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Multivariable Analysis of Indoor VOC Dynamics in a Smart Urban Building: Advancing Evidence-Based and Health-Centered Air Quality Management

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ABSTRACT

This study investigates the dynamics of indoor volatile organic compounds (VOCs), including formaldehyde, xylene, and toluene, within a newly constructed smart urban building in Bangkok, Thailand. It aims to identify key determinants of air quality and to support data-driven strategies for healthier indoor environments. A total of 120 indoor air samples were collected from multiple zones and timeframes, considering building usage patterns, air conditioning operation, and environmental factors such as temperature, humidity, and air velocity. Statistical analyses revealed that air velocity and usage time significantly influenced VOC concentrations, while the time period was a critical factor for formaldehyde levels. Toluene concentrations exceeded the ACGIH guideline (20 ppm) in 13% of samples, and formaldehyde levels surpassed NIOSH thresholds in all samples, indicating potential exposure risks. Higher ventilation rates were linked to reduced pollutant accumulation, particularly during peak occupancy. Strong correlations between toluene and xylene also indicated shared emission sources. Although most values remained within regulatory limits, some exceeded health-based guidelines. These findings highlight the complex interactions among building operations, environmental conditions, and chemical exposure, and suggest targeted ventilation scheduling, particularly early-morning activation, to reduce VOC peaks. The study provides a practical framework for designing adaptive ventilation systems and developing guidelines to improve indoor air quality in new buildings. Insights from this research can inform future policy, urban planning, and smart building design aimed at reducing health risks and enhancing environmental resilience.

INTRODUCTION

Urbanization around the world is increasing rapidly, as the World Health Organization (World Health Organization 2022) and the United Nation (United Nations Human Settlements Programme (UN-Habitat) 2022) estimate that by 2070, the urban population, or population living in cities, will increase by as much as two times from the year 2020. Emerging studies indicate that newly constructed buildings often emit higher levels of indoor pollutants, particularly volatile organic compounds (VOCs) and formaldehyde, compared to older structures, due to emissions from new materials and limited initial ventilation (Hodgson 2004). Formaldehyde and VOCs are common pollutants found in buildings (United States Environmental Protection Agency (US.EPA.) 2021). These challenges are amplified in the context of smart urban buildings, where innovative materials and compact energy systems may exacerbate VOC release during early occupancy. Understanding these emission dynamics is essential for developing health-centered strategies in next-generation building design.

Volatile organic compounds (VOCs), notably formaldehyde, xylene, and toluene, are key contributors to indoor air pollution and are emitted from a range of sources including particleboard, plywood, medium-density fiberboard, insulation, textiles, wallpapers, paints, glues, cleaning agents, and electronic equipment such as photocopiers and computers (World Health Organization 2010, United States Environmental Protection Agency (US.EPA.) 2021, Shin and Jo 2013, Suzuki et al. 2019). Formaldehyde, a colorless, flammable, and highly reactive gas, has been classified as a human carcinogen by the United States Environmental Protection Agency due to its association with long-term cancer risks (National Institutes of Health 2010). At concentrations exceeding 0.1 ppm, formaldehyde can cause acute symptoms including eye and throat irritation, coughing, nausea, and respiratory discomfort (World Health Organization 2010). VOCs are semi-volatile compounds that readily evaporate at ambient conditions, often accumulating indoors at levels up to ten times higher than outdoors, particularly in recently constructed buildings with limited ventilation (United States Environmental Protection Agency (US.EPA.) 2021, Hodgson 2004). Health effects associated with VOC exposure range from mucosal irritation, fatigue, and asthma to systemic damage to the liver, kidneys, and central nervous system (Mølhave 2003, Norback et al. 1995, Norback et al. 2000, Wieslander et al. 1997, Wolkoff and Nielsen 2001). Xylene and toluene, in particular, are highly flammable compounds commonly found in solvents, paints, and coatings. Xylene, a mixture of three isomers, poses significant risks through inhalation and skin contact, with documented effects including eye and respiratory irritation at 400 ppm in humans, and severe toxicological responses at 2,800 ppm in laboratory animals (Jarnstrom et al. 2006, National Research Council (US) Committee on Acute Exposure Guideline Levels 2010). Similarly, prolonged exposure to toluene concentrations up to 4,000 ppm has been shown to cause hepatic, renal, and neurological impairments in animal models (World Health Organization 2022). These findings underscore the necessity of investigating VOC dynamics under real-world conditions, particularly during the early occupancy phase of smart buildings where emissions tend to peak and ventilation is often suboptimal (Klepeis et al. 2001)..

Thailand is a rapidly developing country with continuous growth in many sectors, including transportation. The government has implemented policies to support the livelihoods of the Thai population, which has increased in population growth (Thai Environment Institute 2013). This has led to the construction of numerous new residential and office buildings. Building upon this trajectory, Thailand's ongoing urbanization and smart infrastructure expansion provide a timely context for advancing IAQ research, with implications for health-based building regulations and sustainable urban planning in rapidly developing regions.

Consequently, indoor air quality (IAQ) analysis, particularly in newly constructed smart buildings, is vital for managing measures and developing guidelines to prevent impacts caused by chemical vapors. It will help new building occupants adjust their space usage and prevent the effects of chemical vapors inside new buildings, which can cause Sick Building Syndrome (SBS) or building syndrome (Department of occupational safety and health 2022). However, the study of the relationship between physical factors that affect IAQ still specific analysis of a single variable, as in the case of temperature affecting VOCs in buildings (Jo and Sohn 2009, Zhang et al. 2020, Zhou et al. 2020), humidity affecting VOCs in buildings (Jo and Sohn 2009, Suzuki et al. 2019), and the air exchange rate influencing formaldehyde concentration in the building (Huang et al. 2017). In the same direction as the study of building usage characteristics that affect IAQ, such as usage time and indoor air concentration levels (Hu et al. 2022), the time period of the building affects indoor air concentration (Guo et al. 2013, Kaunelienė et al. 2016). Despite growing awareness of indoor air quality, few studies have employed real-time, multivariable frameworks within operational smart buildings contexts where the dynamic interplay between occupancy patterns and environmental conditions can be most meaningfully observed and analyzed.

To address these research gaps, this study conducts a multivariable analysis of VOC dynamics in a newly constructed smart urban building. Holistic assessments that integrate building usage and environmental variables remain limited. We systematically investigated how patterns of use, air conditioning operation, and factors such as temperature, humidity, and air velocity affect indoor concentrations of VOCs and formaldehyde, based on 120 real-world air samples. These findings contribute to a mechanistic understanding of pollutant behavior, supporting evidence-based IAQ management strategies. Although conducted in a single building, this high-resolution assessment offers insights into real-time exposure dynamics and serves as a foundation for comparative research and policy development.

1. MATERIALS AND METHODS

2.1 Study Design and Site

This study employed a field-based multivariable observational design to investigate the dynamics of indoor air pollutants under actual building-use conditions. The assessment was conducted in a newly constructed smart office building at Navamindradhiraj University, Bangkok, Thailand. The building had been in use for less than one year at the time of data collection. A total of 120 indoor air samples were collected to analyze the concentrations of xylene, toluene, and formaldehyde, in relation to building usage and environmental conditions. Environmental parameters including air temperature, relative humidity, and air velocity were also recorded concurrently with each air sample to assess their potential influence on pollutant dynamics. This comprehensive monitoring aimed to generate evidence-based insights into VOC dynamics that can inform health-centered indoor air quality strategies.

2.2 Sampling and Instrumentation

Air samples were collected from six indoor zones, categorized based on building usage, over two separate monitoring periods spaced five months apart. The sampling zones reflect diverse occupancy conditions and functional areas commonly found in smart building operations, including workspaces with varying occupancy levels, shared and transitional spaces, and educational-use areas (Table 1). Zones 1 to 4 each included two sampled rooms to represent typical conditions under different workplace or classroom settings. In contrast, Zones 5 and 6 were each represented by a single sampling location due to their spatial characteristics, namely the entrance hall of a building and a learning center, respectively. This sampling strategy was designed to capture temporal and spatial variations in VOC dynamics.

Air sampling was performed using personal air pumps (Gilian GilAir Plus, Sensidyne, USA) with calibrated flow rates of 200 mL/min, drawing air through solid sorbent tubes. Prior to and following each sampling session, flow rates were calibrated using a primary standard calibrator to ensure measurement accuracy. Toluene and xylene were analyzed using NIOSH Method 1501, while formaldehyde was analyzed following NIOSH Method 2541. Samples were collected at a height of approximately 1.2 to 1.5 meters to represent the typical human breathing zone. Active sampling was conducted during three distinct time points relative to air conditioning operation: before switching it on, one hour after, and eight hours after. These time points were selected to capture expected diurnal variation in VOC dynamics, including initial accumulation, short-term stabilization, and prolonged exposure under full-day usage conditions. Field blanks were included in each sampling round to assess potential contamination. All analytical procedures followed established QA/QC protocols to maintain data quality and integrity. Although duplicate sampling at identical spatiotemporal points was not conducted, the sampling strategy prioritized broader spatial-temporal coverage across distinct building zones and two operational cycles. This approach enhances the representativeness of the dataset while ensuring methodological reliability in operational settings.

Table 1: Classification of Indoor Zones by Building Usage and Occupancy Patterns.

Period	Day	Usage time	Area
Period1: (After 10 months of building use.) Period2: (After 15 months of building use.)	Monday: (After 2 days closure)) Friday: (After continuous 5-day use)	Time 1: (Before AC turned on.) Time 2: (1 hour after AC turned on.) Time 3: (8 hour after AC turned on.)	Area1: (Area with more than 10 people working.) Area2: (Area with no more than 10 people working.) Area3: (Classroom or meeting room.) Area4: (In front of elevator (semi-open buffer zone.) Area5: Entrance hall of the building Area6: Learning center area.

Note: This classification reflects temporal and spatial variations in building use, air conditioning operations, and occupancy conditions that influence indoor VOC dynamics.

2.3 Statistical Analysis

Statistical analyses were conducted using SPSS software to evaluate differences and relationships among measured variables. Data normality was assessed via skewness and kurtosis, with values of $|ZSkewness| < 3$ and $|ZKurtosis| < 10$ considered acceptable for parametric testing (Kline 2011). Group comparisons were carried out using independent-sample t-tests and one-way analysis of variance (ANOVA) (Ebrahimi et al. 2023). To examine the influence of environmental and usage-related variables on VOC and formaldehyde concentrations, multiple linear regression analysis was applied. Multicollinearity was evaluated using variance inflation factor (VIF) and tolerance values, where VIF < 10 and tolerance > 0.2 indicated acceptable levels of collinearity (Belsley 1991). This analytical approach supported the identification of key predictors in VOC dynamics under actual building-use conditions.

2.4 Causal Structure Analysis and System Visualization

To reveal the underlying system dynamics of indoor air pollution, relationships among key variables were synthesized into causal loop diagrams (CLDs) using Vensim PLE 9.3.0. These diagrams were developed to visually articulate the feedback structures and interdependencies between building usage patterns, environmental conditions, and chemical concentration levels, providing a holistic representation of the system's behavior over time. This modeling approach not only enhances the understanding of VOC dynamics in smart buildings but also supports evidence-based decision-making and policy development for improving indoor air quality management (Sterman 2000, Richardson 2011).

2. RESULTS

3.1 Effect of Building Usage and Environmental Characteristics on Chemical Concentrations.

Indoor air sampling and analysis from 120 samples revealed significant effects of building usage and environmental factors on VOC concentrations. For xylene, significant differences were observed across usage times ($p < 0.05$), with the highest average concentration recorded during Time 1 (before AC operation), followed by Time 3 and Time 2. The air conditioning system status also significantly influenced xylene levels, with higher concentrations occurring when the system was off ($p < 0.05$).

Toluene concentrations were significantly affected by three variables: time period ($p < 0.01$), usage time ($p < 0.01$), and air conditioning system status ($p < 0.01$). Higher toluene levels were consistently observed during Time 1 and in the earlier time period (Period 1), especially when the air conditioning was turned off. Formaldehyde levels were significantly influenced only by time period ($p < 0.01$), with Period 1 showing higher average concentrations than Period 2 (Table 2).

Table 2: VOCs Concentrations by Building Usage and Environmental Conditions.

Usage Variables	Condition	Temp. (°C)	Humidity (%)	Velocity (m/s)	Xylene (ppm)		Toluene (ppm)		Formaldehyde (ppm)	
		x̄	x̄	x̄	x̄	p-value	x̄	p-value	x̄	p-value
Time period	Round 1	25.00	66.62	0.11	0.03	0.31	13.01	0.00**	0.67	0.00**
	Round 2	25.07	65.41	0.12	0.02		7.64		0.32	
Day	Monday	24.99	63.66	0.11	0.02	0.38	10.40	0.78	0.54	0.08
	Friday	25.08	68.37	0.13	0.03		10.26		0.45	
Usage time	Time 1	27.25	70.11	0.09	0.03	0.02*	12.78	0.00**	0.48	0.96
	Time 2	24.05	64.89	0.12	0.02		5.64		0.50	
	Time 3	23.81	63.05	0.14	0.02		12.56		0.49	
Area	Area 1	25.11	66.01	0.11	0.02	0.13	10.43	0.79	0.52	0.31
	Area 2	24.55	65.24	0.15	0.02		9.44		0.41	
	Area 3	24.98	65.50	0.10	0.03		10.87		0.53	
	Area 4	25.71	69.30	0.12	0.02		9.53		0.45	
	Area 5	24.43	66.43	0.12	0.02		10.79		0.49	
	Area 6	25.24	61.60	0.11	0.03		11.93		0.62	
Air condition system	Turning off	27.25	70.11	0.09	0.03	0.01*	12.78	0.00**	0.48	0.80
	Turning on	23.93	63.97	0.13	0.02		9.10		0.50	

Note: *: p-value < 0.05, **: p-value < 0.01

All xylene concentrations were within OSHA, NIOSH, and ACGIH exposure limits (100 ppm, 100 ppm, and 20 ppm, respectively). Toluene concentrations exceeded the ACGIH threshold (20 ppm) in 16 samples, 15 of which occurred during Period 1, though remained within OSHA and NIOSH limits. Formaldehyde concentrations exceeded OSHA limits in 17 samples and surpassed the NIOSH threshold in all samples, emphasizing the need for immediate ventilation strategies during early occupancy periods to mitigate exposure risks. Figure 1a–c illustrates the distribution patterns of xylene, toluene, and formaldehyde across different usage times and monitoring periods, highlighting the temporal dynamics of VOC accumulation and reduction.

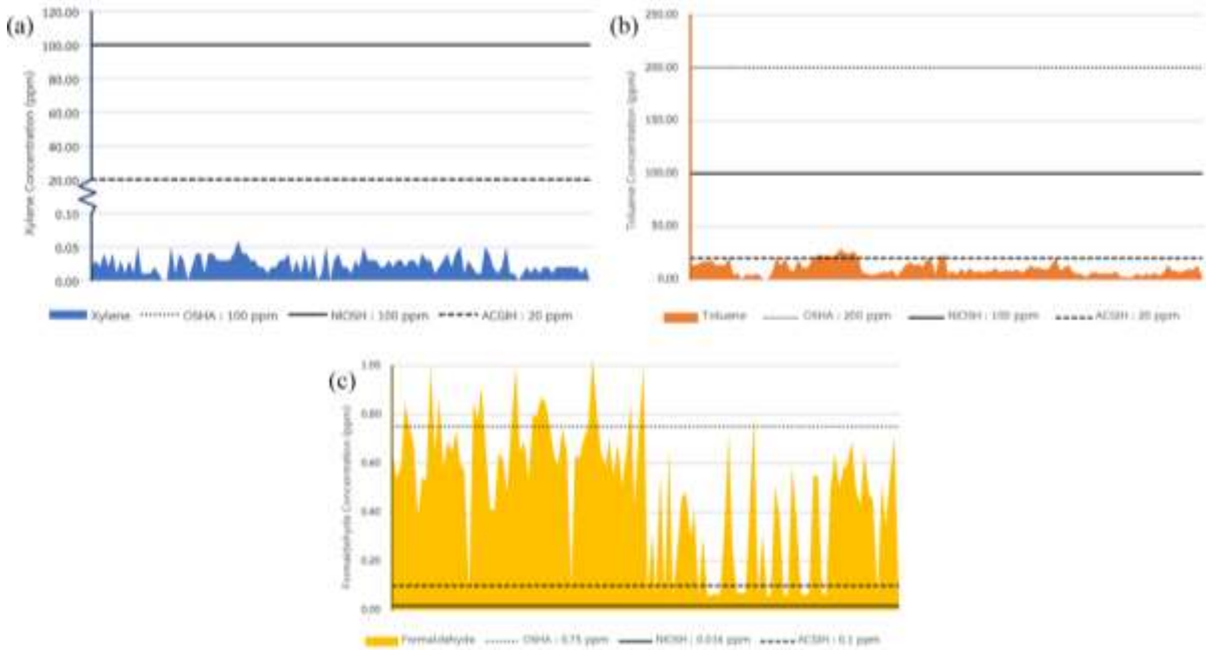

Figure 1a – c: VOC Concentration Distributions Across Sampling Times and Periods.

3.2 Regression Analysis and VOC Interrelationships

Multiple linear regression results revealed that the primary predictor of xylene concentration was toluene ($\beta = 0.38$), followed by air velocity ($\beta = -0.37$), with the model explaining 37% of the variance ($R^2adj = 0.37$). For toluene, key predictors included usage time 2 ($\beta = -0.48$), time period ($\beta = -0.41$), xylene ($\beta = 0.29$), and air velocity ($\beta = -0.16$), with an R^2adj of 0.63. Formaldehyde was most strongly influenced by time period ($\beta = -0.62$), air velocity ($\beta = -0.43$), humidity ($\beta = -0.19$), and toluene ($\beta = 0.14$), explaining 71% of the variance ($R^2adj = 0.71$) (Table 3).

Table 3. Key Predictors of VOCs from Multiple Linear Regression

Independent variable	Correlation coefficient (r)	B	SE	Beta	p-value	R^2adj	Collinearity	
							Tolerance	VIF
Dependent Variable: Xylene (ZSkewness = 1.30, ZKurtosis = -1.14)								
Constant		0.02	0.00		0.00			
Toluene	0.510**	0.00	0.00	0.38	0.00	0.37	0.88	1.14
Air velocity	-0.500**	-0.05	0.01	-0.37	0.00		0.88	1.14
Dependent Variable: Toluene (ZSkewness = 2.99, ZKurtosis = -1.10)								
Constant		12.80	1.21		0.00			
Usage time 2	-0.545**	-6.16	0.73	-0.48	0.00		0.95	1.05
Time period	-0.442**	-4.95	0.68	-0.41	0.00	0.63	0.99	1.01
Xylene	0.510**	133.43	29.98	0.29	0.00		0.71	1.41
Air velocity	-0.346**	-9.68	3.88	-0.16	0.01		0.75	1.34
Dependent Variable: Formaldehyde (ZSkewness = -1.50, ZKurtosis = -2.04)								
Constant		1.27	0.15		0.00			
Time period	-0.636**	-0.34	0.03	-0.62	0.00		0.98	1.02
Air velocity	-0.548**	-1.15	0.16	-0.43	0.00	0.71	0.73	1.38
Humidity	-0.170*	-0.01	0.00	-0.19	0.00		0.96	1.04
Xylene	0.403**	2.93	1.18	0.14	0.01		0.73	1.37

Note: *: p-value < 0.05, **: p-value < 0.01

These regression outcomes build upon the statistical findings by identifying not only key predictors such as air velocity and time period, but also interdependencies among VOCs. The notable correlation between toluene and xylene suggests common emission pathways from interior materials, providing practical insight for emission source control. High adjusted R^2 values, especially for formaldehyde, demonstrate the predictive strength of the models and support the use of multivariable analysis as a foundation for designing targeted, responsive IAQ management strategies. Air velocity consistently emerged as a significant negative predictor of xylene, toluene, and formaldehyde levels, demonstrating the effectiveness of active ventilation in reducing indoor VOC concentrations.

3.3 Causal Loop Analysis

The causal loop diagram (Interactions between VOC concentrations, environmental conditions, and building usage behaviors are visualized in the causal loop diagram in Figure 2, which highlights feedback mechanisms and leverage points relevant to IAQ optimization in smart building environments.) illustrates the complex interactions among building usage patterns, environmental variables, and VOC concentrations. It highlights key feedback mechanisms, such as the reinforcing effect of low air velocity on pollutant accumulation and the balancing effect of increased airflow on pollutant reduction. For example, extended usage time without adequate ventilation increases VOC emissions, which in turn elevates indoor concentrations unless counteracted by enhanced air movement or environmental control.

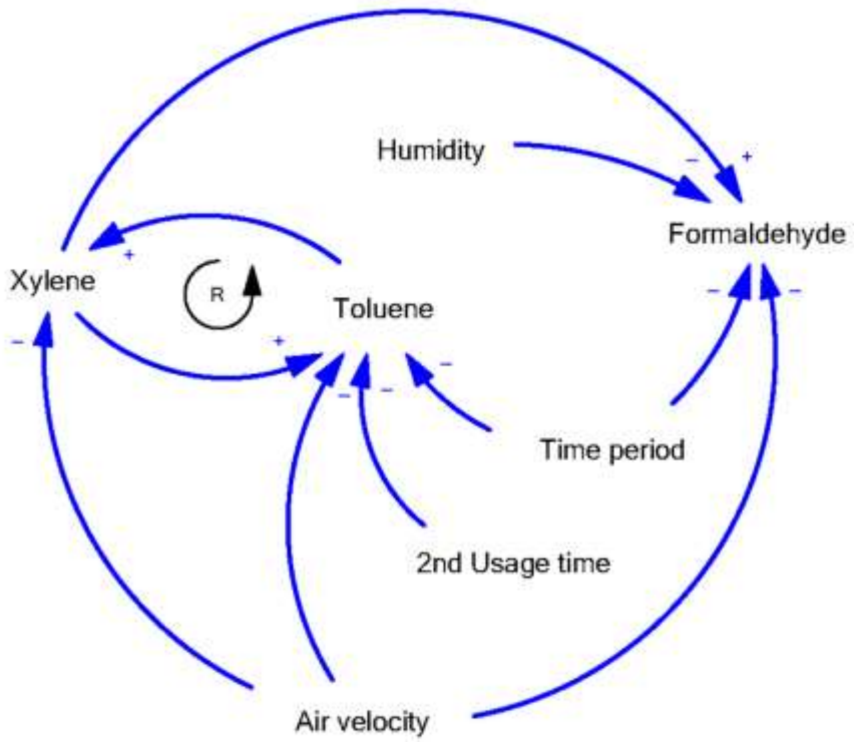

Figure 2: Causal Loop Diagram Illustrating VOC Dynamics in a Smart Building Context.

The diagram also reflects the interdependency among VOCs, particularly the reinforcing relationship between toluene and xylene, as well as their sensitivity to contextual factors such as time of use, humidity, and air conditioning status. This system-level view underscores how even small adjustments in operational settings can result in nonlinear impacts on air quality.

By visualizing these dynamics, the model serves as a decision-support tool for identifying leverage points to optimize IAQ management. It reinforces the need for responsive, health-centered strategies in smart building design, aligning real-time building usage with targeted ventilation interventions and environmental controls. In practice, the diagram can guide policymakers in identifying regulatory leverage points, such as implementing mandatory ventilation schedules during early occupancy periods, while also supporting building managers in refining zone-based air management strategies to reduce VOC exposure.

3. DISCUSSION

4.1 Interpretation of Findings

This study provides evidence-based insights into how building usage characteristics and environmental factors influence indoor air quality (IAQ) in newly constructed smart buildings, reflecting the growing importance of health-centered design in urban development. The findings emphasize that VOC dynamics are shaped not only by emissions from building materials but also by temporal occupancy patterns and operational conditions such as ventilation and air movement.

Among all tested variables, the time period of use emerged as the most statistically significant factor influencing formaldehyde concentrations. This supports prior research showing time-dependent decay of emissions due to off-gassing of construction and furnishing materials (Jo and Sohn 2009, Guo et al. 2013). The decline in formaldehyde over the 15-month period underscores the need to manage exposure during early occupancy phases. Notably, air velocity was also found to be a major mitigating factor for VOCs, consistent with findings from office environments in China (Huang et al. 2017), indicating that airflow regulation, whether mechanical or passive, can substantially reduce pollutant buildup. These findings can directly inform the development of smart ventilation strategies. In particular, increasing airflow during early occupancy periods, when VOC accumulation is highest, may serve as a practical intervention to reduce short-term exposure risks. Integrating such timing-sensitive airflow control into building automation systems can significantly improve IAQ management in smart environments. These findings contribute to the growing body of evidence supporting real-time, usage-aware, and environment-responsive strategies for indoor air quality management. They also align with the principles of modern smart building design and intelligent IAQ control systems that integrate sensor-based environmental data. Specifically, the results highlight that increasing airflow during early occupancy periods, when VOC accumulation tends to peak, may serve as an effective intervention to mitigate short-term exposure. Incorporating such timing-sensitive airflow control into automated building systems can significantly enhance IAQ management in smart urban environments. Furthermore, the consistently elevated levels of formaldehyde underscore the importance of adopting additional measures such as the use of low-emission construction materials and phased occupancy strategies to reduce emissions during the early building use phase.

Despite regulatory thresholds not being breached for xylene and toluene under OSHA and NIOSH limits, 16 air samples exceeded the ACGIH threshold for toluene, mostly during Time 1 (prior to air conditioning operation). This raises potential short-term exposure concerns, particularly during morning hours or reoccupation after periods of closure. A strong correlation between toluene and xylene concentrations also points to shared emission sources or similar dispersion behavior, in line with studies by Ghaffari et al. (Ghaffari et al. 2021).

The study further investigated the roles of environmental parameters. Building size and occupant density were not found to be significant predictors of VOC or formaldehyde levels, echoing the results from apartment complex studies in Harbin (Zhang et al. 2020). Meanwhile, temperature within the observed range (21–29°C) showed no clear association with pollutant levels, though past research suggests more extreme variations could elevate emissions (Lin et al. 2021). Relative humidity was inversely associated with formaldehyde, supporting the theory that increased moisture enhances emission behavior and interactions of formaldehyde with materials, as observed in more recent studies (Huang et al. 2016, World Health Organization 2010). Findings from this study also align with those reported by Seng et al. (2023), who investigated indoor air quality in critical areas of Malaysian hospitals. Their study found elevated TVOC levels in poorly ventilated rooms, highlighting the importance of airflow. This conclusion is consistent with our findings in conditions before air conditioning turned on (Time 1), where pollutant levels reached their peak. The parallel underscores the broader relevance of ventilation control in mitigating VOC exposure across different building types.

The temporal use patterns of the building significantly shaped exposure profiles. Usage Time 1 showed the highest VOC levels due to overnight stagnation, whereas Usage Time 2, marked by high circulation and occupant movement, had the lowest concentrations. Usage Time 3, despite continuous use, showed re-accumulation in the absence of strong ventilation. These usage-sensitive findings reinforce the concept of adaptive ventilation scheduling, particularly during transitional periods of the day (Kwon et al. 2023).

Taken together, the results from this study contribute to the growing body of evidence that supports real-time, usage-aware, and environment-responsive strategies for indoor air quality management. The findings also align with smart building policy frameworks such as those proposed in the Nusantara Capital Authority (Nusantara Capital Authority 2023) and modern IAQ control systems utilizing IoT technologies (Kharbouch et al. 2022). These findings demonstrate that strategic control of ventilation, air velocity, and humidity when aligned with occupancy schedules can significantly enhance health-centered building design in urban environments.

4.2 Methodological Considerations and Limitations

This study was conducted at a single smart building, which may limit generalizability. However, the focused design allowed for detailed, context-specific analysis under controlled conditions. Data collection was limited to fixed weekdays and time points, which may not fully reflect seasonal or behavioral variability. To address this, measurements were repeated across two periods and multiple functional zones. While key environmental and operational parameters such as temperature, humidity, air velocity, and building usage patterns were systematically assessed, the study did not incorporate outdoor VOC measurements or detailed modeling of occupant behaviors, such as ventilation usage patterns, movement, or product application. These factors can influence the short-term variability of indoor VOC concentrations and should be considered in future research to expand model robustness and applicability across building types and usage scenarios.

To enhance the applicability and scalability of findings, future research should explore the integration of IoT-based sensor networks with predictive AI-driven ventilation systems. Such systems can enable real-time, adaptive airflow regulation in response to pollutant levels and occupancy patterns. Additionally, expanding the temporal scope to include multi-seasonal monitoring would help capture environmental variability and strengthen the evidence base for long-term IAQ management strategies.

Despite these limitations, the study offers a solid empirical foundation for health-centered air quality strategies in smart buildings, and its methodological approach provides a replicable framework for further investigations in similar urban contexts.

4.3 Policy Implications and Practical Applications

This study suggests important directions for enhancing indoor air quality (IAQ) policy and design practices in smart urban buildings. First, usage-sensitive ventilation strategies should be incorporated into building codes to address elevated pollutant levels observed during early occupancy. Urban building codes in Thailand should consider mandatory post-construction flush-out procedures and staged occupancy requirements to mitigate VOC exposure during the initial building phase. Second, the strong influence of air velocity supports the integration of adaptive, sensor-driven environmental control systems. Third, to reduce acute exposure to formaldehyde and toluene, phased ventilation protocols should be recommended during initial building use. Furthermore, aligning national IAQ policies with emerging regional frameworks, such as those proposed by the Nusantara Capital Authority, may enhance consistency and accelerate the adoption of health-centered smart building standards across Southeast Asia. Although this study focused on a single building, its methodological approach offers a replicable framework for broader applications in IAQ modeling and evidence-informed policy development across varied urban contexts.

4. CONCLUSION

This study provides comprehensive insights into the dynamics of indoor air pollutants in newly constructed smart buildings by integrating multivariable statistical analysis and system dynamics modeling. Key findings reveal that usage patterns, time of day, and air velocity significantly affect VOC concentrations, with formaldehyde particularly sensitive to early occupancy periods and ventilation conditions. The observed correlations between xylene and toluene emphasize shared emission pathways, while the strong predictive power of the regression models reinforces the relevance of targeted environmental controls.

Through real-time sampling across distinct building zones and operational periods, the study offers practical recommendations for adaptive ventilation, humidity regulation, and evidence-based air quality management. The system-level understanding generated by causal loop modeling further supports the development of smart, health-centered building strategies. These results contribute meaningfully to the ongoing discourse on sustainable indoor environments and offer a decision-support foundation for future policy development, particularly in rapidly urbanizing regions.

Beyond its immediate practical relevance, this study contributes to the evolving scientific understanding of how environmental and operational variables interact to influence VOC behavior in high-density urban settings. Future research should explore longitudinal IAQ monitoring across diverse building typologies, integrate occupant behavior modeling, and evaluate the effectiveness of AI-driven ventilation systems. These directions will strengthen the foundation for sustainable, health-centered indoor environments in rapidly urbanizing cities.

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