



Investigating the Influence of the Building Material on the Indoor Air Quality in Apartment in Dubai

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The residents of Dubai spend more than 90% of their time indoors and this lifestyle makes them easily exposed to Sick Building Syndrome (SBS). Even though Dubai Municipality strictly apply the IAQ (Indoor Air Quality) stipulation, indiscreet use of unproven finishing materials has been increased to deteriorate the health of residents in Dubai. The objective of this paper is to investigate the degree of influence of building material on indoor air pollutants concentration by measurement and prediction. As a methodology, indoor pollutants concentration was measured and investigated, variables were extracted through emission intensity experiments, and the indoor concentration was predicted by applying the double exponential decay model. The result had shown that electronic products, furniture, and textile products become new sources of indoor air pollution. The difference in emission patterns of wallpaper and flooring is confirmed *via* the emission rate test. It is statistically proven that Formaldehyde (CH_2O) and VOCs showed a difference in the cumulative emission amount within 100 h but after that, it was confirmed that the difference in emission amount between materials became very small. In case of CH_2O , the cumulative emission of the flooring material is greater than that of the wallpaper. This study will serve as a basic data to explore the cause of indoor air pollutants in daily life to reduce SBS symptoms in Dubai.

Keywords: indoor air pollutant source, building material, total volatile organic compounds (TVOC), formaldehyde (CH_2O), Dubai

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1 INTRODUCTION

In global metropolis, residents spend more than 90% of their time indoors including housing, office work, and transportation, and indoor air quality (IAQ) has a critical impact on their health as well as their comfort and productivity (Benito et al., 2021; Megahed and Ghoneim, 2021). Formaldehyde (CH_2O), Acetaldehyde ($\text{C}_2\text{H}_4\text{O}$), ($\text{C}_3\text{H}_6\text{O}$), and 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) are representative indoor air pollutants and have been researched in many previous studies (Duan et al., 2016; Skulberg et al., 2019). The emissions of hazardous chemicals from residential buildings have been reported from building materials such as wallpaper, flooring, paints and adhesives and from furniture such as sofas, wardrobes and desks (Son et al., 2013; Xiong et al., 2016). In addition, it has been reported that gas stoves and gas heaters used indoors significantly affect the deterioration of IAQ and many studies have shown that smokers' homes have significantly higher concentrations of VOCs than non-smokers' homes (Canha et al., 2019).

Health disorders caused by various indoor air pollutants can be broadly classified into respiratory diseases represented by asthma, allergies, and chemical syndromes that have not been studied much yet (Huo et al., 2020). The pollution state of the outdoor air is an important factor that affects indoor air pollution, and the amount of the outside air environment flowing into the room varies depending on the season, lifestyle, and housing type and affects indoor air pollution (Sun et al., 2018). IAQ is affected by the characteristics of various indoor pollutant sources along with the current status of outside air (Sun et al., 2019). Indoor pollution sources are broadly classified into types and characteristics of building materials, number of years elapsed, indoor microclimate, and lifestyle. In particular, in new building, the generation of hazardous chemicals from building materials is reported as a major factor in indoor air pollution (Leung, 2015).

The emission of VOCs from the building materials is influenced by the type of material and internal characteristics such as the total amount of VOC contained in the material (elapsed years), as well as the environmental conditions exposed to the material (Zhang et al., 2018). In addition, it is reported that the effect on indoor temperature and humidity causes a large difference in the amount of generation (Zhou et al., 2017). However, this is mostly the result of experiments in which environmental conditions are strictly controllable, and there are actually more factors affecting the emission of chemical substances in the indoor living environment (Wang et al., 2020).

Indoor air pollution in a residential building is affected by many factors such as furniture, temperature and humidity, ventilation rate, indoor living activities, and adsorption effect (Jung et al., 2019). It has a more complex emission mechanism than the release characteristics seen in single materials (Gunschera et al., 2013). Most of the research on hazardous chemicals in a residential building reports on the condition before moving in (Kang et al., 2010). There are not many studies on the evaluation and characteristics of indoor air quality in living conditions. Surveys on indoor air quality in residential buildings are being conducted mainly on multi-purpose buildings and schools. Relatively few studies have been conducted on residential building.

The residents of Dubai in United Arab Emirates (UAE) spend more than 90% of their time indoors due to sweltering outside weather (Jung et al., 2021a). This lifestyle makes them easily exposed to Sick Building Syndrome (SBS) (Jung and Awad, 2021a). According to Dubai Healthcare City report, an estimated 15% of Dubai residents have suffered SBS symptoms such as fatigue, headache, red eyes, eye/nose/throat irritation, dry cough, dry or itchy skin, dizziness, and difficulty in focus on work (Jung and Awad, 2021b). Due to the social phenomenon that threatens public health, the Dubai Municipality initiated the regulation for IAQ (Indoor Air Quality) with less than .08 ppm (parts per million) of CH₂O, less than 300 µg/m³ of TVOC (Total Volatile Organic Compound), and less than 150 µg/m³ of suspended particulates (less than 10 microns) in 8 h of continuous monitoring prior to occupancy (DEWA, 2021). However, indiscreet use of unproven finishing materials has been

increased to deteriorate the health of residents in Dubai (Awad and Jung, 2021).

The important factors of indoor air pollution are the indoor microclimatic factors related to temperature and humidity (Salthammer et al., 2018), the application of building materials made of chemical substances (Schito et al., 2016), lifestyle, and the influence of the external environment (Yu and Kim, 2011). Among them, research has been conducted to reveal the major causes and the degree of their impact on building materials and furniture, as well as harmful substances generated during the construction process (Harb et al., 2018). Also, it has been reported via many research that the emission pattern of hazardous substances from building materials tends to decrease with time (Kaunelienė et al., 2016). However, studies on the degree of influence and emission characteristics of building materials on the living environment after moving in where daily life takes place have not been actively conducted yet (Shrubsole et al., 2019). This is because there are many restrictions and methodological difficulties in determining the influence of pollutants in the environment in which real life takes place (Silva et al., 2017). However, it is a necessary to explore the cause of indoor air pollutants in daily life.

The purpose of this study is to investigate the building materials as the indoor air pollutant source by measuring and predicting the concentration of indoor air pollutants based on the pollutant source survey via the measurement of amount of building materials and daily lifestyle.

2 MATERIALS AND METHODS

Hazardous substances in buildings are emitted from various building materials such as wood, plywood, and furniture (Lee, 2011; Böhm et al., 2012). VOCs are emitted from household appliances and textile products of various clothes (Bari et al., 2015; Lucattini et al., 2018). In particular, the main cause of the release of CH₂O is the adhesive used to attach the building finish (Yu and Kim, 2012) (Table 1).

Indoor air quality is polluted as large amounts of VOCs and CH₂O are emitted from new building (Jazar et al., 2013; Wei et al., 2015). This causes a lot of critical damage to children and the elderly (Cho et al., 2019). In the elderly, a lot of damage occurred, such as fatigue, headache, red eyes, eye/nose/throat irritation, dry cough, dry or itchy skin, dizziness, and difficulty in focus on work (Smedje et al., 2017; Sun et al., 2018), and the effects of each toxic substance on the human body are shown in Table 2.

The simple measurement method refers to measurement through portable equipment and devices that measure indoor air pollutants and know the measured values in the field. A simple measurement method is required as a screening test for precision measurement or a response by a designer, a sanitation manager, and a resident at the site (Tian et al., 2020). However, in order to manage indoor air quality more effectively, it is necessary to present a simple measurement method with reliable measurement results (Kim et al., 2012).

The simplified measurement method can be classified in several ways. It can be divided into continuous measurement

TABLE 1 | Hazardous substances source and pollutants.

Source		Pollutants
MEP	Heating equipment	Carbon dioxide (CO ₂), carbon monoxide (CO)
	Air purifier, copier	Nitrogen dioxide (NO ₂), total suspended particles (TSP)
	Humidifier	Ozone (O ₃), total suspended particles (TSP)
	Air-conditioner	Bacteria, fungi, water vapour Bacteria, fungi, legionella
Building material	Wood, plywood	CH ₂ O
	Paints	CH ₂ O VOCs
	Carpet, curtain	Mite, fungi, total suspended particles (TSP)
	Concrete, gypsum board	Radon
Misc.	Soil	Radon, legionella, water vapour

TABLE 2 | The effects of hazardous substances on the human body.

Hazardous substances	Sources	The effects on human body	
Formaldehyde (CH ₂ O)	- Plywood, particle board - Urea/melamine/phenolic Synthetic resin	- May cause cancer - Minor irritation to the eyes - possible sore throat	
Volatile Organic Compounds (VOCs)	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
	Toluene (C ₇ H ₈)	- Solvent thinner for adhesive paint - Construction adhesive	- Effects on the central nerve system - Eye or airway irritation when exposed to high concentrations - Fatigue, vomiting - Effects on the central nerve system
	Ethylbenzene (C ₈ H ₁₀)	- Building materials and furniture using adhesives	- Irritation to the throat or eyes
	Xylene (C ₈ H ₁₀)	- Interior fitout adhesive - Building materials and furniture using adhesives	- Prolonged skin contact may cause dermatitis - Central nerve 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 nerve system - Causing drowsiness or dizziness
	Dichlorobenzene (C ₆ H ₄ Cl ₂)	- Deodorant, insecticide, pesticide - Organic synthetic products - Dyes	- No evidence of carcinogenic potency

and one-time measurement with manual analysis. In the field, there are cases where changes in elapsed time are continuously observed over a long period of time, and in some cases, the objective can be achieved by measuring in a specific time period. The detection principle is divided into the physical principle with and without chemical reaction (Kim et al., 2013). The physical method is to use infrared absorption (Table 3).

The physical measurement method of CH₂O is limited in principle to chemical reactions (Maruo and Nakamura, 2011). The visual method is divided into indicator tube method, absorptiometry analysis method to measure absorbance, and photoelectric photometer method to measure reflected light. There are also bubbler absorption method and diffusion

absorption method. As an optical principle, there is a chemiluminescence method using light emission during CH₂O absorption reaction. In addition, electrochemical detection methods are classified into electrostatic potential and galvanic cell methods (also called fuel cell methods).

VOCs test method can be classified into optical detection method and conductive detection method (Hwang and Park, 2019). Although the photoacoustic method is mentioned as an optical detection method, in order to detect electrically stable VOCs, large energy must be given to VOCs in order to discriminate it from the air. There are also hydrogen flame ionization method and photoionization method. In the hot-radiation semiconductor method, which confirms the ion conductivity of the semiconductor surface, the element is

TABLE 3 | Classification of measurement methods by indoor air pollutants.

Classification	Indoor air pollutants	Test methods		
		Main test methods	Other test methods	
IAQ Test	Environmental standard tests	Sulfur dioxide (SO ₂)	- Pararosaniline method - Ultraviolet fluorescence spectroscopy (UVFS)	- Solution conductivity method - Pyro photometry
		Carbon monoxide (CO)	- Non-dispersive infrared (NDIR) spectroscopy	- Gas chromatography
		Nitrogen oxide (NO)	- Chemiluminescence (CL)	- Phototherapeutic keratectomy
		Particulate matter (PM)	- High volume air sampler - Beta attenuation monitoring (BAM)	- Low volume air sampler - Light scattering method - Light transmission method (LTM)
		Oxidants	- Ultraviolet photometry	- Chemiluminescence (CL) - Acid potassium iodide method - Alkaline potassium iodide method
VOC test	Asbestos	- N/A	- Phase-contrast microscopy (PCM)	
	VOC	- Thermal desorption (TD) - Automated thermal desorption method	- Solid liquid extraction	
Bad odour test		- Direct sensory test - Instrumental test	- Air dilution sensory test	
IAQ test for underground space	Carbon dioxide (CO ₂)	- Non-dispersive infrared (NDIR) spectroscopy	- N/A	
	Carbon monoxide (CO)	- Non-dispersive infrared (NDIR) spectroscopy	- Gas chromatography	
	Sulfur dioxide (SO ₂)	- Ultraviolet fluorescence spectroscopy (UVFS)	- Pararosaniline method	
	Nitrogen dioxide (NO ₂)	- Chemiluminescence (CL)	- Phototherapeutic keratectomy	
	Formaldehyde (CH ₂ O)	- 2,4-Dinitrophenylhydrazine (DNPH)	- Chromotropic acid method	
	Particulate matter (PM)	- High volume air sampler - Beta attenuation monitoring (BAM)	- N/A	
	Lead (Pb)		- Atomic absorption spectrometry	

heated. In addition, the bilayer adsorption/piezoelectric balance method is only effective for odorous VOCs.

The measurement concentration range generally required for measuring equipment is .01~10 mg/m³ (.008~.8 ppm) for CH₂O and .1~100 mg/m³ (.03~30 ppm) for VOCs (Rizk et al., 2018).

It is better to have a wide range of measurement concentration, but a precise one should be selected considering the low concentration measurement and precision generally refers to accuracy including reproducibility (Gallon et al., 2020). In particular, since the generation of indoor air pollutants is affected by temperature and humidity, it is required that these effects should be minimal.

The measurements of indoor air pollutants were conducted in December 2020 and April and May 2021 for the same units in DAMAC Maison Privé apartment in Business Bay (Figure 1), Dubai. This 36-floor twin tower apartment has identical twin masses with mirrored plan layout and contains a total of 100 units (Figure 2) (DXBOffplan, 2021). The construction began in 2014 and was completed in 2019 by DAMAC Properties (Propsearch, 2021). Regarding these five residential units (Table 4), indoor air pollutant sources such as the number of purchased electronic products, the number of purchased furniture, and the number of built-in furniture were investigated based on the same ventilation rate since one bedroom and two bedroom unit plans are identical (Jung et al., 2021a; Jung et al., 2021b).

In this study, a small chamber system was used to measure the release rate of chemical substances from building materials based on WHO/UNEP (United Nation Environment Program) (UNEP, 2021). The small chamber system is an equipment to analyze the amount of CH₂O and VOCs emitted from building material samples. A small stainless steel 15 L chamber is fixed inside, and there is a display in the upper right corner to check environmental

conditions such as temperature, humidity, flow rate, and pressure (Figure 3). The temperature and humidity sensor and the flow control pump are mounted on the inside right side. The principle is that the outside air is first purified through the filter system, then passes through the temperature and humidity control device, and a constant flow rate of clean air is supplied into the chamber by the flow control device. The air supplied to the inside through the inlet at the bottom of the chamber is discharged through the outlet at the top. At this time, since the air containing the contaminants emitted by the sample is discharged into the chamber, the air contaminants are precisely analyzed by connecting the adsorption tube and sampling.

Based on indoor air quality process test standard by Ministry of Environment in South Korea (Ministry of Environment, 2021), the test conditions were setup at a temperature of 25°C, a relative humidity (RH) of 50%, and a ventilation rate of .5 times/h (Mahyuddin and Awbi, 2010). The sample load rate was 2.2 m²/m³, the area of the test was .044 m², and the blank concentration was measure (Heiselberg and Perino, 2010). The emission intensity was calculated as follows according to the lapse of time after the sample was added (Eq. 1).

$$EF_a = (C_t - C_{tb,t}) \times \frac{n}{L} \quad (1)$$

C_t : Formaldehyde concentration in the chamber at time t (mg/m³); $C_{tb,t}$: background concentration at time t (mg/m³); EF_a : Emission intensity per unit area (mg/m²h); n : number of ventilation (times/h); L : Sample load rate (m²/m³).

Chemicals to be analyzed are VOCs [C₆H₆, C₇H₈, Ethylbenzene (C₈H₁₀), Xylene (C₈H₁₀), C₈H₈] and CH₂O (Wei et al., 2019; Mentese et al., 2020). For sampling of VOCs, after connecting the adsorption tube of Tenax TA to the flow sampling



FIGURE 1 | DAMAC Maison Privé in Business Bay, Dubai.

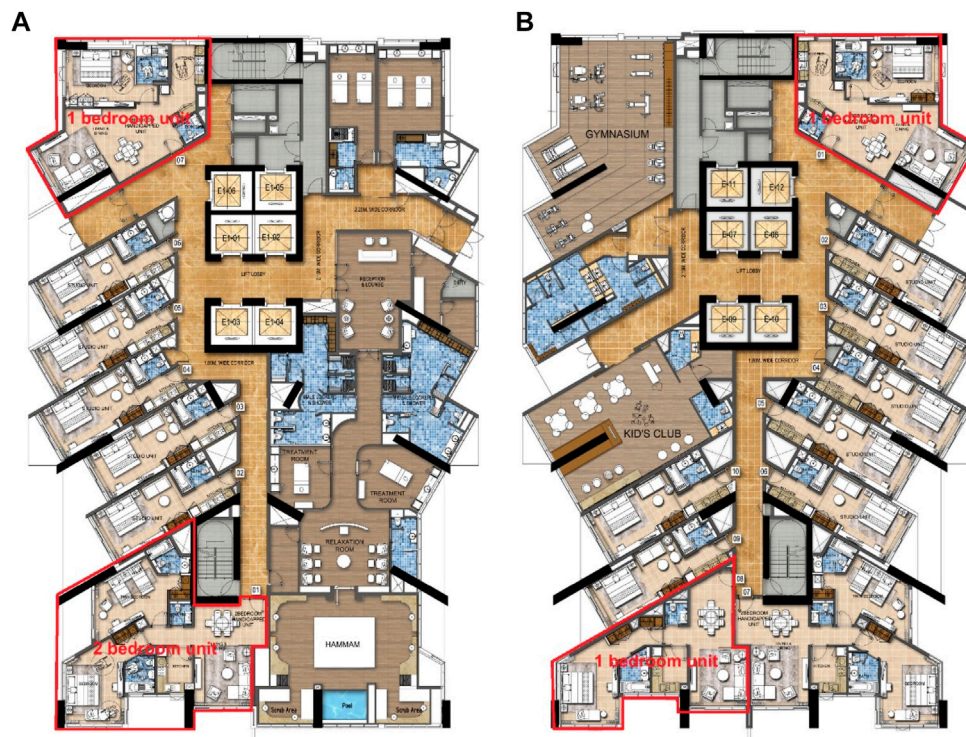


FIGURE 2 | Tower A level 1 plan (A) and tower B level 1 plan (B) in DAMAC Maison Privé.

TABLE 4 | Target residential units in DAMAC Maison Privé.

Tower	Unit#	Floor	Type	Size (m ²)	Ventilation rate (L/s)	Move-in date
Maison Privé	322	32	2-Bedroom	124.2	32	2020.1
Tower-A	231	23	1-Bedroom	91.4	22	2020.3
Maison Privé Tower-B	221	22	1-Bedroom	95.5	22	2020.2
	301	30	2-Bedroom	124.6	32	2020.4
	312	31	2-Bedroom	130.9	32	2020.6

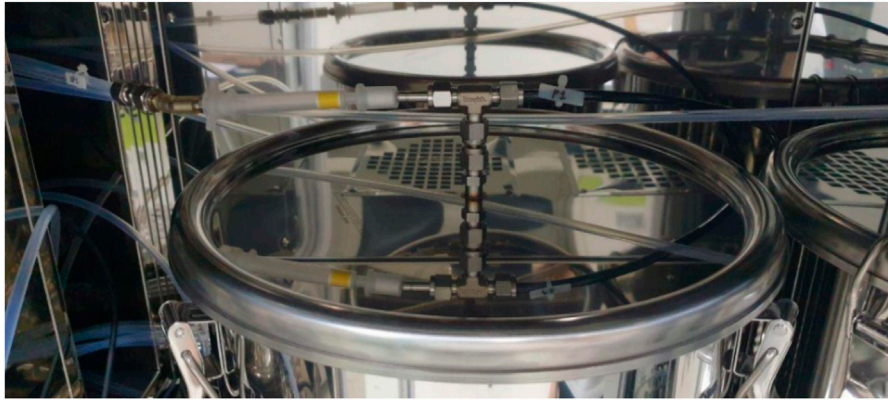


FIGURE 3 | Small chamber system.

pump, a total of 3.0 L of air in the small chamber was collected at 167 ml/min (Yassin and Pillai, 2019). For sampling of CH₂O, LpDNPHS10 cartridge was connected to the flow sampling pump, and a total of 15 L of air in the chamber was collected at 167 ml/min (Hwang et al., 2018). The wallpaper was manufactured in January 2018 and about 18 months had elapsed before the start of the experiment. The flooring material was manufactured in August 2018 and used for about 16 months. As for the storage form after production of the above materials, the wallpaper was sealed in plastic and the flooring was packaged in a general paper box, and the materials stored at room temperature in the warehouse (Choi et al., 2010; Choi et al., 2013).

The measured indoor air pollutants were CH₂O and VOCs. The measurement method is based on the WHO standards, which is measured at a location of 1.5 m from the center of the living room from 10 a.m. to 6 p.m. after 30 min of ventilation and 5 h of sealing before measurement (Table 5) (Saini et al., 2020). 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 (Walgraeve et al., 2011). 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 (.5 ml/min) (Xiong et al., 2015). The air samples in the last step are precisely analyzed by HPLC (High Performance Liquid Chromatography). In the TVOC concentration measurement method, the two steps of the CH₂O sampling method are the same, and a Tenax-TA tube is used in the third step (Wang and Zhang, 2011). 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 (Wang and Zhang, 2011). To avoid the errors of manual reading, two minimum and maximum readings were excluded especially from the measurement of CH₂O.

To investigate the degree of influence of building materials on the indoor air pollution, the indoor concentration was

predicted using the coefficient obtained from the chemical emission rate experiment in the building materials (Thevenet et al., 2018). The emission intensity prediction model used for indoor concentration prediction was Eq. 2, a double exponential decay model based on the emission pattern of building materials proposed by Chang and Guo (1992) (Chang and Guo, 1992). This double exponential decay model was validated by many previous IAQ research (Brown, 1999; Brown, 2002; Deng and Kim, 2004; Zhang et al., 2020a; Zhang et al., 2020b).

$$EF(t) = EF_1 \exp(-k_1 t) + EF_2 \exp(-k_2 t) \quad (2)$$

EF_1 : Amount of Generation at $t = 0$ (mg/m²·h) of Rapid Decay Generation Process; k_1 : Damping Coefficient (h⁻¹) of Rapid Decay Generation Process; EF_2 : Amount of Generation at $t = 0$ (mg/m²·h) of Slow Decay Generation Process; k_2 : Damping Coefficient (h⁻¹) of Slow Decay Generation Process; t : Time.

The double exponential model predicts by dividing the first and second decrease points in the emission pattern of chemical substances. The first reduction point is a point in which the emission intensity is rapidly decreased after passing the maximum point in the emission pattern. The secondary decrease point is the time when the emission intensity slightly decreases, or an equilibrium state is reached after the primary decrease is completed. The indoor concentration was estimated using Eq. 3 below. Assuming that the single room is ventilated with the number of ventilation N using Eq. 2 and $C = 0$ at $t = 0$, the chemical concentration C (mg/m³) in the single room can be expressed as Eq. 3.

$$C = \frac{L \cdot EF_1}{N - k_1} \exp(-k_1 t) + \frac{L \cdot EF_2}{N - k_2} \exp(-k_2 t) - \left(\frac{L \cdot EF_1}{N - k_1} + \frac{L \cdot EF_2}{N - k_2} \right) \exp(-N t) \quad (3)$$

C : Indoor Concentration at Time t (mg/m³); L : Load Factor (Room Surface Area/Room Volume (m²/m³)); N : Number of Ventilation (h⁻¹).

TABLE 5 | Measuring IAQ factors and methods.

Measuring factors		Measuring devices	Range	Resolution	Measuring location
Background Factors	Temperature	Digital Thermo-Hygrometer (TR-72U)	0–50°C	N/A	1.5 m from the floor in the center of the living room
	R.H.		10–95%	N/A	
IAQ Factors	CH ₂ O	PPM Formaldemeter TM-400	0–10.0 ppm	0.01 ppm	
	VOCs	IAQ Monitor (IAQRAE PGM-5210)	0–9.99 ppm	0.01 ppm	
			10.0–99.9 ppm	0.1 ppm	
			100–999 ppm	1 ppm	

TABLE 6 | Investigation on the indoor pollutant sources of target residential units.

	Tower-A 322		Tower-A 231		Tower-B 221		Tower-B 301		Tower-B 312	
Type	2-Bedroom		1-Bedroom		1-Bedroom		1-Bedroom		2-Bedroom	
Size (m ²)	124.2		91.4		95.5		124.6		130.9	
Survey Date	09/12	23/04	10/12	26/4	13/12	8/5	13/12	10/5	15/12	12/5
Average Temperature (°C)	25.8	28.2	23.7	28.6	24.4	30.8	24.7	29.6	23.7	28.3
Average Humidity (%)	43.2	61.3	41.3	63.1	51.5	44.8	23.6	69.7	56.5	73.3
Number of Electronics purchase	3	0	3	2	5	0	6	0	5	0
Number of Furniture purchase	8	0	2	0	4	0	8	0	2	0
Number of Built-In Furniture	3	0	2	0	2	0	2	0	2	0
Number of Textiles purchase	4	0	2	0	1	0	1	0	1	0

3 RESULTS

3.1 Results of Investigation on Residential Units and Pollutant Sources

Measurements were conducted continuously in December 2020 and April and May 2021 for the target units. **Table 6** shows the distribution of indoor temperature and humidity during measurement. In the December 2020 survey, it was distributed between 23.0–25.0°C, but in the April and May 2021 survey, the indoor temperature was distributed in the range of 28.0–31.0°C, showing a temperature difference of about 5.0°C. Humidity was in the range of 45.0–73.5% in April and May 2021, and 23.6–56.4% in December 2020 survey. The humidity difference was about 20.0% by season. Under the general premise that the generation of chemicals in building materials depends on the conditions of temperature and humidity, the probability of lower concentrations appearing in the measured values of the December 2020 survey was confirmed. The number of electronic products purchased at the time of moving in was found to be mostly between three and six in the entire residential units, and it was investigated those two additional electronic products were purchased around the time of the April and May 2021 survey in Tower-A 231. In addition, furniture purchased at the time of moving in was found to be two in all residential units except three in Tower-A 322. The number of textile purchase such as carpet and curtains were four in Tower-A 322, two in Tower-A 231, and one in the rest of the houses.

3.2 The Result of Building Material Emission Rate Test

The interior finishing materials of residential units differ by type, but most of them use eco-friendly building materials certified products. It was confirmed that the main finishing materials, such as wallpaper and flooring, obtained the highest grade of the HB mark. In this

experiment, wallpaper and flooring materials were targeted since they have the largest surface area in residential units. In consideration of the elapsed time from the completion of construction to the measurement time, 18-month-old wallpaper and 16-month-old flooring materials were selected and used in the experiment. The purpose of this study was to calculate the emission intensity of the finishing material after a certain period after construction.

3.2.1 Wallpaper

Figures 4, 5 show the results of emission tests for VOCs (C₆H₆, C₇H₈, Ethylbenzene (C₈H₁₀), Xylene (C₈H₁₀), C₈H₈) for wallpaper 18 months after production. The emission intensities of C₆H₆, Xylene (C₈H₁₀), and C₈H₈ (**Figure 4**) showed relatively low emission levels compared to C₇H₈ and Ethylbenzene (C₈H₁₀) (**Figure 5**). In case of C₆H₆, the emission pattern over time showed the maximum emission intensity when approximately 24 h had elapsed and showed a decreasing pattern thereafter. The emission pattern of CH₂O is different from that of VOCs as shown in **Figures 4, 5**. After the start of the experiment, it started to increase continuously for a certain period, and when about 144 h (6 days) elapsed, the maximum emission intensity appeared as 22 µg/m²h. After that, it showed a release pattern showing a mild decrease (**Figure 6**).

3.2.2 Flooring

The results of the emission test for each VOCs on the flooring materials 16 months after production are as follows. C₆H₆, Xylene (C₈H₁₀), and C₈H₈ (**Figure 7**) showed relatively low emission intensities compared to C₇H₈ and Ethylbenzene (C₈H₁₀) (**Figure 8**). Their emission patterns over time were all similar. VOCs emission from parquet flooring was found to have a low initial value unlike wallpaper, and then slightly increased, and then showed a gradual decrease in all materials after about 24 h. This is different from the wallpaper, which shows the maximum

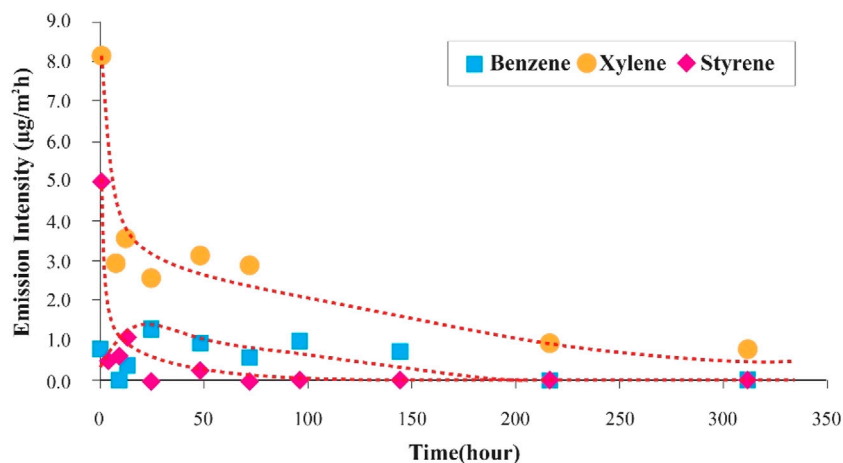


FIGURE 4 | Emission pattern of benzene, xylene, and styrene from wallpaper.

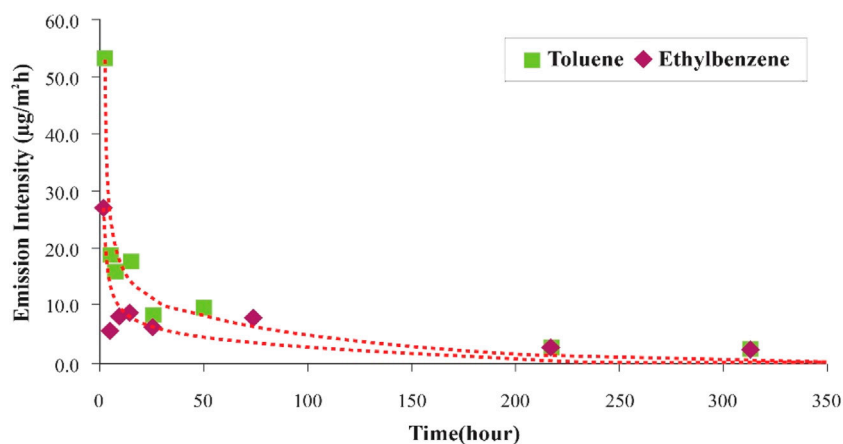


FIGURE 5 | Emission pattern of toluene and ethylbenzene from wallpaper.

emission intensity immediately after the experiment. Xylene (C_8H_{10}) showed only a slight increase in emission intensity when about 24 h and other materials about 12 h had elapsed, so it is judged as a material property showing different emission patterns at the same experimental temperature ($25^\circ C$).

Figure 9 shows the emission intensity of CH_2O from the flooring material over time. After about 100 h, the gentle increase in emission intensity stopped and started to decrease. The values of the concentrations exhibiting these fluctuations were very small. The release pattern of CH_2O showed a large difference between the maximum release intensity and the initial release intensity in case of wallpaper but showed a slight difference in the release pattern in case of flooring.

3.3 Characteristics of Cumulative Emissions of Building Materials

Due to the emission intensity pattern characteristics of building materials, the cumulative emission amount ($\mu g/m^3$) over time

was calculated and compared. Figure 10 shows the characteristics of the cumulative emission amount of each VOC for wallpaper and Figure 11 for flooring. Both building materials showed the largest cumulative emission of C_7H_8 . The accumulated amount up to 300 h was about $600 \mu g/m^3$ for wallpaper and about $710 \mu g/m^3$ for flooring material up to 150 h, indicating that the cumulative emission of flooring materials was larger than that of wallpaper. In particular, the emission of Ethylbenzene (C_8H_{10}) from wallpaper was high, confirming that the emission characteristics of individual VOCs were different depending on the characteristics of the material. On the other hand, in case of CH_2O , the cumulative emission amount from the flooring was significantly higher than that of the wallpaper (Figure 12). The elapsed time after production was shorter than that of wallpaper, and the flooring material, which was stored in a state where natural radiation rather than closed storage, showed higher emission than wallpaper. It can be predicted that the main pollutant source of CH_2O in the room is the influence of the flooring material. The two building materials had

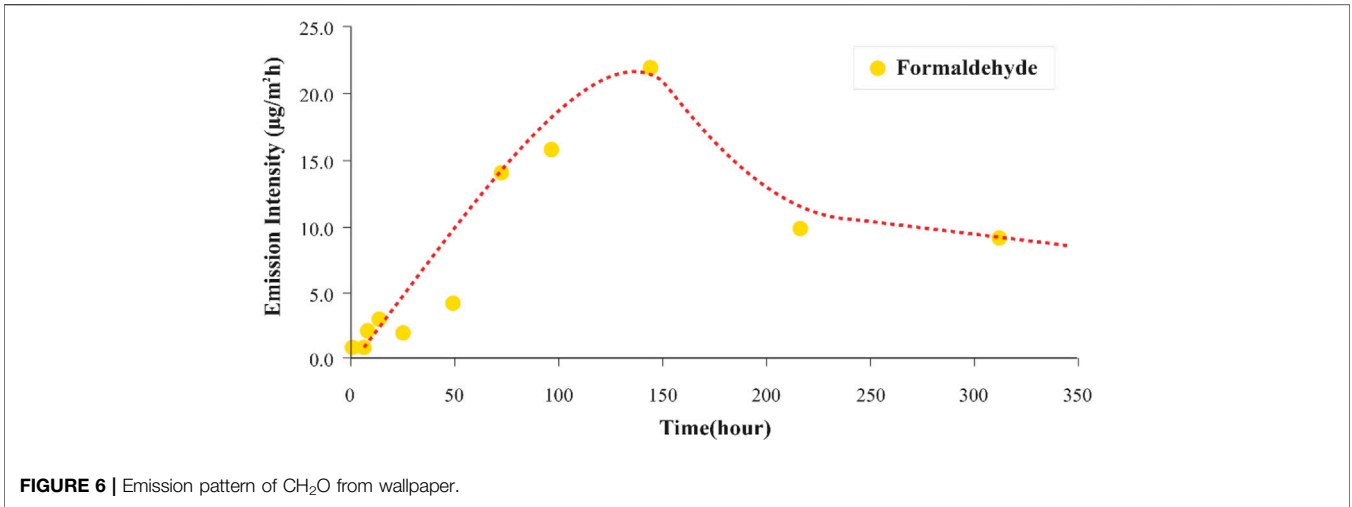


FIGURE 6 | Emission pattern of CH₂O from wallpaper.

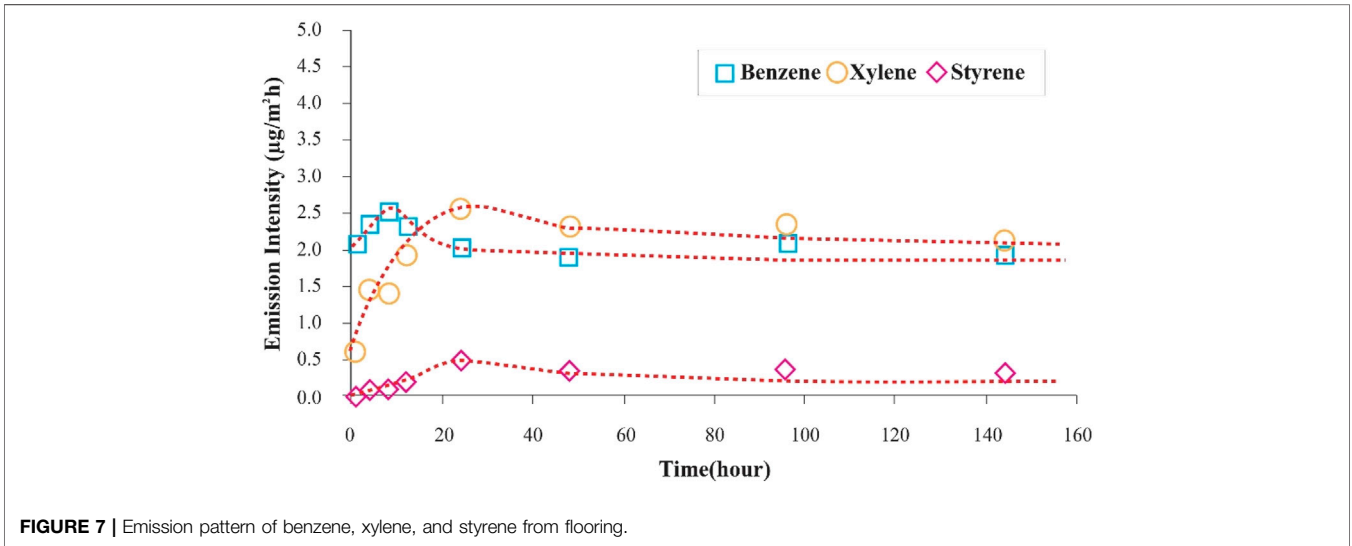


FIGURE 7 | Emission pattern of benzene, xylene, and styrene from flooring.

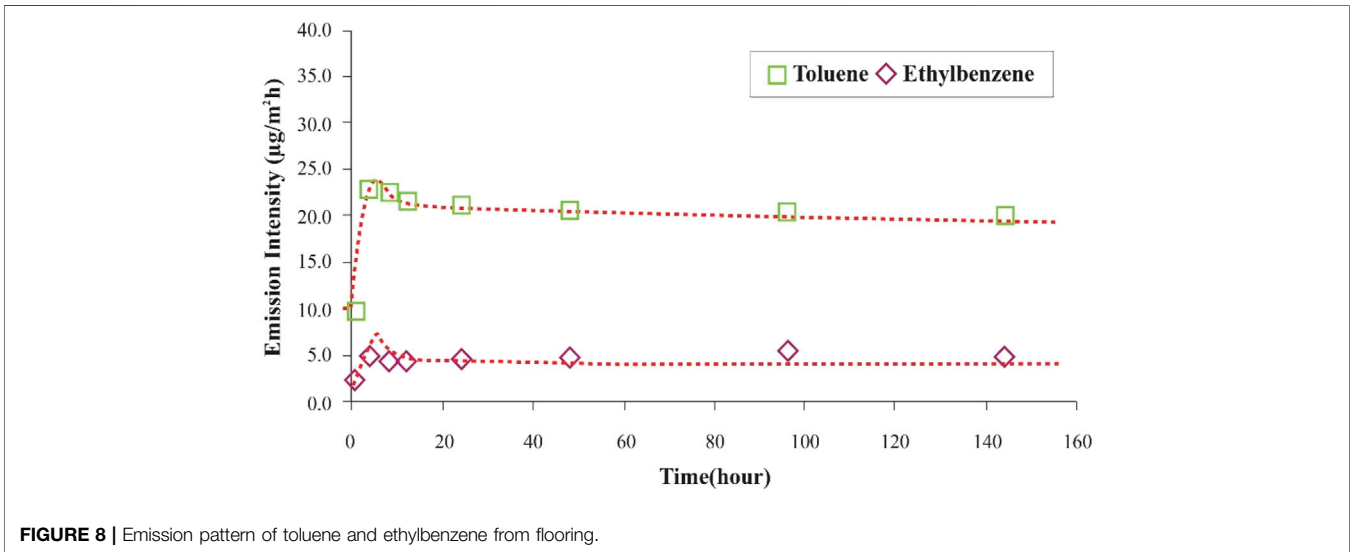


FIGURE 8 | Emission pattern of toluene and ethylbenzene from flooring.

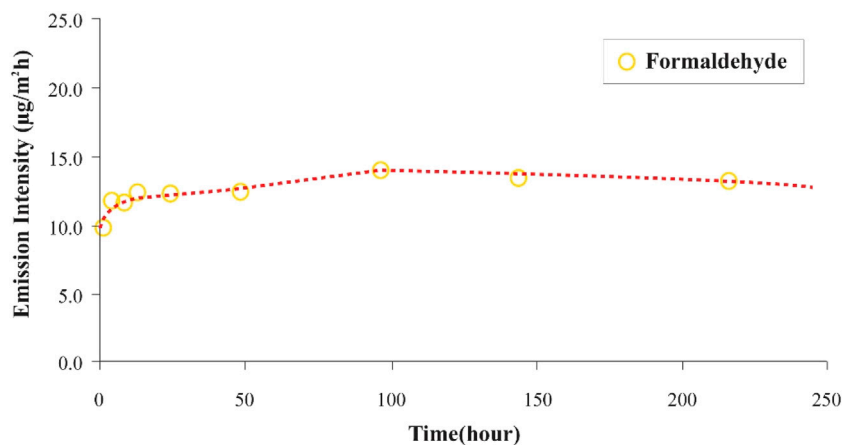


FIGURE 9 | Emission pattern of CH₂O from flooring.

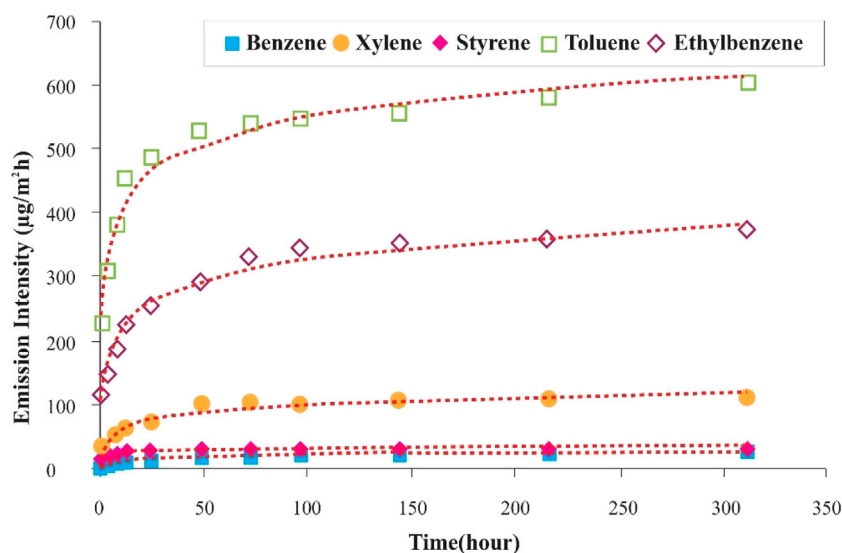


FIGURE 10 | Cumulative emission of VOCs from wallpaper.

a difference in that the elapsed time after production was about 2 months, but in case of VOCs, the wallpaper showed a slightly higher emission amount, and in case of CH₂O, the flooring material showed a high emission amount.

3.4 Indoor Concentration Measurement Results by Residential Units

To understand the distribution of indoor air pollutants by residential unit, the concentration of chemicals in winter (December 2020) and spring (April and May 2021) was measured. Indoor air pollutants analyzed were CH₂O, C₆H₆, C₇H₈, Ethylbenzene (C₈H₁₀), Xylene (C₈H₁₀), and C₈H₈. Except for Tower-B 312 for C₆H₆ and Tower-A 322 for Ethylbenzene (C₈H₁₀), the indoor concentration measurement

in December 2020 clearly showed an increasing trend compared to the measurement in April and May 2021. Although there is a difference in the degree of decrease for each residential unit and for each indoor air pollutants, the trend of increase in C₇H₈, Xylene (C₈H₁₀), and C₈H₈ was the same for residential units (Figure 13). On the other hand, in case of CH₂O, the concentration increased with time in all units except for Tower-A 322 (Figure 14). CH₂O change in Tower-A 322 was not investigated for increasing factors in interviews and lifestyle surveys. This is judged as the uncertainty of general measurement that can occur in everyday life.

3.5 Indoor Concentration Prediction Results

For VOCs and CH₂O, the indoor concentration of the residential units was predicted. Table 7 shows the variable values related to

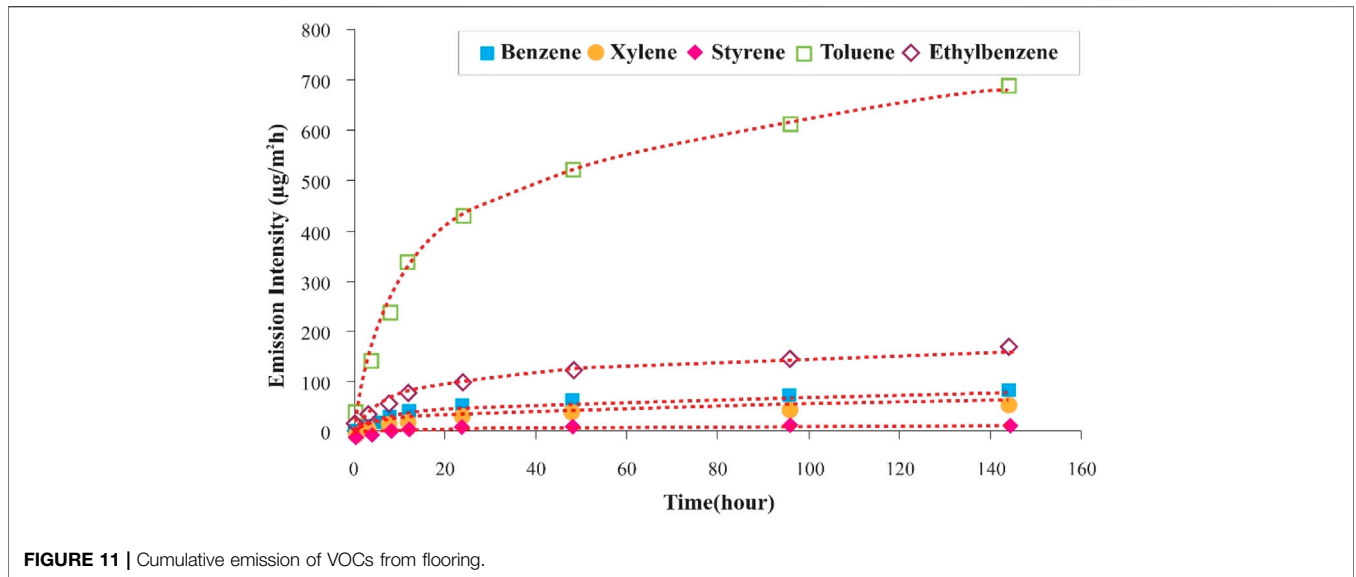


FIGURE 11 | Cumulative emission of VOCs from flooring.

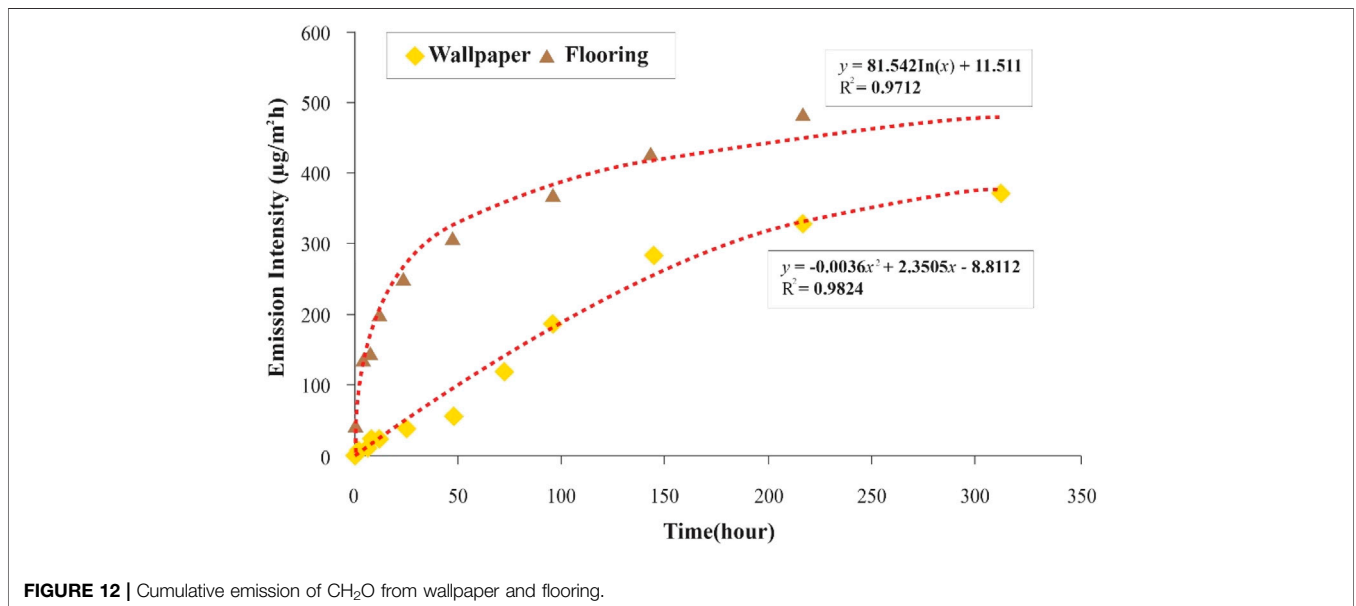


FIGURE 12 | Cumulative emission of CH₂O from wallpaper and flooring.

the prediction of VOCs and CH₂O based on the emission patterns of the two building materials. To use the double exponential decay model Eq. 2, the coefficients related to the amount of generation in building materials require the initial emission intensity and attenuation coefficient at the time of the first decrease, and the initial emission intensity and the attenuation coefficient at the time of the second decrease. In addition, the contents of various parameters applied to predicting the indoor concentration using Eq. 3 described above are shown in Table 8. In this study, the indoor concentration was predicted for a living room. The main parameters to be applied for this purpose are the age of the material, the time of measuring the indoor concentration, the time to be predicted, the surface area and volume (load factor) of the wallpaper and flooring, and the

number of ventilations. As shown in Table 9, the load ratio of building materials in the target house was found to exist between .84–.98 m²/m³ for wallpaper and .41–.43 m²/m³ for flooring. Therefore, this indoor concentration prediction is premised on the existence of a difference in the load factor from 2.2 m²/m³ conducted in the building material test.

For the period of predicting the indoor concentration, the indoor concentration was predicted for the period from 16 to 27 months after moving in with the consideration of the elapsed years of materials and the period of indoor concentration. The number of ventilations was set to .5 times/h, and the initial emission intensity and attenuation coefficient were substituted for the data on material characteristics using the variables derived from Table 6. In addition, the concentration up to 27 months was

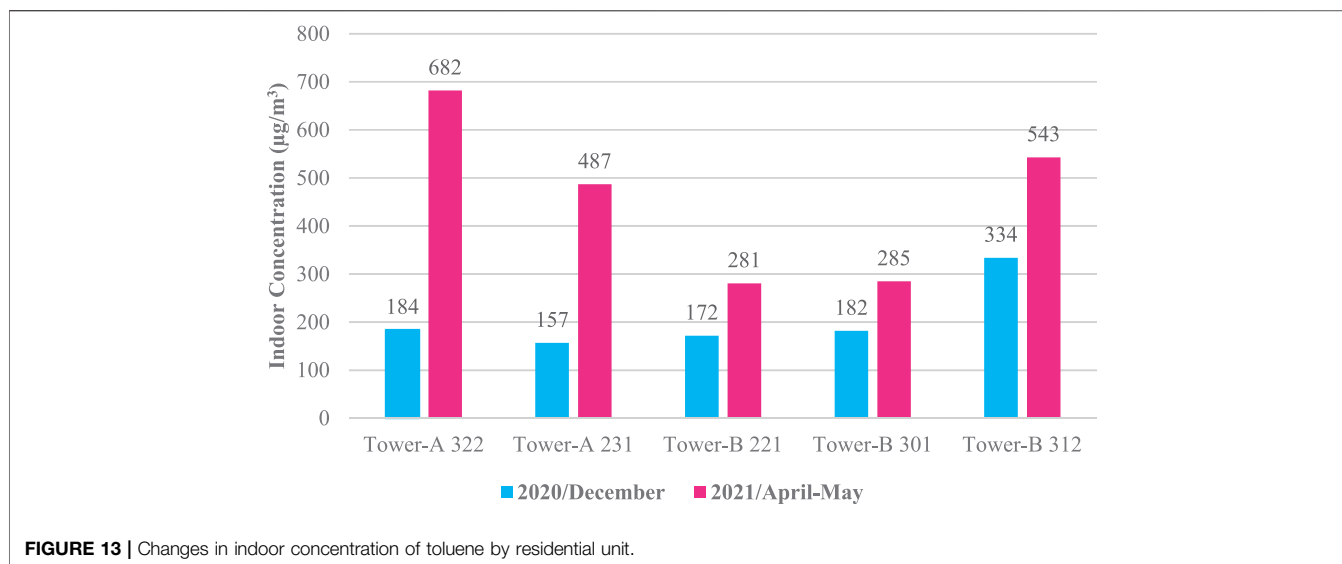


FIGURE 13 | Changes in indoor concentration of toluene by residential unit.

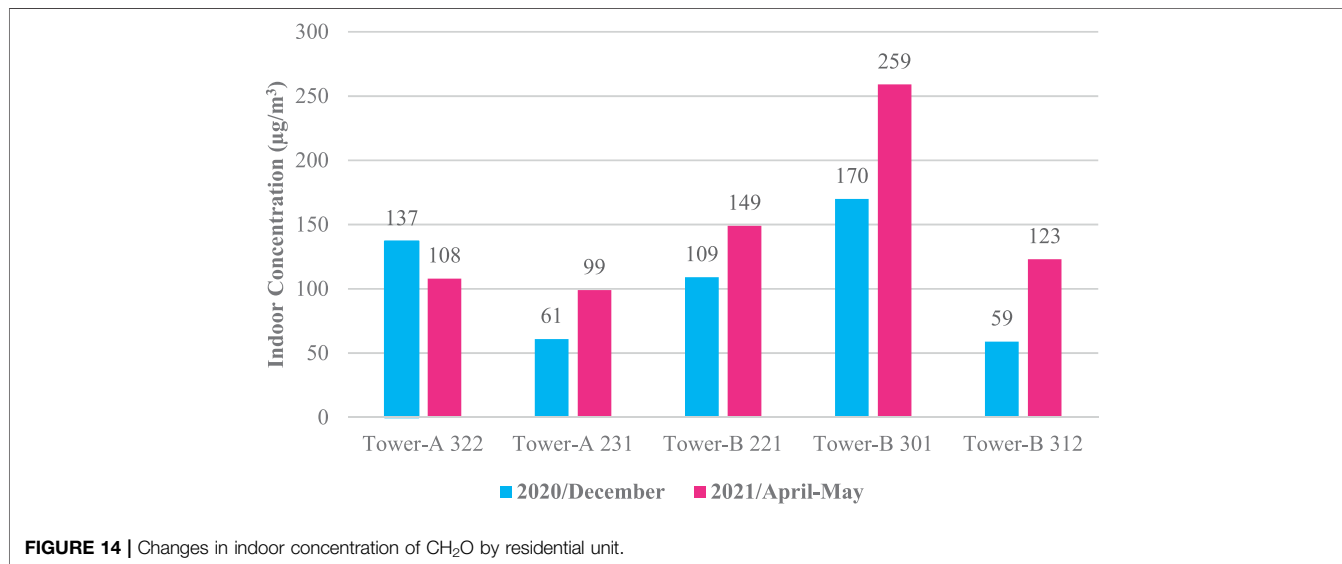


FIGURE 14 | Changes in indoor concentration of CH₂O by residential unit.

TABLE 7 | Variables related to Predicting the Emission Intensity.

Categories	Pollutants	1st decline period		2nd decline period	
		Initial emission intensity	Attenuation coefficient	Initial emission intensity	Attenuation coefficient
Wallpaper	VOCs	.0928	.4446	.0122	.1563
	CH ₂ O	.0222	.0111	.0099	.0008
Flooring	VOCs	.0322	.0053	.0312	.0051
	CH ₂ O	.0138	.0011	.0136	.0031

predicted (the predicted value) by using the data obtained from 16 months for flooring and 18 months for wallpaper. Comparison with data measured in an actual residential unit was conducted. Figures 15, 16 show the comparison of the predicted and measured values for the living concentration of VOCs and CH₂O in the houses under investigation. VOCs are higher in

all units than the actual concentration predicted, suggesting that there is a high probability of factors other than building materials. In case of VOCs, the fact that the measured value is higher than the predicted value even though there is no specific source of contamination or introduction of household goods that affect the occurrence of VOCs at the beginning of move-in means that there

TABLE 8 | Parameters for prediction of indoor concentration.

Parameters		Tower-A 322	Tower-B 221
		Tower-A 231	Tower-B 301 Tower-B 312
Elapsed time since production of the material	Wallpaper	Approximately 18 months passed	
Indoor concentration measurement time	Flooring	Approximately 16 months passed	
	spring	19 months passed	23 months passed
	winter	23 months passed	27 months passed
Number of ventilation (N)	.5 times/h		
Load factor (L)	Material application surface area and volume (Table 8)		
Material pattern data	Wallpaper	Initial emission intensity and attenuation coefficient for each point	
	Flooring	Initial emission intensity and attenuation coefficient for each point	

TABLE 9 | Surface area and volume of the living rooms in target units.

Units	Volume (m ³)	Wallpaper		Flooring	
		Surface area (m ²)	Load factor (m ² /m ³)	Surface area (m ²)	Load factor (m ² /m ³)
Tower-A 322	39.44	36.08	.91	16.42	.41
Tower-A 231	2,942	29.04	.98	12.24	.41
Tower-B 221	33.54	33.12	.98	13.97	.41
Tower-B 301	44.52	39.14	.87	19.35	.43
Tower-B 312	52.46	44.28	.84	21.86	.41

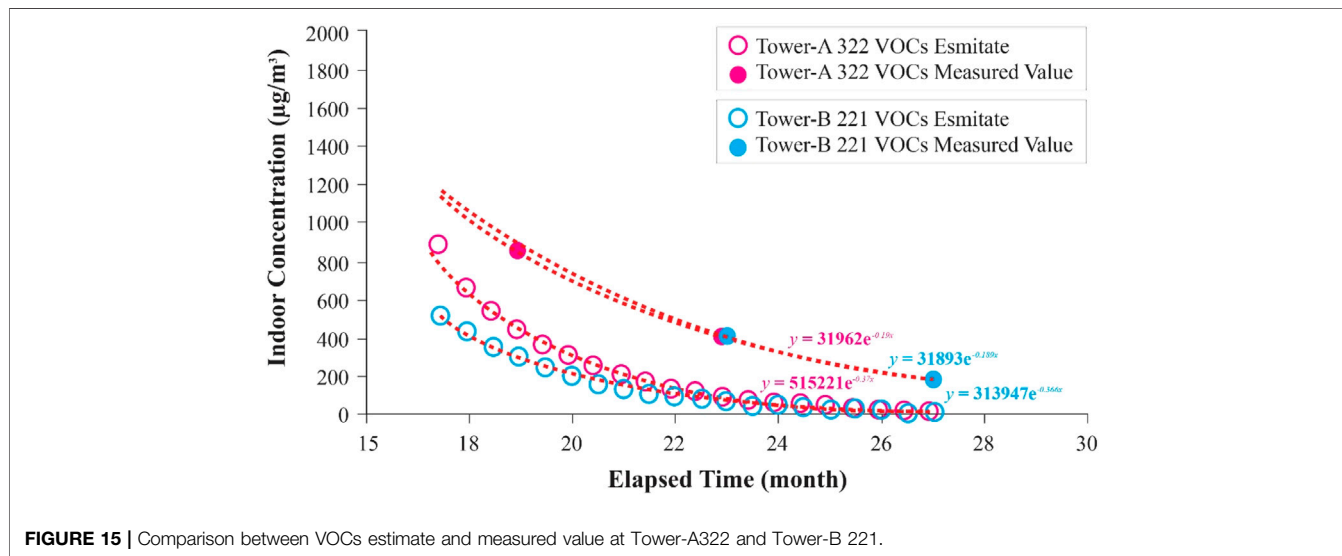
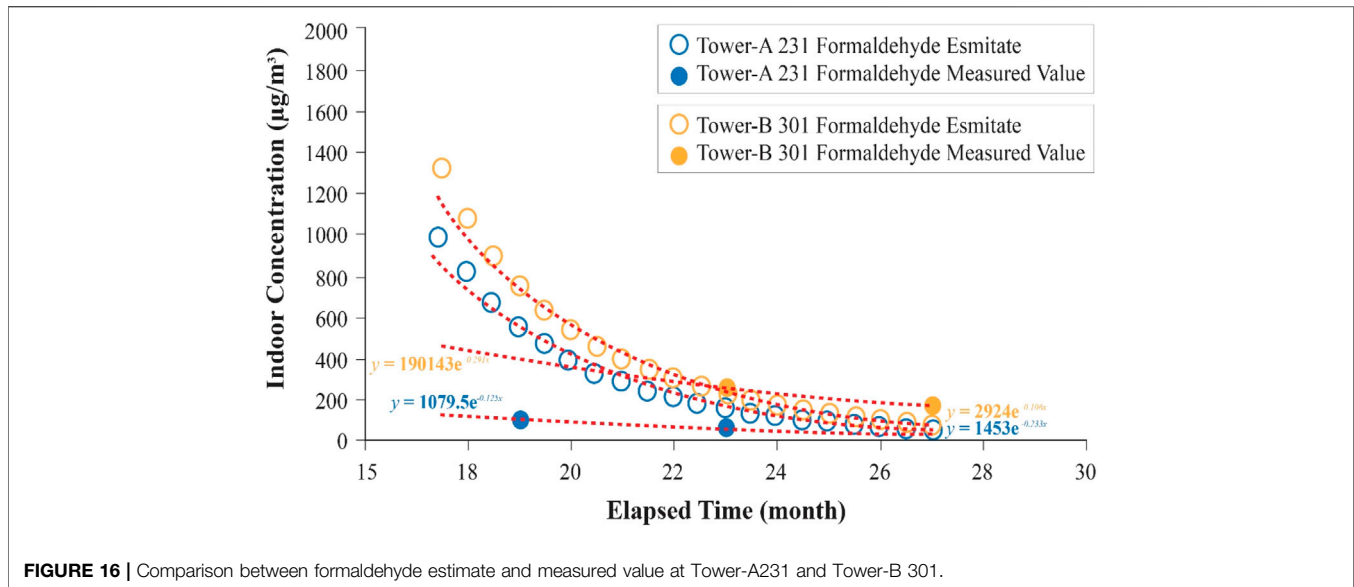


FIGURE 15 | Comparison between VOCs estimate and measured value at Tower-A322 and Tower-B 221.

is a possibility of the introduction of pollutants from the outside during daily life. On the other hand, the actual value of CH₂O showed that the emission amount was lower or close to the predicted value in all houses. In the review of the amount of internal generation described above, it is estimated that the amount of emission calculated from materials is at the same level despite the presence of built-in furniture and newly purchased furniture that affect the emission of CH₂O at the beginning of move-in after 16 months or more. At this point, the influence on the number of pollutants generated from furniture in the living room was attenuated.

4 DISCUSSION

In the current situation in the UAE, there are no studies on the identification of the material properties of building materials and the dominant influencing factors. Therefore, the lack of database on the basic properties of building materials suitable for the UAE situation brings many limitations to research development such as verification and development of prediction models via modeling or simulation, and there is a limit to suggesting practical measures. The emission of hazardous chemicals from building materials is affected by the environmental conditions to



which the materials are exposed, as well as the effects of material characteristics such as the type of material and the total amount of hazardous chemicals contained in the material. In particular, in the case of the UAE, which has a high temperature and low humidity desert climate, there are many factors that change the material temperature due to changes in the outdoor temperature during the day and night and excessive use of air conditioners. As such, it is an urgent issue to accumulate data on the amount of emission of hazardous substances on the influencing factors of basic building materials in a situation where they are exposed to various temperatures, humidity, and wind.

The limitation of this study is a premise that there is a difference between the load factor applied in the emission rate test of building materials and that applied to the living room of the residential units. The emission of VOCs should be further investigated with influencing factors in daily life.

In future studies, an in-depth study on the age, emission pattern, and emission coefficient of building materials, is indispensable since these are important variables for predicting indoor concentration.

In addition, it is necessary to establish a database and methodologies for load factor, ventilation frequency, and measurement points for actual application to residential units.

5 CONCLUSION

The purpose of this study is to understand the degree of influence of building material on indoor pollutants concentration by measuring and predicting the indoor concentration of target residential units. To this end, indoor concentration was measured, and pollutant source was investigated, variables were extracted through emission intensity experiments of applied building materials, and the indoor concentration was predicted by applying the double exponential decay model. Therefore, the degree of influence of the building materials

applied to the residential units was analyzed by comparing it with the actual value and evaluating the influencing factors. The conclusion based on the analysis of the results are as follows.

First, it was found that there are many purchases of electronic products, furniture, and textile products, which can become new sources of indoor air pollution after moving in.

Second, there was a difference in indoor temperature and humidity during winter and spring measurements, so that the indoor temperature in winter was about 5.0°C and the humidity was about 20.0% lower. In addition, the indoor concentration measurement result of the residential units also clearly shows the tendency of the indoor concentration to increase with the passage of time in winter and spring in most units, confirming that this experimental data can be applied as data for prediction.

Third, the difference in the emission patterns of wallpaper and flooring was confirmed via the emission rate test of building materials in an environment of 25°C, 50%, and ventilation frequency of .5 times/h. The wallpaper showed a typical chemical emission pattern, with the initial value being the highest during the experimental period and decreasing thereafter. CH₂O also showed a longer initial rise period and decreased after increasing for a certain period. However, in case of flooring materials, the initial values of both VOCs and CH₂O were low, and a difference was confirmed in the emission pattern, which rose to a fine concentration within 24 h, reached a maximum value, and then gradually decreased thereafter. Understanding the difference in emission patterns is an essential process of parameter calculation for prediction, and parameters were calculated based on this.

Fourth, the cumulative emission amount was reviewed to understand the relationship between the difference in the emission patterns of the two materials and the internal content of the building materials. VOCs showed a difference in the cumulative emission amount due to the difference in emission patterns within 100 h after the start of the experiment, but after that, it was confirmed that the difference in emission amount between materials became very small.

Therefore, it is important to understand the emission pattern at the initial time point until the maximum emission intensity is exhibited, and the difference in the cumulative amount appeared at this time point.

Fifth, in case of CH₂O, the cumulative emission of the flooring material is greater than that of the wallpaper, and there is no period in which the flooring material exhibits a sudden emission with respect to temperature. However, it was confirmed that the high emission amount was continuously displayed. Although the chemical content inside the flooring material is greater than that of the wallpaper, it does not show the form of a general emission pattern. Therefore, it is judged that it is necessary to grasp the emission pattern according to the content, each building material, and environmental conditions (temperature, humidity, number of ventilation) for the emission pattern of chemical substances for prediction.

Sixth, VOCs were predicted to be lower than the actual values in the simulations predicted by applying the parameters calculated based on the building materials and emission patterns. CH₂O was predicted to be slightly higher or at about the same level. Therefore, in predicting the indoor concentration of the residential unit, the characteristics of the building material to which CH₂O is applied are effective and can be predicted.

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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 MA identified and secured the example buildings used in the study. The data acquisition system and installations of sensors were designed and installed by CJ and MA. MA were responsible for data collection. Data analysis was performed by CJ and NA. The manuscript was compiled by CJ and NA and reviewed by MA and NA. All authors have read and agreed to the published version of the manuscript.

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