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Analyzing the Bake-Out Effect in Winter for the Enhancement of Indoor Air Quality at New Apartments in UAE

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Abstract: Indoor air pollution has become a pressing issue in the United Arab Emirates (UAE) due to poor ventilation, inadequate airtightness, and using chemicals in building materials. Accordingly, the UAE is currently experiencing more cases of sick building syndrome (SBS) than any other country. This study aims to assess the effectiveness of the bake-out strategy in reducing indoor air pollutants in a new apartment building in the UAE. The study evaluated a reduction in toluene (C_7H_8), ethylbenzene (C_8H_{10}), xylene (C_8H_{10}), styrene (C_8H_8), and formaldehyde (HCHO) at room temperature and relative humidity. The airtight unit without winter bake-out had higher indoor concentrations of hazardous chemicals than the ventilated units, and the emission of dangerous substances increased with temperature. Moreover, harmful chemicals were only effectively reduced with ventilation times of at least seven days after the heating period. The release rate of contaminants after the bake-out was lower than before. The indoor concentration of hazardous chemicals was lower when bake-out and mechanical ventilation were combined, resulting in a reduction of 92.8% of HCHO. Furthermore, units with a certain amount of ventilation maintained a low indoor pollutant concentration, regardless of whether a bake-out was performed.

Keywords: bake-out; indoor air pollutants; hot desert climate; volatile organic compounds; formaldehyde; United Arab Emirates

Citation: Abdelaziz Mahmoud, N.S.; Jung, C. Analyzing the Bake-Out Effect in Winter for the Enhancement of Indoor Air Quality at New Apartments in UAE. *Buildings* **2023**, *12*, 846. https://doi.org/10.3390/buildings13040846

Academic Editors: Lina Šeduikytė, Jakub Kolarik and Christopher Yu-Hang Chao

Received: 31 January 2023
Revised: 7 March 2023
Accepted: 20 March 2023
Published: 23 March 2023

1. Introduction

Recently, the issue of indoor air pollution has become a significant concern in apartments and structures in the United Arab Emirates (UAE), where individuals spend 90% of their time indoors due to the sweltering summers and the absence of a clear demarcation between seasons [1–3]. This is largely due to the lack of ventilation, airtightness, and the utilization of new chemicals in building materials [4–6]. Reports have indicated that sick building syndrome (SBS) is becoming more prevalent in the UAE compared to other countries [7–9]. SBS is caused by the presence of volatile organic compounds (VOCs) and formaldehyde (HCHO), which are produced by finishing or construction materials [10–12]. Consequently, several methods have been proposed to enhance indoor air quality (IAQ), including the use of eco-friendly building materials, ventilation, the utilization of functional auxiliary materials, and management procedures such as bake-out after applying materials [13–15]. Recently, bake-out has gained attention as a strategy for decreasing indoor air pollutants [16–18].

It is worth noting that the concentration levels of VOCs and HCHO in the interiors of public housing in the UAE have surpassed the standard levels [19,20]. Additionally, air conditioning is a standard residential feature that is utilized nearly 24 h a day, year-round. Therefore, it is necessary to consider the specific circumstances in the UAE when implementing remediation techniques, especially since the outdoor concentrations of pollutants were lower than indoor concentrations due to the limited industrial activity in the surrounding area and the relatively low traffic volume during winter in the UAE [21]. While several techniques are available to improve indoor air quality, it is essential to compare the effectiveness of bake-out with other remediation approaches or no remediation at all [22,23]. However, a standardized method for bake-out has yet to be established, particularly for use in apartments [24,25]. The effectiveness of bake-out in reducing indoor air pollutants varies depending on factors such as heating time, temperature, and ventilation status [26,27]. The implementation method of bake-out may differ based on the season [28,29]. Therefore, this study proposes an effective implementation plan for bake-out by evaluating the reduction in indoor air pollutants using the winter bake-out method in a new apartment building in the UAE.

Bake-out is a technique that can reduce or eliminate pollutants and volatile compounds present in building materials by temporarily elevating the room temperature for a specific duration [30]. The buildings' bake-out concept is relatively straightforward. The term refers to the process of intentionally increasing the temperature within a building for a short period to hasten the drying of paints, mastics, or other finishes [31].

The bake-out process has shown promising results in reducing formaldehyde levels in raw wood composite panels. Longer bake-out durations may be required to achieve the desired reductions in formaldehyde concentrations. Given the significant variation in furniture and construction materials across different structures, it is crucial to investigate the bake-out treatment of numerous buildings under various conditions, such as temperature, time, and ventilation rate, before drawing conclusive results [32].

In one study, Park found that raising the room temperature from 30 °C to 50 °C, maintaining it for 24 h, and keeping the ventilation at 1.59 times per hour resulted in a 29% decrease in the total volatile organic compound (TVOC) concentration in both residential and office buildings [33]. Typically, various parameters, such as heating time, heating temperature, and ventilation rate during or after the bake-out, are measured to evaluate the effectiveness of the bake-out [34,35].

Shin et al. conducted a study on the effect of bake-out on a 14-story apartment building with a Reinforced Concrete (R/C) structure 4 months after completion, using a heating temperature of approximately 32 °C and a heating time of 24 h. The study revealed a 23–33% reduction in HCHO and 50% in TVOC concentrations [36]. Notably, indoor relative humidity control during bake-out can significantly affect its effectiveness [37,38]. Despite numerous studies on bake-out, a unified understanding of its efficacy in reducing chemical substances has not been reached [39]. Lv et al. demonstrated that formaldehyde emissions in construction materials mainly originate from water-based treatment agents and solvent-thinned adhesives and have low emission and delayed decomposition rates [40]. External heat sources have been proposed to supplement the existing HVAC system, including electric room heaters for truck-sized systems requiring portable generators [41]. This is due to the impact of different experimental conditions, the lack of a standardized evaluation method regarding heating conditions and evaluation methods, and the influence of finishing material specifications on reducing indoor chemical pollution by bake-out [42,43].

However, a study reported conflicting results from previous research on bake-out due to temperature, humidity, and ventilation variations that affect contaminant concentrations after the treatment [44]. Differences in ventilation requirements and rates during bake-out also contribute to these discrepancies [45,46]. Zuo et al. used simulation to identify optimal implementation conditions for bake-out, including increased ventilation rates during the treatment to minimize adsorption and desorption phenomena [47,48].

To reduce VOCs after construction and before occupancy, Leadership in Energy and Environmental Design (LEED) recommends using flush-out and limiting concentrations to 900 $\mu g/m^3$ for Styrene, 700 $\mu g/m^3$ for Xylene, 300 $\mu g/m^3$ for Toluene, 2000 $\mu g/m^3$ for Ethylbenzene, and 32 $\mu g/m^3$ for Formaldehyde during the first 14 days of occupancy in retail projects. These guidelines should be followed under typical occupancy ventilation conditions.

The research hypotheses are as follows:

- Bake-out reduces indoor air pollutants in apartments located in the UAE.
- Units with airtight construction have higher indoor concentrations of hazardous chemicals without bake-out.
- The emission of hazardous chemicals increases with temperature.

2. Materials and Methods

2.1. Methods for Measurement and Analysis of VOCs and HCHO

Toluene (C_7H_8), Ethylbenzene (C_8H_{10}), Xylene (C_8H_{10}), and Styrene (C_8H_8) were selected as representative VOCs, along with HCHO to evaluate the effectiveness of bake-out in reducing harmful indoor air pollutants [49,50]. In addition, the room temperature and relative humidity were also measured. The measuring equipment used in this experiment is outlined in Table 1.

Indoor air samples were collected after 30 min of ventilation, followed by 5 h of sealing [51,52]. Furthermore, indoor air samples were collected under natural and mechanical ventilation conditions, with front and rear balcony windows open by 10 cm [53]. VOCs were collected by attaching an adsorption tube filled with TenaxTA 200 mg in a 0.6 × 9 cm stainless tube to a low-flow sampling pump (SIBATA) at 150 mL/min for 30 min [54,55]. In the GC/MS system, an automatic thermal desorption device (ATD-400, Perkin Elmer, Waltham, MA, USA) was directly connected to a GC column and was used to analyze the VOCs in standard and emission test samples. Table 1 provides details of the analysis conditions for the GC/MS.

Table 1. The measuring instruments and the related analysis conditions.

Measuring Items		Measuring Instruments	Analysis Conditions
VOCs	Toluene (C_7H_8)	- Gas Chromatograph	- HP-1 Capillary Column
	Ethylbenzene (C_8H_{10})	(Agilent 8890 GC, Agilent, Santa Clara, CA, USA)	(60 m × 0.32 μg/m × 0.25 nm)
	Xylene (C_8H_{10})	- Mass Spectrometer	- Column Low: 1 mL/min
	Styrene (C_8H_8)	(Agilent 5973N MSD, Agilent, Santa Clara, CA, USA) - Thermal Desorber (Agilent 7667A Mini Thermal Desorber, Agilent, Santa Clara, CA, USA)	- MS Ion Source Temperature: 260 °C - Column Temperature Rate: 60 °C (5 min) >> 5 °C/5 min to 260 °C - Split 20:1
Formaldehyde (HCHO)		- High-Performance Liquid Chromatography (Shimadzu 10AVP Series HPLC System, Shimadzu, Kyoto, Japan)	- UV detector: 360 nm - Mobile ACN:H_2O = 60:40 - Extract Acetonitrile: 5 mL
Room Temperature Relative Humidity		- Digital Thermo-Hygrometer (TR-72U, Tecpel, New Taipei City, Taiwan)	

The collection of HCHO samples was carried out using an LpDNPH S10 cartridge (Supelco Inc., Bellefonte, PA, USA), which contains 350 mg of 2,4-DNPH-coated silica (1 mg DNPH) in a 1 cm (id) × 4 cm (total length) polypropylene tube [56]. A low-flow sampling pump (SIBATA) equipped with a flow control device was used, and the total sampling volume was 21 L. To remove interference caused by ozone, an ozone scrubber filled with potassium iodide (KI) in a polypropylene tube was connected to the front of the LpDNPH S10 cartridge to collect samples and then stored in a cold and dark place until extraction [57]. The carbonyl derivative of DNPH formed by the reaction with DNPH was extracted using 5 mL of HPLC-grade acetonitrile. The carbonyl compound from the extracted DNPH derivative was then analyzed using HPLC. The DNPH derivative has light absorption in the ultraviolet (UV) region, and the maximum wavelength was set at 360 nm [58].

2.2. Experiments Location

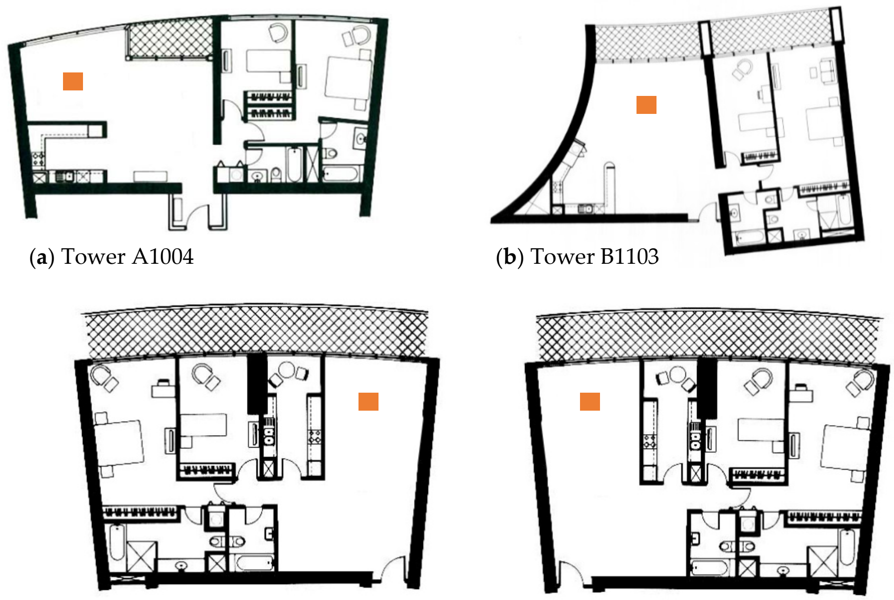
AQAAR constructed the Ajman Corniche Residence on Ajman Corniche Road (Figure 1) in the heart of Ajman Emirate, one of the UAE's Emirates [59,60]. The Residence comprises seven interlinked towers with one, two, and three-bedroom units on the same floor, same direction, and same environmental conditions [61].

Figure 1. Ajman Corniche Residence apartment.

Four apartment units in Tower A1102, Tower B1203, Tower C1501, and Tower D1302 at Ajman Corniche Residence did not undergo bake-out. Tower A1102, Tower B1203, and Tower C1501 maintained airtightness with natural ventilation or operated supply/exhaust ventilation units to keep airtightness [62,63]. Tower D1302, on the other hand, was an experimental unit that only used the exhaust fan of the kitchen range hood instead of the ventilation unit while maintaining airtightness by default, similar to Tower C1501. These experimental units were compared with those that underwent bake-out.

Meanwhile, Tower A1004, Tower B1103, Tower D1404, and Tower E1504 were the 4 units that underwent bake-out. Tower A1004 underwent bake-out as the primary method. Tower A1004 and Tower B1103 underwent bake-out while maintaining ventilation instead of continuous sealing after bake-out to review the appropriate ventilation period. Tower D1404 and Tower E1504 kept airtightness during the bake-out process, but Tower D1404 operated the supply/exhaust ventilation unit throughout the test period. Additionally, Tower E1504 used the exhaust fan of the kitchen range hood instead of the ventilation unit while undergoing bake-out and maintaining different ventilation types [64,65]. The sealing and ventilation conditions of the experimental units are shown in Figure 2. Figure 3 shows the measurement point on the plans of the 4 units consecutively: (a) Tower A1004, (b) Tower B1103, (c) Tower D1404, and (d) Tower E1504. These positions are similar in the 4 apartments at the same height level for the bake-out vacuum ovens (Thermo Scientific™ 3608, Waltham, WA, USA).

Figure 2. Sealed unit (Tower A1102) and ventilated unit (Tower B1203).



(**a**) Tower A1004 (**b**) Tower B1103 (**c**) Tower D1404 (**d**) Tower E1504

Figure 3. The measurement point on the 4 units' plans of the same floor level is (**a**) Tower A1004, (**b**) Tower B1103, (**c**) Tower D1404, and (**d**) Tower E1504.

2.3. The Experiment Design and Process

- Duration: the experiment was conducted between 2 December and 22 December 2020, in empty units prior to occupancy.
- Experimental units: there were 8 units, and Table 2 details each unit's composition and experimental content.
- Area and volume of units: the experiment units had an area of 1558 ft^2 (144.74 m^2) and a volume of 405.27 m^3.
- Ventilation rates: Tower C1501 and Tower D1404 were ventilated at approximately 6.23 ACH (air changes per hour) using the ventilation system. Tower D1302 and Tower E1504 were circulated at about 2.28 ACH through a kitchen exhaust fan.
- Cross ventilation: in the natural ventilation experiment, cross ventilation was achieved by opening the front and rear external windows in Tower B1203.
- Exhaust ventilation: units that employed exhaust ventilation (Tower C1501 and Tower D1404) supplied air from 5 points in each room (bedroom and living room) through a central air supply unit.
- Exhaust vent arrangement: Exhaust vents were placed in one location around the entrance and two areas in the living room to prevent exhaust from mixing with air supplied from the front. The exhaust was then expelled through the exhaust unit installed in the kitchen to the rear balcony.
- Local exhaust: in Tower D1302 and Tower E1504, the local exhaust was achieved using an exhaust fan in the kitchen range hood.

Table 2. Compositions and experiment details.

#	Units	Before Bake-Out	During Bake-Out	Ventilation/Measurement	After Bake-Out	Bake-Out/ No Bake-Out
		2 December 2020	4 December 2020–6 December 2020–8 December 2020	10 December 2020–15 December 2020	15 December 2020–22 December 2020	
1	Tower A1102	Exterior Doors/Windows Kept Sealed				No Bake-out
2	Tower B1203	Exterior Doors/Windows Kept Open (Natural Ventilation)				
3	Tower C1501	Airtight with Air Supply/Exhaust Ventilation				

4	Tower D1302	Airtight with Kitchen Hood Exhaust Fan			
5	Tower A1004	Doors/Windows Sealed	Natural Ventilation	Airtight	Bake-out
6	Tower B1103	Doors/Windows Sealed	Natural Ventilation	Natural Ventilation	
7	Tower D1404	Exterior Doors/Windows are Kept Sealed, and Air Supply/Exhaust Ventilation			
8	Tower E1504	Exterior Doors/Windows are Kept Sealed, and Kitchen Hood Exhaust Fan			

2.4. Bake-out Experiment

The bake-out process involved heating the room to 32–34 °C for 4 days, as shown in Table 2 for Tower A1102, followed by 7 days of ventilation, considering the winter conditions in the UAE, and maintaining an airtight environment. Figure 4 displays the anticipated indoor concentration levels achieved through this method. C2b represents the average indoor concentration before the bake-out process, and C1b indicates the concentration level after 4 days have passed since reaching the target temperature. On the other hand, C2a represents the initial concentration in the room, and C1a represents the concentration level after the bake-out process [66,67]. The indoor concentration level was measured in the same position in all units, including the one where bake-out was not conducted, to compare the concentration variation with the essential bake-out generation [68–70].

All measurement points were based on the primary household of the bake-out in Tower A1102. Before baking (4 December), the concentration level was measured 4 days after reaching the target temperature and maintaining the temperature above 32 °C (8 December). Additionally, measurements were taken after 2 and 7 days of ventilation (10 and 15 December) and when the room was airtight after 7 days (22 December) [71,72]. During the experiment, “during bake-out” refers to the heating period, while “after bake-out” refers to the time after heating ceased and ventilation started, as shown in Figure 4. In total, there were five measurement points, including the initial measurement before the bake-out process, and measurements after four days of heating, two and seven days of ventilation, and seven days of airtight condition.

To summarize, the bake-out process involved heating the room for four days, followed by seven days of ventilation. Measurement points were taken after two and seven days of ventilation and seven days after the room was airtight. The initial measurement was taken before the bake-out process.

Five measurement points were taken in all units, including when the bake-out was not conducted. The initial measurement was taken before the bake-out process. Measures were taken after four days of heating, two and seven days of ventilation, and seven days of airtight condition. Therefore, the total number of VOC and formaldehyde samples collected and analyzed is five.

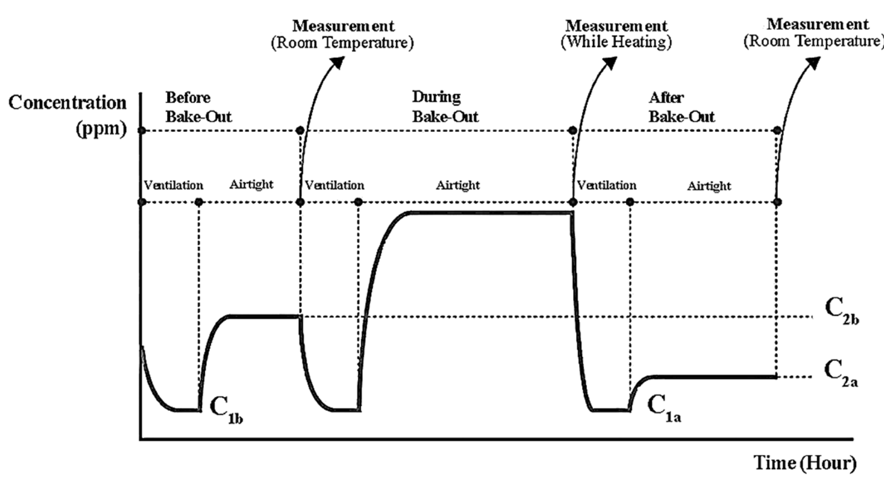


Figure 4. Rising pattern of the indoor concentration of the general bake-out.

3. Results

3.1. Temperature and Relative Humidity (RH) Distribution

Figures 5 and 6 display the indoor temperature and relative humidity (RH) in housing units that did not undergo bake-out, including Tower A1102, Tower B1203, Tower C1501, and Tower D1302. The indoor temperature ranged from 26.3 °C to 33.4 °C, lower than the outdoor temperature. Furthermore, the RH was maintained at approximately 60.5–77.8%, higher than most outside humidity as time passed. In contrast, in the housing units where bake-out was performed (Tower A1004, Tower B1103, Tower D1404, and Tower E1504), the temperature was generally between 26.7 °C and 35.6 °C, confirming the distribution was at the set temperature of 34 °C higher than the outside temperature until the heating period (4–8 December 2020), as depicted in Figure 7. The difference in the indoor temperature distribution between the two-unit groups was found when the temperature was heated for approximately four and seven days after turning off the heating. In the units where bake-out was performed, the RH decreased during the heating period, and there was no significant change as time passed after the heating was finished. The RH distribution was approximately 50.7–77.8%, as presented in Figure 8. Meanwhile, the indoor temperature was relatively higher, and the RH was lower in units that underwent bake-out than those that did not.

In Tower D1404, which had some ventilation and underwent bake-out, and Tower E1504, the temperature ranges were in the field of 31.2–34.5 °C and 32.8–35.2 °C, respectively. Both units reached a sufficient target temperature. Additionally, RH is one of the factors that affect the effectiveness of bake-outs. When the indoor temperature rises during the heating period, moisture in the concrete is released into the room, increasing the generation of hydrophilic substances such as HCHO. This can positively impact the abatement effect but is expected to impair hydrophobic substances such as C_7H_8 and C_6H_6.

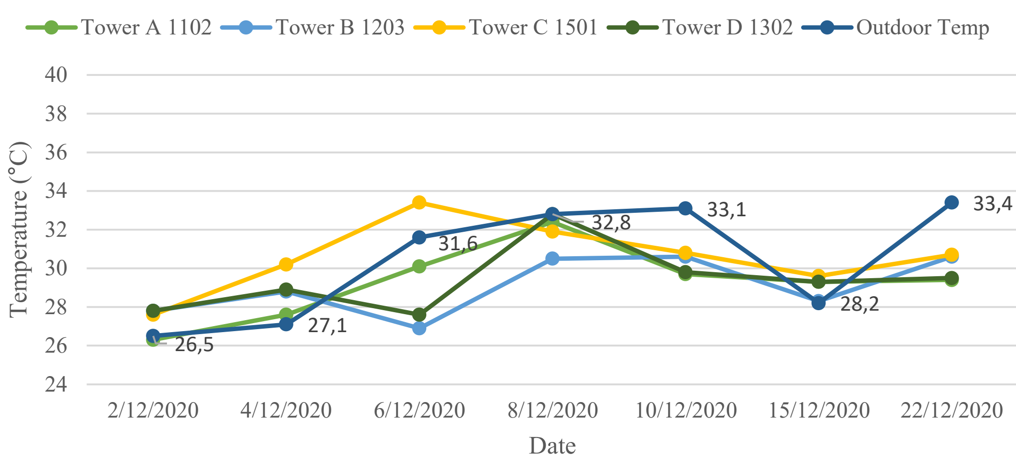


Figure 5. Temperature distribution of the units without bake-out.

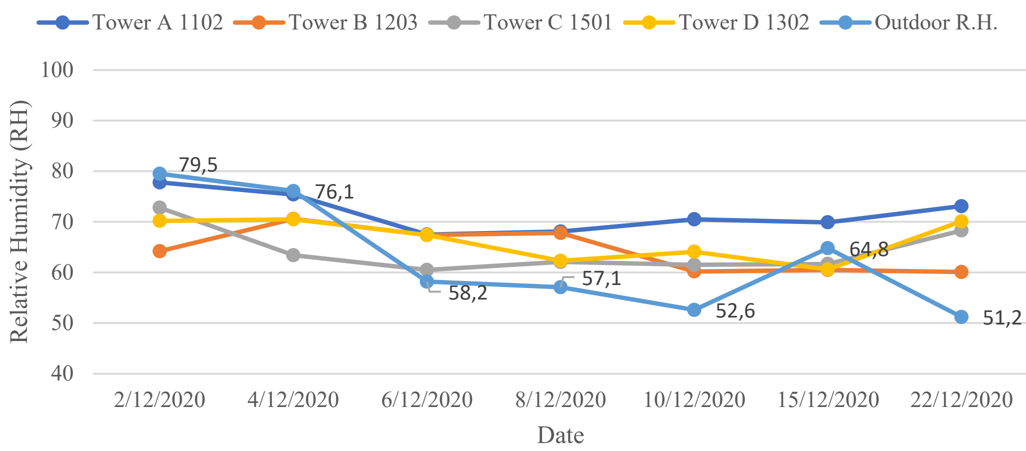


Figure 6. Relative humidity distribution of the units without bake-out.

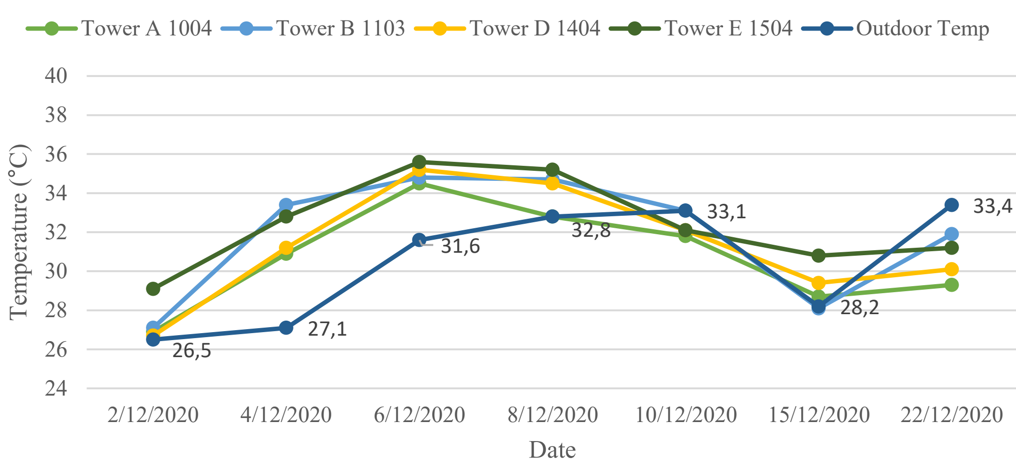


Figure 7. Temperature distribution of the bake-out units.

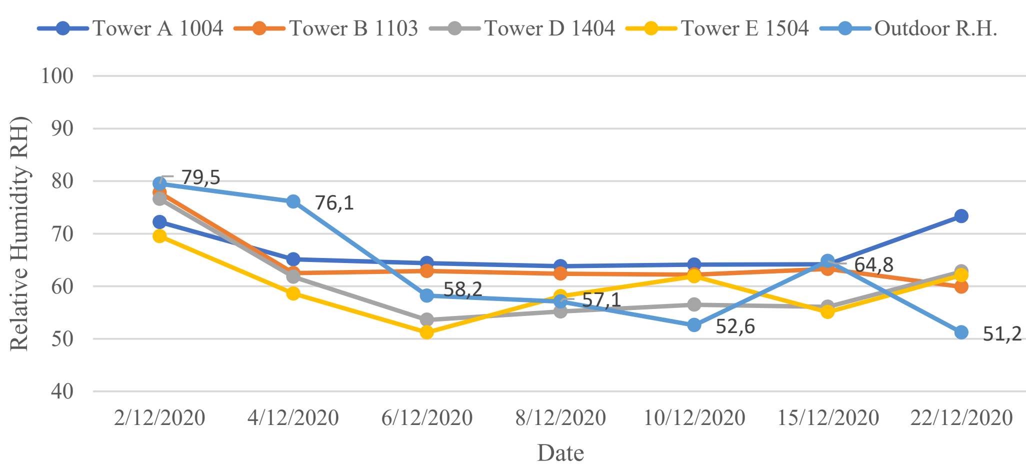


Figure 8. Relative humidity distribution of the bake-out units.

3.2. Characteristics of Changes in Indoor Air Pollutants by Housing Unit

3.2.1. Tower A1102 (Exterior Doors/Windows Kept Sealed)

During the experimental period, the changes in indoor air pollutant concentrations in Tower A1102 were measured by sealing all doors and windows in contact with the outside [51,52]. Figure 9 displays the changes in pollutant concentrations from the test start date (2 December 2020) to 20 days after (22 December 2020). The emission of HCHO increased with indoor and outdoor temperature, resulting in a high indoor concentration that exceeded the recommended standard of 210 μg/m^3 during the experimental period. This confirmed the need to remove and manage HCHO during the winter [51,52]. Additionally, C_7H_8, ethylbenzene (C_8H_{10}), xylene (C_8H_{10}), and C_8H_8 also had high indoor concentrations. Specifically, C_7H_8 had a consistently high concentration that exceeded the recommended standard of 1000 μg/m^3 for 10 days after the start of the test [51,52]. Although the difference between outdoor and indoor temperatures was slight due to winter conditions in the UAE and the openings were sealed during the experimental period, slight concentration reduction and reduction of concentration due to infiltration and adsorption, respectively, can still be predicted.

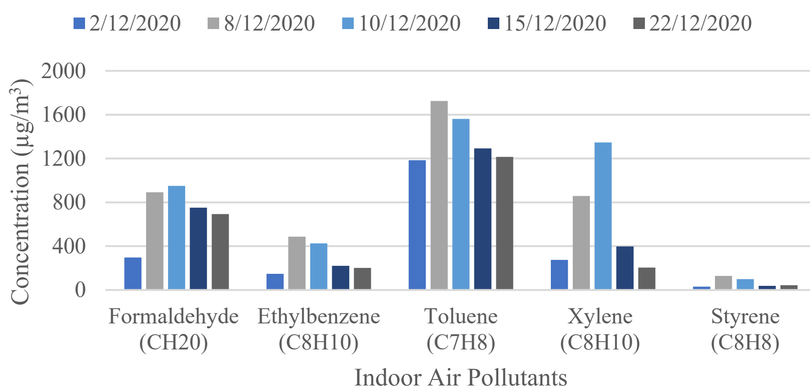


Figure 9. Changes in indoor air pollutants concentration over time (Tower A1102).

3.2.2. Tower (B1203) (Natural Ventilation: Exterior Doors/Windows Kept Open)

The indoor air pollutant concentrations in Tower B1203 were evaluated based on natural ventilation by opening the doors and windows facing the outside by 10 cm during the experimental period to assess the reduction or increase. Figure 10 displays the change in the concentration of each pollutant at the start of the test (2 December 2020) and when 20 days had elapsed (22 December 2020). The air was collected in the experimental unit while maintaining natural ventilation throughout the experiment. Figure 5 illustrates that the temperature distribution was generally lower than the outside temperature, enabling a certain amount of ventilation to ensure that the indoor concentration was much lower than that of the sealed Tower A1102. The measured values up to 22 December showed repeated increases and decreases for each substance. On 22 December, the indoor concentration of HCHO was 58.05 μg/m^3, and C_7H_8 was 298.55 μg/m^3. These values were relatively low compared to the sealed Tower A1102, where the indoor concentration of HCHO was 702.01 μg/m^3, and C_7H_8 was 1242.35 μg/m^3. The two units had different initial values for each substance.

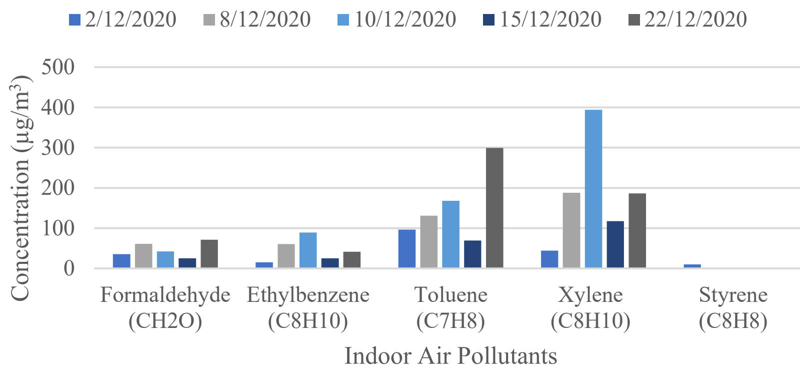


Figure 10. Changes in indoor air pollutants concentration over time (Tower B1203).

3.2.3. Tower C1501 (Airtight with Air Supply/Exhaust Ventilation)

Tower C1501 was evaluated by sealing all the doors and windows in contact with the outside, providing mechanical ventilation, and maintaining ventilation of 6.23 ACH. Figure 11 depicts the change in the concentration of each contaminant at the test start date (2 December 2020) and when 20 days had elapsed (22 December 2020). The measured values up to 22 December, 20 days after the start of the experiment, showed repeated increases and decreases for each substance but revealed a decreasing trend over time. For instance, after 16 days, HCHO slightly increased from the initial value of 130.2 to 141.2 μg/m^3, whereas C_7H_8 decreased from the initial value of 839.6 to 243.4 μg/m^3.

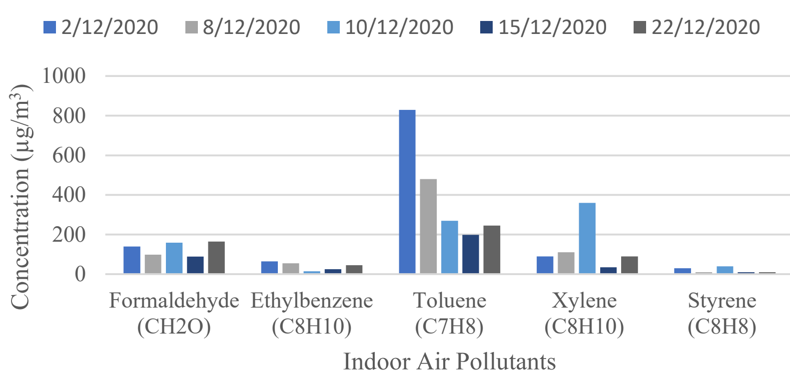


Figure 11. Changes in indoor pollutant concentration over time (Tower C1501).

3.2.4. Tower D1302 (Airtight with Kitchen Hood Exhaust Fan)

The study conducted in Tower D1302 measured the change in hazardous chemicals while maintaining ventilation of approximately 2.28 ACH by operating only the range hood exhaust fan in the kitchen, based on sealing the doors and windows facing the outside. Figure 12 illustrates the change in each contaminant's concentration from the experiment's start date (2 December 2020) to when 20 days had elapsed (22 December 2020). The initial concentration of 1346.29 μg/m^3 was reduced to 175.14 μg/m^3 after 20 days, showing a reduction of about 86.9%. The reduction in pollutants due to bake-out was also confirmed, with ethylbenzene (C_8H_{10}), xylene (C_8H_{10}), and C_8H_8 showing a 29.7% reduction of 55.0%, and 19.9%, respectively.

The indoor concentration of pollutants tended to increase slightly when airtight conditions were maintained for 7 days after 7 days of ventilation (22 December 2020). However, after 3 days of heating, 7 days of ventilation, and 7 days of airtight conditions, it showed a consistent re-increasing phenomenon with the indoor concentration prediction pattern of bake-out presented in Figure 4. This trend was also observed in the case of HCHO, with the release rate from the pollutant increasing during the heating period and the measured values of high contaminants repeatedly increasing and decreasing for up to five days. Overall, there was a decreasing trend over time, with HCHO showing 157.6 from an initial value of 177.9 μg/m^3 and C_7H_8 decreasing from an initial value of 1228.9 μg/m^3 to 429.1 μg/m^3 after 16 days.

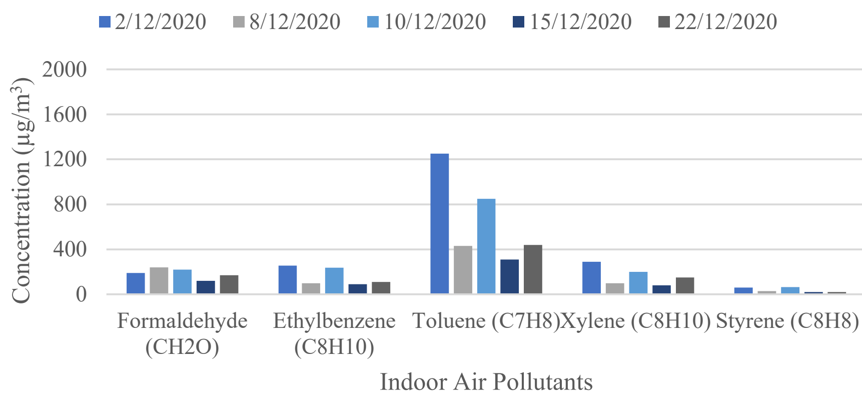


Figure 12. Changes in indoor pollutant concentration over time (Tower D1302).

3.2.5. Tower A1004 (Airtight after Bake-Out)

Tower A1004 serves as the control unit for the bake-out experiment, where the room is sealed for 7 days after the bake-out to measure the indoor pollutants' changes. The primary method of bake-out involves heating the room to a target temperature of 32–34 °C for 3 days, followed by natural ventilation for 7 days. Figure 13 depicts each substance's concentration change from the experiment's start date (2 December 2020) to when 20 days had elapsed (22 December 2020). All substances showed an increasing trend until the 20th day when the temperature was raised, indicating active emission of pollutants from building materials due to the higher target temperature, as shown in Figure 4. The concentration of C_7H_8 decreased after 2 days of ventilation following the bake-out, which was higher than the initial concentration before the bake-out, implying that 2 to 3 days of winter ventilation is insufficient in discharging emitted pollutants. However, the concentration was still high after seven days of ventilation. Additionally, a stable concentration reduction of about 75.6% from the initial concentration of 228.09 to 29.06 μg/m^3 was observed after 7 days. Subsequently, a slight increase was observed after maintaining the seal for seven days.

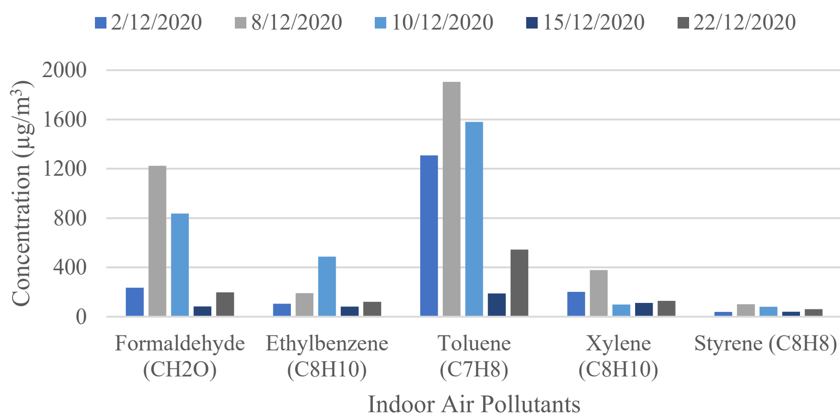


Figure 13. Changes in indoor pollutant concentration over time (Tower A1004).

3.2.6. Tower B1103 (Natural Ventilation after Bake-Out)

Tower B1103 measures the level of pollutant reduction by maintaining natural ventilation continuously after the bake-out. Figure 14 illustrates the changes in the concentration of pollutants at the experiment's start date (2 December 2020) and when 20 days had elapsed (22 December 2020). It was observed that the temperature rises during the bake-out resulted in an increase in the pollutant emission rate.

The concentration of pollutants reduced significantly during natural ventilation for seven days after the bake-out. HCHO was decreased by 92.8%, ethylbenzene (C_8H_{10}) by 70.0%, C_7H_8 by 94.1%, and xylene (C_8H_{10}) by 26.6%. Additionally, C_8H_8 was not detected on the 29th day, confirming that bake-out effectively reduces pollutant concentrations. Moreover, continuous ventilation was carried out throughout the experiment, and no significant concentration increase was observed during this period. Therefore, ongoing ventilation management was found to be necessary even after completing the bake-out process.

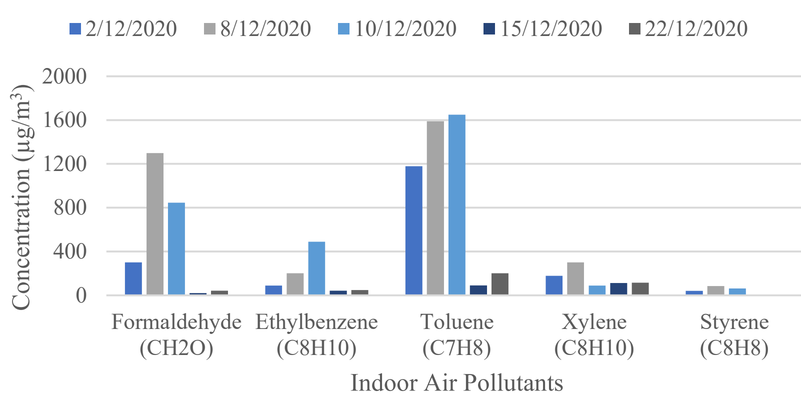


Figure 14. Changes in indoor pollutant concentration over time (Tower B1103).

3.2.7. Tower D1404 (Bake-Out and Air Supply/Exhaust Ventilation Simultaneously)

Tower D1404 performed the bake-out and utilized supply/exhaust ventilation during the experimental period, allowing for the identification of the effects of both bake-out and mechanical ventilation. Unlike other units, this housing unit did not use natural ventilation by opening windows facing the outside world after the bake-out, relying solely on mechanical ventilation. Figure 15 illustrates the change in the concentration of each substance at the beginning of the test and after 20 days.

Low concentrations of pollutants were observed even on the 23rd day of measurement, indicating that the number of pollutants emitted during the bake-out or heating period was minimal in this unit. However, it was confirmed in Figure 4 that the target temperature during bake-out was reached while maintaining mechanical ventilation of 6.23 ACH, which suggests that emissions from finishing materials may have increased. The indoor pollutant concentration remained low due to the continuous discharge of pollutants through the ventilation system. Compared to Tower A1004 and Tower B1103, which were baked out without ventilation, the indoor concentration in Tower D1404 remained relatively low during the experiment, indicating a lower possibility of re-adsorption.

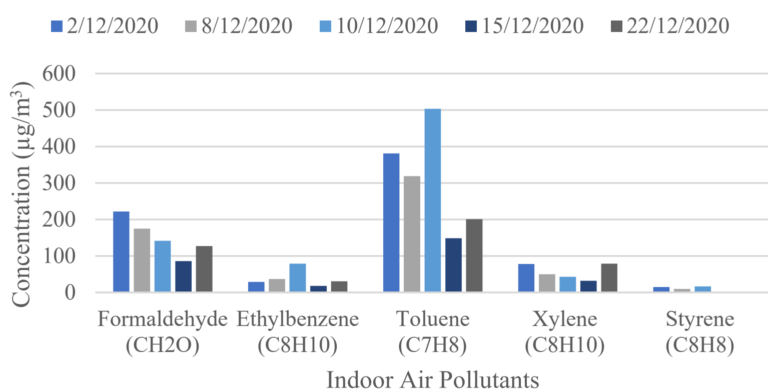


Figure 15. Changes in indoor pollutant concentration over time (Tower D1404).

3.2.8. Tower E1504 (Bake-Out and Kitchen Hood Exhaust Fan Simultaneously)

Tower E1504 conducted a bake-out while operating an indoor hood exhaust fan in the kitchen range. This unit aimed to identify the combined effect of the bake-out and the indoor exhaust fan on indoor pollutants. Instead of opening the outside window, this unit used the indoor exhaust fan for ventilation after the bake-out. Figure 16 illustrates the concentration changes of each contaminant at the beginning of the experiment and after 20 days, and all pollutants demonstrated a stable decrease.

At the start of the experiment, the concentration of C_7H_8 was very high but decreased after the exhaust fan was operated during the heating period of the bake-out. As shown in Figure 4, the experimental unit reached the target temperature due to the characteristics of the UAE winter while maintaining a ventilation rate of 2.28 ACH through the operation of the range hood exhaust fan. It was observed that the pollutants released during the heating period were effectively discharged to the outside through ventilation, similar to the results of Tower D1404.

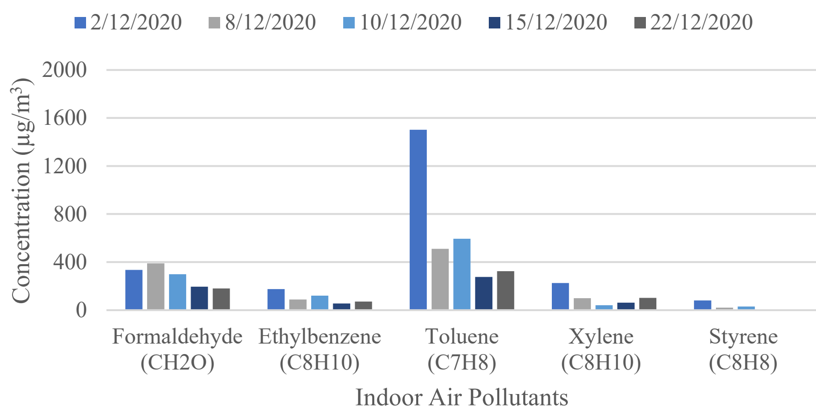


Figure 16. Changes in indoor pollutant concentration over time (Tower E1504).

4. Discussion

The experiments' results show significant changes in indoor air quality in all the units which applied or did not use the bake-out procedure in the new apartment in the hot desert climate in the UAE.

4.1. Units without Bake-Out

Figures 17 and 18 display the results of an experimental study conducted in Tower A1102, where the building was sealed. The levels of HCHO and C_7H_8 were measured and compared to those of Tower B1203, which had natural ventilation. The study observed that in Tower A1102, HCHO increased from 311 µg/m^3 to 670 µg/m^3, and C_7H_8 increased from 1189 µg/m^3 to 1224 µg/m^3. Conversely, Tower B1203 with natural ventilation had lower concentrations, with HCHO increasing from 35 µg/m^3 to 71 µg/m^3 and C_7H_8 increasing from 96 µg/m^3 to 299 µg/m^3 over time.

The study also investigated the effects of different ventilation conditions on the concentrations of HCHO and C_7H_8. When Tower C1501 had a sealed ventilation unit, HCHO slightly increased from 140 µg/m^3 to 165 µg/m^3, while C_7H_8 decreased from 830 µg/m^3 to 245 µg/m^3. Similarly, when Tower D1302 had a closed hood exhaust fan, HCHO slightly increased from 140 µg/m^3 to 165 µg/m^3, while C_7H_8 slightly decreased from 190 µg/m^3 to 170 µg/m^3.

These results support previous research indicating that airtight conditions increase HCHO concentrations. However, the study also found that exhaust ventilation positively impacts the concentration of C_7H_8. The findings suggest that using exhaust ventilation systems can effectively reduce C_7H_8 concentrations but may not have the same effect on HCHO concentrations.

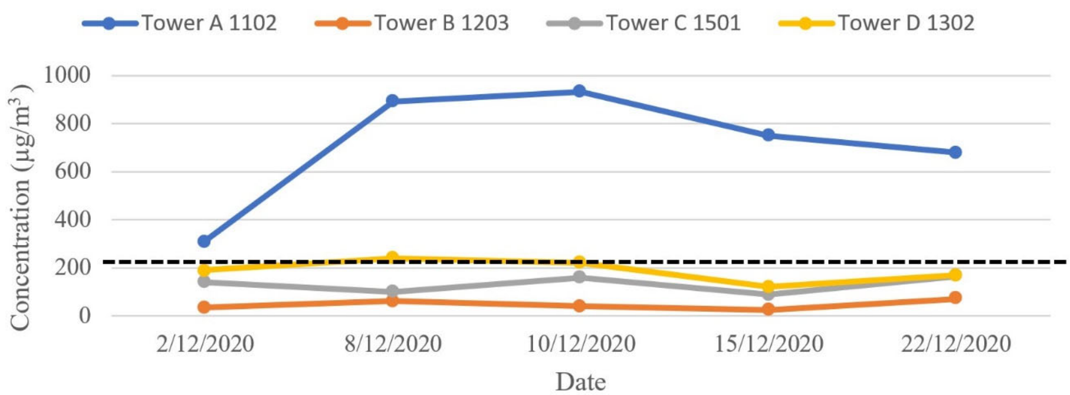


Figure 17. Comparison of HCHO concentration by units without bake-out (the dashed line shows the international standard level).

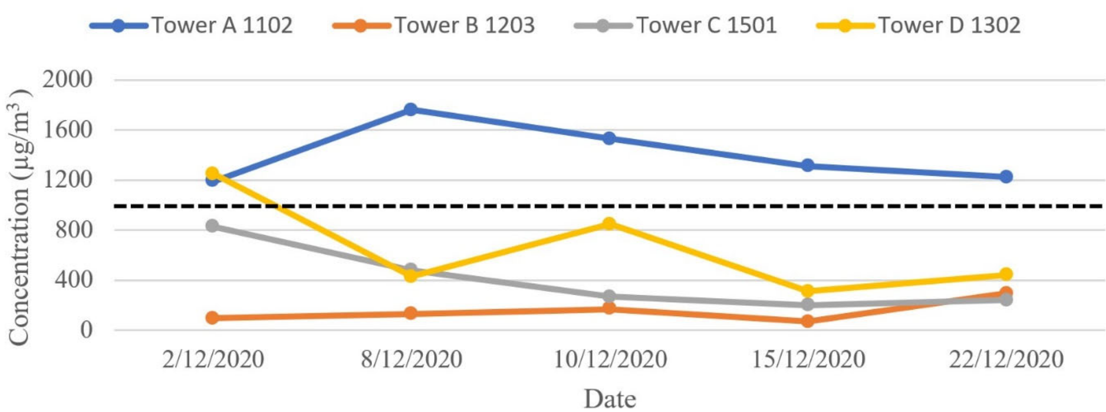


Figure 18. Comparison of C_7H_8 concentration by units without bake-out (the dashed line shows the international standard level).

4.2. Units with Bake-Out

Figures 19 and 20 present the results of bake-out treatments conducted in different units. In Tower A1004, which was sealed after the bake-out, HCHO decreased from 236 μg/m³ to 198 μg/m³, with an interstitial measurement of 1224 μg/m³, and C_7H_8 decreased from 1309 μg/m³ to 546 μg/m³, with an interstitial height of 1905 μg/m³. Meanwhile, in Tower B1103, which had natural ventilation continuing after the bake-out, HCHO decreased from 301 μg/m³ to 42 μg/m³, with an interstitial measurement of 1298 μg/m³, and C_7H_8 decreased from 1178 μg/m³ to 201 μg/m³, with a measurement of 1650 μg/m³. A comparison of pollutant concentration changes is shown for Tower D1404, which used bake-out and exhaust ventilation, and Tower E1504, which used both exhaust ventilation and the kitchen range hood's exhaust fan. In Tower D1404, HCHO decreased from 222 μg/m³ and 334 μg/m³ to 127 μg/m³ and 180 μg/m³, and C_7H_8 decreased from 381 μg/m³ and 1502 μg/m³ to 201 μg/m³ and 325 μg/m³.

The effectiveness of bake-out treatments depends on various factors, such as the temperature dependence of pollutant emission rates from building materials, adsorption and desorption phenomena, and ventilation rates. The emission rate of pollutants from building materials increases with temperature, and ventilation rates play a critical role in reducing pollutant concentrations. Additionally, the initial indoor pollutant concentrations varied across units, with Tower B1203 relying on natural ventilation, while

Tower C1501 and Tower D1302 had mechanical ventilation of 2.28 ACH from a hood fan and 6.23 ACH from exhaust ventilation, respectively.

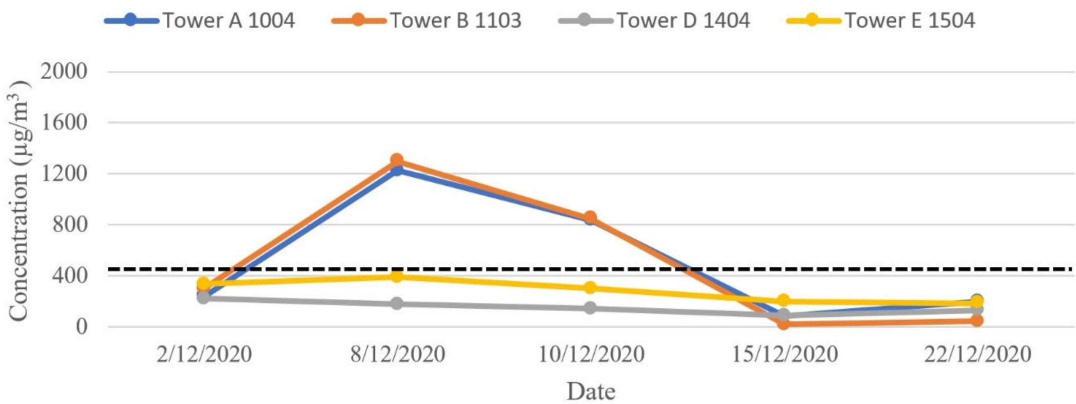


Figure 19. Comparison of HCHO concentration by units with bake-out (the dashed line shows the international standard level).

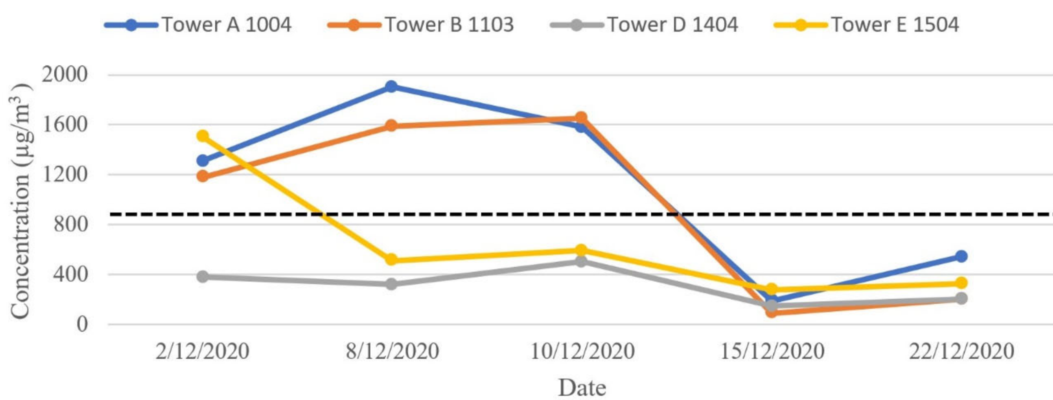


Figure 20. Comparison of C_7H_8 concentration by units with bake-out (the dashed line shows the international standard level).

During the experimental period, Tower A1102, which is an airtight unit, had indoor pollutant concentrations that exceeded recommended standards [51,52]. This highlights the need for specific management strategies to maintain indoor air quality during winter in the UAE, as the small temperature difference between indoor and outdoor environments makes ventilation difficult and causes pollutants to dissipate slowly [2,19].

In contrast, Tower D1404 and Tower E1504, which utilized mechanical ventilation systems (including ventilation units and range hood exhaust fans) and bake-out simultaneously, exhibited a continuous decrease in indoor pollutant concentrations, resulting in relatively low levels. On the other hand, Tower A1004 and Tower B1103, which lacked ventilation during the bake-out, exhibited extremely high concentrations during the heating period.

Furthermore, Tower D1404 and Tower E1504 reached the target temperature in the UAE winter, even with a certain level of ventilation during the bake-out heating period. Additionally, these towers had significant pollutant emissions from finishing materials. However, using ventilation systems ensured that pollutant concentrations remained low, as indicated by the analysis. Therefore, paying close attention during the bake-out process makes it possible to prevent the re-emission of contaminants effectively.

Figures 19 and 20 provide evidence that Tower A1004 and Tower B1103, which underwent bake-out, increased indoor air temperature and subsequent emissions from building materials that demonstrated temperature dependence. In Tower A1004, indoor pollutant concentrations slightly increased after 7 days without bake-out and sealing, indicating that reduced ventilation volume resulting from sealing led to an increase in the release rate of pollutants from the source. Furthermore, the indoor pollutant concentration pattern caused by the bake-out showed that the release rate of indoor contaminants decreased after the bake-out, as shown in Figure 4.

During the bake-out process, no indoor hazardous chemicals were discharged on 8 December 2020, when the air conditioner was turned off, or on 10 December 2020, when ventilation was performed for 2 days in Tower A1004 and Tower B1103. It was only on 15 December 2020, after 7 days of ventilation, that pollutant concentrations were sufficiently reduced.

This study provides important insights into the effectiveness of various methods for reducing the concentration of hazardous chemicals in indoor air during the winter in the UAE. However, it is essential to acknowledge the study's limitations to ensure that its findings are interpreted within their appropriate context.

Firstly, the study only measured indoor pollutant concentrations during limited ventilation periods, with the most extended period being seven days. Further sub-division of the intervals is necessary to determine the appropriate ventilation period to reduce indoor pollutants. Therefore, while the study provides valuable insights into the effectiveness of bake-out and mechanical ventilation in reducing indoor pollutants' concentration, more extensive research is required to establish the optimal ventilation periods.

Secondly, the study's findings indicate that the reduction effect of hazardous chemicals through bake-out is limited under certain conditions, and pollutant concentrations may increase when ventilation is stopped. Although the study's results suggest that sufficient ventilation time after bake-out is critical to reducing hazardous chemicals in indoor air, the effects of re-diffusion after bake-out were not fully understood. Thus, further research is needed to better understand the re-diffusion phenomenon and determine its implications for indoor air quality.

Finally, the study also highlights the need for future research to elucidate the mechanisms affecting building pollutant concentration, such as the surface layer of building materials, temperature, and ventilation volume. Obtaining more reliable results from field experiments requires a better understanding of these factors and their effects on indoor air quality.

In conclusion, while this study's findings are valuable, they should be interpreted in light of its limitations. Addressing these limitations through further research can lead to more comprehensive and reliable findings, informing future efforts to improve indoor air quality.

5. Conclusions

The study offers valuable insights into the effectiveness of different methods for reducing the concentration of hazardous chemicals in indoor air during winter in the UAE. The results demonstrate that implementing bake-out can effectively lower the concentration of harmful substances in units, but the effectiveness is limited when maintaining a temperature of 32–34 °C for 72 h and providing ventilation for only 7 days by opening windows and doors. The study emphasizes the need for sufficient ventilation time after bake-out completion to reduce hazardous chemicals in indoor air effectively. However, the study only measured indoor concentration during ventilation periods of two and seven days, and further subdivision of the intervals is necessary to determine the appropriate ventilation period.

Furthermore, the study found that the concentration of hazardous chemical substances increased when the seal was maintained for seven days compared to the case where ventilation was continued after bake-out completion. Further research is needed to understand the re-diffusion phenomenon after bake-out by observing the changing trend over seven days or more. The study also suggests that future research should investigate the mechanisms affecting the surface layer of building materials, temperature, and ventilation volume to obtain more reliable results based on the findings of these field experiments.

- The study documents a significant reduction of more than 70% for HCHO, highlighting the need for intensive management of emitted pollutants under high indoor temperatures to reduce harmful chemicals in indoor air in the UAE during winter.
- In Tower A1102, without bake-out during winter, the indoor concentrations of hazardous chemicals were HCHO = 931 μg/m^3 and C_7H_8 = 1761 μg/m^3.
- Tower B1203, Tower C1501, and Tower D1302 with ventilation had significantly lower concentrations of HCHO and C_7H_8 than Tower A1102.
- Performing bake-outs in Tower A1004 and Tower B1103 during winter in the UAE resulted in reduced hazardous chemicals, but the reduction effect is limited.
- To effectively reduce harmful chemical substances during winter in the UAE, sufficient ventilation time of at least seven days after bake-out is necessary.
- Concentrations of hazardous chemical substances increase when ventilation is not continued after bake-out, and future research is necessary to understand the re-diffusion phenomenon.
- During winter in the UAE, indoor pollutant concentration can be maintained low through ventilation, even during heating.
- Units with natural or mechanical ventilation maintained low indoor pollutant concentrations regardless of whether they performed bake-out.

After conducting the study, it can be concluded that managing the pollutants emitted in indoor air during high indoor temperatures is crucial to reduce the concentration of harmful chemicals in indoor air during winter in the UAE. In addition, the study indicates that a combination of bake-out and mechanical ventilation can effectively reduce indoor pollutant concentration during winter in the UAE. Moreover, it was observed that units with specific ventilation types, including natural or mechanical ventilation, maintained low indoor pollutant concentration levels, regardless of whether they underwent bake-out.

Furthermore, the study highlights the importance of securing sufficient ventilation time after bake-out. This is because hazardous chemical substances can only be effectively reduced when sufficient ventilation time of at least seven days is provided after bake-out during winter in the UAE. It was also observed that the concentration of hazardous chemical substances increases when ventilation is not continued after the bake-out. Therefore, future research is necessary to understand the re-diffusion phenomenon.

To obtain more reliable results based on the field experiments, the study suggests conducting future research to elucidate the mechanisms affecting the surface layer of building materials, temperature, and ventilation volume. This would help to develop more effective methods for reducing indoor pollutant concentration in the UAE during winter.

Author Contributions: C.J. and N.S.A.M. identified and secured the example buildings used in the study. The data acquisition system was designed, and C.J. and N.S.A.M. installed the sensors. N.S.A.M. was responsible for data collection. C.J. and N.S.A.M. performed data analysis. The manuscript was compiled by C.J. and reviewed by N.S.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: New data were created and analyzed in this study, which can be shared upon request at the authors' consideration.

Acknowledgments: The authors would like to express their gratitude to Ajman University for APC support and to the Healthy and Sustainable Buildings Research Center at Ajman University for providing an excellent research environment.

Conflicts of Interest: The authors declare no conflict of interest.

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