Mitigating indoor air pollution in UAE's high-rise apartment buildings: a study on eco-friendly materials and adsorbents

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Abstract

Purpose – This study aims to evaluate the efficiency of various techniques for enhancing indoor air quality (IAQ) in construction. It analyzed the alterations in the concentration of indoor air pollutants over time for each product employed in controlling pollution sources and removing it, which included eco-friendly substances and adsorbents. The study will provide more precise and dependable data on the effectiveness of these control methods, ultimately supporting the creation of more efficient and sustainable approaches for managing indoor air pollution in buildings.

Design/methodology/approach – The research investigates the impact of eco-friendly materials and adsorbents on improving indoor air quality (IAQ) in Dubai's tall apartment buildings. Field experiments were conducted in six units of The Gate Tower, comparing the IAQ of three units built with "excellent" grade eco-friendly materials with three built with "good" grade materials. Another experiment evaluated two adsorbent products (H and Z) in the Majestic Tower over six months. Results indicate that "excellent" grade materials significantly reduced toluene emissions. Adsorbent product Z showed promising results in pollutant reduction,

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but there is concern about the long-term behavior of adsorbed chemicals. The study emphasizes further research on household pollutant management.
Findings – The research studied the effects of eco-friendly materials and adsorbents on indoor air quality in Dubai's new apartments. It found that apartments using "excellent" eco-friendly materials had significantly better air quality, particularly reduced toluene concentrations, compared to those using "good" materials. However, high formaldehyde (HCHO) emissions were observed from wood products. While certain construction materials led to increased ethylbenzene and xylene levels, adsorbent product Z showed promise in reducing pollutants. Yet, there is a potential concern about the long-term rerelease of these trapped chemicals. The study emphasizes the need for ongoing research in indoor pollutant management.
Research limitations/implications – The research, while extensive, faced limitations in assessing the long-term behavior of adsorbed chemicals, particularly the potential for rereleasing trapped pollutants over time. Despite the study spanning a considerable period, indoor air pollutant concentrations in target households did not stabilize, making it challenging to determine definitive improvement effects and reduction rates among products. Comparisons were primarily relative between target units, and the rapid rise in pollutants during furniture introduction warrants further examination. Consequently, while the research provides essential insights, it underscores the need for more prolonged and comprehensive evaluations to fully understand the materials' and adsorbents' impacts on indoor air quality.
Practical implications – The research underscores the importance of choosing eco-friendly materials in new apartment constructions for better IAQ. Specifically, using "excellent" graded materials can significantly reduce harmful pollutants like toluene. However, the study also highlights that certain construction activities, such as introducing furniture, can rapidly elevate pollutant levels. Moreover, while adsorbents like product Z showed promise in reducing pollutants, there is potential for adsorbed chemicals to be rereleased over time. For practical implementation, prioritizing higher-grade eco-friendly materials and further investigation into furniture emissions and long-term behavior of adsorbents can lead to healthier indoor environments in newly built apartments.
Originality/value – The research offers a unique empirical assessment of eco-friendly materials' impact on indoor air quality within Dubai's rapidly constructed apartment buildings. Through field experiments, it directly compares different material grades, providing concrete data on pollutant levels in newly built environments. Additionally, it explores the efficacy of specific adsorbents, which is of high value to the construction and public health sectors. The findings shed light on how construction choices can influence indoor air pollution, offering valuable insights to builders, policymakers and residents aiming to promote public health and safety in urban living spaces.

Keywords Indoor air quality, Eco-friendly materials, Toluene (C_7H_8), Adsorbents, Formaldehyde (HCHO)
Paper type Research paper

1. Introduction

In the last four decades, Dubai has seen a surge in the construction of tall apartment buildings, attracting developers from all over the world and making it a hub for modern urban living and architectural innovation (Herbert and Murray, 2015; Arar *et al.*, 2022; Awad and Jung, 2022). However, due to the improved airtightness of these new buildings, their ventilation efficiency has decreased (Jung *et al.*, 2021a, b; Al Qassimi and Jung, 2022). As a result, there has been a rise in indoor air quality (IAQ) pollution caused by the increased usage of building materials and furniture containing numerous chemical substances such as urea, phenolic synthetic resin, adhesives solvent thinner, plasticizer and synthetic rubber (Arar and Jung, 2021; Awad and Jung, 2021; Jung and Awad, 2021a, b). This pollution includes volatile organic compounds (VOCs) and formaldehyde (HCHO), which can cause various health issues such as sick building syndrome (SBS) and chemical substance hypersensitivity (Arar and Jung, 2022; Mahmoud and Jung, 2023). Hence, it is a growing concern that indoor air pollution adversely affects human health (Jung and El Samanoudy, 2023; Mahmoud *et al.*, 2023a).

Dubai has implemented several measures to ensure that the air inside buildings is safe and healthy for occupants (Jung and Mahmoud, 2022; Jung *et al.*, 2022a, b; Jung and Awad, 2023). The Dubai Green Building Regulations and Specifications, first introduced in 2010, set out minimum requirements for IAQ and other environmental factors in buildings, including proper ventilation systems, acceptable pollution levels and low-emission building materials (Jung *et al.*, 2022a, b; Mahmoud *et al.*, 2023b). The Dubai Municipality and Dubai Health Authority are responsible for monitoring and enforcing compliance with these standards such as IAQ standards with less than 0.08 ppm (parts per million) of HCHO, less than 300 micrograms/m^3 of

TVOC (total volatile organic compound) and less than 150 micrograms/m^3 of PM10 (particulate matter) (less than 10 microns) in 8 h of continuous monitoring before occupancy for a new apartment (Jung and Awad, 2021a, b; AlGurg *et al.*, 2022).

In the wider context, various methods have been developed to control and manage indoor air pollution. Demanega *et al.* (2021) tested pollution source monitors, while Gonzalez-Martin *et al.* (2021) reviewed methods to eliminate indoor air pollution. Further, Megahed and Ghoneim (2021) examined dilution control to reduce the effects of indoor air pollution. Pollution source control uses eco-friendly and alternative materials to reduce indoor air pollutants, while elimination control involves converting or directly removing pollutants (Meena *et al.*, 2021). Products such as photocatalysts, plant-derived substances and air purifiers are used for elimination control (Fenibo *et al.*, 2022; Noor *et al.*, 2022). Dilution control via natural or mechanical ventilation is mandatory in new apartments and can be applied during construction and management (Singer *et al.*, 2020). Pollutant removal materials can be used during the construction stage, while air purifiers can be added during the occupancy stage to improve indoor air quality (Liu *et al.*, 2017; Steinemann *et al.*, 2017). A previous study focuses on the effectiveness of pollutant source removal control methods in the construction stage in addressing indoor air pollution and improving public health and safety (Megahed and Ghoneim, 2021). Pollution source identification is also important in preventing adverse health consequences in children in schools (Madureira *et al.*, 2016; Gabriel *et al.*, 2021). Further, pollution source control is a representative method used to address indoor air pollution in buildings, and one approach is to use eco-friendly materials or alternative materials (Wei *et al.*, 2015; Bhavya *et al.*, 2021). Examples of eco-friendly materials are products certified by the Dubai Green Building Regulations and Specifications and Green Building Code (Riadh, 2022). Among removal controls, adsorbents are known to improve IAQ more than other products (Kelly and Fussell, 2019). Various adsorbents are currently commercially available and installed in new apartments (Chao *et al.*, 2021). However, most products lack verification and related research data on their IAQ improvement effect (Zhang *et al.*, 2011).

While previous studies have conducted field or laboratory experiments to investigate the effects of eco-friendly materials on improving indoor air quality, studies that apply these materials to actual apartment buildings and examine long-term pollutant concentrations are scarce (Sarkhosh *et al.*, 2021). Nevertheless, the prediction of indoor air quality is becoming more accurate by utilizing machine learning based on data captured through measurements of real-occupied environments (Wei *et al.*, 2019), and IAQ for residential buildings has been thoroughly reviewed (Mannan and Al-Ghamdi, 2021). Having said that, studying the effectiveness of eco-friendly materials and adsorbents in actual buildings under construction is important for strengthening Dubai’s regulations, advocating their benefits and adding to the body of knowledge.

1.1 Eco-friendly materials and absorbents

The term “eco-friendly materials” can encompass a wide range of materials with low environmental impacts, such as those produced using minimal energy or those made from recycled materials (Tham, 2016; Naldzhiev *et al.*, 2020). In IAQ, eco-friendly materials generate fewer indoor air pollutants when used as finishing materials or parts of building structures in buildings, making them less harmful to occupants than traditional materials (Gopalan *et al.*, 1854; Vijayan *et al.*, 2023). Using eco-friendly materials is one of the pollution source control methods used to address indoor air pollution in buildings (Maraveas, 2020). In Dubai, eco-friendly materials are certified by the Dubai Green Building Regulations and Specifications and the Green Building Code (Alsulaili *et al.*, 2020; Meena *et al.*, 2022). Although alternative materials such as stone or metal can be used as finishing materials for apartment houses, their applications are limited, making eco-friendly materials a more suitable target for indoor air pollution control (Rybak-Niedziółka *et al.*, 2023). While a previous study by Ekhaese and Ndimako (2023) has investigated the effects of eco-friendly materials on indoor air quality in hotels, further research is needed to apply these materials to actual apartment buildings and examine long-term pollutant concentrations.

Indoor air pollution is caused by various pollutants, which differ depending on the building (Leung, 2015). In multi-unit housing, chemical substances from building materials and gaseous substances from living activities are common pollutants (Manisalidis *et al.*, 2020). Chemicals are also found in furniture and household items, including pesticides and air fresheners (Tham, 2016). Although varying in degree, indoor air pollutants are present in most objects and products (Ranabhat *et al.*, 2015; Nath *et al.*, 2016). VOCs are a major contributor to SBS, which has become a growing social concern (Jiang *et al.*, 2017; Meena *et al.*, 2021). VOCs are predominantly emitted by construction materials in new buildings (Leung, 2015). To address this, it is necessary to use materials that produce lower levels of pollutants or are free of them altogether (McLeod *et al.*, 2022).

Adsorption is the process by which a solid material, called an adsorbent, physically or chemically captures solutes from gas or liquid phases (Mohamed Hatta *et al.*, 2022). Adsorbents are classified into physical and chemical adsorption based on the mechanism of adsorption (Gunawardene *et al.*, 2022). These materials have a large porous surface area that allows for greater adsorption of solutes (Enaime *et al.*, 2020). The adsorption rate is inversely proportional to particle size (Nallathambi *et al.*, 2020). Adsorbents are primarily silicate minerals of aluminum-containing metals like sodium, potassium and calcium (Yadav *et al.*, 2021). They also include activated carbon, artificial Olite and water of crystallization (Kurda *et al.*, 2020). Their high adsorption, moisture absorption and cation exchange capabilities make them useful as pollutant purifiers, odor removers, desiccants and catalysts (Harja *et al.*, 2022).

Based on knowledge gained from the literature, this study aims to evaluate the efficiency of eco-friendly and adsorbent materials for enhancing indoor air quality in actual construction projects in Dubai. Through two experiments, it analyzed the changes in the concentration of indoor air pollutants over time for each product employed in controlling pollution sources and removing them. Consequently, this study provides precise and dependable data on the effectiveness of these control methods, ultimately supporting the creation of more efficient and sustainable approaches for managing indoor air pollution in buildings.

2. Materials and methods

2.1 Overview of experiment on eco-friendly materials

An experiment was conducted on six apartment units of The Gate Tower (Plate 1) under construction in Sharjah, which aimed to evaluate the effect of eco-friendly building materials on indoor air quality. The experiment involved constructing three units with Dubai Green Building's "excellent" grade materials and three units with "good" grade materials. Please refer to Table 2 for TVOC and HCHO levels for "excellent" and "good" materials. The experiment period was from November 10, 2022, to February 12, 2023, during which 12 measurements were conducted over four months.

Table 1 shows the test period and construction schedule. The construction schedule was divided into "excellent" and "good" units, with the former using the highest-rated paint, flooring, adhesives and wood materials, and the latter using paint, flooring and adhesives with a good rating. An excellent-grade flooring product was used as no PVC flooring material had obtained a good grade. The material application status of "excellent" and "good" households is detailed in Table 2. The experiment examined the concentration change of indoor air pollutants after the furniture was brought in. The experimental and target households' floor plan and photo are as in Figure 1.

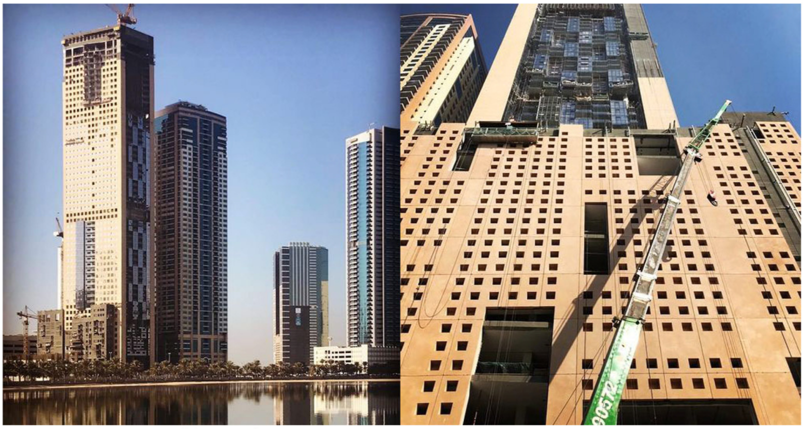

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Plate 1. The Gate Tower, Sharjah

Table 1. Test period and experiment schedule for eco-friendly materials

Target building	Measurement period
Two-bedroom unit - The Gate Tower Al Khan, Sharjah - Three "excellent" units and three "good" units	November 10, 2022–February 12, 2023 (12 measurements) - November 12; initial caulking and wallpaper work - November 20; painting completed - November 26; flooring completed - December 2; furniture move-in completed

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2.2 Overview of experiment on adsorbents

Another experiment was conducted to evaluate the effectiveness of two adsorbent products (A and B) in removing indoor air pollutants through adsorption and catalytic action. Product A is made of white charcoal with artificial oleate, while product B is also white charcoal but with liquid ceramic. The experiment was conducted in two two-bedroom units and one unoccupied unit at the Majestic Tower in Sharjah (Plate 2). The floor plan and photo of the target households are shown in Figure 2.

The adsorbents were commercially available in Dubai, and the experiment was conducted over six months before and after construction. Four measurements were taken during this time to examine the trends in pollutant concentration changes (after 5 days, 44 days and 185 days). In addition to measuring the concentration of pollutants before and after construction, the IAQ improvement effect of the adsorbent was examined by comparing the measurement results of one unoccupied unit without adsorbent. The outdoor and indoor air quality was also measured simultaneously. The experimental period and construction schedule are presented in Table 3.

2.3 Indoor air pollutants measurement and analysis method

The IAQ measurement and analysis method utilized the "Dubai Municipality Indoor Air Quality (IAQ) compliance" notified in 2008. The measurement included six items, such as HCHO, which is a recommended standard for new apartment houses, and major individual substances of VOCs, including benzene (C_6H_6), toluene (C_7H_8), ethylbenzene (C_8H_{10}), xylene

Table 2.
Applied material specifications for "excellent"/"good" units based on Dubai Green Building Regulations and Specifications

Category		Description	"Excellent" grade unit ($\mu g/m^3$)	"Good" grade unit ($\mu g/m^3$)
Living room	Floor	PVC flooring	TVOC < 0.10 HCHO < 0.03	TVOC < 0.10–0.20 HCHO < 0.03–0.05
	Wall	Silk wallpaper	TVOC < 0.10 HCHO < 0.03	TVOC < 0.10–0.20 HCHO < 0.03–0.05
	Ceiling	Water paint	N/A	N/A
Master bedroom	Floor	PVC flooring	TVOC < 0.10 HCHO < 0.03	TVOC < 0.10–0.20 HCHO < 0.03–0.05
	Wall	Water paint	N/A	N/A
	Ceiling	Water paint	N/A	N/A
Child bedroom	Floor	PVC flooring	TVOC < 0.10 HCHO < 0.03	TVOC < 0.10–0.20 HCHO < 0.03–0.05
	Wall	Water paint	N/A	N/A
	Ceiling	Water paint	N/A	N/A
Adhesive	Wallpaper	Wallpaper adhesive	TVOC < 0.25 HCHO < 0.06	TVOC 0.25–0.50 HCHO 0.06–0.12
Kitchen furniture		Frame: particle board Door: MDF	HCHO < 0.5 mg/L	HCHO < 1.5 mg/L
Shoe closet		Frame: particle board Door: MDF	HCHO < 0.5 mg/L	HCHO < 1.5 mg/L
Living room closet		Frame: particle board Door: MDF	HCHO < 0.5 mg/L	HCHO < 1.5 mg/L
Bedroom closet		Frame: particle board Door: MDF	HCHO < 0.5 mg/L	HCHO < 1.5 mg/L

Source(s): Created by author

Figure 1.
Plan and photo of a studied two-bedroom apartment at The Gate Tower

Source(s): Created by author

(C_8H_{10}) and styrene (C_8H_8). The analysis conditions and equipment for measuring VOCs and HCHO are presented in Table 4 and Plate 3, respectively.

3. Results

3.1 Test results for eco-friendly materials

After applying eco-friendly building materials to the six units of The Gate Tower (under construction in Sharjah), indoor air pollutants were measured over time. The experiment was

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Plate 2. The Majestic Tower, Sharjah

Source(s): Created by author

Figure 2. Plan and photo of a studied two-bedroom apartment at the Majestic Tower

Target building	Measurement period
Two-bedroom unit - The Majestic Tower Al Khan, Sharjah - Two two-bedroom units and one unoccupied unit	August 12, 2022–February 14, 2023 (4 measurements) - August 14; test equipment installation - September 21; wallpapers completed - September 26; flooring completed

Source(s): Created by author

Table 3. Test period and experiment schedule for adsorbents

conducted by applying the same "good" and "excellent" grade materials for each of the three units, and the results were averaged from the results of each graded unit. The field test results for eco-friendly materials are shown in Figures 3–8.

3.1.1 Benzene (C_6H_6). The concentration of Benzene (C_6H_6) continuously increased during the experiment period, and then the overall increase in concentration decreased at the point of

Volatile organic compounds (VOCs) Category	Description	Analysis conditions
ATD	Desorb flow/Outlet/Inlet	40 ml/18 ml/0 ml
	Head Pressure/Split Ratio	13.0 psi/10:1
	Desorption	1st (10 min), 2nd (5 min)
	Tube/Trap/Valve/Transfer Temp	300 °C/−30 to 300 °C/175 °C/220 °C
GC/MS	Manufacturer	Agilent 8890 GC
	Temperature program	35 °C > 5 °C/min > 220 °C (10 min) > 10 °C/min >250 °C (6 min)
	Detector	MS
	Column	HP-1 (0.32 mm × 60 m × 1.80 μm)
	Carrier, flow	He (99.999%), 2 ml/min
	Detection energy	TIC (Scan), m/z: 35–350
	Electronic energy	70 ev
	Mode	EI/Scan
HCHO		
HPLC (UV, 360 nm)	Column	Eclipse XDB-C18 5um, 4.6 × 150 mm
	Mobile phase	ACN/Water (50/50 V/V)
	Analysis time	30 min
	Injection volume	10 μl
	Column temperature	25 °C
	Flow rate	1.0 ml/min

Source(s): Created by author

Table 4.
Equipment specifications for VOCs and HCHO analyses

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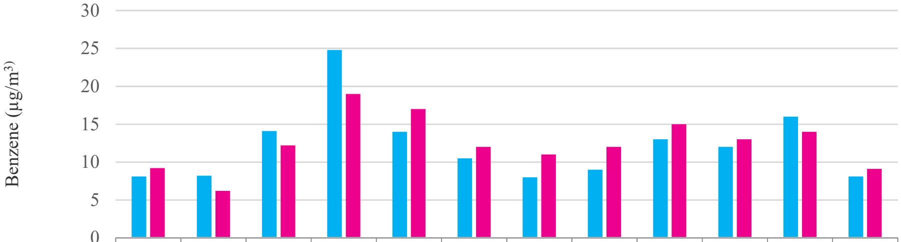
Plate 3.
ATD-GC/MS for VOCs (left), and HPLC for HCHO (right)

furniture move-in. Concentrations, 50 days after the furniture was brought in, decreased by 58% in the "good" unit and by 69% in the "excellent" unit (Figure 3). From the time the furniture was brought in, the concentration of the "excellent" unit was slightly lower than that of the "good" unit.

3.1.2 Toluene (C_7H_8). The concentration of toluene (C_7H_8) tended to decrease gradually while repeating the increase and decrease. In the construction process, the toluene concentrations at both "excellent" and "good" units rise after the wallpaper work is completed. Still, at the time of completion of the flooring, the concentration decreased, and

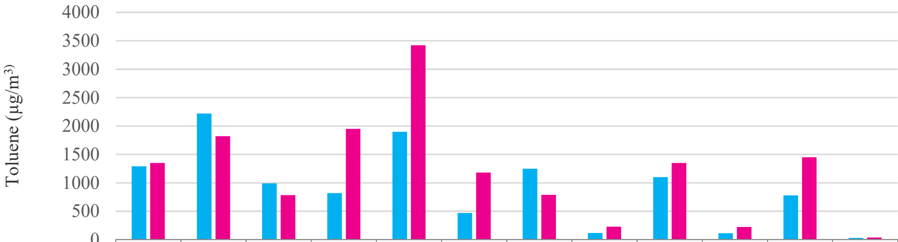


	−21 IW CA PA	−13 WC	−7 FC	0 FM	7	10	14	18	24	31	37	50
Excellent	8.1	8.2	14.1	24.8	14	10.5	8	9	13	12	16	8.1
Good	9.2	6.2	12.2	19	17	12	11	12	15	13	14	9.1

Elapsed Time (Days)

Note(s): IW: Initial Wallpaper/CA: Caulking/PA: Paint/WC: Wallpaper Completion /FC: Floor Completion/FM: Furniture Move-in
Source(s): Created by author

Figure 3. Average concentration of benzene in the eco-friendly material test unit



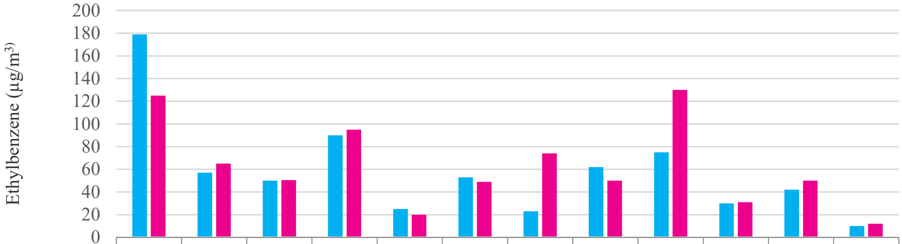
	−21 IW CA PA	−13 WC	−7 FC	0 FM	7	10	14	18	24	31	37	50
Excellent	1290	2220	990	820	1900	470	1250	120	1100	115	780	30
Good	1350	1820	785	1950	3420	1180	790	230	1350	225	1450	40

Elapsed Time (Days)

Note(s): IW: Initial Wallpaper/CA: Caulking/PA: Paint/WC: Wallpaper Completion/ FC: Floor Completion/FM: Furniture Move-in
Source(s): Created by author

Figure 4. Average concentration of toluene in the eco-friendly material test units

even after the furniture was brought in, the concentration tended to rise and then gradually decrease (Figure 4). The pre-move-in period, after the completion of construction and moving in of the furniture, is when the IAQ of the newly built unit is measured and is an important point in determining the degree of pollution of the indoor air of the new housing. Looking at the measurement results of toluene at 0, 7 and 10 days before moving in, it was found that the concentration at "excellent" units was significantly lower than that of "good" units. Toluene is an indoor air pollutant that accounts for the largest portion of VOCs and is also a major item for evaluating the indoor air quality of the target unit.

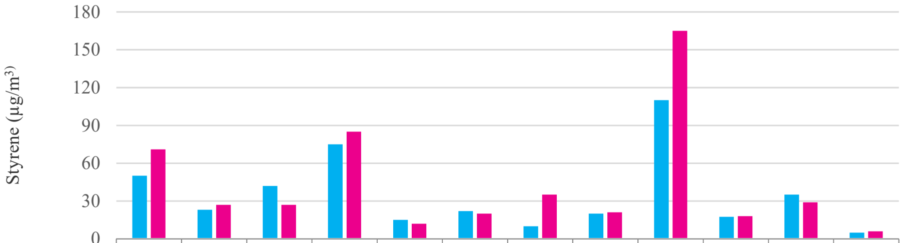


	−21 IW CA PA	−13 WC	−7 FC	0 FM	7	10	14	18	24	31	37	50
Excellent	179	57	50	90	25	53	23	62	75	30	42	10
Good	125	65	50.5	95	20	49	74	50	130	31	50	12

Elapsed Time (Days)

Figure 5.
Average concentration of ethylbenzene in the eco-friendly material test units

Note(s): IW: Initial Wallpaper/CA: Caulking/PA: Paint/WC: Wallpaper Completion /FC: Floor Completion/FM: Furniture Move-in
Source(s): Created by author



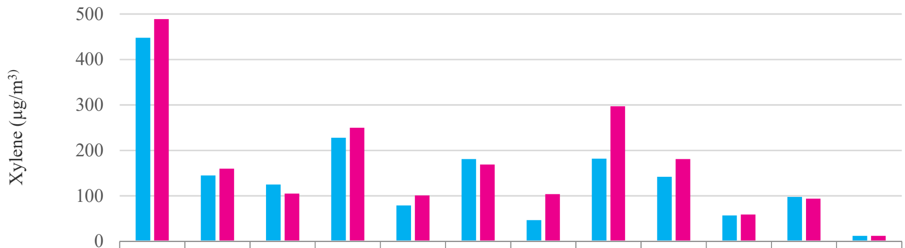
	−21 IW CA PA	−13 WC	−7 FC	0 FM	7	10	14	18	24	31	37	50
Excellent	50	23	42	75	15	22	10	20	110	17.5	35	5
Good	71	27	27	85	12	20	35	21	165	18	29	6

Elapsed Time (Days)

Figure 6.
Average concentration of styrene in the eco-friendly material test units

Note(s): IW: Initial Wallpaper/CA: Caulking/PA: Paint/WC: Wallpaper Completion /FC: Floor Completion/FM: Furniture Move-in
Source(s): Created by author

Compared to the toluene concentration at the beginning of construction, the concentration on the last measurement day, the 50th day, decreased by an average of 97% in both the “excellent” (820 µg/m^3 down to 30 µg/m^3) and “good” (1950 µg/m^3 down to 40 µg/m^3) units. In addition, as a result of measuring 50 days after the materials were installed and compared to the concentration at the time of furniture introduction, the overall concentration in the “excellent” units was lower than the “good” units. Among pollutants, the reduction of toluene was highly effective in improving IAQ.

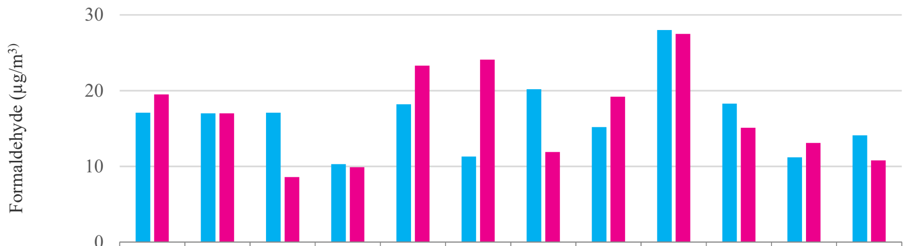


Elapsed Time (Days)	−21 IW CA PA	−13 WC	−7 FC	0 FM	7	10	14	18	24	31	37	50
Excellent	448	145	125	228	79	181	47	182	142	57	98	12
Good	489	160	105	250	101	169	104	297	181	59	94	12

Elapsed Time (Days)

Note(s): IW: Initial Wallpaper/CA: Caulking/PA: Paint/WC: Wallpaper Completion/ FC: Floor Completion/FM: Furniture Move-in
Source(s): Created by author

Figure 7. Average concentration of xylene in the eco-friendly material test units



Elapsed Time (Days)	−21 IW CA PA	−13 WC	−7 FC	0 FM	7	10	14	18	24	31	37	50
Excellent	17.1	17	17.1	10.3	18.2	11.3	20.2	15.2	28	18.3	11.2	14.1
Good	19.5	17	8.6	9.9	23.3	24.1	11.9	19.2	27.5	15.1	13.1	10.8

Elapsed Time (Days)

Note(s): IW: Initial Wallpaper/CA: Caulking/PA: Paint/WC: Wallpaper Completion/ FC: Floor Completion/FM: Furniture Move-in
Source(s): Created by author

Figure 8. Average concentration of formaldehyde in the eco-friendly material test units

3.1.3 Ethylbenzene (C_8H_{10}). In the case of ethylbenzene (C_8H_{10}), the highest concentration value was shown after the completion of the initial wallpaper, caulking and paint. So, the increase in the concentration of ethylbenzene is judged to be due to the influence of the initial wallpaper, caulking material and paint. After the completion of the wallpaper and flooring construction, the concentration continues to decrease without further impact on the indoor environment (Figure 5).

Overall, it satisfies the Dubai Green Building Regulations and Specifications standard of 360 µg/m^3, and the concentration of the "excellent" unit was lower than that of the "good" unit. In the measurement result of the 24th day, the concentration increased rapidly compared to the previous concentration, but the concentration on the 31st day decreased again. The concentration of ethylbenzene (C8H10) decreased by 96% in the "excellent" unit, and by 93% in the "good" unit, compared to the concentration at the initial stage of construction.

3.1.4 Styrene (C_8H_8). Styrene (C_8H_8) seems to gradually decrease in concentration as it fluctuates after the application of eco-friendly materials, and it satisfied the recommended standard of 300 $\mu g/m^3$. The emission concentration of styrene was high when finishing paper and paint, and when furniture was brought in. The concentration gradually decreased thereafter. However, data after the 24th day showed that styrene concentration increased rapidly (Figure 6).

After 24 days, the "good" unit was lower than the "excellent" unit. The concentration of styrene decreased by 92% in both the "excellent" and "good" units compared to the concentration at the initial stage of construction.

3.1.5 Xylene (C_8H_{10}). Like ethylbenzene, the concentration of xylene (C_8H_{10}) was highest after the initial wallpaper, caulking and paintwork, but the concentration decreased again during the construction of wallpaper and flooring. However, the concentration increased as the furniture was brought in. After the 18th day after the furniture was brought in, the overall concentration was high, and then the concentration fluctuated and gradually decreased (Figure 7).

In addition, all units satisfied the recommended Dubai Green Building Regulations and Specifications standard of 700 $\mu g/m^3$. Except for some result values, the "excellent" unit showed a lower concentration than the "good" unit. The concentration of xylene decreased by 97% in the "excellent" unit, and by 98% in the "good" unit, compared to the concentration at the initial stage of construction.

3.1.6 Formaldehyde (HCHO). HCHO generally decreased during material construction, but the concentration increased for about three weeks after the furniture was brought in. The effect of furniture, which is the main source of HCHO, is greater than the effect of interior finishing materials. One month after the completion of the furniture move-in, the three measurement results showed that HCHO concentration gradually decreased in both the "good" and "excellent" units.

As a result of comparing the average concentration of the "good" and the "excellent" units from the point of decrease, the measured concentration after the 31st day was higher in the "excellent" unit than in the "good" unit. Concentrations measured after the 37th day showed the opposite result, and concentrations measured after the 50th day showed higher results in the "excellent" unit.

HCHO decreased by 44% in "good" units and 19% in "excellent" units at the beginning of construction. In the case of HCHO, as with toluene, the measurement results of HCHO on the 7th and 10th day before moving in showed that the concentration of "excellent" units was lower than that of "good" units. However, after the 10th day, the "good" unit showed about twice the concentration.

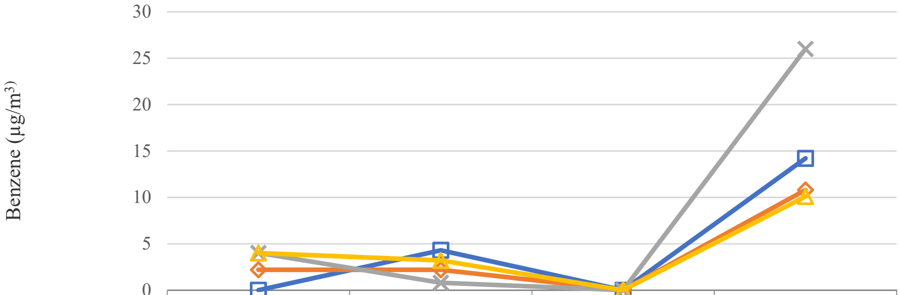
HCHO measurement result showed that the total average concentration was about 20 $\mu g/m^3$, which satisfies the recommended indoor air quality standard of 210 $\mu g/m^3$ for newly built residential buildings. The difference in concentration between the "good" and "excellent" units was not large. So in the case of HCHO, there was no significant difference between the "excellent" and "good" units.

3.2 Test results for adsorbents

An on-site test was conducted at a construction site to evaluate the effectiveness of two adsorbent-related products when applied directly to the building structure. The measurement results were analyzed before and after application (one measurement before application, and three measurements after application at 5, 44 and 185 days). To compare the improvement effect of the adsorbent-applied unit, the indoor air quality of the first apartment unit without adsorbent was measured simultaneously with the outdoor air quality. The field test results for the adsorbent can be seen in Figures 9–14.

Upon examining the results, it was observed that the concentrations of all substances decreased 44 days after construction. However, unexpectedly, the measured concentrations increased again after 185 days.

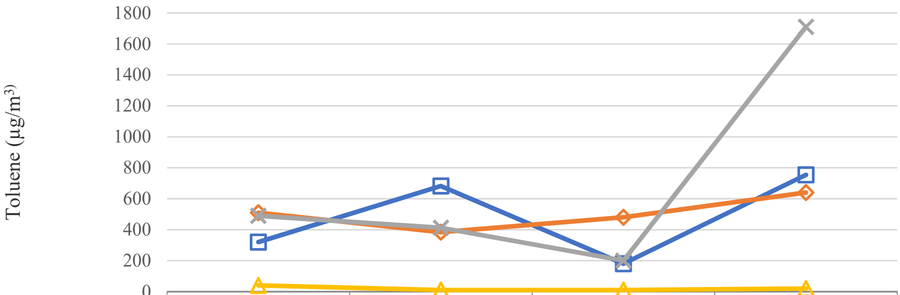
This indicates that the pollutant emission mechanism from the material and the pollutant reduction mechanism by the adsorbent vary over time and are influenced by changes in external environmental conditions. In particular, it is believed that the effect of the adsorbent is still greater than the effect of the passage of time, considering that the external temperature and humidity after 185 days are lower than those after 44 days. The analysis of the



	0 Day	5 Days	44 Days	185 Days
A Product	0	4.3	0	14.2
B Product	2.2	2.2	0	10.8
No Product	4	0.8	0	26
Outdoor Air	4	3.2	0	10.1

Source(s): Created by author

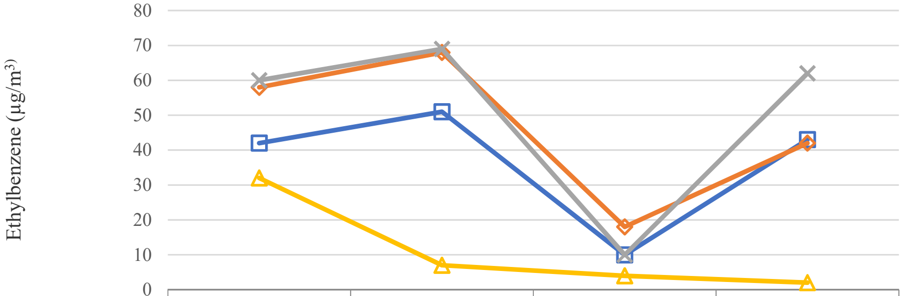
Figure 9. The concentration of benzene in tested units



	0 Day	5 Days	44 Days	185 Days
A Product	320	682	180	754
B Product	510	384	480	640
No Product	490	412	200	1710
Outdoor Air	40	10	10	20

Source(s): Created by author

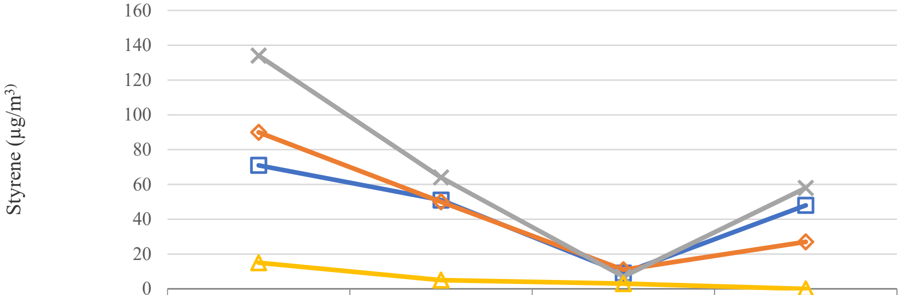
Figure 10. The concentration of toluene in tested units



	0 Day	5 Days	44 Days	185 Days
A Product	42	51	10	43
B Product	58	68	18	42
No Product	60	69	10	62
Outdoor Air	32	7	4	2

Source(s): Created by author

Figure 11. The concentration of ethylbenzene in tested units



	0 Day	5 Days	44 Days	185 Days
A Product	71	51	9	48
B Product	90	50	11	27
No Product	134	64	7	58
Outdoor Air	15	5	3	0

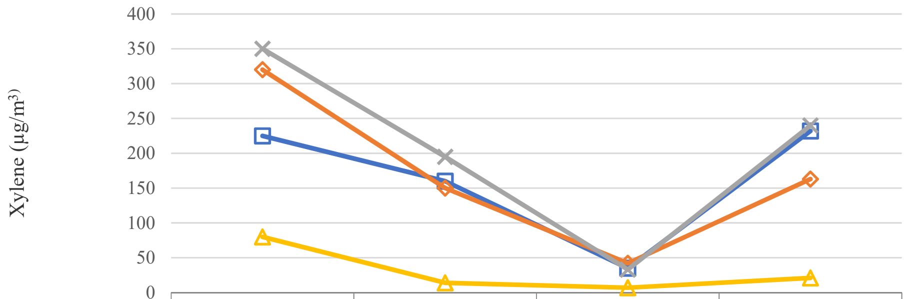
Source(s): Created by author

Figure 12. The concentration of styrene in tested units

experimental results for the adsorbent focused on comparing the rate of indoor air pollutants' concentration change between before and after adsorbent application.

3.2.1 Benzene (C_6H_6). Benzene (C_6H_6) concentration before construction was significantly below the recommended standard of 30 µg/m^3 for newly constructed apartment buildings, and this low concentration was maintained even after five days of application. However, after 44 days, benzene was undetectable in all tested apartment units. Surprisingly, after 185 days, benzene concentration increased more than threefold in all measured units (Figure 9). Notably, the concentration levels in the outdoor air were similar to those observed in product A and B units.

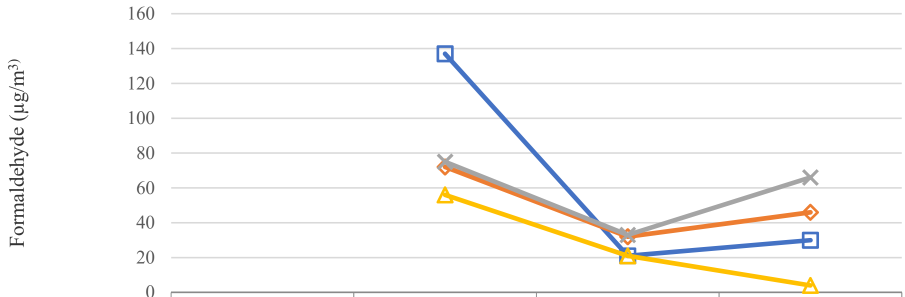
3.2.2 Toluene (C_7H_8). The pre-construction results for toluene indicated compliance with the recommended standard of 1,000 µg/m^3 for toluene (C_7H_8) in new apartment buildings. However, product A pollutant concentration increased in the five-day post-application



	0 Day	5 Days	44 Days	185 Days
A Product	225	160	35	232
B Product	320	150	42	163
No Product	350	195	33	240
Outdoor Air	80	14	7	21

Source(s): Created by author

Figure 13.
The concentration of xylene in tested units



	0 Day	5 Days	44 Days	185 Days
A Product		137	21	30
B Product		72	32	46
No Product		75	33	66
Outdoor Air		56	21	4

Source(s): Created by author

Figure 14.
The concentration of formaldehyde in tested units

results. After 45 days of application, a general decreasing trend in concentration was observed for all tested apartment units except for product B unit. Surprisingly, the concentration increased again after 185 days. Like other substances, the concentrations increased for all households after 185 days of construction (Figure 10).

However, the rate of increase was 347% for product A, 44% for product B and 785% for the apartment unit without adsorbent. The increase rate for households without adsorbent was 2–18 times higher than those with adsorbent. Considering the concentration increase rate, product A showed a 126% increase compared to the initial concentration. Product B exhibited a 24% increase, and considering the increase rate in the unit without adsorbents, it can be concluded that it positively reduces indoor air quality emissions.

3.2.3 Ethylbenzene (C_8H_{10}). The concentration change rate for ethylbenzene (C_8H_{10}) was similar across all tested units. In all tested apartment units, the concentration slightly increased after five days compared to the pre-construction result but rapidly decreased after 44 days. Like other substances, the concentration increased in all households after 185 days of the experiment. However, the concentration increase rate was 340% for product A unit, 187% for product B unit and 455% for the apartment unit without adsorbent. This indicates that the increase in concentration was greater without the application of adsorbents A and B (Figure 11).

When considering the overall rate of change compared to the initial concentration, there was no change (0%) for product A unit, a 25% increase for product B unit and a 2% increase for the apartment unit without adsorbent. These findings suggest that product B has an effect in reducing the concentration of ethylbenzene.

3.2.4 Styrene (C_8H_8). In the case of styrene (C_8H_8), the concentration increase or decrease rate was consistent across all tested units, resembling the overall pattern observed for xylene and other measured substances. Compared to the initial concentration before construction, there was a rapid decrease until 44 days after construction. However, after 185 days, the concentration increased again to a level similar to that observed on the 5th day. Like other substances, the concentration increased in all studied apartment units after 185 days of the experiment. However, the concentration increase rates were 525% for product A, 145% for product B and 729% for apartment units without adsorbent, showing significant increases (Figure 12).

When considering the overall rate of change compared to the initial concentration, product A exhibited a reduction effect of 29%, product B showed a reduction of 70% and there was a 57% reduction in the apartment unit without adsorbent.

3.2.5 Xylene (C_8H_{10}). For xylene (C_8H_{10}), the concentration change rate trend and the overall pattern of increase and decrease across all units were similar to those observed for styrene (C_8H_8). As observed, the concentration of xylene rapidly decreased after 44 days compared to the initial concentration, and then increased again in all units after 185 days (Figure 13).

When examining the overall change rate compared to the initial concentration, product A showed a 5% increase, product B exhibited a 52% increase and the apartment unit without adsorbent demonstrated a 31% decrease, indicating the effectiveness of product B.

3.2.6 Formaldehyde (HCHO). In the case of HCHO, direct comparison between the results before and after construction is challenging due to damage to the sample used for measuring the initial concentration before application. When comparing the results of the third measurement taken 185 days after construction, it can be observed that the concentration of HCHO decreases over time compared to the concentration after five days. Looking at the overall results, the concentration measured after 44 days was higher than that measured after 185 days (Figure 14).

However, even in the case of households without adsorbents, the measured concentration increased after 185 days compared to 44 days. Therefore, the results after the adsorbent application showed a higher concentration decrease rate compared to the unit without adsorbent. In terms of the concentration reduction rate compared to the initial application, product B unit exhibited a reduction rate of 44%, and product A unit exhibited a reduction rate of 27%.

4. Discussion

The experiments on eco-friendly materials revealed that households using the "excellent" materials generally outperformed those using the "good" materials. A significant improvement effect was observed for toluene among the measured pollutants. It was found that toluene (C_7H_8) concentration at the end of the experiments decreased by an average of 97% compared to the completion of construction and furniture move-in (820 $\mu g/m^3$

down to 30 μg/m^3 for "excellent" units, and 1950 μg/m^3 down to 40 μg/m^3 for "good" units), meeting the recommended standard of 1,000 μg/m^3 set by the Dubai Municipality. However, toluene emissions remain above this recommended level in the "good" apartment units even at 37 days, which could cause health issues to occupants who move in early into a newly constructed unit. Besides toluene, it is observed that all other pollutants are well below the Dubai Municipality recommendation level throughout the experiment duration.

The concentration results for all measured pollutants were higher after the furniture was brought in compared to the beginning of construction. This situation is confirmed by Na *et al.* (2019) who conducted emission concentration tests in small chambers using building materials commonly used in apartment houses and found that HCHO emission concentrations were high in wood products. This is perhaps the reason why HCHO concentration in apartments constructed with "excellent" and "good" materials increased from 10.3 μg/m^3 to 14.1 μg/m^3, and from 9.9 μg/m^3 to 10.8 μg/m^3, respectively. The use of non-timber furniture and flooring material could mitigate this issue.

The field test results for the adsorbent demonstrated a gradual decrease in concentration after 44 days of construction compared to the initial concentration. However, after 185 days, the measured concentrations of the tested substances increased simultaneously in all units. Products A and B, the subjects of the experiment, utilize white charcoal as the primary raw material, with the addition of artificial oleate for product A and liquid ceramic for product B. Thus, there may be differences in the construction methods and effects of the two products. It is hypothesized that white charcoal, with its physical adsorption and desorption mechanisms, tends to rerelease contaminants after adsorption.

Although the experiment spanned a relatively long period, the concentration of indoor air pollutants in the target households did not stabilize. Therefore, it was challenging to determine the comparative improvement effects and reduction rates among the products. The analysis primarily relied on relative comparisons between the target units, where all items exhibited increases.

However, for all six measured pollutants, the concentration in households with adsorbents was lower than in the one without adsorbents. Moreover, for toluene, the pollutant with the highest concentration among indoor air pollutants in newly built apartment houses, the rate of increase in households without adsorbents was 246% (1710 μg/m^3) and exceeded the Dubai Municipality recommended level of 1,000 μg/m^3. In comparison, for product A, it was 126% (754 μg/m^3), and for product B, it was 24% (640 μg/m^3), indicating a reducing effect on toluene emissions. In the case of HCHO, product A demonstrated an improvement effect, while product B showed an improvement effect for individual VOCs.

5. Conclusions

This study aimed to investigate the actual indoor air quality improvement and the long-term effects of eco-friendly materials and adsorbents used in new apartment houses. Two field experiments were conducted in newly constructed apartment units, and the concentration changes of indoor air pollutants were measured and analyzed over time for each product. Based on the findings, the following conclusions were made:

(1) It was observed that households using "excellent" materials generally outperformed those using the "good" materials. However, variations were noted depending on the specific material and measurement period. Notably, the concentration of toluene, a crucial indicator of indoor air quality, was significantly lower in the "excellent" households compared to the "good" households. This suggests that using "excellent" materials as specified in Table 2 can be an effective control method for improving indoor air quality.

(2) In the eco-friendly material experiment, most pollutants exhibited a decrease in concentration compared to the initial levels after 50 days of furniture introduction. However, the analysis revealed that the effect on HCHO emission was not substantial.

(3) Ethylbenzene and xylene showed relatively high concentrations following the application of wallpaper, caulking and paint, followed by a rapid decrease in concentration. The changes in concentration for these substances were not considered significant. Other pollutants gradually decreased over time, with fluctuating patterns of increase and decrease.

(4) Product B (white charcoal with liquid ceramic) demonstrated a relatively superior trend among the tested adsorbent products. The increased concentration observed after 185 days is believed to be attributed to the rerelease of adsorbed chemicals. Therefore, further long-term measurements are necessary to understand this phenomenon better besides conducting deeper studies into the characteristics of adsorbent materials.

(5) Considering the rapid increase in pollutant concentrations observed during furniture introduction in the eco-friendly material experiment, it is essential to conduct further research on pollutant evaluation in not just newly constructed housing units but also in occupied households, besides managing and reducing pollutant concentrations.

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