with measured exposure levels. A field test was carried out in the UAE among 628 households, where SO_2, NO_2, and H_2S were detected at different concentrations and were correlated with symptoms including wheezing and asthma. HCHO exposure was associated with neurologic symptoms and difficulty concentrating. The purpose of the study was to measure the pollutants emitted from occupant activities and to investigate their effect on occupant health conditions (Yeatts et al. 2012). In another study by Abdel-Salam (2012), PM concentrations within Egyptian residences were found to be higher than outdoor concentrations during occupancy. In Bangladesh, a study has indicated that building materials including brick, thatch, mud, and tin affected the measured concentrations of PM10 indoors (Dasgupta et al. 2009).

Measurements of VOCs, HCHO, and NH_3 in residential buildings have been taken in many countries, including Korea and Finland (Kim et al. 2008; Tuomainen 2001). These studies have shown that the compounds exist at levels as low as 1 μg/m^3 and as high as 4000 μg/m^3 for TVOCs and from 9 μg/m^3 to 500 μg/m^3 for HCHO. Based on the literature review, it is evident that very few field studies were conducted to quantify the levels of pollutants prior to occupancy, particularly the measurement of PM in unoccupied residential buildings. In a study by Jodeh et al. (2017), PM concentrations in residential buildings in Nablus were recorded during summer and winter, showing that PM levels are higher during summer. However, the study was conducted during occupancy and the results have been associated with user activity rather than building construction or renovation.

On the other hand, the effect of finishing materials on VOCs, HCHO, and NH_3 has been addressed in some experiments. It has been proven that the selection of materials plays an important role in reduction of VOCs, as seen in the study by Tuomainen (2001) where the effect of decomposing agents on VOCs was tested with results demonstrating that decomposing agents can contribute to the reduction of formaldehyde in indoor environments. Other studies have measured the effect of temperature, humidity, and the age of buildings on air pollutants, all of which indicated that these factors have differing effects on measured HCHO and VOC (Khoder 2006; Khoder et al. 2000). The HCHO levels were found to increase with higher temperature and relative humidity (Khoder et al. 2002). Furthermore, higher concentrations of HCHO were found in new offices with recent renovation as compared with old offices (Khoder 2006). Therefore, source characteristics have been identified as influential contributors to indoor pollutants (Guo et al. 2013).

In a study by Järnström (2006), the results indicated that HCHO levels reached the target values regardless of the use of low-emitting materials; VOCs were reduced after 6 months to reach the target values with the help of mechanical ventilation, while ammonia levels remained above acceptable levels for 12 months. In addition, while VOC contamination from construction sources decreased over time, additional sources of VOCs were introduced during occupancy. While studies have investigated the effect of materials on different types of indoor pollutants, very few have examined the cumulative effect of multiple pollutants.

IAQ index

Previous studies, which have assessed multiple IAQ parameters and developed an IAQ index, have been reviewed. Many of these focus on evaluating multiple pollutants in a post-occupancy setting to test the effect of perceived indoor environmental quality (IEQ) factors on occupant satisfaction and performance. This includes a study by Choi et al. (2014) which examines the effect of IEQ satisfaction on performance of students, analyzing the combined effect of multiple parameters. Ncube and Riffat (2012) also developed an IAQ assessment tool which includes relative humidity, air velocity, and CO_2 concentration, comparing the methodology adopted to the analytical hierarchy process (AHP) method used in a previous study. The AHP was used in the current study to provide weighting to all proposed parameters in a more comprehensive setting with regards to IAQ, as demonstrated in the IAQ index section of the paper. Zheng et al. (2011) have included a wider range of IAQ parameters in their study and have used the AHP method with the application of fuzzy theory and Delphi technique to develop their index. Marino et al. (2012) have also presented an Environmental Quality Index; however, air quality parameters have been simplified to include only temperature, air velocity, and CO_2 concentration.

On the other hand, the current study mainly focuses on evaluating the combined effect of different pollutants in a pre-occupancy setting. The developed index differs from previous indexes since it is used to compare the IAQ after application of materials through the measurement of pollutant levels (as compared to predefined benchmarks post-occupancy); thus, it is not subjective to occupant perception and satisfaction.

Standards and exposure limits

The agreement on specific criteria and standardization of IAQ levels is necessary for developing countries with higher outdoor pollution rates and with a vast availability of uncertified materials in the construction market. Since the US EPA identified indoor air pollution as among the top five environmental risks to public health (EPA 2017), and since the World Health Organization (WHO) in 2012 indicated that the highest death rates are associated with acute lower respiratory infections in children[1] as well as heart diseases caused by indoor air pollution (WHO 2016), there have been several attempts to address this problem. Studies were conducted to investigate factors affecting occupants in non-occupational settings, the results of which identified indoor contaminants and their sources, thus enabling the definition of exposure limits. This includes efforts on the national scale in many countries including Australia, Canada, China, Korea, Malaysia, Sweden, Russia, and Germany. On a global scale, the WHO and the American Standards for Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) have set international standards and guidelines for acceptable levels of IAQ.

Upon comparing benchmarks from the aforementioned sources, applicable baseline values were identified through the following criteria:

1. Available national standards supersede other national/ international standards.
2. ASHRAE standards are considered for the factors where national standards are not identified.

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[1] Scientific studies found more than 300 industrial chemicals in umbilical cord blood in sampling of babies. These include carcinogens, neurotoxins, and reproductive toxins (Houlihan et al. 2005).

3. Other national standards are then compared taking into consideration the most stringent limits.
4. If none of the above apply, occupational standards based on 8-h exposure limits are adopted.

The baseline values identified based on these criteria are also in line with the values specified by the WELL[2] Building standard for healthy buildings as per the Air Quality Standards feature. The intent of the Air Quality Standards feature is to ensure a basic level of high IAQ in buildings, which is in line with the goal of this study.

Materials and method

Selection of materials and buildings

Cairo is a city located in a subtropical region with an arid desert climate, where ambient relative humidity (RH) ranges from a minimum of 15.8% to a maximum of 68% (Egyptian Typical Meteorological Year). In this study, the tests were carried out in January and February 2015, during which the outdoor temperature ranged from 8 to 25 °C. Nine rooms in residential building units in Cairo were selected to perform the studies, five of which were constructed 6 to 12 months before the start of the study and four of which were under construction. The rooms under construction were monitored each time new materials were installed/applied. Windows and doors had been installed in all study locations, and all studies were conducted over a period of 8 h during which measurement devices were uninterrupted. To quantify the levels of pollutant groups emitted due to the finishing materials used and common construction practices, the following material types were studied.

Wall construction material

Residential buildings in Egypt commonly use clay bricks for the construction of walls. All rooms included in this experiment were constructed using clay bricks from the same manufacturer. A thin layer of primer was applied to the wall to provide a smooth and flat finish.

Structure

The structural system is composed of concrete columns and slabs in all rooms used for this study.

Indoor finishing material

Since the ceiling finish is typically the same material used for the wall finish, and wall surfaces account for the largest surface area of the interior space, the coating was applied only to the walls. The most commonly used finishing materials for interior walls in Egypt are emulsion paints. For this study, the selected materials were based on available and economically feasible options which are used in standard middle-income housing. Only one layer of paint was applied in each of the rooms before measurements were taken.

Floor finishing material

The type of flooring commonly used in middle-income houses is ceramic tiles. In rare cases, wooden flooring (parquet) is installed. Therefore, only two types of flooring were used in the current study: medium-density fiberboard (MDF) and ceramic tiles. In each room, the flooring was installed before the wall finish was applied.

The following figure (Fig. 1) illustrates the framework of the field study:

Measurement of indoor parameters

On-site monitoring can be achieved by two means: direct reading instruments and laboratory analysis. Both methods were utilized in this study for data collection. Direct reading instruments and data loggers were used to provide time-weighted averages for PM, radon, temperature, and humidity. Laboratory analysis was also used to analyze VOCs, formaldehyde, and ammonia. The devices were placed at a height of 1.5 m in the center of the room and were set up as shown in Fig. 2 and described below. Several precautions were considered in the performance of this experiment. The experiment was conducted at a steady state and controlled (sealed) environment to eliminate the effect of ventilation, air velocity, and outdoor pollutants. The experiment was conducted prior to operation of HVAC equipment and windows and doors remained closed and locked for the duration of the experiment. Further precautions were set in place to limit access to the experimental area, with only two authorized persons accessing the rooms during the study, including the worker to apply paint and install flooring and the author to set up equipment. On average, the time spent in the room before measurements were taken was limited to 1 h per study area.

Particulate matter (PM2.5, 10, and TSP) These were measured using the Metone, model 831, which is a real-time monitoring instrument. At each location, the device was operated continuously for 8 h and the data was retrieved at the end of each

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[2] The WELL building standard is based on a thorough review of the existing research on the effects of spaces on individuals and has been advanced through a thorough scientific and technical review.

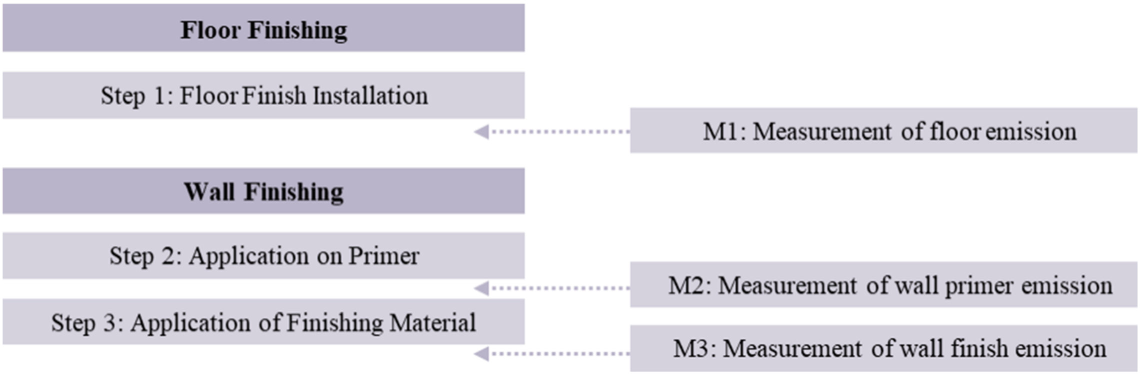

Fig. 1 Field study framework

study. The concentration range measured by this device is 0–1000 μg/m^3 with a resolution of 0.1 μg/m^3, accuracy ± 10%, and a flow rate of 2.83 l/ min.

The particulates monitored in this range are coarse (10 μm or less) and fine particulates (2.5 μm in diameter) known as PM10 and PM2.5, respectively. The device also records PM1 (less than 1 μm), PM4 (less than 4 μm) in diameter, and total suspended particulates (TSP).

Volatile organic compounds, formaldehyde, and ammonia were monitored using carbon-based adsorbents (charcoal sorbents) to determine the levels of VOCs according to the standard developed in the USA by OSHA. The collection tubes contained 150 mg of coconut charcoal subdivided into two portions of 100 and 50 mg. The front portion (100 mg) collects VOCs, while the 50 mg backup section determines if solvent breakthrough occurs. This method requires drawing a sample of air (active sampling) through a pump, so the edges of the tube were broken and connected to the air pump. The airflow is measured and recorded, and then the pump is left to draw air for 8 h into the tube. The tubes are then closed, wrapped in aluminum foil, and refrigerated. Finally, the adsorbent (activated charcoal) in the tube is extracted to a glass test tube containing 2.00 mL of trichloroethylene. Using a gas chromatograph flame ionization detector (FID), the VOC samples were analyzed to identify the compounds present in the collected sample.

Fig. 2 Experimental setup in test room (after construction)

HCHO was collected in a 0.05% aqueous solution of 3-methyl 2-benzothiazolone hydrazone hydrochloride (MBTH) while ammonia was collected in 0.005 M sulfuric acid solution. The solutions were filled in glass impingers that were connected to an air pump at the outlet, drawing air into the impingers.

Radon gas was monitored using Corentium Digital Radon Monitor. The device samples indoor air through a passive diffusion chamber and uses alpha spectrometry to calculate the radon level (Fig. 3). Silicon photodiodes are utilized to detect both count and energy of alpha particles resulting from the decay chain of radon gas. The instrument was calibrated to reference instruments in accredited laboratories. The detection range for this device is 0–9999 Bq/m, with an accuracy of ± 5 Bq/m^3.

RH and temperature were monitored continuously for the duration of the experiment. Data loggers were used for this purpose for indoor monitoring. For this purpose, an Extech RHT20: Humidity and Temperature Datalogger was used for indoor measurements. Temperature and humidity affect the concentration levels of other parameters like VOCs, ammonia, and formaldehyde, which will be observed and recorded in this study. Maintaining temperature and relative humidity within human comfort zones is also necessary to avoid distress.

A summary of the equipment used for monitoring each parameter is provided in the illustration below.

IAQ index development

Considering the efforts made by governments in several countries such as the UK, Finland, and China to monitor ambient air quality to inform policy making and strategic planning, developing a similar tool for IAQ would be of great significance, especially considering that 90% of an individual's time is spent indoors (US EPA). Thus, this

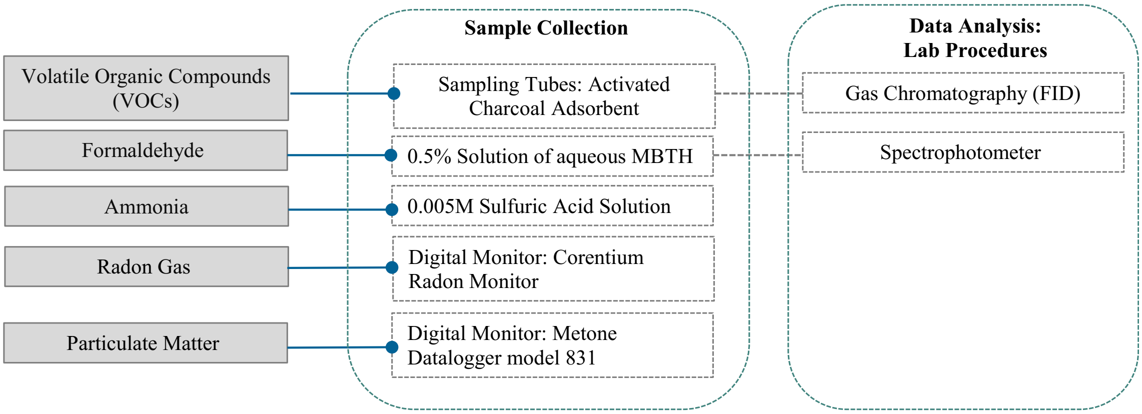

Fig. 3 Experimental sampling and monitoring devices

study provides an IAQ index which combines the effect of multiple pollutants to assist designers and engineers in monitoring buildings prior to occupancy to ensure healthy environments for tenants.

The index is a single number aggregated mathematically from two or more indicators, where each indicator denotes a single quantity associated with a variable. This tool combines data from a complex system to describe that system. The first step in the design of this index was the identification of measurable parameters. Step two involved the identification of benchmarks, which was completed by comparing benchmarks listed in existing international and local standards and guidelines. The third step was to provide appropriate weightings for each of the categories and individual parameters. Finally, the weighted scores were calculated to formulate the index.

Identifying parameters As explained in the Introduction section, there are several pollutants that contribute to IAQ. For this study, pollutants considered in the design of the index are either directly emitted from materials or affected by the material compositions in the long term. Table 2 below lists the IAQ index parameters considered as part of this study.

Identifying benchmarks The specification of benchmarks was completed according to the criteria listed in the "Standards and exposure limits" section.

According to ASHRAE 62.1/62.2-2007 and 2013 (A.3), there is no specific organization responsible for the identification of exposure standards for all indoor air contaminants nor are values available for all contaminants of potential concern. This is due to insufficient epidemiological and toxicological evidence and defined data regarding indoor air contaminants. Therefore, the selection of concentrations and exposure levels should be determined considering the following:

- The purposes and setting for which they are developed compared to where they are applied.
- Not all standards and guidelines recognize the presence of susceptible groups or address typical populations found in occupancies.

Weighting: analytical hierarchy process The AHP was used to obtain the weights for factors 1 to 6 in Table 2. The pairwise comparison between indicators was based on a nominal ratio scale of 1 to 9, which was input in each cell in a positive reciprocal matrix. The process was repeated twice. The first set of weights is used in acceptable thermal comfort conditions (when factors 7 and 8 are within an acceptable range), and the second set would be used when either one of the factors 7 or 8 is unacceptable, thus altering the weights on factors 1 to 6. Table 3, 4, and 5 demonstrate the normalization of relative weight by dividing the element of each matrix with the sum of its column to obtain the final sum of columns = 1. Next, the average for each row is calculated obtaining the final weights for each factor.

Table 2 IAQ index parameters

Contaminants
1.VOCs
- Benzene
- Toluene
- Xylene
2. Formaldehyde
Inorganic compounds
3. Radon
4. Ammonia
Particulate matter
5. PM2.5
6. PM10
Thermal comfort
7. Temperature
8. RH

Table 3 Analytical hierarchy process: paired comparison matrix

	1	2	3	4	5	6
1	1.00	0.25	8.00	6.00	5.00	4.00
2	4.00	1.00	8.00	9.00	4.00	9.00
3	0.13	0.13	1.00	0.33	6.00	6.00
4	0.17	0.11	3.00	1.00	4.00	6.00
5	0.20	0.25	0.17	0.25	1.00	8.00
6	0.25	0.11	0.17	4.00	0.13	1.00
Σ	5.7	1.9	20.3	20.6	20.1	34.0

Obtained final weights

Final score The input data is compared to the corresponding benchmark for each parameter, and the following scores are given for the individual spaces accordingly:

- Measurement below benchmark: score is 0
- Measurement = benchmark: score is 0.5
- Measurement above benchmark: score is 1.

Each score is then multiplied by a weight identified by the AHP (Table 6).

Input data

The obtained measurements (M1 to M10) are compared to the benchmark levels (HR). The score (S_S) is then calculated for each case and multiplied by the corresponding weight (S_W), where A, B, and C represent the stage of completion for each room. In this study, A represents floor application, B represents the application of the primer, and C shows the results after the paint was applied (Table 7).

Computation and rating

The weighted score = total score (S_S) × total weight (S_W).

The weighted score was then compared to the following scale to provide the final index (1 to 4) for each room. The rating was defined by calculating quartiles, where the acceptable range lies in the first quartile, the second quartile needs improvement, and the third and fourth quartiles are poor and unacceptable respectively (Table 8). The "acceptable" limit indicates that the space is ready for occupancy, "needs improvement" indicates a space that can reach an acceptable limit with time depending on the type of contaminant that is present, "poor" environment requires mitigation by removing the source of the contaminant or by dilution treatments (e.g., ventilation flush out), and "unacceptable" environments require both removal of contaminant source as well as dilution treatment to remediate extreme problem areas.

Table 4 Analytical hierarchy process: final weights calculation

	1	2	3	4	5	6	Σ
1	0.17	0.14	0.39	0.29	0.25	0.12	0.40
2	0.70	0.54	0.39	0.44	0.20	0.26	0.25
3	0.02	0.07	0.05	0.02	0.30	0.18	0.06
4	0.03	0.06	0.15	0.05	0.20	0.18	0.11
5	0.03	0.14	0.01	0.01	0.05	0.24	0.10
6	0.04	0.06	0.01	0.19	0.01	0.03	0.08

Table 5 Final weights

Contaminant	Weight-1	Weight-2
1. VOCs - Benzene	0.42	0.40
- Toluene		
- Xylene		
2. Formaldehyde	0.21	0.25
Inorganic compounds		
3. Radon	0.05	0.06
4. Ammonia	0.09	0.11
Particulate matter		
5. PM2.5	0.12	0.10
6. PM10	0.11	0.08
Thermal comfort		
7. Temperature	N/A	
8. RH	N/A	

N/A not applicable

Results and discussion

Table 9 presents the data for the average values of each parameter in the studied rooms and the corresponding calculated index. The measured concentrations of air pollutants revealed that PM, VOCs, HCHO, NH_3, and radon gas are present at different concentrations in the monitored locations. The concentrations of these pollutants exceeded the benchmark for the locations tested immediately after construction (highlighted in red). Rooms (R1 to R4) were monitored during the application of flooring and wall finishing compositions. Their ratings are from 2 to 4 reflecting poor or unacceptable conditions, except for room 4 where more favorable materials were applied.

After construction completion (S1-S5)

Temperature and relative humidity Thermal comfort parameters, temperature, and RH were monitored. Indoor temperature was in the range of 13.4 to 19.9 °C, i.e., below thermal

Table 6 Score assessment conditions and weights

Contaminant	Units	Assessment condition			Weights (S_W)	
		Healthy range (HR) score = 0	Benchmark score = 0.5	Non-healthy range (NR) score = 1		
1. TVOCs	μg/m^3	< 500	500	> 500	0.35	0.40
2. Formaldehyde	ppb	< 27	27	> 27	0.35	0.40
3. Radon	pCi	< 4	4	> 4	0.15	0.09
4. Ammonia	ppb	< 43	43	> 43	0.10	0.17
5. PM2.5	μg/m^3	< 15	15	> 15	0.07	0.05
6. PM10	μg/m^3	< 50	50	> 50	0.05	0.05
7. Temperature	°C	21.8–30	–	< 21.8 or > 30	N/A	
8. RH	%	20–50	–	< 20 or > 50	N/A	

N/A not applicable

comfort levels specified by the Egyptian code, with only one exception. The main reason observed for this exception was the orientation of the room on the east façade, which benefitted from solar heat gain. RH readings were acceptable in five sites, while three were out of the acceptable range (20 to 50%).

Particulate matter After the completion of construction, suspended particulates are recorded at high concentrations. With time, the suspended particulates settle and adsorb on the surfaces of walls and floors, decreasing the measured concentrations. Several years after construction, adsorbed particulate concentrations increase and are re-suspended into the air. The studies revealed that PM2.5 and PM10 were highest in three different rooms. This observation strongly correlated the age of the building to PM2.5 and PM10 levels where $r = 0.57$ and 0.52, respectively. The recorded concentrations of particulates were higher in apartments located in older buildings, for example, in a room which was constructed 25 years before the study. Another factor which affected the concentration is the time since the finishing was applied, which showed a strong negative correlation ($r = -0.71, -0.88$) for PM2.5 and PM10, respectively.

Volatile organic compounds, formaldehyde, and ammonia The application of materials in these studies demonstrated that the concentration of HCHO and NH_3 increased with the application of primer (the first wall coating used to provide a smooth surface). Buildings where construction work had been completed at least 12 months before the study have shown lower levels of HCHO, indicating that HCHO concentrations decrease with time.

Ammonia levels were highest in rooms where porcelain tiles and emulsion paint were used. This is followed by another location where parquet was used for flooring. According to

Table 7 Input data (obtained measurements) for IAQ parameters

Parameters	Indoor measurements		
	A	B	C
TVOCs	$T1_A = M1_A + M2_A + M3_A$	$T2_B = M1_B + M2_B + M3_B$	$T3_C = M1_C + M2_C + M3_C$
Benzene	$M1_A$	$M1_B$	$M1_C$
Toluene	$M2_A$	$M2_B$	$M2_C$
Xylene	$M3_A$	$M3_B$	$M3_C$
HCHO	$M4_A$	$M4_B$	$M4_C$
Radon	$M5_A$	$M5_B$	$M5_C$
Ammonia	$M6_A$	$M6_B$	$M6_C$
PM2.5	$M7_A$	$M7_B$	$M7_C$
PM10	$M8_A$	$M8_B$	$M8_C$
Temp	$M9_A$	$M9_B$	$M9_C$
Humidity	$M10_A$	$M10_B$	$M10_C$
Index	I_A	I_B	I_C

Table 8 Index rating scale

0–0.59	0.60–1.19	1.2–1.79	1.8–2.5
1 (Acceptable)	2 (Needs improvement)	3 (Poor)	4 (Unacceptable)

previous studies conducted, the concentration of ammonia increases with increasing RH (Järnström 2006). Therefore, it is necessary to repeat this study during different seasons to assess the effect of climatic conditions on the readings obtained, especially in the case of ammonia, which has exceeded recommended standards.

As for the analysis of VOCs, the results indicated that locations where construction work was completed 10 months before the study had a high concentration of total VOCs based on the quantification of benzene, toluene, and xylene in the collected sample. The measured concentration was 396.29 μg/m^3 for the three compounds only. Another location, which was also renovated 10 months before the study, has shown a lower concentration of 160.53 μg/m^3. This is mainly because the type of renovation work, which took place in site 1, was minor compared to the application of materials in site 2.

Radon Radon levels in the indoor environment ranged between 1.02 to 3.07 pCi/L. The lowest levels were recorded when porcelain tiles were used, while the highest levels were recorded where marble flooring was used.

During material application (R1-R4)

The readings recorded during material application indicated that wall coatings have contributed to the highest levels of HCHO and NH_3. Another observation was that particulate matter levels decreased with the application of the first preparatory coating (primer), reducing the initial readings in each room. This was accompanied with an increase in relative humidity levels in each space.

Temperature and relative humidity The mean values for temperature and humidity recorded during this part of the study were 16.1 °C and 64.5%, respectively. The range of these measurements was from 11.8 to 19.9 °C and 38.4 to 94.5%, respectively. The first reading was recorded after installing flooring, the second following the application of primer, and the third and final reading following the application of paint. The temperature increased as new materials were applied in each room, with only two exceptions. For the duration of the study, RH remained above recommended limits, demonstrating a clear association with the application of coatings.

Particulate matter The recorded levels of particulate matter were higher before the application of wall coatings, exceeding acceptable benchmarks. The initial level of suspended particulates was inconsistent among all rooms. The variation may occur due to the release and suspension of particles as the materials are installed and due to movement during the application of materials and experimental setup. The concentration of larger particulates was higher than smaller particulates in all spaces. For both PM2.5 and PM10, the concentration decreased by approximately 25% following the application of the first wall coating. At the end of the study, PM10 was reduced by 40 to 60% as compared to the level at the start of the experiments.

A similar pattern was seen in PM10 as PM2.5, where the initial values in all rooms are higher than the final readings. A higher concentration of PM10 was measured in all spaces compared to PM2.5. In three rooms, the concentrations of particulates showed a more significant decrease than in room 4, where fewer coatings were applied.

Table 9 Field study results

Parameters	Indoor measurements								
	After construction completion					During material application			
	S1	S2	S3	S4	S5	R1	R2	R3	R4
HCHO	10.00	15.47	13.84	10.00	5.70	24.85	67.30	32.57	15.47
Radon	1.02	2.02	0.20	0.80	0.08	1.51	1.28	0.55	0.11
PM2.5	17.24	8.11	6.93	7.48	26.42	15.20	20.76	35.55	54.45
PM10	41.86	27.86	26.96	18.64	74.28	75.23	94.27	99.05	198.7
Ammonia	–	64.46	37.24	–	42.27	51.69	41.60	28.38	18.65
VOCs	160.53	396.29	17.80	–	–	69.89	179.70	175.07	142.34
Temp	14.70	15.80	14.90	15.20	19.40	16.30	14.17	17.55	17.60
Humidity	61.00	48.60	54.90	68.30	47.30	55.83	69.17	71.50	55.75
Index	*1*	*1*	*1*	*1*	*2*	*3*	*4*	*4*	*1*

Volatile organic compounds, formaldehyde, and ammonia The VOCs analyzed in this study are benzene, toluene, and xylene,[3] where the mean concentrations were found in the ratio of 12:2:1. Other types of volatile compounds were detected during the analysis process; however, further investigation is required to identify the types and concentrations of the individual compounds. It is important to identify the different types of VOCs detected in addition to measuring the TVOCs. This helps to identify the type and source of the VOCs, especially considering that some VOCs may not be considered harmful as mentioned in a study by Son et al. (2013) where natural VOCs were detected.

In locations where ceramic flooring was applied, the measured TVOCs were less than in rooms where high-density fiberboard (HDF) was used. In the room where low VOC paint was used, the lowest concentration was recorded, while paint samples used in the remaining rooms indicated higher concentrations for the levels of benzene, toluene, and xylene. Although these levels did not exceed the specified benchmark 500 μg/m^3, other compounds which were detected but not quantified in each sample indicate that the total VOC levels may exceed the recorded numbers by three to four times.

Higher levels of formaldehyde were recorded after the application of wall coatings, compared to the application of flooring. With regard to the type of flooring used, formaldehyde concentration was higher in rooms finished using ceramic tiles than in those where HDF flooring was installed. Applications of primer and paint have shown increased levels of formaldehyde in all rooms tested. The same type of primer was applied in all rooms, increasing the HCHO by approximately three to four times as compared to the original levels. Paint samples which were applied after the coating of primer showed higher HCHO concentrations than a paint sample which was used without primer coating. Finally, the level of HCHO measured after the application of wallpaper was below the benchmark.

The concentration of ammonia exceeded the benchmark in three cases, with the application of paint, primer, and wallpaper. The initial levels recorded were higher in rooms with ceramic tiles than rooms with HDF. The increase in levels of ammonia is mainly due to the application of coatings, primer, and paint as well as wallpaper. However, the choice of paint can significantly contribute to the reduction of the measured concentration. This can also be linked to the quantity of different materials which were applied. Where more materials were used, the measured concentration of pollutants increased.

Radon The results show that radon readings have not exceeded recommended levels in any of the monitored spaces. However, the final reading in each room shows an increase compared to the initial reading recorded. Moreover, primer application, again, increases the recorded levels of radon in the air although the values decrease after its application. Rooms where the finish flooring was ceramic show higher initial readings than rooms where the flooring installed was HDF.

Comparison with previous studies

The purpose of the current study was to measure the emission of multi-pollutants, providing a comprehensive assessment of IAQ. The results of previous studies, as shown in Table 10 below, were compared to the present study. The results indicate that formaldehyde concentrations measured in the current study in rooms under construction show values that are higher than those presented in previous studies by Järnström (2006) and Tuomainen (2001). However, the values in the study conducted by Kim et al. (2008) exceeded the values in the present study; the cause of this was that materials installed in the study conducted in Korea included furnishings and cabinets made of pressed wood, which is expected to emit high levels of formaldehyde. Other studies conducted in Egypt post-occupancy have shown that the measured concentrations of HCHO in residential buildings are higher than those in office buildings (Khoder et al. 2000; Khoder 2006).

The values recorded post-occupancy in Egypt also appear to be four to seven times higher than in the current study due to furniture and other factors considered. Although the emission of HCHO from building materials may diminish with time, older buildings during occupancy still show high concentrations that exceed the 27 ppb benchmark. The investigation conducted by Khoder et al. (2002) was conducted during summer while the current study was conducted during winter. This may be another factor that has influenced the readings. The Finnish Society of IAQ has specified allowable levels for formaldehyde and ammonia such that the benchmarks are 40 and 57 ppb, respectively. The two studies that have tested ammonia levels indoors in Finland (Järnström 2006; Tuomainen 2001) show that the mean and maximum levels measured are higher than in the present work. These studies were conducted during summer and winter, indicating that ammonia and formaldehyde levels measured during summer were higher than those in winter.

The literature review on particulate matter showed that the investigations are mainly conducted post-occupancy and indicate that measured particulate matter of all sizes is expected to increase during building operation. Preoccupancy readings in this study were lower than in previous studies conducted in Egypt as well as other countries (Dasgupta et al. 2009; Cattaneo et al. 2011; Abdel-Salam 2012; El-Batrawy 2011).

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[3] The most widely used solvents in manufacturing of paint include the aromatic hydrocarbons, benzene, toluene, mixed xylene (*o*-xylene, *p*-xylene, and *m*-xylene), and ethyl benzene (Sigma 2015).

Table 10 Comparison with previous studies

Measurement (unit)	Ref.	Range			Season	Location	Comments
		Min	Mean	Max			
Formaldehyde HCHO (ppb)	Khoder et al. (2002)	43	89	147	Spring and summer	Egypt	Old residential buildings included
	Khoder (2006)	28.9	59.79	135.5	Winter	Egypt	Office building
	Guo et al. (2013)	4.07	87.12	631.81	Winter	China	Post-occupancy
	Sakai et al. (2004)	–	4.277.57	–	Winter	Sweden, Japan	Post-occupancy
	Järnström et al. (2006)	0 months: 0.74	15.47	41.52	Summer and winter	Finland	Preoccupancy and post-occupancy
		12 months: 0.71	35.01	46.41			
	Tuomainen et al. (2001)	–	0 months 10.015 months 13.27	–	Summer and winter	Finland	Preoccupancy and post-occupancy with ventilation
	Kim et al. (2008)	170.16	265.4	372.08		Korea	Preoccupancy fully furnished
	Present study	U.C: 6 F.A: 5.29	3510.9	9914.4	Winter	Egypt, Cairo	Residential- new apartments During construction
Ammonia NH_3 (ppb)	Järnström et al. (2006)	0 months: 1.31	60.16	73.05	Summer and winter	Finland	Preoccupancy and post-occupancy
		12 months: 1.24	61.59	81.64			
	Tuomainen et al. (2001)	–	0 months 43.97 5 months 26.5	–	Summer and winter	Finland	Preoccupancy and post-occupancy with ventilation
	Present study	U.C: 11.5 F.A: 5.7	34.1 11.67	54.56 15.47	Winter	Egypt	Residential—new apartments
Radon gas (pCi/L)	Abd-Elzaher (2013)	0.4	1.12	3.57	_	Egypt	Residential buildings—3 months
	Maged and Ashraf (2005)	0.65	_	1.49	_	Egypt	Residential buildings—3 months
	Present study	U.C: 0 F.A: 0.05	0.39 0.25	0.78 0.81 1.4 (after 24 h)	Winter	Egypt	Residential buildings (8-h readings)

U.C under construction (pilot study results), *F.A* finished apartments (core study results)

Radon levels measured in this current work ranged from 0 to 2.29 pCi/L. These measurements were obtained from 8- and 24-h readings. Sakai et al. (2004) conducted an in-depth study in Alexandria, Egypt and has recorded readings in the range (0.4 to 3.57 pCi/L) when radon was monitored for 3 months in different apartment buildings. The present study is an indicator that building materials influence the emission of radon in indoor spaces. However, further analysis and longer durations are needed to provide more accurate results. In another study by Maged and Ashraf (2005), 17 types of building materials were tested for radon emission. This included bricks, wood, marble, granite, and ceramic tiles. The highest exhalation rate was recorded for clay brick, followed by granite and marble. Lower rates were recorded for different types of ceramic tiles. Radon exhalation rates from wood samples were very low. This coincides with the results of this research, where the highest concentration for radon gas was measured in the site which uses marble flooring, followed by rooms where ceramic tiles were installed. The lowest concentrations were measured where parquet and HDF flooring were used. However, the increase in the readings after application of putty and primer requires further investigation to explain the effect of applying wall coatings to the increase in radon concentrations.

Limitations

Due to the availability of resources, this study was conducted during January and February. The study can be extended by measuring the air quality over a longer period or by repeating the same study during the summer months. This can provide empirical data over a prolonged time, which can be an indicator of the effect of outdoor temperature and humidity on the application of materials. Due to the absence of a clear material classification system in Egypt, selected mainstream materials were tested in the core study. These were identified based on the most commonly used and widely available materials in the market within the economic budget for middle-income housing. It is recommended to use a wider range of materials with varying costs in future studies. It is also recommended to use advanced data loggers and direct monitoring devices to monitor the same parameters throughout the 8 h of testing to eliminate sources of human error due to laboratory analysis. Regarding the quantification of VOCs, different types of VOCs were detected, yet not identified in this study. Qualitative analysis by gas chromatography-mass spectrometry (GC/MS) carried out directly after the sample collection can be used to identify all possible compounds. Next, the quantification can occur for compounds that appear at high concentrations in the preliminary qualitative analysis.

Conclusion

Based on the materials used, environmental conditions, and other parameters associated with this study, the following outcomes can be stated:

1. Air pollutants, including PM, VOCs, radon, and ammonia, are present at different concentrations in residential buildings in Egypt before occupancy.
2. As for VOCs, benzene was detected in higher concentration compared to toluene and xylene.
3. The age of the building and time of occupancy contribute to the types and concentration of indoor pollutants in residential buildings.
4. The development of an IAQ index can help aggregate readings of multiple pollutants to provide a rating scheme and serve as an indicator of the combined effect of pollutants on an indoor environment.
5. The application of mainstream materials available in the Egyptian market, using common construction practices, does not fulfill thermal comfort requirements specified by the Egyptian Building Code for housing and residential environments during January and February.
6. Building materials, especially preparatory coatings and finish coatings, are sources of multiple pollutants including formaldehyde and ammonia.
7. Among flooring materials, rooms with wooden flooring have shown lower concentrations of radon and formaldehyde, as well as improved temperature and relative humidity levels, compared to rooms with ceramic and porcelain tiles.
8. Ceramic tiles, porcelain, and marble contribute to higher radon levels than wooden flooring including parquet and high-density fiberboard (HDF). The types of wooden floors used in this study were not treated with any coatings and have shown acceptable results as compared to pressed wood and laminates used in previous studies.

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