Future Cities and Environment

Correlating Temperature, Airtightness, and Pollutant Concentrations: Insights into Indoor Air Quality in Ajman Apartment Buildings

TECHNICAL ARTICLE

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ABSTRACT

This paper presents a comprehensive assessment of indoor air quality (IAQ) in newly constructed apartment buildings in small and medium-sized cities, with a specific focus on formaldehyde (HCHO) and volatile organic compounds (VOCs) as major contributors to sick building syndrome (SBS). The study aims to measure using the World Health Organization (WHO) process test method and compare the concentrations of HCHO and TVOC indoors and outdoors, assess the indoor temperature levels, evaluate the airtightness performance, and analyze the impact of these factors on IAQ. The research was conducted in Yasmeen Tower and Al Wahat Tower in Ajman Al Jurf area. The results showed that in Yasmeen Tower, unoccupied one-bedroom units had high concentrations of HCHO and TVOC. The average HCHO concentration was 198 μg/m^3, with the highest recorded concentration at 265 μg/m^3. The average TVOC concentration was 1,244 μg/m^3. In Al Wahat Tower, even higher levels of HCHO were observed. The highest recorded concentration reached 445 μg/m^3, with an average of 323 μg/m^3. Airtightness performance was assessed, with the effective leakage area ranging from 139 cm^2 to 301 cm^2 for the 7 units, averaging at 193 cm^2. One-bedroom units exhibited higher airtightness. Correlation analysis revealed a strong relationship between room temperature and both HCHO and TVOC concentrations, indicating that higher room temperatures were associated with increased pollutant levels. Moreover, improved airtightness performance correlated with decreased HCHO and TVOC concentrations. The findings emphasize the importance of effective ventilation systems, temperature control, and airtightness measures to mitigate indoor air pollutants and enhance IAQ in multi-unit dwellings. The study provides valuable insights for policymakers, architects, and residents to address IAQ concerns and promote healthier indoor environments. However, the study's limitations should be considered, and further research is recommended to broaden the understanding of IAQ in residential buildings.

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1. INTRODUCTION

Apartments in Dubai have gained significant attention as a housing solution that accommodates numerous households on limited land (Alawadi, 2017; Alawadi, Khanal and Almulla, 2018; Mushtaha *et al*., 2021). In the United Arab Emirates (UAE), the prevalence of apartment housing is on the rise, not only in Dubai but also in Sharjah and Ajman. Compared to conventional residential buildings, apartments offer the advantage of reduced cooling energy consumption, as they have fewer exterior walls exposed to the outside environment (Costanzo *et al*., 2019). Moreover, they provide cost efficiencies by enabling the construction of multiple households simultaneously, resulting in reduced construction costs per unit floor area (Alawadi and Benkraouda, 2019). Currently, it is evident that the proliferation of apartment housing is unstoppable, given the prevailing circumstances (Alawadi, Khanal and Almulla, 2018).

In the context of apartments, particularly in the case of core-type structures, addressing the issue of inadequate ventilation presents a significant challenge. Due to the overlapping nature of households in all directions – upward, downward, left, and right – there are limited external-facing walls, resulting in minimal natural airflow or infiltration. Furthermore, tower-type apartment buildings, which have gained popularity in recent times, pose challenges for cross-ventilation, thereby limiting the use of natural ventilation strategies (Choi and Kim, 2023). In response to these concerns, Dubai Municipality has implemented regulations stipulating a minimum ventilation requirement in line with the latest edition of ASHRAE Standards 62.1, 62.2 and 170 for all new buildings (Dubai Municipality, 2020). However, this approach may not be considered a comprehensive solution, as it may not be the most practical method for the actual occupants (Awad and Jung, 2021). Besides, such a regulation is unavailable in Ajman.

Additionally, newly built apartments face another air quality issue known as Sick Building Syndrome (SBS) (Jung and Al Qassimi, 2022). As new construction materials are introduced and an array of convenient and aesthetically pleasing products incorporating novel chemical industrial materials enter the market, there is an increasing risk of indoor air quality deterioration. Many individuals who move into new residences may experience health issues such as atopic dermatitis, nasal congestion, and cough-induced asthma (Jung, C and Awad, J, 2021). This problem is especially pronounced for children and the elderly, who spend more time in apartment buildings than adults and have weaker immune systems, exacerbating the impact on their well-being (Arar and Jung, 2021; Jung *et al*., 2021).

The primary causes of sick house syndrome are Formaldehyde (HCHO) and Volatile Organic Compounds (VOCs) (Jung and El Samanoudy, 2023). These indoor air pollutants are predominantly produced in newly constructed or renovated buildings and are emitted from various sources such as adhesives, polishes, paints, and tiles (Jung, Alqassimi and El Samanoudy, 2022). Even in small quantities, they can significantly impact human health (Arar, Jung and Al Qassimi, 2022).

In 2013, the Public Health and Safety Department of Dubai Municipality took the initiative to conduct an extensive assessment of IAQ in various public buildings, encompassing educational institutions, universities, schools, nurseries, kindergartens, and healthcare centers. This comprehensive evaluation led to the establishment of stringent regulations governing IAQ standards. As per the established guidelines, the presence of HCHO should not exceed 0.08 parts per million (ppm), while the levels of Total Volatile Organic Compounds (TVOC) must not exceed 300 micrograms per cubic meter (μg/m^3) (Arar and Jung, 2022). Additionally, suspended particulate matter measuring less than 10 microns in size (PM_{10}) should not surpass 150 g/m^3 during continuous monitoring over an 8-hour period prior to occupancy (Arar and Jung, 2022). These stipulations were implemented to ensure the maintenance of optimal IAQ conditions, promoting a healthy and safe environment for occupants in these public buildings.

1.1. SBS AND WHO IAQ STANDARDS

Sick Building Syndrome (SBS), which primarily stems from HCHO and VOCs emitted by building materials, has gained significant attention as a research area in the last decade (Sherzad and Jung, 2022). Symptoms associated with SBS include irritation of the eyes, nose, and throat, as well as headaches, fatigue, difficulty concentrating, and occasionally dizziness, nausea, and chest tightness (Jung and Mahmoud, 2022). Table 1 provides an overview of the effects of each hazardous substance on the human body.

As shown in Table 2, unrated building materials, including adhesives, varnishes, paints, and tiles used in newly constructed or renovated buildings, are major sources of these chemicals. Even in small amounts, these chemicals can have a significant impact on the human body (Arar, Jung and Al Qassimi, 2022). HCHO is released from wood, plywood, and furniture, while VOCs are emitted from textile products found in household appliances (Arar, Jung and Al Qassimi, 2022).

Table 3 presents the IAQ standards of the World Health Organization (WHO), outlining their comprehensive regulations and detailed specifications based on the duration of exposure.

1.2. AJMAN AND UAE BUILDING STANDARDS

Ajman is the location for the selected case studies as it is a unique city in the UAE where most of its inhabitants live in apartment buildings rather than landed dwellings. This situation is in contrast to cities

HAZARDOUS SUBSTANCES		SOURCES	THE EFFECTS ON HUMAN BODY
Formaldehyde (HCHO)		- Plywood, Particle board - Urea/Melamine/Phenolic Synthetic Resin	- May cause cancer - Minor irritation to the eyes - Possible sore throat
Volatile Organic Compounds (VOCs)	Benzene (C_6H_6)	- Dye, Organic pigment, Plasticizer - Chemical Intermediates for Synthetic Rubber, Nitrobenzene, Phenol and Synthetic Compounds	- May cause cancer - Dizziness during acute exposure, Vomiting, headache, drowsiness, - Effects on the central nerve system
	Toluene (C_7H_8)	- Solvent Thinner for Adhesive Paint, - Construction Adhesive	- Eye or airway irritation when exposed to high concentrations - Fatigue, vomiting - Effects on the central nerve system
	Ethylbenzene (C_8H_{10})	- Building Materials and Furniture using Adhesives	- Irritation to the throat or eyes - Prolonged skin contact may cause dermatitis
	Xylene (C_8H_{10})	- Interior Fit-out Adhesive - Building Materials and Furniture using Adhesives	- Central nerve system depressant action - Inducing fatigue, headache, insomnia, excitement, etc.
	Styrene (C_8H_8)	Adhesive Raw Material - Synthetic Resin Paint - Insulation and Carpet	- Affects the lungs and central nerve system - Causing drowsiness or dizziness

Table 1 The Effects of Hazardous Substances on the Human. Adapted from (Jung, Mahmoud and Alqassimi, 2022).

SOURCE		POLLUTANTS
Mechanical Eelectrical Plumbing (MEP)	Heating Equipment	Carbon Dioxide (CO_2), Carbon Monoxide (CO) Nitrogen Dioxide (NO_2), Total Suspended Particles (TSP)
	Air Purifier, Copier	Ozone (O_3), Total Suspended Particles (TSP)
	Humidifier	Bacteria, Fungi, Water Vapor
	Air-Conditioner	Bacteria, Fungi, Legionella
Building Material	Wood, Plywood	HCHO
	Paints	HCHO VOCs
	Carpet, Curtain	Mite, Fungi, Total Suspended Particles (TSP)
	Concrete, Gypsum Board	Radon
Misc.	Soil	Radon, Legionella, Water Vapor

Table 2 Hazardous Substances Source and Pollutants. Adapted from (Jung, Alqassimi and El Samanoudy, 2022).

HAZARDOUS SUBSTANCES		CONCENTRATION (μG/M³)
Formaldehyde (HCHO)		210
Volatile Organic Compounds (VOCs)	Benzene (C_6H_6)	30
	Toluene (C_7H_8)	1000
	Ethylbenzene (C_8H_{10})	360
	Xylene (C_8H_{10})	700
	Styrene (C_8H_8)	300

Table 3 WHO IAQ Standard. Adapted from WHO European Centre for Environment and Health (2010).

in other Emirates due to the availability of land for sprawling residential developments such as in Dubai, Abu Dhabi and Sharjah. Ajman is currently the fifth largest city in the UAE with a population of 417,695 (World Population Review, 2024) within a land area of 143.26 km^2 (Municipality and Planning Department – Ajman, 2022b). It is the capital of the Emirate of Ajman which is the smallest among the seven Emirates in the UAE. The population density is approximately 2,915 person/km^2 making Ajman one of the densest cities in the UAE. Ajman has a similar climate to Dubai and Sharjah. Despite having a Sustainability Strategy vision of achieving a healthier, happier and sustainable Ajman (Municipality and Planning Department – Ajman, 2022a), Ajman does not have a set of green building laws such as the Dubai Green Building Regulations and Specifications, which stipulates acceptable indoor pollutant levels. Therefore, this study uses WHO's IAQ Standards.

Nonetheless, the Dubai Green Building Regulations and Specifications is UAE's best environment-friendly international set of standards. It prescribes desired green building design features as well as performance standards for various environmental parameters encompassing IAQ, thermal comfort, energy efficiency, and water resource effectiveness (Dubai Municipality, 2020). This set of standards can be adopted in other Emirates including Ajman. Similarly, the Municipality and Planning Department – Ajman oversees the use of Abu Dhabi Building Codes for construction specifications and building safety.

Ultimately, this study focuses on the measurement and analysis of HCHO and total volatile organic compounds (TVOC), which are known to be the main causes of SBS in IAQ (Jung, Mahmoud and Alqassimi, 2022). The research specifically targets newly constructed apartments at Ajman Al Jurf area. The primary objectives of this study are to measure and compare the concentrations of HCHO and TVOC both indoors and outdoors within the selected apartment houses, assess the indoor temperature levels, determine the amount of infiltration occurring in these apartment houses, evaluate the impact of these factors on indoor air quality, and collect and analyze relevant data to understand the IAQ of local apartments. By achieving these objectives, this study aims to contribute valuable insights into the IAQ issues prevalent in apartments and provide a basis for improving IAQ in similar settings.

2. MATERIALS AND METHODS

2.1. MEASUREMENT AND ANALYSIS METHOD

In the assessment of IAQ in apartments, the World Health Organization (WHO) process test method is employed as a means to measure the concentrations of HCHO and total TVOC (Stamp *et al*., 2020). The WHO process test method is recognized for its precision and involves collecting air samples from the center of the living room at a height of 1.2 m to 1.5 m from the floor, which corresponds to a position with the greatest impact on human exposure (Canha *et al*., 2021).

For the measurement of HCHO concentration, the procedure consists of three steps. First, prior to sample collection, natural ventilation is initiated by opening all windows facing the outdoor environment and doors of built-in furniture continuously for at least 30 minutes (Meiss *et al*., 2021). Second, to prevent air exchange between indoor and outdoor areas, all openings such as windows, doors, and vents are closed for a duration of more than 5 hours (Ding *et al*., 2023). However, during this time, the doors of interior decoration cabinets and built-in cabinets are kept open to allow air movement between the cabinets and the room, facilitating the collection of emitted pollutants (Lueker *et al*., 2020). Third, after the 5-hour period, air samples are collected twice for 30 minutes each using DNPH (2,4-Dinitrophenylhydrazine) cartridges. The cartridges are wrapped in tinfoil to minimize any potential light interference (Poza-Casado *et al*., 2021). Both natural and forced ventilation are sealed during the sample collection process (Alias *et al*., 2021). An Ozone Scrubber is used to ensure the removal of ozone, and a precise mini suction pump (0.5 mL/min) is employed to collect a total of 15 L of air samples. In the final step, the collected air samples are subjected to precise analysis using High Performance Liquid Chromatography (HPLC) to determine the concentration of HCHO (Figueroa-Lopez *et al*., 2023).

The measurement method for TVOC concentration follows a similar approach as the HCHO sampling method, with two steps. Tenax-TA Tubes are used in the third step of the process. Using a precise mini suction pump (0.1mL/min), air samples are collected twice, with each collection lasting 30 minutes and totaling 3L. In the last step, the collected air samples are analyzed precisely using Gas Chromatographic/Mass Spectroscopy (GC/MS) to quantify the TVOC concentration (Hou, Zhang and Lai, 2023).

The procedure involved a ventilation period of 30 minutes, followed by keeping the target unit's room open for over 5 hours (Singer *et al*., 2020). Subsequently, the openings were sealed, and samples were collected twice, each time lasting approximately 30 minutes (Guyot, Sherman and Walker, 2018).

Consistent with the prescribed test method, the sampling period took place between 1:00 pm and 5:00 pm (Yin *et al*., 2023). The samples were collected at the center of the living room in each unit, which served as the primary sampling location. To measure HCHO levels, a portable pump (Flec-FL1001, Sibata) was employed in conjunction with an ozone scrubber containing high-purity potassium iodide (KI). This configuration effectively eliminated any interference from ozone. Additionally, a 2,4-DNPH (dinitrophenylhydrazine) cartridge coated with 350 mg of silica was utilized for HCHO sampling [0,0]. For the collection of VOCs, a Tenax tube was connected to the same pump and samples were collected for 30 minutes (Kim, Kang and Kim, 2018).

For the analysis of HCHO, a series of standard solutions ranging from 0.1 to 10 ppm were prepared by diluting the standard stock solution. A calibration curve was subsequently established using these solutions (Stabile *et al*., 2019). The collected DNPH cartridges were affixed onto a solid phase extraction (SPE) vacuum manifold and subjected to extraction using 5 ml of acetonitrile of high-performance liquid chromatography (HPLC) grade (Figure 1) (Asif, Zeeshan and Jahanzaib, 2018). The resulting extracts were then injected into an HPLC-UV system for analysis. Specific analysis conditions for HCHO can be found in Table 4.

Figure 1 High-Performance Liquid Chromatography.

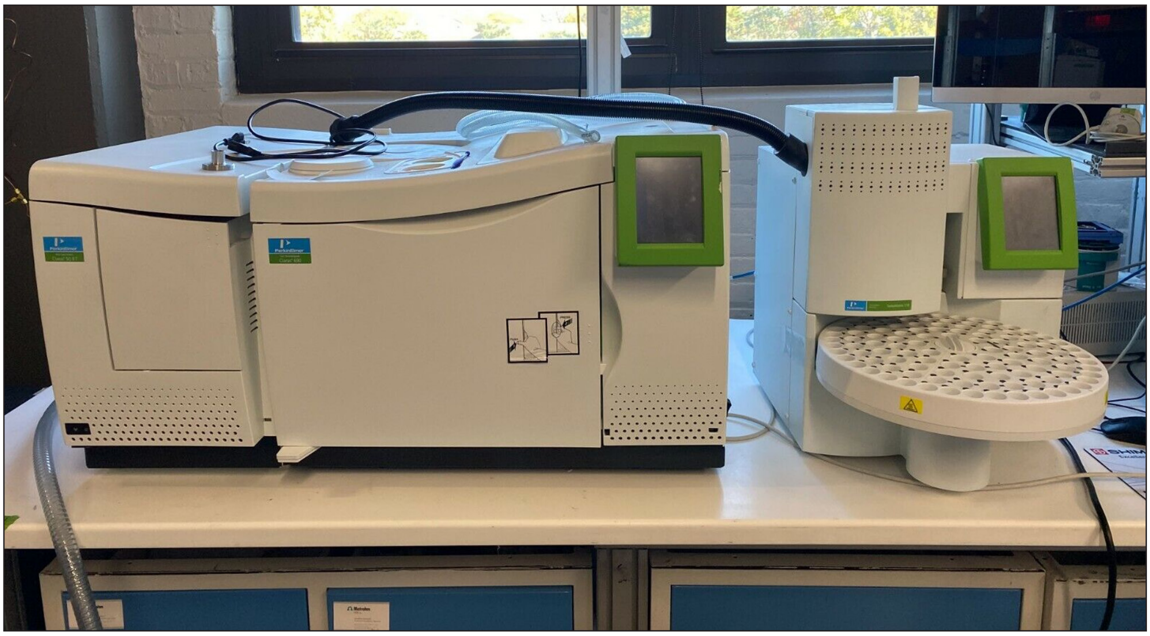

Figure 2 Gas Chromatography-Mass Spectrometry.

HPLC	AGILIENT TECHNOLOGIES (1220 INFINITY II LC SYSTEM)
Detector	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 Range	0.1–100 µl
Column Temperature	25°C
Flow Range	0.2–10 ml/min

Table 4 HCHO Analysis Conditions.

Regarding the analysis of VOCs, a standard gas was diluted, and two or three standard substances were prepared within the concentration range of 0.1 to 1 ppm. These standards were utilized to establish a calibration curve (Table 5). Following sample collection, the solid adsorption tubes were subjected to desorption and concentration processes. Subsequently, two-stage thermal desorption was performed, and the desorbed samples were injected into a gas chromatography/mass spectroscopy (GC/MS) system for analysis (Figure 2).

2.2 AIRTIGHT PERFORMANCE MEASUREMENT METHOD AND PERCOLATION RATE STANDARD

Within the context of natural ventilation, infiltration refers to unintended ventilation that occurs through gaps in the building envelope, such as the outer walls and window frames (Cardoso *et al*., 2020; Rieser *et al*., 2021). The amount of infiltration plays a significant role in calculating the cooling load of indoor pollutants and maintaining an appropriate indoor temperature (Evola *et al*., 2017). Infiltration transpires in the crevices of buildings, driven by pressure differences between

ATD	Manufacturer	Perkin Elmer (TurboMatrix 350 ATD)
	Primary desorption oven Temp Range	50°C to 400°C; Desorption time 1.0 min
	Low temp range	–40°C to +150°C (Peltier cooling – standard); –100°C to +150°C (LN2 cooling – optional)
	High temp range	–100°C to 400°C
	Time at high temp	0.0 to 999.0 min
	Heating rates	5°C/sec, 20°C/sec, 40°C/sec and ballistic
	Carrier gas flow	0–20 mL/min
	Carrier gas pressure	0 to 60 psig (0 to 400 kPa)
	Carrier gas split flow	0 to 200 mL/min
GC/MS	Manufacturer	Agilient Technologies (5977C GC/MSD)
	Temperature program	35°C >> 5°C/min>>220°C(10 min)>>10°C/min>>250°C (6.17 min)
	Detector	MS
	Column	HP-1(0.32 mm × 60 m × 1.80 um)
	IDL Sensitivity	EI – 100 fg, 1 μL OFN injected: IDL 20 fg
	Mass Range	m/z 0.6–1091
	Scan Speed	≦20,000 Da/s
	Carrier, Flow	He(99.999%), 2 ml/min
	Detection Energy	TIC(Scan), m/z: 35–350
	Electron Energy	70 ev
	Mode/Detection mode	EI/scan

Table 5 VOCs Analysis Conditions.

indoor and outdoor air, including factors like outdoor air conditions and temperature differentials (Ji, Duanmu and Hu, 2023).

Methods for measuring infiltration include the pressure difference method (decompression method/pressurization method), which utilizes the pressure differential between indoor and outdoor air, and the gas tracking method, which measures the exchange of indoor and outdoor air by tracing specific gases (such as SF6 or CO_2) (Rodrigues *et al.*, 2019). The pressure difference method involves assessing airflow rates by measuring pressure disparities inside and outside the room using a manometer or pressure difference gauge, with the pressure inside the room adjusted by a fan (Chen *et al.*, 2020). Typically, the airtightness performance of individual rooms or the entire building is measured at pressure differences ranging from 10 Pa to about 50 Pa, with incremental increases of 5 Pa to 10 Pa to determine the unique airflow characteristics of the building (Etheridge, 2015). Based on these measurements, the standard pressure difference used for calculations is generally set at 1–4 Pa or 9.8 Pa. There are two types of pressure difference methods: the pressure reduction method and the pressurization method (Pinto and Carrilho da Graça, 2018). Despite the weaknesses and practical issues regarding conventional steady pressurization method and proposed alternatives by Zheng, X. *et al.* (2020), this study utilizes the single point fan pressurization technique to measure the airtightness of selected apartment units. The pressure difference was increased incrementally to 50 Pa in line with previous studies.

When utilizing soundproofing and windproof windows designed to minimize infiltration, the ventilation within the room is significantly reduced, potentially exacerbating the occurrence of sick house syndrome (Salthammer and Morrison, 2022). In recent times, as a countermeasure to address SBS, apartment houses have been encouraged to have a minimum ventilation rate of 0.7 air changes per hour (ACH) (Costanzo and Donn, 2017).

2.3 TARGET BUILDINGS AND MEASUREMENT OVERVIEW

Ajman, a rapidly growing city with a high population growth rate, is witnessing a significant surge in apartment construction (Nazzal *et al.*, 2021). To assess the indoor environment, measurements were conducted for temperature, relative humidity, HCHO concentration, TVOC concentration, and airtightness performance in 6 units of Yasmeen Tower (Figure 3) and 5 units of Al Wahat Tower (Figure 4), all located in Al Jurf, Ajman (Bayut, 2024). These towers were newly constructed at the time of study and many units were allocated for Ajman University male students. The authors secured access to them to conduct

Figure 3 Yasmeen Tower from the street (left) and in the living room at one of the measured units (right). Source: Authors.

Figure 4 Al Wahat Tower from the street (left) and in the living room at one of the measured units (right). Source: Authors.

CATEGORY		YASMEEN TOWER	AL WAHAT TOWER
Measurement Date		12/11/2022–14/11/2022	30/11/2022–2/12/2023
Measurement Units		6 Units (201,202, 601,602, 1201,1202)	5 Units (302,602,704,1202,1204)
Measurement Items	Temperature/Humidity	6 Units, Outdoor Air	5 Units, Outdoor Air
	HCHO	6 Units, Outdoor Air, Corridor	5 Units, Outdoor Air, Corridor
	TVOC	2 Units, Outdoor Air	4 Units, Outdoor Air
	Airtight Performance	2 Units	5 Units

Table 6 Target Building Field Survey Overview.

this study as part of the university's effort in providing high quality accommodations for all students.

Table 6 presents an overview of the field measurements conducted in the selected units. The households varied in size, consisting of studio and small one-bedroom units (Glumac and Islam, 2020). To investigate the influence of different floors during the actual measurements, the units were categorized as low, middle, and high floors

(Sekhar *et al*., 2020). Additionally, measurements were taken for outdoor air and corridor spaces for comparison. It is worth noting that some units were in a pre-move-in condition during the measurements, reflecting their status prior to occupancy.

3. RESULTS

3.1 HCHO AND TVOC MEASUREMENT RESULTS AND ANALYSIS

The research findings regarding HCHO concentration, TVOC concentration, and airtightness performance, as measured in this study, are presented in Table 7. For Yasmeen Tower, which consisted solely of one-bedroom units that were unoccupied, the average HCHO concentration was 198 μg/m^3, with the highest concentration recorded at 265 μg/m^3. The ground floor had an outdoor HCHO concentration of 10 μg/m^3, while the stairwells on the 7th and 14th floors had an average concentration of 18 μg/m^3.

In the case of Al Wahat Tower, a one-bedroom apartment building where some households had moved in 1–2 months prior, the highest recorded HCHO concentration was 445 μg/m^3, exceeding the WHO standard. The average concentration was 323 μg/m^3, which can be attributed to elevated indoor temperatures. Unit 302, which had already been occupied by a household, experienced minimal symptoms of SBS due to ample ventilation. The ground floor showed a considerably low outdoor HCHO concentration of 8 μg/m^3, indicating clean air, while the concentration in the 13th floor stairway was 39 μg/m^3. The average TVOC concentration, measured in four households, was 4,017 μg/m^3, surpassing the standard limit, while the outdoor concentration was 34 μg/m^3.

Figure 5 illustrates the concentration of HCHO, while Figure 6 presents the concentration of TVOC. The average concentrations recorded were 357 μg/m^3 for HCHO and 3,092 μg/m^3 for TVOC. No significant variations in HCHO concentration were observed between the lower and upper floors of the target building units and corridors.

The airtightness performance of the measured target building units was evaluated in terms of the effective leakage area (cm^2), as indicated in Table 6. The actual measurements indicated that the airtightness performance of the 7th floor units ranged from 139 cm^2 to 301 cm^2, with an average of 193 cm^2. Notably, the 1-bedroom units exhibited relatively higher airtightness. Comparison with previous studies that employed the decompression method revealed similar findings. Figure 7 provides a comparative analysis of the airtightness performance across different floors.

3.2 CORRELATION ANALYSIS OF HCHO, TVOC, ROOM TEMPERATURE, AND AIRTIGHTNESS

A comparative analysis was conducted to examine the correlation between HCHO concentration and TVOC

CATEGORY		ID NUMBER	ROOM NUMBER	TEMPERATURE (°C)	RELATIVE HUMIDITY (%)	HCHO (μg/m^3)	TVOC (μg/m^3)	AIRTIGHT PERFORMANCE (cm^2)
Yasmeen Tower	Inside	YT01	201	24.8	58.4	266	–	–
		YT02	202	23.9	60.5	164	–	–
		YT03	601	25.4	57.3	182	–	–
		YT04	602	25.0	52.7	154	696	302
		YT05	1201	24.4	60.1	232	–	–
		YT06	1202	24.2	57.8	190	1792	232
	Outside			25.8		10	194	–
	7th Floor Corridor			–		20	–	–
	14th Floor Corridor			–		16	–	–
Al Wahat Tower	Inside	AW01	302	24.1	56.8	104	1634	139
		AW02	602	24.2	58.3	444	–	162
		AW03	704	26.3	59.2	298	6282	148
		AW04	1202	25.2	52.1	396	3328	202
		AW05	1204	24.8	60.3	372	4822	168
	Outside			26.0		8	34	–
	13th Floor Corridor			–		39	–	–

Table 7 Target Building Measurement Result.

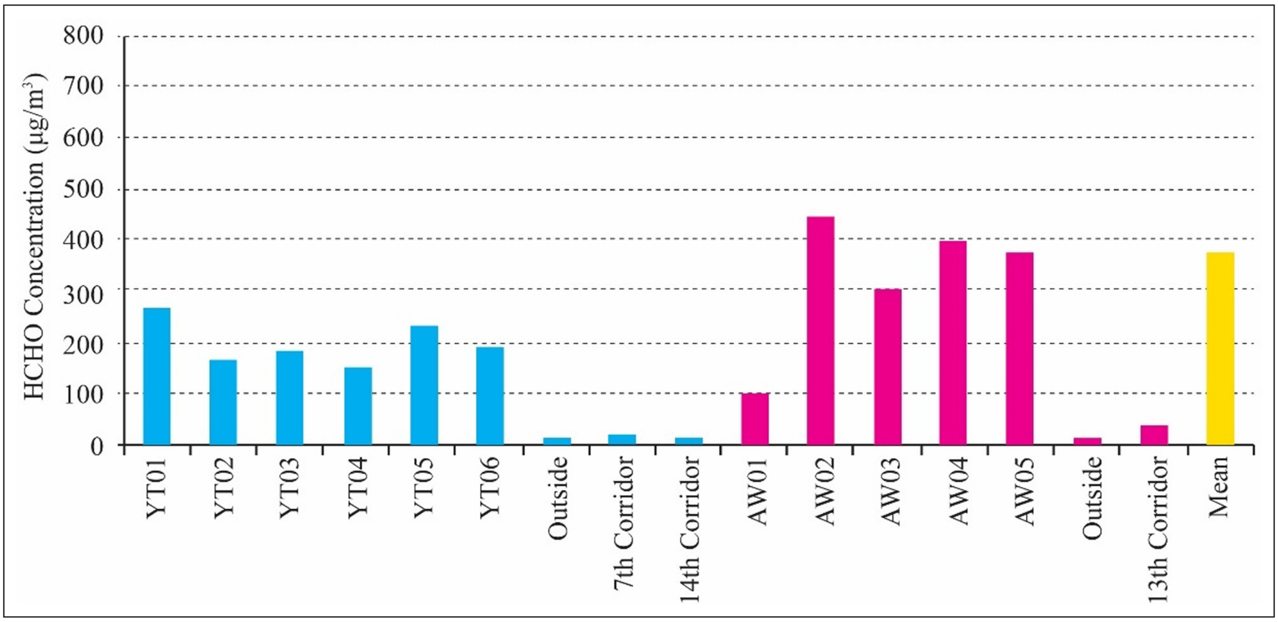

Figure 5 Average Concentration of HCHO.

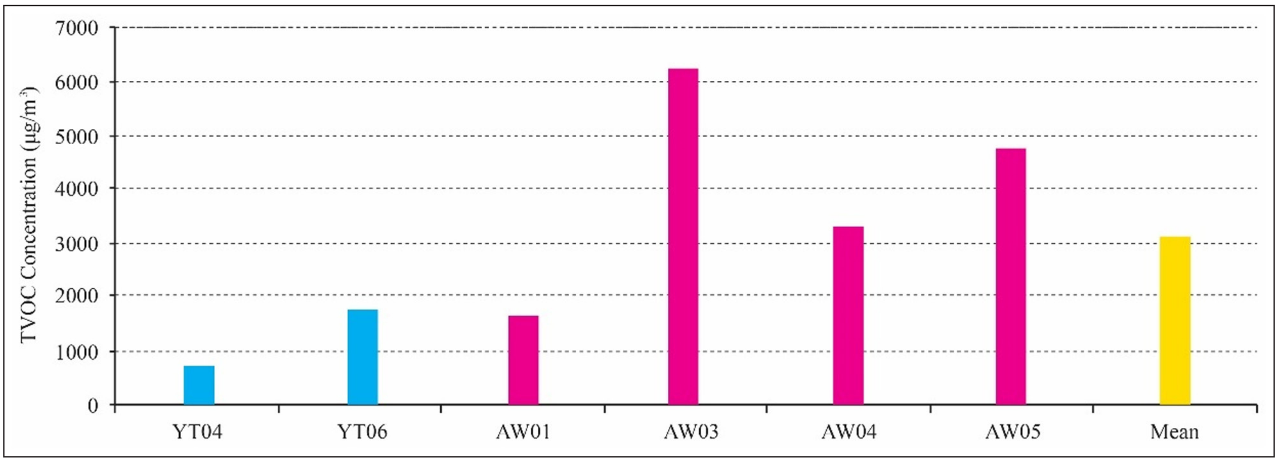

Figure 6 Average Concentration of TVOC.

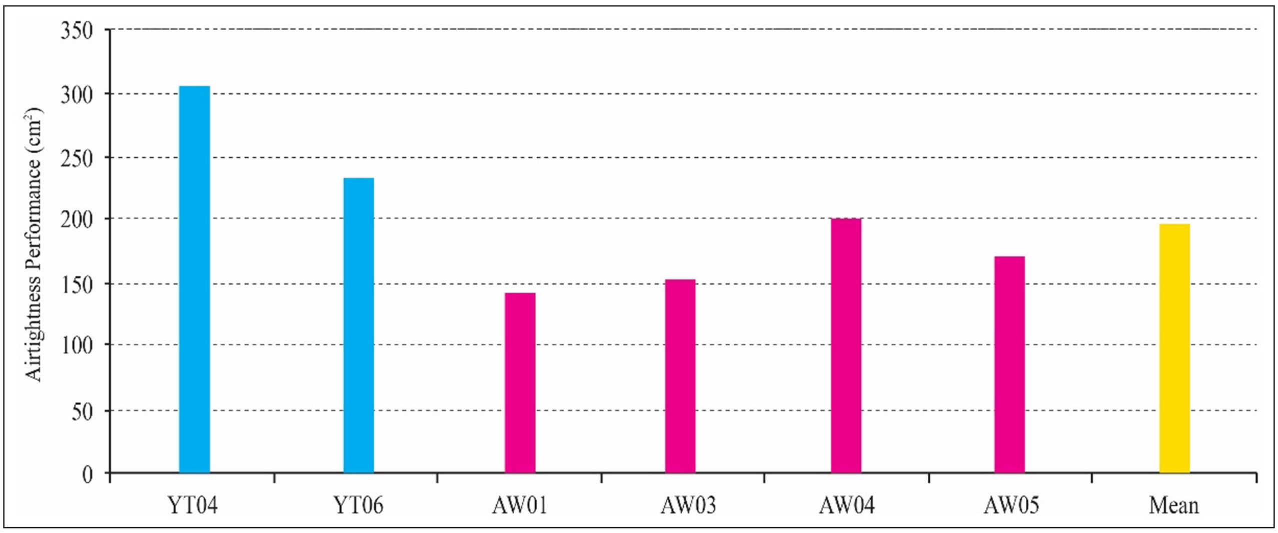

Figure 7 Airtightness Performance Comparative Analysis.

concentration with respect to room temperature. For the purpose of the analysis, the results of Al Wahat Tower unit 302, which exhibited rare occurrences of SBS, were excluded due to its unique characteristics. Upon examining Figures 8 and 9, it was observed that both HCHO and TVOC concentrations increased with higher room temperatures, indicating a strong correlation between these variables.

The study further investigated and analyzed the correlation between airtightness performance, HCHO concentration, and TVOC concentration through on-site measurements conducted in Yasmeen Tower and

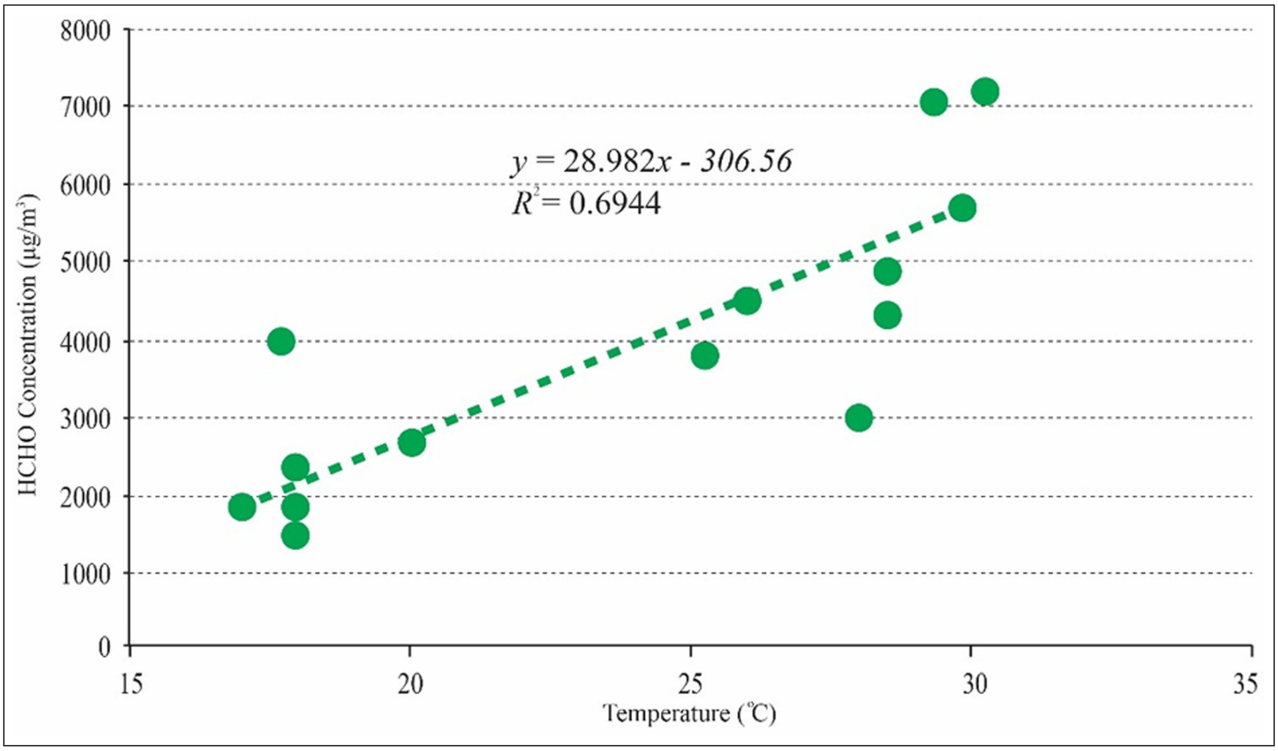

Figure 8 Comparative Analysis of Room Temperature and HCHO.

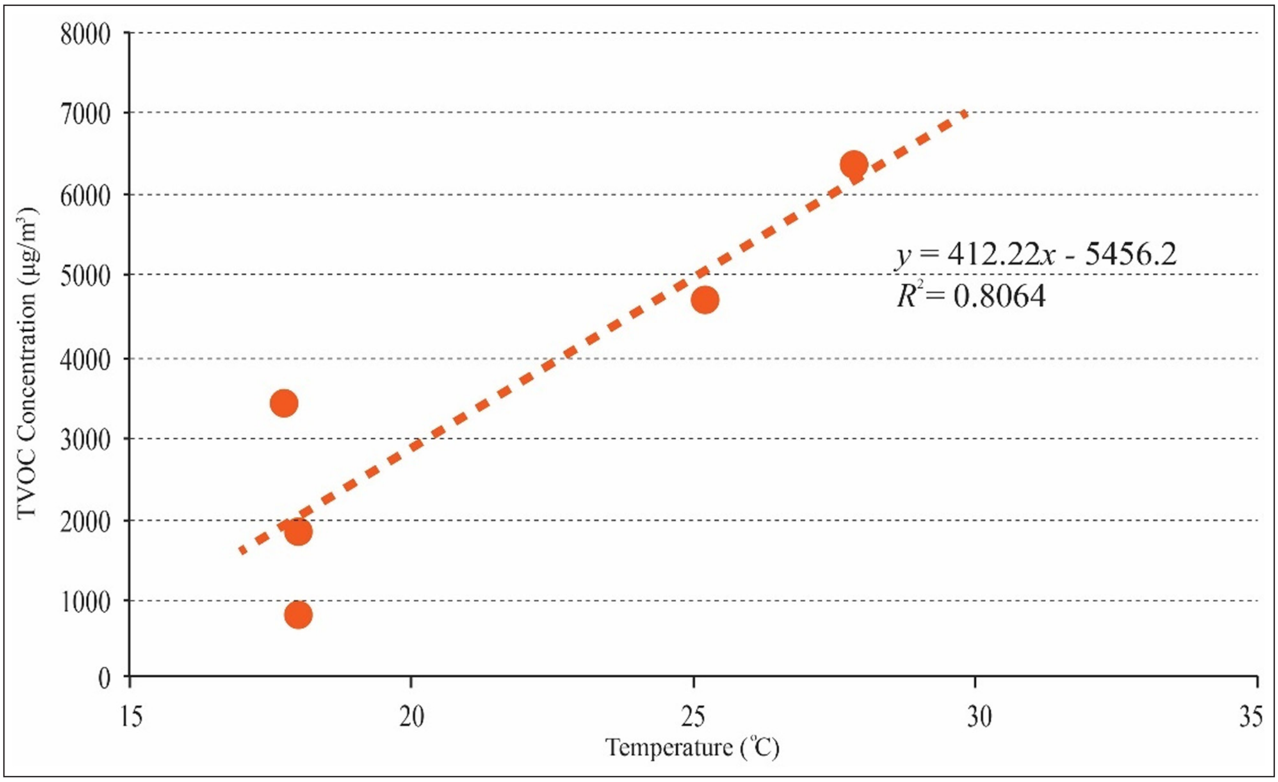

Figure 9 Comparative Analysis of Room Temperature and TVOC.

Al Wahat Tower. Figures 10 and 11 demonstrate the findings, indicating that as the airtightness, measured by the effective leakage area, increased, there was a notable decrease in both HCHO and TVOC concentrations. This observation highlights a significant correlation between these factors.

3.3 TVOC AND VOCs ANALYSIS

The TVOC concentrations measured in 7 units were analyzed along with the concentrations of specific VOCs according to their types. As depicted in Table 8, the majority of units exhibited a relatively high concentration ratio of Toluene, followed by Ethylbenzene. Unknown

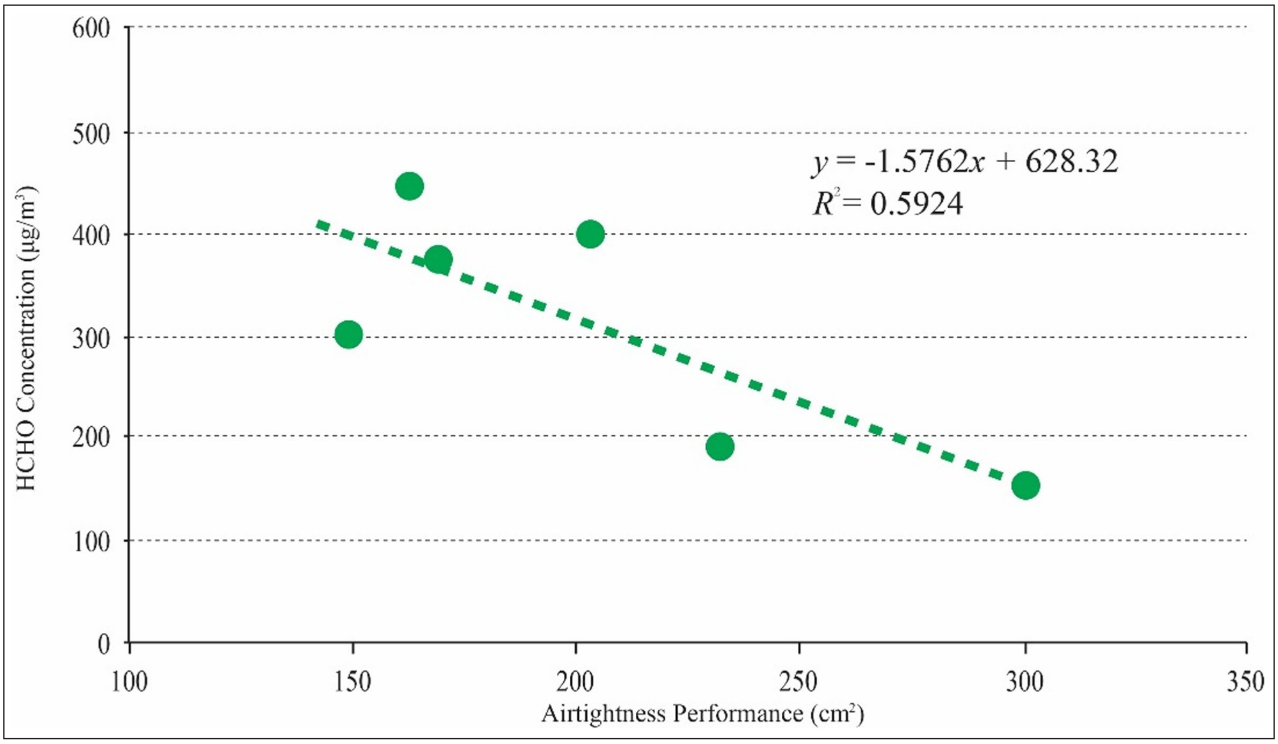

Figure 10 Comparative Analysis of Airtightness Performance and HCHO.

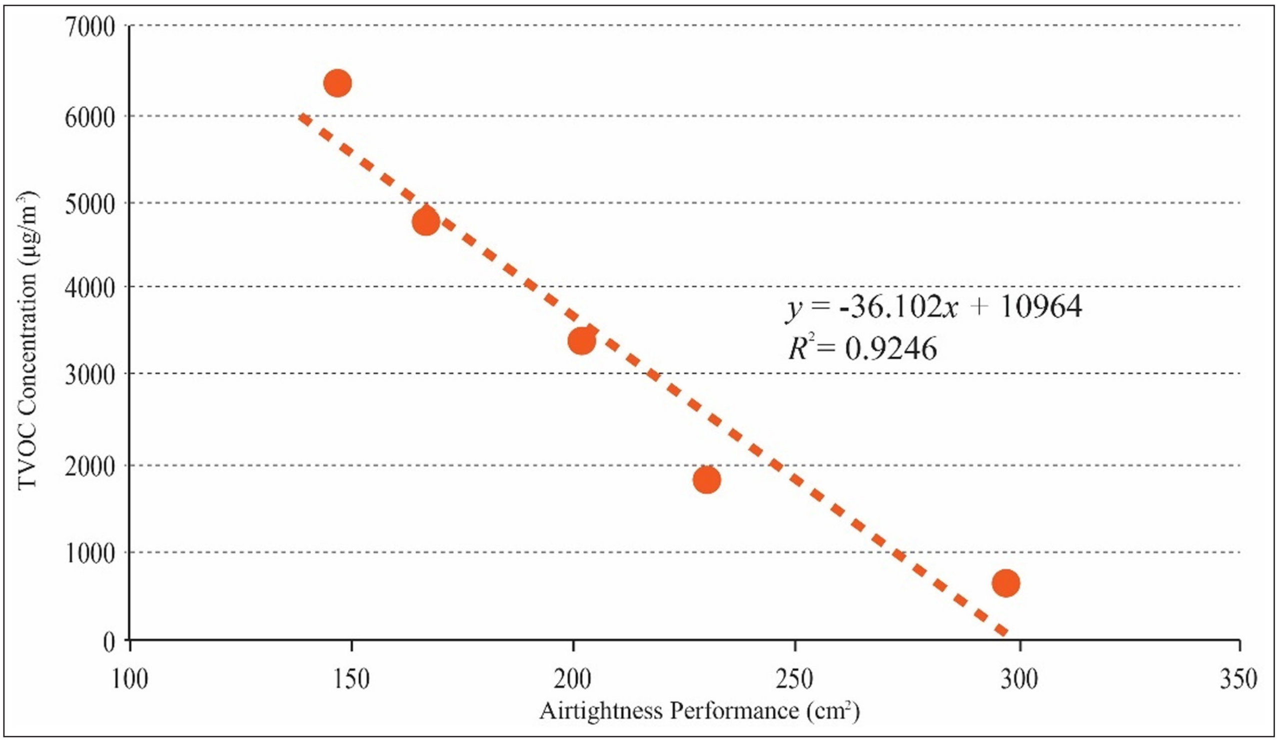

Figure 11 Comparative Analysis of Airtightness Performance and TVOC.

TARGET BUILDINGS		TVOC (μg/m³)	TOLUENE (μg/m³)	ETHYLBENZENE (μg/m³)	XYLENE (μg/m³)	STYLENE (μg/m³)	BENZENE (μg/m³)	UNKOWN (μg/m³)
Yasmeen Tower	YT04 (602)	696	66	11	11	6	2	610 (88%)
	YT06 (1202)	1790	302	24	30	17	2	1446 (81%)
	Outside	194	16	5	5	4	3	161 (83%)
Al Wahat Tower	AW01 (302)	1635	396	284	142	84	2	724 (44%)
	AW02 (602)	6282	894	526	172	228	3	4453 (71%)
	AW04 (1202)	3328	745	314	156	94	2	2046 (61%)
	AW05 (1204)	4822	1302	434	206	152	3	2722 (56%)
	Outside	34	0	0	0	0	0	34 (100%)

Table 8 Average concentration of TVOCs and VOCs in Target Buildings.

materials accounted for a significant portion, comprising more than half of the average concentration, with a range of 45% to 88% (average of 69%).

Furthermore, the TVOC and VOC components in the outdoor air on the ground floor were examined. The outdoor air TVOC concentration in Yasmeen Tower was recorded as 194 μg/m³, which was higher compared to Al Wahat Tower. In the case of Al Wahat Tower, the VOC composition was entirely composed of unknown materials, while Yasmeen Tower had 83% unknown materials in its VOC composition.

4. DISCUSSION

The results of the study provide valuable insights into the HCHO concentration, TVOC concentration, and airtightness performance of units at newly constructed apartment buildings in Ajman, UAE. The findings demonstrate significant variations in indoor air quality parameters across different buildings and floors.

In Yasmeen Tower, which comprised exclusively of one-bedroom units that were unoccupied during the study, the average HCHO concentration was 198 μg/m³, with the highest recorded concentration reaching 265 μg/m³. These levels exceeded the recommended WHO IAQ standard of 100 μg/m³. The ground floor had a relatively low outdoor HCHO concentration of 10 μg/m³, while the stairwells on the 7th and 14th floors had an average concentration of 18 μg/m³. Furthermore, the average TVOC concentration measured in these units exceeded the permissible limit, registering at 1,244 μg/m³. In comparison, the outdoor air concentration of TVOC was 194 μg/m³.

Similarly, in Al Wahat Tower, where some households had moved in 1–2 months prior to the study, the HCHO concentration exhibited even higher levels. The highest recorded concentration was 445 μg/m³, while the average concentration stood at 323 μg/m³. Unit 302, already occupied, experienced minimal symptoms of SBS due to adequate ventilation. These figures indicate a significant deviation from the recommended standards. On the other hand, the ground floor of Al Wahat Tower exhibited a remarkably low outdoor HCHO concentration of 8 μg/m³, suggesting cleaner air in that area. However, the TVOC concentration measured in four units within Al Wahat Tower exceeded the acceptable limit, averaging at 4,017 μg/m³. The analysis of specific VOCs indicated that Toluene had a relatively high concentration ratio in most units, followed by Ethylbenzene. Unknown materials accounted for a significant portion, ranging from 45% to 88% of the average concentration.

Considering all the measured units, the average HCHO concentration was found to be 357 μg/m³, while the average TVOC concentration reached 3,092 μg/m³. These values underscore the significance of addressing IAQ concerns in multi-unit dwellings to achieve the Ajman Municipality and Planning Department's Sustainability Strategy.

Airtightness performance, as measured by the effective leakage area, was evaluated for the units under investigation. The results indicated that the 7th floor units exhibited a range of airtightness performance, with values ranging from 139 cm² to 301 cm² and an average of 193 cm². Notably, the studio-type units demonstrated relatively higher levels of airtightness. These findings align with previous studies conducted using the decompression method, confirming the consistency of the results.

Furthermore, we analyzed the correlation between HCHO concentration, TVOC concentration, room temperature, and airtightness performance. By excluding Unit 302 in Al Wahat Tower, which exhibited rare occurrences of SBS, we found a strong correlation between room temperature and both HCHO and TVOC concentrations. As room temperature increased, so did the levels of HCHO and TVOC, indicating a close relationship between these variables. Moreover, the analysis revealed that as the airtightness performance, represented by the effective leakage area improved, there was a noticeable decrease in both HCHO and TVOC concentrations. This finding emphasizes the importance of effective ventilation and airtightness in mitigating indoor air pollutants.

Additionally, we conducted a detailed analysis of VOC components, focusing on their concentrations and types. Toluene exhibited a relatively high concentration ratio across the majority of the units, followed by ethylbenzene. Notably, unknown materials constituted a significant proportion, accounting for more than half of the average VOC concentration, ranging from 45% to 88% (average of 69%). This suggests the presence of unidentified VOC sources within the apartment buildings. The impact of RH on HCHO and TVOC levels can be complex. Generally, higher humidity levels can lead to increased off-gassing of VOCs from materials. However, the relationship in this experiment is not linear and can be influenced by other factors such as temperature, air exchange rates, and the specific characteristics of the VOCs present.

While this study provides valuable insights into IAQ conditions and their correlations with various factors, it is important to acknowledge certain limitations. The measurements were conducted in a specific set of apartment buildings in Ajman which may limit the generalizability of the findings. Further, the measurement period is 3 days instead of an extended monitoring period of up to 6 months due to access restrictions and to limit disturbance to the Al Wahat Tower occupants. Nonetheless, the recorded measurements present a snapshot of the indoor pollutants' levels that could help occupants at the Al Wahat Tower to address the elevated levels of HCHO and TVOC. Additionally, the study focused on HCHO, TVOC, and airtightness performance, thereby excluding other potential IAQ parameters. Moreover, the IAQ measurements relied on high-performance quantitative analysis, which can be challenging to conduct consistently.

5. CONCLUSIONS

This study aimed to contribute valuable insights into the IAQ issues prevalent in apartments and provide a basis for improving IAQ in similar settings. A field experiment was conducted at 11 apartment units in two residential buildings in Ajman, UAE. The concentration changes of indoor air pollutants were measured and analyzed over time. Based on the findings, the following conclusions were made:

1. Building regulations and guidelines should prioritize the implementation of measures to control HCHO and TVOC concentrations, including the use of low-emission construction materials and furnishings. Promoting airtightness measures and proper ventilation systems should be encouraged to improve indoor air quality. Further research is also recommended to explore the long-term effects of IAQ on the health and well-being of occupants.
2. Findings from this study are important for policymakers, architects, and residents in improving indoor air quality in multi-unit dwellings. They highlight the need for effective ventilation systems, temperature control, and attention to VOC emissions from construction materials and furnishings. The study also emphasizes the importance of airtightness measures in reducing indoor pollutant levels.
3. We recommend that HCHO concentration, TVOC concentration, and airtightness performance in multi-unit dwellings are considered in efforts to enhance IAQ and mitigate the risks associated with SBS.
4. We recommend conducting more extensive measurements in a broader range of buildings to further enhance our understanding of IAQ in residential buildings around Ajman. This will help in obtaining more reliable data and a comprehensive understanding of IAQ concerns, enabling the development of effective strategies to improve indoor air quality and promote occupants' well-being.

DATA AVAILABILITY STATEMENT

New data were created or analyzed in this study. Data will be shared upon request and consideration of the authors.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

All authors contributed significantly to this study. CJ, MAI, JA and AC identified and secured the example buildings used in the study. The data acquisition system and installations of sensors were designed and installed by CJ and MAI. AC and JA were responsible for data collection.

Data analysis was performed by CJ. The manuscript was compiled by CJ and MAI and reviewed by JA and AC. All authors have read and agreed to the published version of the manuscript.

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