



The Analysis of Indoor Air Pollutants From Finishing Material of New Apartments at Business Bay, Dubai

Chuloh Jung*, Nahla Al Qassimi, Mohammad Arar and Jihad Awad

Ajman University, Ajman, United Arab Emirates

Due to fast economic development, Dubai has built many high-rise apartments in a short period of time. The Dubai Municipality attempts to control indoor air quality with strict regulations, but the detailed provisions are still not comprehensive. The objective of this paper is to conduct on-site measurements for new high-rise apartments before moving on to investigate indoor air pollution and to analyze pollutant emissions by type of finishing material. As a methodology, on-site measurements were conducted for nine different housing units (three lower, three middle, and three higher floors) before moving on to investigate the status of indoor air pollution in new apartments. Based on the on-site measurements data, lab experiments with a small chamber for the same finishing materials from the most polluted housing unit (a lower two bedroom unit) were conducted to measure the emission of pollutants over 30 days. The result shows that the average of CH₂O (64.4 µg/m³ for studio, 64.5 µg/m³ for one bedroom, and 83.4 µg/m³ for two bedroom) was lower than the standard (100 µg/m³) in all units, while the average TVOC (520.1 µg/m³ in the studio, 509.5 µg/m³ in one bedroom, and 754.7 µg/m³ in two bedroom) exceeded the standard (500 µg/m³) in most of the units. It was proven that regarding the CH₂O, silk wallpaper, initial wallpaper, and wallpaper adhesive had the highest emissions and for the TVOC, tile and tile adhesive had the highest emission. During small chamber experiments, CH₂O and TVOC emissions tended to decrease gradually over time, but the emission amount changed significantly in high pollutant emission material especially from day 1–10. Therefore, Dubai municipality should establish the regulation for residents to move into their new apartment after at least 10 days to avoid the high polluted emission from the curing process of the interior finishing material.

Keywords: sick building syndrome, IAQ (indoor air quality), new apartments, Dubai, United Arab Emirates (UAE)

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*Correspondence:

Chuloh Jung
c.jung@ajman.ac.ae

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INTRODUCTION

The United Arab Emirates (UAE) has experienced rapid population growth due to the fast growth of its economy (Elbadawi and Soto, 2012; Giuffrida et al., 2020). It has created unprecedented urbanization with massive immigration of foreign laborers into the UAE (Alawadi and Dooling, 2016; Ewers, 2017). The UAE has experienced an annual rate of urbanization of approximately 2.87% since 2010 and 85.3% of the population lives in metropolitan areas (Alawadi, 2017). According to United Nations data, the population of the country has grown from over two million in 1997 to 9.9 million in 2020 (UNFPA, 2021). The population density of the country is about 118 individuals per square kilometer in 2020 (WORLDMETER, 2021; Boussaa, 2016). The rapid growth of the population has led UAE to build

many high-rise apartments in a short period to accommodate the increased population in a limited metropolitan area (Alawadi et al., 2018). People in the UAE spend more than 90% of their time indoors due to the sweltering hot weather (Behzadi and Fadeyi, 2012). This lifestyle exposes them to indoor pollutants that can cause Sick Building Syndrome (SBS) (Boldi, 2014; Amoatey et al., 2018; Yao et al., 2020). Many physicians in UAE started to recognize the increase in respiratory problems from exposure to polluted indoor air (The National, 2016; Arabian Business, 2007). According to the Dubai Healthcare City report, an estimated 15% of people in the United Arab Emirates have a chronic respiratory disease such as asthma (Khaleej Times, 2011). However, there are more SBS symptoms from poor quality indoor air such as fatigue, headache, red eyes, eye/nose/throat irritation, dry cough, dry or itchy skin, dizziness, and difficulty in focusing on work (Edmond, 2020; Basińska et al., 2019).

A social phenomenon that threatens public health is emerging under the name of Sick Building Syndrome (SBS) because of indoor air quality problems in new apartment buildings (Funk et al., 2014; Jung and Awad, 2021a). Due to the SBS phenomenon, the Dubai Municipality initiated the regulation for IAQ (Indoor Air Quality) with less than 0.08 ppm (parts per million) of formaldehyde, less than 300 $\mu\text{g}/\text{m}^3$ of TVOC (Total Volatile Organic Compound), and less than 150 $\mu\text{g}/\text{m}^3$ of suspended particulates (less than 10 microns) in 8 h of continuous monitoring prior to occupancy (DEWA, 2021; Gulf News, 2020). Even though IAQ standards need to be continuously adhered to in a stringent manner, indiscriminate use of unproven finishing materials has increased to the detriment of the health of residents (Tsai, 2018; Babu and Suthar, 2020; Tokazhanov et al., 2020). With this in mind, this study intends to conduct on-site measurements of new apartments before moving on to investigate the indoor air pollution of new apartments and to analyze pollutant emissions by type of finishing materials (Saijo et al., 2011; Senitkova, 2014; Morawska et al., 2017; Gou et al., 2018). This study will serve as basic data that can be used to approve interior finishing materials and improve the indoor air quality in new apartments and the IAQ stipulation of the UAE.

MATERIALS AND METHODS

Sick Building Syndrome (SBS) is mainly caused by formaldehyde (CH_2O) and volatile organic compounds (VOCs) (Hou et al., 2021; Oliveira et al., 2019; Lan et al., 2011). These chemicals, which are mainly generated in newly built or renovated buildings, are released from adhesives, varnishes, paints, and tiles, and have a large effect on the human body in even minimal amounts (Zuo et al., 2021; Biler et al., 2018; Deng et al., 2016). Hazardous substances in buildings are emitted from various building materials such as wood, plywood, and furniture, and volatile organic compounds are emitted from textile products of household appliances and various clothes (Fonseca et al., 2019; Dodson et al., 2017; Maddalena et al., 2015). In particular, the main cause of the release of formaldehyde (CH_2O) is the adhesive used to attach the finishing material in **Table 1** (Kanazawa et al., 2010; D'Amico et al., 2020).

As a large amount of Volatile Organic Compounds (VOCs) and formaldehyde (CH_2O) are emitted from a new apartment building, the indoor air quality is polluted and causes serious health issues to children and the elderly (D'Amico et al., 2021; Petersen et al., 2016; Kolarik et al., 2016). The elderly and the infirm have suffered from SBS symptoms such as fatigue, dry cough, dry or itchy skin, dizziness, headaches, vomiting, and sore throats (Maula et al., 2017; Zee et al., 2017; Yang et al., 2021). **Table 2** shows the effects of each hazardous substance on the human body.

Table 3 shows the standards of most advanced countries with detailed regulations for IAQ. The standards for more detailed items such as toluene (260 $\mu\text{g}/\text{m}^3$) are set in Japanese School Hygiene Standards (JSHS) (Takaoka et al., 2016; Ferguson et al., 2020). According to the WHO standard guidelines, the average exposure time is also specified, suggesting the standards according to long and short exposure times (Sahlberg et al., 2013; Nehr et al., 2017). Regarding European IAQ standards, the Air Quality Guidelines for Europe were already established in 1987 with WHO (KalenderSmajlović et al., 2019). In the United States, the EPA (Environmental Protection Agency) and ASHRAE (The American Society of Heating, Refrigerating and Air Conditioning Engineers) set the ventilation regulations for maintaining the indoor air quality (Jansz, 2011; EPA, 2019).

Compared to other countries, Europe and South Korea have more detailed guidelines for IAQ standards. For example, many reference documents, guidelines, agreements, and protocols are set up by the European Collaborative Action (ECA), the World Health Organization (WHO), and the International Agency for Research on Cancer (IARC) such as the European Union (EU) regulations (regulation 305/2011, for harmonized conditions for the marketing of construction products), European Standards (EN) ISO 16000—Indoor air quality, and European technical specification (CEN/TS) 16,516: construction products—determination of emission into indoor air (Wei et al., 2015; Settimo et al., 2020). In Korea, with the enactment of the 'Underground Living Space Air Quality Management Act' (Ministry of Environment) in 1996, standards for indoor air quality were established. The institutions currently in charge of indoor air quality-related tasks in Korea are the Ministry of Labor (MOL, Rules on Industrial Health Standards), the Ministry of Environment (Indoor Air Quality Management Act for Multi-Use Facilities), the Ministry of Construction and Transportation (Parking Lot Act), the Ministry of Health and Welfare (Public Sanitation Act), and the Ministry of Education and Human Resources Development (School Health Act) (Kang, 2020).

Site Description

As shown in **Figure 1**, SOL Bay and SOL Avenue located in Dubai's Business Bay were selected to measure the indoor air quality in new apartment buildings. SOL Bay, completed in November 2020, has 23 floors and consists of studio (48.1 m^2), one bedroom (84.2 m^2), and two bedroom (137.6 m^2) apartments/units (SOL Properties, 2021), and SOL Avenue, completed in April 2021, has 20 floors and consists of studio (45.5 m^2), one bedroom (83.6 m^2), and two bedroom (137.4 m^2) apartments/units (Bayut, 2021).

TABLE 1 | Hazardous substances source and pollutants (source: Jung, 2021).

Source	MEP	Pollutants
Nitrogen Dioxide (NO ₂), Total Suspended Particles (TSP)	Heating Equipment Air Purifier, Copier Humidifier	Carbon Dioxide (CO ₂), Carbon Monoxide (CO) Ozone (O ₃), Total Suspended Particles (TSP) Bacteria, Fungi, Water Vapor
Building Material	Air-Conditioner Wood, Plywood Paints	Bacteria, Fungi, <i>Legionella</i> Formaldehyde (CH ₂ O) Formaldehyde (CH ₂ O) Volatile Organic Compounds (VOCs)
Misc	Carpet, Curtain Concrete, Gypsum Board Soil	Mite, Fungi, Total Suspended Particles (TSP) Radon Radon, <i>Legionella</i> , Water Vapor

TABLE 2 | The effects of hazardous substances on the human body (source: Jung, 2021).

Hazardous substances		Sources	The effects on human body
Formaldehyde (CH ₂ O)		- Plywood, particleboard - Urea/Melamine/Phenolic Synthetic resin	- May cause cancer - Minor irritation to the eyes - Possible sore throat
Volatile	Benzene (C ₆ H ₆)	- Dye, Organic pigment, Plasticizer - Chemical Intermediates for Synthetic Rubber, Nitrobenzene, Phenol, and Synthetic Compounds	- May cause cancer - Dizziness during acute exposure, Vomiting, headache, drowsiness - Effects on the central nervous system
Organic Compounds (VOCs)	Toluene (C ₇ H ₈)	- Solvent Thinner for Adhesive paint, - Construction Adhesive	- Eye or airway irritation when exposed to high concentrations - Fatigue, vomiting - Effects on the central nervous system - Irritation to the throat or eyes
	Ethylbenzene (C ₈ H ₁₀)	- Building Materials and Furniture using Adhesives -	- Prolonged skin contact may cause dermatitis
	Xylene (C ₈ H ₁₀)	- Interior Fitout Adhesive - Building Materials and Furniture using Adhesives	- Central nervous system depressant Action - Inducing fatigue, headache, insomnia, excitement, etc.
	Styrene (C ₈ H ₈)	- Adhesive Raw Material - Synthetic Resin Paint - Insulation and Carpet	- Affects the lungs and central nervous system - Causing drowsiness or dizziness -
	Dichlorobenzene (C ₆ H ₄ Cl ₂)	- Deodorant, Insecticide, Pesticide - Organic Synthetic Products - Dyes	- No evidence of carcinogenic potency -

The apartments to be measured were completed in November 2020 (SOL Bay) and April 2021 (SOL Avenue) (Propsearch, 2021). The on-site measurement was performed for two apartment buildings 15 days before moving in, and the indoor air quality was measured in the center point of the living room for a total of 9 units, one each in the lower (studio), middle (1 bedroom), and high (2 bedroom) floors (Figure 2). To collect samples of indoor air pollutants, all the windows and openings of the household were measured, opened, and ventilated for 30 min, then all windows and openings to outside air closed and sealed for 60 min. Finally, a pump was operated for 1 h to collect samples (Pitarma et al., 2017; Sarkhosh et al., 2021). Formaldehyde (CH₂O) and VOCs were collected from the central point of the living room at the same time, taking into consideration a location at least 1 m away from the wall and a height of 1.5 m from the floor (Cochran Hameen et al., 2020; Kubota et al., 2021). Field blank, duplicate, and outdoor samples were obtained from each point, immediately sealed, and stored in a cool and dark

place below 4°C until analysis by blocking light with aluminum foil (Andargie et al., 2019).

Measuring Instruments

The measured indoor air pollutants were formaldehyde (CH₂O) and Total Volatile Organic Compounds (TVOC). The measurement method is based on the WHO standards, which are measured at a location of 1.5 m from the center of the living room from 10 AM to 6 PM (Table 4). For the first step to measure formaldehyde (CH₂O) concentration, all windows and interior furniture doors are opened for 30 min to perform natural ventilation in advance before sampling. As the second step, all windows are closed for more than 5 h to prevent airflow. At this time, the doors of the furniture and the built-in cabinets are opened to allow air movement for indoor air pollutant collection. In the third step, a sample is collected with a DNPH (2,4-Dinitrophenylhydrazine) cartridge after 5 h, which is rolled up with tinfoil to block any possible light effects (Awad and Jung,

TABLE 3 | Global standards for indoor air quality (source: Jung, 2021).

Hazardous substances	United States	Europe (WHO)	Japan	South Korea	UAE (Dubai)
Formaldehyde (CH ₂ O)	0.1 ppm (ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers)	100 µg/m ³ (30 min)	100 µg/m ³ (JSHS: Japanese School Hygiene Standard)	100 µg/m ³ (MOE: Ministry of Environment)	0.08 ppm (Municipality)
Carbon Dioxide (CO ₂)	1,000 ppm (ASHRAE)	920 ppm (24 h)	1,000 ppm (JBSA: Japanese Building Standard Act) (JSHS)	1,000 ppm (MOE)	N/A
Carbon Monoxide (CO)	25 ppm (EPA: Environmental Protection Agency) (8 h)	10 ppm (8 h)	10 ppm (JSHS) (JBSA)	10–25 ppm (MOE) (MOHW: Ministry of Health and Welfare)	N/A
Nitrogen Dioxide (NO ₂)	0.053 ppm (EPA)	40 µg/m ³ (1 year)	N/A	0.05–0.03 ppm (MOE)	N/A
Ozone (O ₃)	N/A	120 µg/m ³ (8 h)	N/A	0.06–0.08 ppm (MOE)	N/A
Radon	4.0 pCi/L (EPA)	2.7 pCi/L	N/A	4.0 pCi/L (MOE)	N/A
Total Suspended Particles (TSP)	25 µg/m ³ (24 h)	100–120 µg/m ³ (8 h)	0.1 mg/m ³ (JSHS)	150 µg/m ³ (MOE) (MOHW)	150 µg/m ³ (Municipality)
Volatile Organic Compounds (VOCs)	N/A	0.2–0.6 mg/m ³	0.5 mg/m ³ (JSHS)	400–µg/m ³ (MOE) 1,000	300 µg/m ³ (Municipality)

**FIGURE 1** | Target apartments: Sol bay (A) and SOL avenue (B).

2021). At this time, both the natural and forced ventilation are sealed and samples are collected. Ozone scrubber is used when collecting air samples, and 15 L is collected for 20 min using a precise mini suction pump (0.5 ml/min) (Jung and Awad, 2021b). The air samples in the last step are precisely analyzed by HPLC (High Performance Liquid Chromatography). In the TVOC concentration measurement method, the first two steps are the same as the formaldehyde (CH₂O) sampling method, and a Tenax tube is used in the third step (Jung et al., 2021). In the last step, the air sample is analyzed by GC/MS (Gas Chromatography/Mass Spectroscopy). However, since the device used in this study is a direct-reading method for instantaneous values, it is a method of measuring instantaneous concentrations multiple times, unlike

the collection method of process test methods (Huang et al., 2011; Ala-Kotila et al., 2020). In addition, since this study also aims to identify the influencing factors, it has the meaning of multiple measurements to collect time-variation values rather than one-time measurements in one building. To avoid the errors of manual reading, two minimum and maximum readings were excluded especially from the measurement of formaldehyde (CH₂O).

Data Analysis Methods

To analyze indoor air pollution by building finishing materials, on-site measurements are conducted for nine different housing units before residents moved in to the new apartments (Tupenaite et al., 2018; Li et al., 2019). To identify the pollutant emission

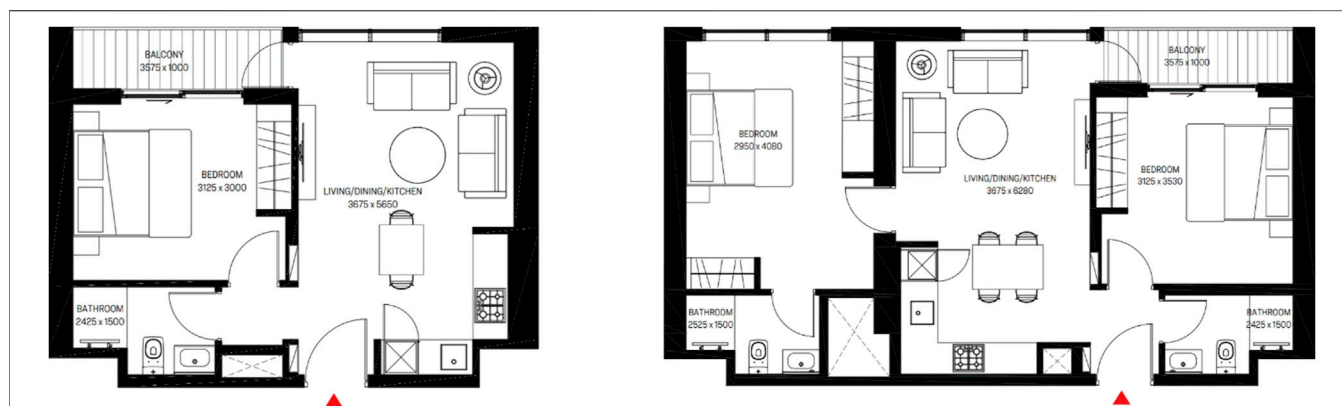


FIGURE 2 | The plan of one bedroom (A) and two bedroom (B) in SOL bay.

characteristics of walls and floors of housing units with high pollutant emission rates, the same finishing materials as in actual construction were manufactured for small chambers to identify the emission characteristics in detail (Zhang et al., 2011; Piasecki et al., 2018). The emission of pollutants over 30 days, the emission characteristics due to the composition of building materials, and the amount of emission over time are investigated using small chambers (Kim et al., 2011).

As seen in **Table 3**, the Korean government has thoroughly defined the IAQ standards, the measurement and analysis conducted in this study use the WHO Guidelines for IAQ, IAQ Test Method by the Ministry of Environment in South Korea, and the residential part of the “Indoor Air Quality Management Act for Multi-Use Facilities” in South Korea (Yu and Jeong Tai Kim, 2011; McGill et al., 2015; Sun et al., 2021). Based on these, the indoor air pollutants to be analyzed are limited to formaldehyde (CH_2O), and six types of Volatile Organic Compounds (VOCs) such as Benzene (C_6H_6), Toluene (C_7H_8), Ethylbenzene (C_8H_{10}), Xylene (C_8H_{10}), Styrene (C_8H_8), Dichlorobenzene ($\text{C}_6\text{H}_4\text{Cl}_2$), and Total Volatile Organic Compounds (TVOC).

RESULTS

Data Analysis of Field Measurements

In the field measurement, the average indoor temperature (dry-bulb temperature) was 25°C and the average indoor humidity (relative humidity) was 68%. As shown in **Table 5**, formaldehyde (CH_2O) has an average of $64.4 \mu\text{g}/\text{m}^3$ for a studio unit, $64.5 \mu\text{g}/\text{m}^3$ for a one bedroom unit, and $83.4 \mu\text{g}/\text{m}^3$ for a two bedroom unit. Compared to

WHO IAQ standard and Korean MOE standard of $100 \mu\text{g}/\text{m}^3$, the studio unit is $35.6 \mu\text{g}/\text{m}^3$ lower, the one bedroom unit is $35.5 \mu\text{g}/\text{m}^3$ lower, and the two bedroom unit is $16.6 \mu\text{g}/\text{m}^3$ lower.

As shown in **Table 5**, the formaldehyde (CH_2O) emission amount according to the floor height and unit type shows the highest emission amount in the order of lower floor < middle floor < higher floor in the studio. The one bedroom unit shows the highest emission amount in the order of middle floor < lower floor < high floor, and the two bedroom unit shows the highest in the order of high floor < middle floor < lower floor.

The average TVOC amount was $520.1 \mu\text{g}/\text{m}^3$ in the studio, $509.5 \mu\text{g}/\text{m}^3$ in the one bedroom, and $754.7 \mu\text{g}/\text{m}^3$ in the two bedroom unit. Compared to the WHO IAQ standard and Korean MOE standard of $500 \mu\text{g}/\text{m}^3$, the studio is $20.1 \mu\text{g}/\text{m}^3$ higher, the one-bedroom apartment is $9.5 \mu\text{g}/\text{m}^3$ higher, and two-bedroom is $254.7 \mu\text{g}/\text{m}^3$ higher. As for the TVOC emission according to the floor height and unit types, as shown in **Table 5**, the studio shows the highest emission in the order of the lower floor < middle floor < higher floor, the one-bedroom apartment shows the highest emission in the order of the middle floor < lower floor < higher floor, and the two-bedroom apartment shows the highest emission in the order of the higher floor < middle floor < lower floor. The average emission of VOCs for studio is, in descending order, Toluene (C_7H_8) $156.8 \mu\text{g}/\text{m}^3$, Xylene (C_8H_{10}) $16.8 \mu\text{g}/\text{m}^3$, Styrene (C_8H_8) $6.3 \mu\text{g}/\text{m}^3$, Ethylbenzene (C_8H_{10}) $5.1 \mu\text{g}/\text{m}^3$, and Benzene (C_6H_6) $1.6 \mu\text{g}/\text{m}^3$. The one-bedroom unit emits VOCs in the order of Toluene (C_7H_8) $208.3 \mu\text{g}/\text{m}^3$, Styrene (C_8H_8) $26.1 \mu\text{g}/\text{m}^3$, Xylene (C_8H_{10}) $17.1 \mu\text{g}/\text{m}^3$, Ethylbenzene (C_8H_{10}) $4.2 \mu\text{g}/\text{m}^3$, and Benzene (C_6H_6) $1.9 \mu\text{g}/\text{m}^3$. The two-bedroom unit emits VOCs in the order of Toluene (C_7H_8) $262.3 \mu\text{g}/\text{m}^3$, Styrene (C_8H_8) $25.7 \mu\text{g}/\text{m}^3$, Xylene (C_8H_{10})

TABLE 4 | Measuring IAQ factors and methods.

Measuring factors		Measurement	Measuring time	Measuring location
Background Factors	Indoor Temperature	Digital Thermo-Hygrometer (TR-72U)	10:00 am–18:00 pm (Autosave every 5 min for 8 h)	1.5 m from the floor in the left of the living room
	Relative Humidity			
IAQ Factors	CH_2O	DNPH Cartridge $\Sigma 300$ Pump	10:00 am–18:00 pm (Measured every 20 min)	
	TVOC	Tenax Tube $\Sigma 300$ Pump	10:00 am–18:00 pm (Measured every 20 min)	

TABLE 5 | Indoor air pollutants measurement for nine different housing units.

Unite types	Hazardous substances	Lower Floor	Middle Floor	Higher Floor	Mean	
Studio (45.5–48.1 m ²)	Formaldehyde (μg/m ³)	41.4	63.7	88.1	64.4	
	TVOC (μg/m ³)	316.9	550.8	692.8	520.1	
	VOCs (μg/m ³)	Benzene (C ₆ H ₆)	1.5	1.8	1.4	1.6
		Toluene (C ₇ H ₈)	105.6	163.7	201.2	156.8
		Ethylbenzene (C ₈ H ₁₀)	2.6	4.2	8.5	5.1
		Xylene (C ₈ H ₁₀)	7.9	10.9	31.8	16.8
		Styrene (C ₈ H ₈)	4.2	12.4	2.3	6.3
		Dichlorobenzene (C ₆ H ₄ Cl ₂)	N/D	N/D	N/D	N/D
	Average Temp (DBT) (°C)	25.5	25.0	24.5	25.0	
	Average Humidity (RH) (%)	68	66	70	68	
1 Bedroom (83.6–84.2 m ²)	Formaldehyde (μg/m ³)	72.1	47.6	73.6	64.5	
	TVOC (μg/m ³)	432.6	392.5	703.3	509.5	
	VOCs (μg/m ³)	Benzene (C ₆ H ₆)	2.4	1.9	1.5	1.9
		Toluene (C ₇ H ₈)	203.4	176.9	244.7	208.3
		Ethylbenzene (C ₈ H ₁₀)	3.6	2.8	6.3	4.2
		Xylene (C ₈ H ₁₀)	9.7	9.2	32.5	17.1
		Styrene (C ₈ H ₈)	27.5	15.6	35.2	26.1
		Dichlorobenzene (C ₆ H ₄ Cl ₂)	N/D	N/D	N/D	N/D
	Average Temp (DBT) (°C)	25.0	25.0	25.0	25.0	
	Average Humidity (RH) (%)	65	69	66	67	
2 Bedroom (137.4–137.6 m ²)	Formaldehyde (μg/m ³)	113.1	102.3	34.9	83.4	
	TVOC (μg/m ³)	1,206.7	632.1	425.3	754.7	
	VOCs (μg/m ³)	Benzene (C ₆ H ₆)	2.0	0.9	2.2	1.7
		Toluene (C ₇ H ₈)	342.2	282.1	162.3	262.3
		Ethylbenzene (C ₈ H ₁₀)	12.1	5.3	2.7	6.7
		Xylene (C ₈ H ₁₀)	45.6	22.1	8.5	25.4
		Styrene (C ₈ H ₈)	43.8	24.4	8.7	25.7
		Dichlorobenzene (C ₆ H ₄ Cl ₂)	N/D	N/D	N/D	N/D
	Average Temp (DBT) (°C)	24	25	25	24.7	
	Average Humidity (RH) (%)	69	69	70	69.3	

25.4 μg/m³, Ethylbenzene (C₈H₁₀) 6.7 μg/m³, and Benzene (C₆H₆) 1.7 μg/m³. Among VOCs, Benzene (C₆H₆) is emitted less compared to other hazardous substances, and Toluene (C₇H₈) is the most emitted. Xylene (C₈H₁₀) and Styrene (C₈H₈) are emitted similarly, and Dichlorobenzene (C₆H₄Cl₂) is not emitted.

Data Analysis of Pollutants From Interior Finishing Material

For the pollutant emission analysis of indoor finishing materials, four types of samples (A, B, C, D) were produced from the same indoor finishing materials of the two-bedroom apartment, since it had the highest emission of formaldehyde (CH₂O) and Total Volatile Organic Compounds (TVOC) from the on-site measurements. To compare with the WHO indoor exposure product standards (WHO, 2010) (Table 6), four small chambers (20 L) were designed and manufactured to measure and analyze the amount of pollutant emission from indoor finishing materials according to the passage of time (1–30 days).

Based on the finishing materials for the two bedroom unit in Table 7, which has the highest emission of pollutants, the A finishing material (tile) sample was made with general II grade tile adhesive. The B finishing material sample was made of flooring

material and general I grade floor adhesive. The C finishing material sample was made with silk wallpaper, wallpaper adhesive, and woodworking adhesive used for silk wallpaper in the field. The D finishing material sample was made with general grade I MDF and woodworking adhesive. Table 8 shows the experimental conditions of the small chamber to measure the amount of formaldehyde (CH₂O) and TVOC emitted from building material samples.

RESULT

Table 9 shows the results of measuring the amount of emission over time from four samples of indoor finishing materials in the two bedroom unit, which shows the highest emission in the field measurements. Formaldehyde (CH₂O) emission of finishing materials A (tile and tile adhesive) was 0.002–0.003 mg/m²·h from the first to the fifth day. With the lapse of time, it decreased to 0.001 mg/m²·h from the seventh to the 20th day, and formaldehyde (CH₂O) was not released after the 25th day. TVOC showed a high emission of 7.2 mg/m²·h on the first day due to the tile adhesive, which is a general II grade building material. On the fifth day, it decreased to 4.2 mg/m²·h and on the 30th day, the emission amount decreased to 2.2 mg/m²·h.

TABLE 6 | WHO Product Standard for Indoor Exposure (source: WHO Guidelines for indoor air quality).

Category		General material and paint (mg/m ² ·h)	Adhesive (mg/m ² ·h)	Wood panels (HB, PB, MDF) (mg/m ² ·h)
Excellent	TVOC	<0.10	<0.10	<0.10
	VOCs	<0.03	<0.03	<0.03
	CH ₂ O	<0.008	<0.008	<0.010
Good	TVOC	0.10–0.20	0.10–0.30	0.10–0.20
	VOCs	<0.06	<0.09	<0.06
	CH ₂ O	0.008–0.015	0.008–0.015	0.010–0.030
General	TVOC	0.20–0.40	0.30–0.60	0.20–0.40
	VOCs	<0.12	<0.18	<0.12
	CH ₂ O	0.015–0.020	0.015–0.020	0.030–0.050

TABLE 7 | Indoor air pollutants from finishing material in two bedroom.

Interior finishing material	CH ₂ O (mg/m ² ·h)	Grade	TVOC (mg/m ² ·h)	Grade
Flooring Material	0.006	Excellent	0.111	Good
Floor Adhesive	0.031	Excellent	1.669	General I
Wallpaper	0.001	Excellent	0.031	Excellent
Wallpaper Adhesive	0.001	Excellent	0.012	Excellent
Tile Adhesive	0.006	Excellent	8.572	General I
MDF	0.012	Excellent	0.822	General I
Woodworking Adhesive	0.007	Excellent	0.287	Good

TABLE 8 | Configuration of experimental small chamber.

Criteria	Unit	IAQ pollutants	
		Formaldehyde	TVOC
Emission Gathering Capacity	V (l)	4.5	4.5
Measurement Time	T (min)	30	30
Flux Capacity	Q (ml/min)	150	150
Ventilation Capacity	q (m ³ /hr)	0.02	
Number of Ventilation	N (number of time/hour)	0.5	
Chamber Capacity	v (m ³)	0.02	
Load Factor	L (m ³ /m ²)		2 (Fluid 0.4)
Sample Size	A (m ²)		0.0225 × 2 EA
Temperature	Temp. (°C)		25 ± 1
Humidity	RH (%)		50 ± 5

Formaldehyde (CH₂O) emission of finishing materials B (flooring materials and flooring adhesives) was as low as 0.018 mg/m²·h or less, and the gradual decrease over time was found to become insignificant, like that of finishing materials . After the 20th day, it was found to decrease to 0.01 mg/m²·h, which is the highest grade level of emission. TVOC showed a high emission of 4.0 mg/m²·h on the first day due to the floor adhesive, which is a general I grade of the building material. As time passed, it gradually decreased to 0.3 mg/m²·h on the 30th day.

Formaldehyde (CH₂O) emission of C finishing materials (silk wallpaper, woodworking adhesive, initial wallpaper, and wallpaper adhesive) was 0.272 mg/m²·h on the first day and reached 0.082 mg/m²·h on the 30th day. Compared with the highest grade silk wallpaper emission of 0.001 mg/m²·h, it was found to be very high. Unlike the A, B, and D finishing materials, the emission of TVOC gradually decreased to 1.4 mg/m²·h on the

first day, then became 0.1 mg/m²·h on the 15th day. After that, it showed the highest grade level of emission from the 20th day.

Formaldehyde (CH₂O) emission of finishing material D (MDF and woodworking adhesive) showed a low emission of less than 0.02 mg/m²·h, the same as that of A and B finishing materials. TVOC showed a rather high emission of 4.1 mg/m²·h on the first day due to MDF, which is a general I grade building material but decreased to 0.2 mg/m²·h on the 15th day. It was found that it gradually decreased to zero-emissions after the 20th day.

As shown in **Figure 3**, according to the time elapsed, formaldehyde (CH₂O) emission by finishing material was in the order of C > D > B > A. Material C had the highest emission amount and finishing material A had the lowest emission amount. The reduction in emission over time was 0.15 mg/m²·h for finishing material C and 0.001 mg/m²·h for finishing material A from day 1–10. From day 10–30, finishing material C decreased by 0.04 mg/

TABLE 9 | Amount of indoor air pollutants from finishing material samples.

Material	Day	VOCs ($\mu\text{g}/\text{m}^3$)				
		Benzene (C_6H_6)	Toluene (C_7H_8)	Ethylbenzene (C_8H_{10})	Xylene (C_8H_{10})	Styrene (C_8H_8)
A (Tile and Tile Adhesive)	1	0.0	321.4	158.6	297.8	19.4
	3	0.0	189.8	90.3	168.7	10.7
	5	0.0	102.6	49.4	53.8	3.9
	7	0.0	94.1	33.8	68.9	4.9
	10	0.0	44.7	27.4	50.9	3.5
	15	0.0	49.0	29.1	55.7	3.7
	20	0.0	22.2	17.0	31.3	2.6
	25	0.0	24.4	14.6	29.8	2.2
	30	0.0	14.8	14.3	27.4	2.1
	B (Flooring materials and Flooring Adhesives)	1	0.0	156.6	193.6	1,115.0
3		0.0	36.3	53.1	448.7	2.9
5		0.0	21.7	44.8	359.4	2.8
7		0.0	20.4	29.3	247.1	2.1
10		0.0	7.0	23.3	237.2	1.5
15		0.0	12.7	27.8	199.4	2.0
20		0.0	2.8	18.8	167.1	1.2
25		0.0	0.1	13.4	121.9	0.6
30		0.0	0.0	9.1	85.8	0.3
C (Silk Wallpaper, Initial Wallpaper, and Wallpaper Adhesive)		1	0.0	18.0	1.1	1.9
	3	0.9	41.1	1.4	10.5	1.4
	5	0.0	0.0	0.0	0.5	0.1
	7	0.0	0.0	0.0	0.4	0.1
	10	0.0	0.0	0.0	0.4	0.1
	15	0.0	1.5	0.1	0.0	0.1
	20	0.0	0.7	0.0	0.0	0.1
	25	0.0	1.1	0.0	0.0	0.0
	30	0.0	0.1	0.0	0.0	0.0
	D (MDF and Woodworking Adhesive)	1	0.6	65.1	7.1	12.8
3		0.0	28.6	2.6	4.7	0.3
5		0.0	5.8	0.7	1.1	0.1
7		0.1	8.3	0.6	1.1	0.0
10		0.0	2.4	0.2	0.1	0.0
15		0.0	1.4	0.1	0.1	0.0
20		0.0	0.7	0.1	0.1	0.0
25		0.0	0.2	0.1	0.1	0.0
30		0.0	0.0	0.0	0.0	0.0

$\text{m}^2\cdot\text{h}$, and finishing material A decreased by $0.001 \text{ mg}/\text{m}^2\cdot\text{h}$. As shown in **Figure 4**, the amount of emission over time for TVOC is in the order of $A > B > D > C$. Unlike formaldehyde (CH_2O), it was found that finishing material A had the highest emission amount, and the emission amount of finishing material C was the lowest. As for the decrease in emission over time, the finishing material A decreased by $4.2 \text{ mg}/\text{m}^2\cdot\text{h}$ and the finishing material C decreased by $1.3 \text{ mg}/\text{m}^2\cdot\text{h}$ from day 1–10. From day 10–30, finishing material A decreased by $0.8 \text{ mg}/\text{m}^2\cdot\text{h}$, and finishing material C decreased by $0.1 \text{ mg}/\text{m}^2\cdot\text{h}$.

DISCUSSION AND CONCLUSION

In this study, two indoor air pollutants, formaldehyde (CH_2O) and TVOC, were investigated via on-site measurement in two new apartment buildings (SOL Bay and SOL Avenue). Based on the field measurements, finishing materials from the most polluted unit (two-bedroom) were selected and tested in a small chamber. The following results were obtained by

comparative analysis of the emission of indoor air pollutants according to the time elapsed.

In the case of formaldehyde (CH_2O), it was lower than the WHO standard ($100 \mu\text{g}/\text{m}^3$) in all housing units, while TVOC exceeded the WHO standard emission ($500 \mu\text{g}/\text{m}^3$) in the studios on higher floors, one-bedroom units on higher floors, and two-bedroom units on lower floors. In particular, TVOC in the two-bedroom unit on the lower floor was 2.6 times higher than WHO standard. Regarding the emissions of formaldehyde (CH_2O) and TVOC according to the housing type and floor level, the studio apartment showed the highest emissions in the order of lower floor < middle floor < high floor. The one-bedroom units showed the highest emissions in the order of middle floor < lower floor < high floor, and the two-bedroom units showed the highest emission in the order of high floor < middle floor < lower floor. Since the apartment buildings have a large number of housing units, the fit-out process for each unit is different because subcontractors with slightly different technical levels did the various interior fit-outs. Moreover, the completion of interior fit-out and furniture bring-in time are all

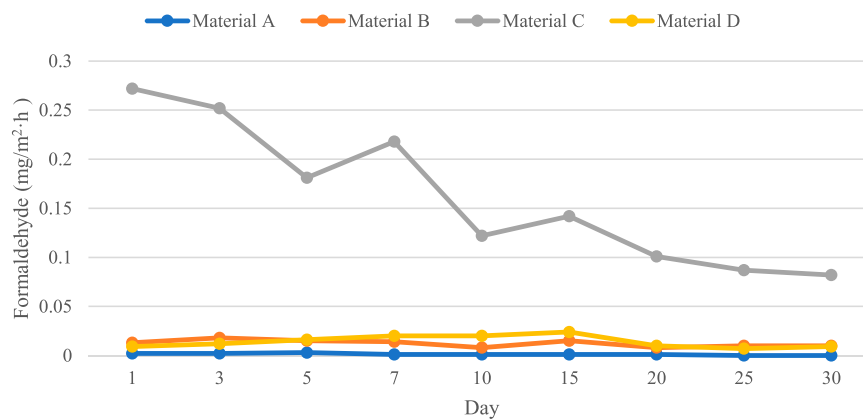


FIGURE 3 | Change of formaldehyde (CH₂O) emission in 30 Days.

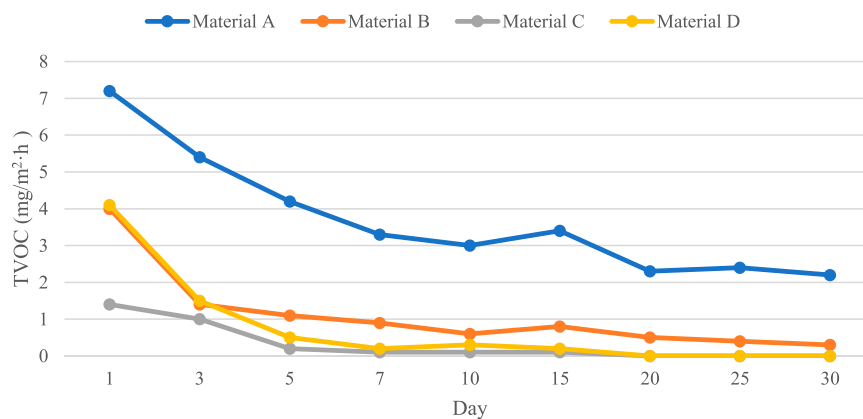


FIGURE 4 | Change of TVOC emission in 30 Days.

different. Control and management of the interior fit-out process with firm stipulations from the Dubai Municipality are required to improve indoor air quality and secure the health of Dubai residents.

As a result of the small chamber experiment, formaldehyde (CH₂O) and TVOC emissions tended to decrease gradually over time. The emission of formaldehyde (CH₂O) was in the order of C (silk wallpaper, initial wallpaper, and wallpaper adhesive) > D (MDF and woodworking adhesive) > B (flooring materials and flooring adhesives) > A (tile and tile adhesive). Finishing material C (silk wallpaper, initial wallpaper, and wallpaper adhesive) had the highest emission, and material A (tile and tile adhesive) had the lowest emission. The emission amount of TVOC was in the order of A (tile and tile adhesive) > B (flooring materials and flooring adhesives) > D (MDF and woodworking adhesive) > C (silk wallpaper, initial wallpaper, and wallpaper adhesive), and unlike formaldehyde (CH₂O), finishing material A (tile and tile adhesive) had the highest emission and finishing material C (silk wallpaper, initial wallpaper, and wallpaper adhesive) has the lowest emission amount. Not only strict regulation regarding the interior Fitout process, but the regulation for construction material, paint, adhesives, and wood panels should be imposed by

Dubai Municipality to the interior fit-out companies to improve indoor air quality to secure the health of Dubai residents.

Regarding TVOC, all finishing materials showed the highest emission amount on day 1, and as time elapsed from day 1 to day 15, the emission amount decreased rapidly. When the emission amount is lowered to a certain level, the decrease was found to be insignificant. The finishing material such as tile, floor materials, and wallpapers showed the highest CH₂O emission amount between day 1 and day 15, and as time elapsed from day 16 to day 30, the emission amount decreased. When the emission amount is lowered to a certain level, the decrease was found to be insignificant. Therefore, due to the high polluted emission caused by the curing process of the interior fit-out material, residents should be required to move in after at least 15 days after the interior finishing material is installed on-site, not 8 h as is currently regulated by the Dubai Municipality.

The limitation of this research is that it was performed with nine different units on different floors and then conducted a small chamber experiment with most emitted finishing materials from these housing units. However, for further study, the number of newly built target housing units with the same interior finishing material and built-in furniture should be increased to get more

reliable results with more diverse parameters which could affect indoor air quality.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors contributed significantly to this study. CJ and JA identified and secured the example buildings used in the study. The data acquisition system and installations of sensors were

designed and installed by CJ, NA, and MA, CJ and NA was responsible for data collection. Data analysis was performed by CJ. The manuscript was compiled by CJ and reviewed by NA and MA. All authors have read and agreed to the published version of the manuscript.

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