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Indoor Air Quality Investigation of Fresh Markets in Hot and Humid Climates: A Case Study in Thailand

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Abstract

The issue of poor air quality in fresh market facilities poses a public health threat, particularly in association with the food supply chain. This study assessed the indoor air quality (IAQ) of various food retailers and aimed to (a) identify IAQ problems, (b) investigate the source of indoor air contamination in the fresh market, and (c) recommend better design practices for IAQ in fresh markets. The IAQ of 33 food retailers in four fresh markets in Bangkok, Thailand, was measured for ten parameters: temperature (T), relative humidity (RH), air velocity, particle matter ($PM_{2.5}$, PM_{10}), carbon dioxide (CO_2), ozone (O_3), formaldehyde (HCHO), total volatile organic compounds (TVOC), and bioaerosols. The result found mean values of IAQ parameters in 33 food retailers that exceeded the threshold limit values (TLVs) of the SOOK, Thailand's well-being building standards, were $PM_{2.5}$ of 30 µg/m^3, HCHO of 124 µg/m^3, and TVOC of 733 µg/m^3. The retail stall provides fresh food products that produce wastewater from product displays and preparation, which had the highest averages of RH and bioaerosols, with RH of 66.4% and bioaerosols of 1,346 CFU/m^3. The retail facilities with cooking activities, such as open kitchen restaurants, noodle restaurants, and cafés, had high averages, with $PM_{2.5}$ of 51 µg/m^3, HCHO of 216 µg/m^3, TVOC of 922 µg/m^3, and bioaerosols of 1,154 µg/m^3. The stall provides dry food products with an average TVOC of 986 µg/m^3, exceeding TLVs. A zoning-based approach was proposed as a design guideline to improve IAQ in fresh markets. Fresh food (FF), Dry Food (DF), and Cooking Food (CF) zoning should be carefully designed to lower the risk of cross-contamination.

Keywords

Indoor air quality; Bioaerosols; $PM_{2.5}$; Fresh market; Hot and humid climate

1. Introduction

The recent respiratory infection pandemic (COVID-19) raised public concern about indoor air quality (IAQ), particularly in fresh markets. The majority of the first coronavirus cases (55%) were linked to the Huanan Seafood Wholesale Market in Wuhan, China (Mizumoto et al., 2020; Wu et al., 2020). In Thailand, a major cluster emerged from fresh markets. In December 2020, 4,000 positive COVID-19 cases were detected at the Mahachai Fresh Market, Samut Sakhon province (Suanburi et al., 2021), the largest seafood market in Thailand. The market was closed for 72 days from 19 December 2020 to 28 February 2021. Samut Sakhon province was locked down. However, these restrictions could only delay the spread of the pandemic. From April to

August 2021, clusters arising from fresh markets were reported countrywide. The Thai government announced the temporary closure of markets for periods ranging from 15 to 45 days if infected individuals had been detected, a measure which led to food shortages. The impacts were massive, severely affecting food security, the economy, and society. The non-resiliency of traditional markets was empirically proven through this experience. This pandemic generated specific questions related to IAQ parameters, such as its origin, how to fix the situation, and what preventative methods should be implemented for the future. Alongside temperature and humidity, IAQ is the set of parameters that correlates with both the pandemic crisis and occupant health in indoor environments (Agarwal et al., 2021).

Environmental conditions in fresh markets, such as hot, wet floors; pungent odors; and infection from microbes, are directly impacted by IAQ. Exposure to bioaerosols has been linked to the incidence of various health effects, such as infectious diseases, acute toxic effects, allergies, and cancer (Chang et al., 2023). Fresh food contains many bacteria that could spread through the air. Bioaerosols generated by fresh foods in traditional wet markets in Taiwan led to biological hazard risks. Here, hotspots were associated with vendors of live poultry, raw meat, and fresh seafood. Pseudomonas species pluralis (spp) and Clostridium perfringens were the dominant species (Wei et al., 2021). These microorganisms can be transmitted by an airborne route, including fine mist, dust, aerosols, or liquids. Additionally, pesticides and cleaning agents are sources of indoor air pollution. Temperature, relative humidity, and particulate matter concentration ($PM_{2.5}$ and PM_{10}) have been associated with the indoor bacterial load (Andualem et al., 2019). Cooking is a main activity that is unavoidable in the fresh market. The kitchens emit $PM_{2.5}$ and volatile organic compounds (VOCs) (Chen et al., 2020). Previous studies have shown that the average $PM_{2.5}$ concentration in a kitchen can exceed 300 $\mu g/m^3$ even with ventilation in place (Zhao & Zhao, 2020). The peak $PM_{2.5}$ exposure of the chef can be linked to the cooking and frying activities (Te Kulve et al., 2022). Cooking experiments involving the frying of bacon were shown to emit 2.35×10^3 (SD of 2.22×10^3) µg/min of $PM_{2.5}$ (Liu et al., 2022). Furthermore, the study determined that the TVOCs generated in the kitchen area of a barbecue restaurant and frying restaurant varied between 200.4 $\mu g/m^3$ and 426.4 $\mu g/m^3$, and the median value was 237.1 $\mu g/m^3$ with a sum of 60 analyzed species (Arı et al., 2020).

Indoor air pollution can be an invisible health threat. IAQ problems involve indoor air contaminated with substances that exceed guidelines and are harmful to human health (Tran et al., 2020). Poor quality air can lead to Sick Building Syndrome (SBS), which is associated with occupant symptoms such as headache, fatigue, difficulty concentrating, eye-nose-throat irritation, and poor work performance (Hawkins et al., 2020). The future built environment must focus on developing more human-centered designs (Goh & Chong, 2023; Megahed & Ghoneim, 2021). With these resiliency challenges, it would be useful to address fresh markets' clean air and prepare for future crises.

Despite the importance of IAQ, there has been a lack of data collected from fresh markets. Additionally, there is a gap in routine IAQ monitoring and assessment. The fresh market building code, Thailand Ministerial Regulation for Food Selling Place Hygiene B.E. 2561 (A.D., 2018), mandates adequate ventilation in places that sell food. However, threshold limit values (TLVs) were not proposed. Without measurement equipment, methods, and assessment policies, the IAQ in Thailand's fresh markets has not been thoroughly investigated. Our study fills this crucial research gap by providing quantitative IAQ data and assessing the health and well-being of indoor markets based on building standards.

The study hypothesizes that various food products, consumer goods, and cooking activities release indoor air contaminants. The research question is to find the sources of air contaminants within various vendor areas. This research aimed to (a) identify IAQ problems inside fresh markets located in a hot and humid climate and compare the IAQ parameter levels to health and well-being building standards, (b) investigate the source of indoor air contamination in fresh markets, and (c) recommend better design practices for IAQ in fresh markets. The research will benefit building innovation researchers in designing resiliency and well-being in fresh markets. It also will provide qualitative IAQ information and awareness to fresh market stakeholders, including architects, engineers, facilities managers, and entrepreneurs/vendors in the public and private sectors.

2. Methodology

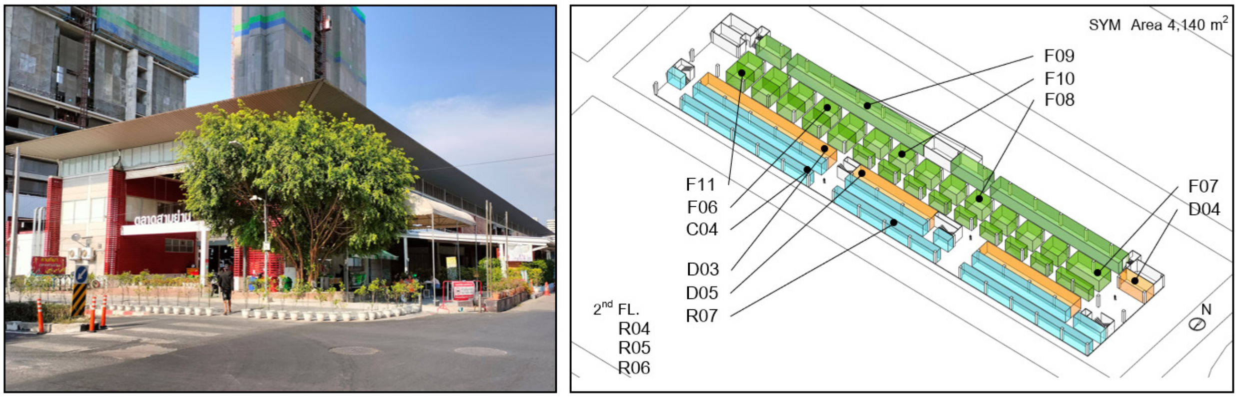
This study uses the field observation method to investigate IAQ problems in fresh markets. The data were collected during fresh market business hours (8:00 – 12:00) using a real-time IAQ device that measured nine parameters, including temperature (T), relative humidity (RH), air velocity, particle matter ($PM_{2.5}$, PM_{10}), carbon dioxide (CO_2), ozone (O_3), formaldehyde (HCHO), and total volatile organic compounds (TVOC). Bioaerosol samples were collected using a nutrient agar (NA) petri dish with a passive air sampling method. The data for ten indoor air parameters were obtained and statistically analyzed.

2.1 Study Sites

Four fresh markets in Bangkok, KU Avenue (KUA), Or Tor Kor (OTK), Samyan (SYM), and Yodpiman (YPM), were selected for IAQ investigation. The criteria for selection were (1) the market is a permanent building; (2) the fresh market provides similar products and services, including fresh products, dry goods, and ready-to-eat food or a food court; and (3) natural ventilation (NV) was the main ventilation system. The retail spaces in the four case studies are divided into open floor plans with internal walls. The primary ventilation systems were NV, though mechanical fans also were installed in the food court areas. In the market hall, all four fresh markets permit interior decoration and air conditioning systems. Typically, the rental areas are organized by product type, with the shops selling similar products being located near one another. SYM has two designated areas for rental spaces offering cooked food: one on the first floor at the south entrance and the other occupying the entire second floor.

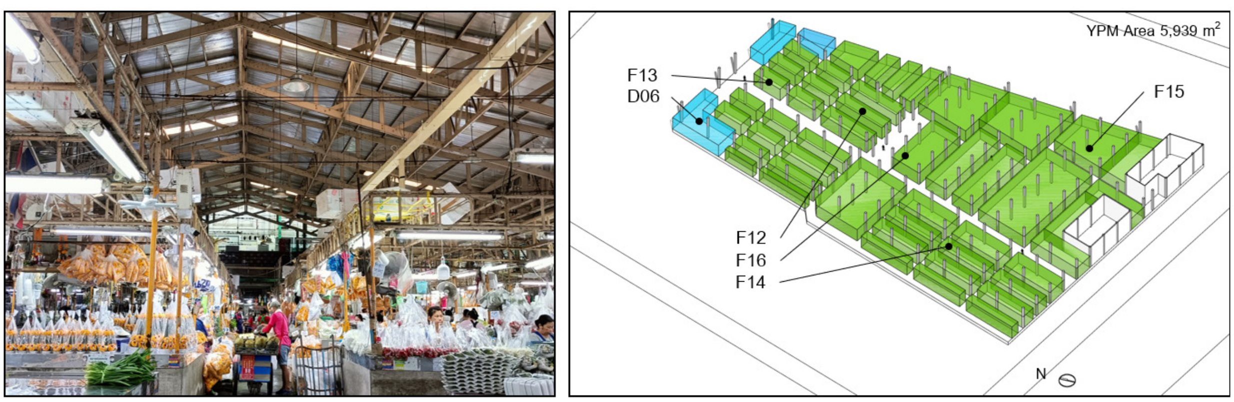
The criteria for stall selection were based on product categories: (1) fresh food products, such as vegetables, fruits, flowers, meat, and seafood; (2) dry food goods, such as dried food, rice, and eggs; and (3) cooking, such as restaurants, cafés, and food courts. After obtaining the necessary approval for our research field study from the management department of each market, we contacted stall owners for permission to undertake the IAQ assessment. Due to space limitations for sampling, the assessed rental block in the market hall needed to be 4 - 8 m^2. Furthermore, the IAQ station and NA petri dish location must not obstruct business operations. Photo of case studies and layout diagrams are shown in Figure 1.

(a) KU Avenue (KUA) is a small fresh market with an area of 1,110 m^2. The 32 rental spaces are 8 - 120 m^2.



(b) Samyan Fresh Market (SYM) has a usable area of 4,140 m^2. The 120 rental spaces are 6 - 16 m^2.

(c) Or Tor Kor Fresh Market (OTK) has a usable area of 4,530 m^2. The 170 rental spaces are equally 4 m^2.



(d) Yodpiman Fresh Market (YPM) is the largest, with an area of 5,939 m^2. The rental spaces are 2 – 16 m^2.

Figure 1. The photo and layout diagram of study sites: KUA, SYM, OTK, and YPM.

Zoning areas are represented by color: green is fresh food (FF), orange is dry food (DF), and blue is cooking food (CF).

2.2 Equipment, Monitoring System, and Sample Collection

The real-time measurement devices used in this field study were KIMO AMI310, BLATN BR Smart 126, Dienmern DM509 O_3 Ozone Meter, and HOBO UX100-023A. The equipment for Bioaerosol sampling is nutrient agar (NA) in a 90 mm petri dish. Photos of the devices and equipment are shown in Figure 2.

Four real-time measurement devices were positioned on a tripod to create the IAQ station at a height of 1 - 1.20 meters above the floor, which represents the level of the human breathing zone. An IAQ station was installed for one hour at each sampling point, and the data were logged every fifteen minutes. The instruments were calibrated before each use using the calibration function in the devices. Table 1 provides details on the logging rate, air parameters, measuring range, and accuracy of the four instruments. The limitation was that there was only one IAQ station. Therefore, data collection was scheduled during business operations from 8:00 to 12:00 to ensure data consistency.

(1) (2) (3) (4) (5)

Figure 2. Indoor air quality monitoring instruments from left to right, (1) KIMO AMI310, (2) BLATN BR-Smart 126, (3) Ozone Meter, (4) HOBO UX100-023A, and (5) Nutrient agar 90 mm petri dish.

Table 1. Details of the logging rate, parameters, measuring range, and accuracy of the instruments used for the field research.

Tools	Logging Rate	Parameters	Units	Measuring Range	Accuracy
KIMO AMI310	15-minute intervals	Temperature Relative Humidity Air Velocity Carbon Dioxide	°C % m/s ppm	-20 to +80 3 to 98 0.15 to 5 0 to 5000	±0.25 ±1.8 ± 0.03 ±50
BLATN BR-Smart 126	1-minute intervals	$PM_{2.5}$ PM_{10} Formaldehyde TVOC	μg/m^3 μg/m^3 μg/m^3 μg/m^3	0-999 0-999 0 to 3 0 to 9.99	±0.1 ±0.1 ±0.1 ±0.1
Dienmern DM509 O3 Ozone Meter	15-minute intervals	Ozone	μg/m3	0 to 1000	±0.2
HOBO UX100-023A	1-minute intervals	Temperature Relative Humidity	°C %	-20 to 70 1 to 100	±0.025 ±0.21

The nutrient agar (NA) in the petri dish, size 90 mm × H 15 mm and with a surface area of 58 cm^2, was used for bioaerosol sampling. The NA is a positive control for Staphylococcus aureus, Escherichia coli, and Pseudomonas aeruginosa and a negative control for the uninoculated medium. The mediums were kept cool at 4°C before use. Using the passive air sampling method, the NA petri dish was placed 1 meter above the floor at the nearest activity surface for 20 minutes. After collection, samples were brought to the laboratory at the center of building innovation and technology (CBIT) on the same day for incubation at 37°C for 48 hours (Manibusan & Mainelis, 2022). Total Colony Forming Units (CFU) were counted and CFU/m3 microbial concentration was determined using the following equation (Andualem et al., 2019):

$$N = (a \times 10{,}000) / (bt \times 0.2),$$

where N = microbial CFU/m^3 of indoor air, a = number of colonies per petri dish, b = dish surface area (cm^2), and t = exposure time (min).

The limitation of the NA petri dishes was that they needed to be prepared in advance, which restricted their availability. When data collection encountered obstacles, we were unable to effectively substitute for the sampling process due to the insufficient quantity of NA petri dishes, which could not be acquired promptly.

2.3 IAQ Assessment and Well-Being Building Standards

Acceptable IAQ is "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80 percent or more) of the people exposed do not express dissatisfaction" (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2022) . Threshold limit values (TLVs) were used to evaluate indoor air contamination parameters. This research utilized TLVs from the SOOK Building Standards V1.0, 2021, (The SOOK V1.0), Thailand's health and wellbeing building standards developed by the Thai Green Building Institute (TGBI). For comparison purposes, the TLVs established by the WELL Building Standard (WELL V2), an international health and well-being building standard, were also examined. The WELL V2 assesses IAQ by referencing TLVs, which are evaluated through structured performance verification conducted by certified professionals using real-time monitoring devices. Additionally, the standard encourages continuous monitoring to support ongoing air quality management. According to The SOOK V1.0, building owners or facility managers are required to conduct IAQ testing under the supervision of qualified architects, mechanical engineers, or project consultants and present the results. Both The SOOK V1.0 and WELL V2 define TLVs and require performance verification through real-time monitoring at designated intervals. The bioaerosols are compared based on the regulations in the announcement of Thailand's Department of Health, Ministry of Public Health (MOPH): Indoor Air Quality Monitoring Inside Public Buildings, 2022. However, the standard does not provide detailed protocols for measurement or verification. The TLVs of local standards and WELL V2 are summarized in Table 2.

Table 2. Indoor air parameter threshold limit values (TLVs) developed by WELL V.2, the SOOK V1, and the Department of Health, Ministry of Public Health Thailand (MOPH).

Parameters	Units	IAQ TLVs in Building Standards		
		WELL V2	The SOOK	MOPH
CO_2	ppm	900	1,100	1,000
O_3	µg/m^3	100	100	100
HCHO	µg/m^3	50	33	100
TVOC	µg/m^3	500	500	1,000
$PM_{2.5}$	µg/m^3	25[1/]	25	25
		35[2/]		
PM_{10}	µg/m^3	50[1/]	50	50
Total Microbial Count (TMC)	CFU/m^3	-	-	500

[1/] WELL v2, Q3 – Q4 2024, modified thresholds in polluted regions

[2/] PM2.5 threshold for commercial and industrial kitchen spaces

3. Results

The field study was conducted in Thailand during the rainy season, from May to July 2022. Thirty-three stalls in four fresh markets were investigated. The IAQ station was set up inside the stalls. The NA petri dishes were placed in every stall for 20 minutes at 1 meter above the floor at the nearest activity surface to collect bioaerosol samples. Permission from the vendors for the 33 stalls was obtained to ensure that the business and service were not disrupted. Mechanical ventilation (MV), such as portable fans, was turned off. Figure 3 shows typical installations of the IAQ station. During one hour of monitoring, data were logged every fifteen minutes for the nine parameters. In total, 132 IAQ data sets were used for statistical analysis.

Figure 3. The IAQ station was set up at individual food stalls that sell different goods: (F02) fruit, (R02) food court, (D01) eggs, (D03) rice, (R04) Restaurant, (F10) pork, (F15) flowers, and (D06) groceries.

3.1 Climatological and Particulate Matter Reports

The Thai Meteorological Department, Bangkok Metropolis Station, reported that the daily mean temperature in Bangkok from May to July 2022 was 29.6°C. Bangkok Metropolitan Administration (BMA), Patumwan Air Quality Station reported an average $PM_{2.5}$ of 19 µg/m^3 from May to July 2022, which is the rainy season in Thailand. The ambient $PM_{2.5}$ was considered healthy, and there was no risk of exposure under the minimum requirement of 25 µg/m^3 under the Thai National Ambient Air Quality Standards (NAAQSs). The monthly average meteorological data from May to July 2022 were used as an outdoor ambient comparison and are summarized in Table 3.

The average indoor air parameters, including temperature, relative humidity, air velocity, $PM_{2.5}$, and PM_{10}, values obtained from field measurements in the four fresh market sample sites are shown in Table 4. Indoor $PM_{2.5}$ and PM_{10} were lower than the values obtained from the BMA weather station, except for SYM.

Table 3. The average monthly temperature and rainfall from May to July 2022 were reported by the Thai Meteorological Department (TMD), Bangkok Metropolis Station, and $PM_{2.5}$ was reported by the Bangkok Metropolitan Administration (BMA), Patumwan Air Quality Station.

2022	Temperature (°C)			Rainfall (mm)		$PM_{2.5}$
	Max.	Min.	Mean	Actual	Accumulative	(µg/m^3)
May	38.5	13.6	29.5	116.0	362.4	21
June	39.4	20.0	30.1	231.3	659.1	18
July	38.6	20.1	29.3	403.4	1,062.5	17

Table 4. The average indoor air parameters, temperature, relative humidity, air velocity, $PM_{2.5}$, and PM_{10}, values obtained from field measurements in four fresh market study sites.

Study Site	N	T	RH	Air Velocity	PM2.5	PM10
		°C	%	m/s	(µg/m^3)	(µg/m^3)
KUA	5	28.6	60.0	0.3	4	5
OTK	8	29.4	58.6	0.2	14	10
SYM	14	28.7	61.4	0.3	58	86
YPM	6	28.7	72.0	0.2	13	19

3.2 Fresh Market IAQ Assessment

Six air contaminant parameters were measured by a real-time IAQ device, including carbon dioxide (CO_2), ozone (O_3), formaldehyde (HCHO), total volatile organic compounds (TVOC), $PM_{2.5}$, and PM_{10}, and then assessed according to the SOOK building standards. However, O_3 was not detected except for one sample in the pharmacy with a concentration of 105 µg/m^3. Hence, O_3 was excluded from this analysis. The remaining five air contaminant parameters were subjected to descriptive statistical analysis, as shown in Table 5. The results found that the mean value of three air contaminants, TVOC, HCHO, and $PM_{2.5}$, exceeded the TLVs of the SOOK standards.

Table 5. Descriptive statistical analysis, Minimum, Maximum, Mean, and Standard Deviation (SD) of five indoor air parameters measurements from 33 food stalls in four fresh markets (n=132).

Air Parameters	Units	TLVs[1/]	Minimum	Maximum	Mean	SD
CO_2	ppm	1,100	20	1,043	403	200
TVOC	µg/m^3	500	8	2,498	733	575
HCHO	µg/m^3	33	1	950	124	209
$PM_{2.5}$	µg/m^3	25	1	519	30	70
PM_{10}	µg/m^3	50	2	812	43	111

[1/] The SOOK Building Standards V1.0, 2021

[2/] The red colored number represents the value that exceeds the TVLs.

The average of the indoor air contamination value categories from the individual study sites gave the same statistical results as the overall data. The problems of air contamination in each of the four fresh markets had similar characteristics. The parameters that exceeded the TLVs of the SOOK building standards were TVOC, HCHO, and $PM_{2.5}$. The mean and standard deviations of IAQ in each fresh market are shown in Table 6.

Table 6. Descriptive statistical analysis of means and standard deviations (SD) of five indoor air parameters concentrations compared between four sampling groups, clustered according to the fresh market case study (n=132).

Parameters	Units	TLVs[1/]	KUA		OTK		SYM		YPM	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
CO_2	ppm	1,100	488	293	366	218	419	169	341	101
TVOC	µg/m³	500	687	736	778	507	853	587	435	390
HCHO	µg/m³	33	315	328	134	219	82	105	51	91
$PM_{2.5}$	µg/m³	25	4	4	14	20	58	84	13	4
PM_{10}	µg/m³	50	5	7	10	10	86	134	19	7

[1/] The red colored number represents the value that exceeds the TVLs.

3.2.1 IAQ in natural ventilation (NV) and air conditioning (AC) systems

Natural ventilation (NV) systems were commonly used across the four fresh market study sites. However, some vendors, especially those in restaurants, cafés, grocery stores, pharmacies, and flower shops, had installed air conditioning (AC) systems in their leased spaces. This analysis divided the sample data into two groups, those with NV systems and those with AC systems, to compare the impact of ventilation systems on IAQ. The results found that average CO_2, $PM_{2.5}$, and TVOC levels were higher in spaces with AC, as shown in Table 7. The CO_2 level is essential in the IAQ and is often used as a proxy for the ventilation rate (Ma et al., 2021). The results revealed that less ventilation was observed in the AC group, with an average CO_2 of 574 ppm, which was higher than the 305 ppm in the NV group. TVOC and $PM_{2.5}$ exceeded the TLVs in both ventilation systems. Additionally, CO_2, $PM_{2.5}$, and TVOC in the AC groups were higher than those of the NV group, as illustrated in Figure 4. TVOC concentration in the AC group was 101% higher than in the NV group, and $PM_{2.5}$ levels in the AC group were 54% higher than in the NV group.

Table 7. Descriptive statistical analysis of Mean and standard deviations (SD) of CO_2, $PM_{2.5}$, and TVOC concentrations compared between two sampling groups, clustered according to air ventilation system: natural ventilation (NV) and air conditioning (AC) systems (n=132).

Parameters	Units	TLVs[1/]	Natural Ventilation (n=84)		Air Conditioning (n=48)	
			Mean	SD	Mean	SD
CO2	ppm	1,100	305	100	575	202
TVOC	µg/m³	500	549	301	1,151	584
PM2.5	µg/m³	25	26	39	40	58

[1/] The SOOK Building Standards V1.0, 2021

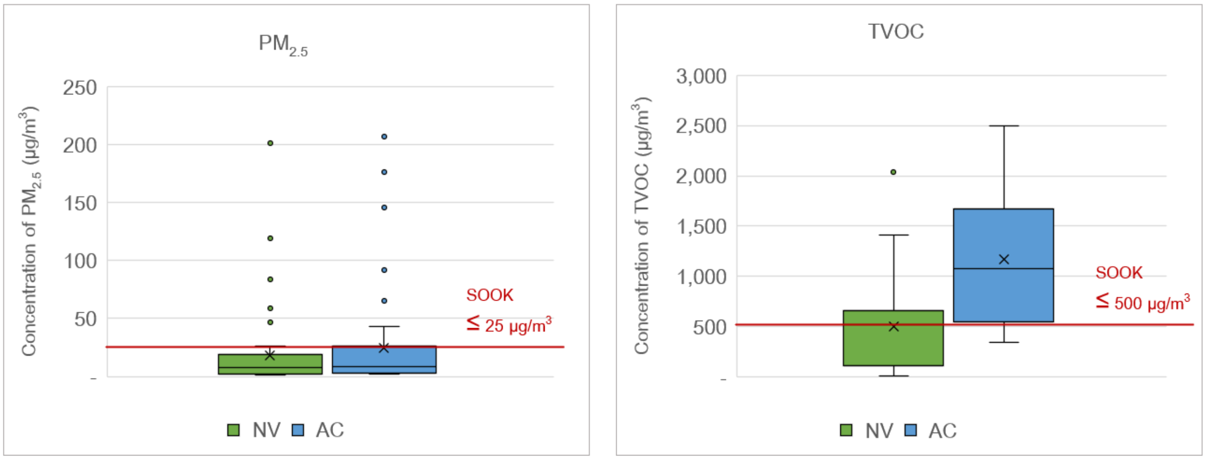


Figure 4. Box plot diagram comparing $PM_{2.5}$ and TVOC in food retail stores with natural ventilation (NV) and air conditioning (AC) systems. The box represents the interquartile range (IQR) from Q1 to Q3, the horizontal line inside the box is the median, the cross inside the box is the mean, the whiskers indicate the local minimum and maximum values, and the dot outside the box is outliers.

3.2.2 The sources of indoor air contaminants

TVOC ranged from 8 to 2,498 µg/m^3, with a mean of 733 µg/m^3. Twenty-two locations (66% of the sampling) had an average TVOC higher than the SOOK standard of 500 µg/m^3. The mean TVOC for the 22 locations were ranked in descending order and presented as a box plot diagram in Figure 5. The majority of high TVOC averages were found in locations where cooking was performed. The highest average TVOC was found in restaurants selling pork noodle (R07) at 2,498 µg/m^3, followed by Café (C02) at 2,299 µg/m^3. Pharmacy (D05) was the hotspot in the dry food category, with an average TVOC of 1,967 µg/m^3. Pharmacy carried cleaning products, including chlorine, which could be the source of TVOC.

HCHO ranged from 1 to 950 µg/m^3, with a mean of 124 µg/m^3, higher than the SOOK standard of 33 µg/m^3. Fifteen locations had an average HCHO greater than the standard, and nine locations had cooking activities. Figure 6 presents the box plot diagram with ranked average HCHO in descending order. The highest value of HCHO was found in café (Oe) at 616 µg/m^3, café (Kb) at 597 µg/m^3, and beef noodle restaurants (Kc) at 496 µg/m^3.

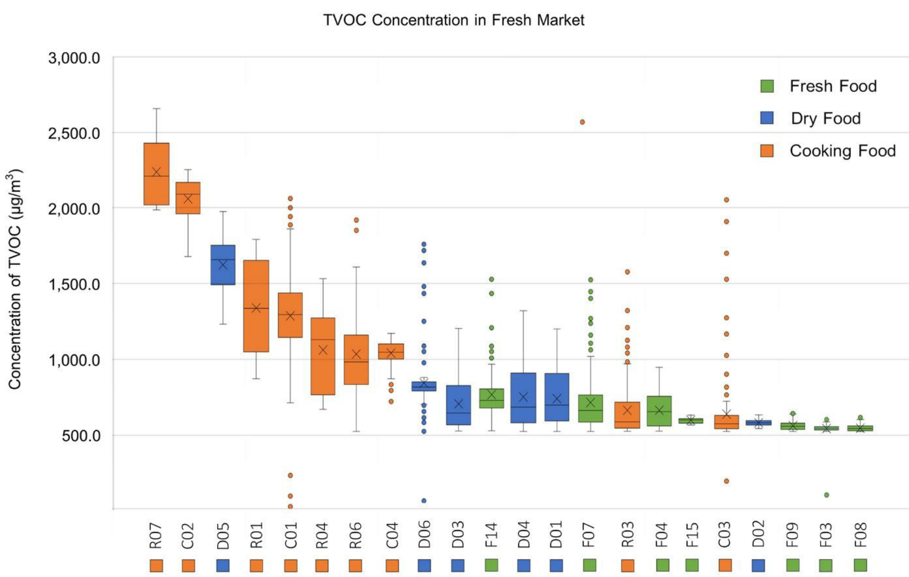


Figure 5. Box plot diagram showing the average and range between maximum and minimum values of the 22 locations where the average TVOC concentration exceeded the well-being building standards (> 500 µg/m^3).

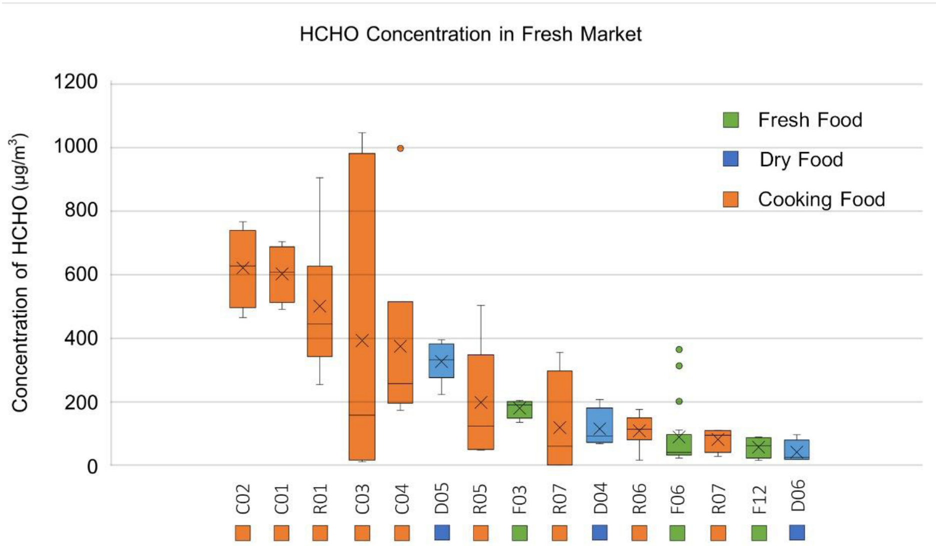


Figure 6. Box plot diagram showing the average and range between maximum and minimum values of the 15 locations where the average HCHO concentration exceeded the well-being building standards (>33 μg/m^3).

$PM_{2.5}$ ranged from 1 to 519 μg/m^3, with a mean of 30 μg/m^3. The average indoor $PM_{2.5}$ was higher than the ambient $PM_{2.5}$ of 19 μg/m^3 reported by the BMA Patumwan station. Seven locations with an average $PM_{2.5}$ higher than the SOOK standard at 25 μg/m^3 are presented as a box plot diagram in Figure 7. A hazardous maximum concentration $PM_{2.5}$ of 519 μg/m^3 was found in a restaurant that uses charcoal grill stoves on the customer's tables. The hotspots of average $PM_{2.5}$ were K restaurant (Sb) at 216 μg/m^3, M restaurant (Sa) at 178 μg/m^3, and J restaurant (Sc) at 97 μg/m^3, which were higher than the commercial kitchen standards of WELL V.2 of 35 μg/m^3. The top three locations, indicated by the orange color in the box plot diagram, were restaurants with charcoal grill at the table and open-plan kitchens.

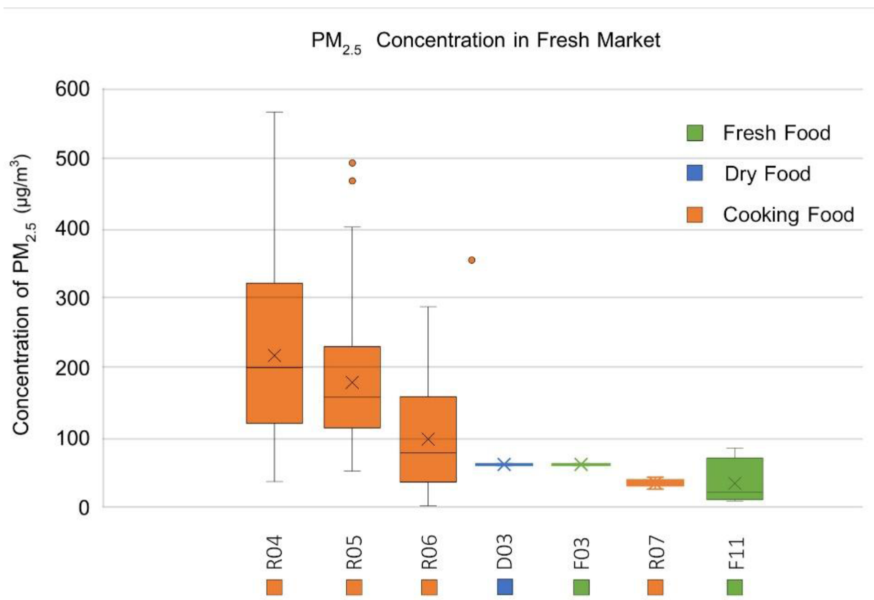


Figure 7. Box plot diagram showing the average and range between maximum and minimum values of the 7 locations where the average $PM_{2.5}$ concentration exceeded the well-being building standards (>25 μg/m^3).

3.3 Fresh Market Bioaerosol Assessment

The 24 bioaerosol concentration samples varied widely, from 86 to 38,578 CFU/m^3, with an arithmetic mean of 3,897 CFU/m^3, the standard deviation of 8,424.61 CFU/m^3, and geometric mean of 1,026 CFU/m^3. This research adopts the geometric mean to evaluate bacterial concentrations (CFU/m^3) across different areas, aligning with microbiology and environmental health practices.

The bioaerosol samples were collected simultaneously with the IAQ station monitoring in thirty-three locations. However, only 24 bioaerosol samples could be enumerated. The incomplete samples were caused by three factors. First, pests entered and ate the agar on the plate. Nutrient agar provides essential nutrients for the growth of various microorganisms. This nutrient-rich environment attracts various pests, such as flies and cockroaches. Second, the samples were unintentionally removed by cleaning teams. Third, condensation formed inside the plates during incubation, causing water droplets to drip onto the agar surface and spoil the microbial colonies. To minimize risk of this technical problem, the NA plates and lids were placed together for 20 minutes to let the lids completely dry. After the sample collection, the NA plate was placed face down, and the lid was closed from the bottom. Additionally, each sample was kept separately in a plastic bag to prevent contamination between samples. The samples were face down during delivery to the laboratory and cultivation in the oven to prevent the condensation droplets from dripping on the agar surface.

The hotspot location was a food court (R02) at 38,578 CFU/m^3. Figure 8 shows the food court with a large opening surrounded by trees and a five-meter-wide canal. The second was flower stall (F12) which located in the center of the market hall at 15,948 CFU/m3, follow by pork stall (F16) at 13,578 CFU/m^3, flower bouquet stall (F13) at 5,862 CFU/m^3, and a fruit stall (F02) at 2,500 CFU/m^3. Moreover, hotspots were also found in the fresh meat stalls selling pork, poultry, and seafood. The geometric mean concentration of bioaerosols was 1,026 CFU/m^3 indicating that the dataset is positively skewed. Table 8 shows the descriptive statistical analysis of the bioaerosols, temperature, relative humidity, and air velocity. Figure 9 shows the ten sampling locations that exceeded the threshold set by Thailand's Department of Health of 500 CFU/m^3. The majority of high-concentration bioaerosol averages were found in stalls that sold fresh products, as represented by the green bars in Figure 9. The results are consistent with those of a traditional wet market in Taiwan, which showed that the bacterial concentrations were highest near vendors selling animal meat, poultry, fish, and seafood (Chang et al., 2023).

Figure 8. Left: The food court had a full opening and was surrounded by landscape; Middle: The IAQ station during observation at the food court; Right: A Petri dish sample collected from the food court revealed the bioaerosol concentration of 38,577 CFU/m^3.

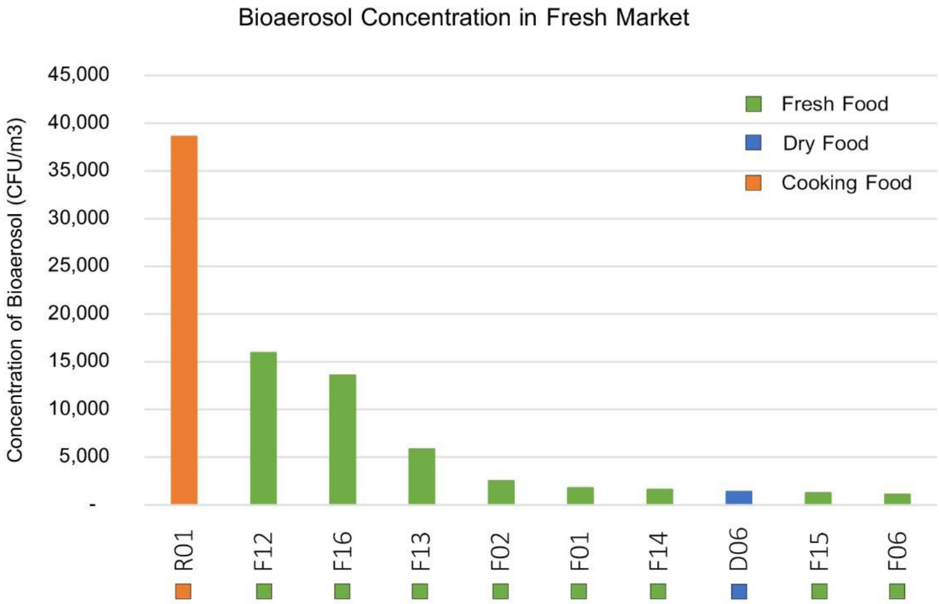


Figure 9. Bar diagram showing the values of ten locations where the concentration of bioaerosols exceeded the guidelines of Thailand's Department of Health, Ministry of Public Health (MOPH) of 500 CFU/m^3.

Table 8. Descriptive statistical analysis, Minimum, Maximum, Mean, and Standard Deviation (SD) of bioaerosols, temperature, relative humidity, and air velocity from 24 food stalls in four fresh markets.

Parameters	Units	Minimum	Maximum	Mean	SD
Bioaerosols	CFU/m^3	86	38,578	1,026[1/]	8,447
T	°C	18.6	34.0	29.7[2/]	3.6
RH	%	40.0	77.9	62.8[2/]	9.0
Air Velocity	m/s	0.1	0.7	0.2[2/]	0.2

[1/] Geometric mean
[2/] Arithmetic mean

A non-parametric Mann-Whitney U test was applied to assess whether airborne bacterial concentrations (CFU/m^3) significantly differed among the product and service providers in the stall. The groups were categorized as Fresh Food (FF), Dry Food (DF), and Cooking Food (CF). The geometric mean concentrations of bioaerosols were 1,346 CFU/m^3 in the FF group, 217 CFU/m^3 in the DF group, and 1,154 CFU/m^3 in the CF group. The Mann–Whitney U test results show that there is no statistically significant difference in bacterial concentrations (CFU/m^3) among the three groups (FF vs CF: p = 0.457; FF vs DF: p = 0.123; CF vs DF: p = 0.368). This suggests that group classification alone does not account for variation in airborne bacterial levels.

A comparison of bioaerosol concentrations based on four fresh markets was conducted, the values of which are shown in Table 9. The geometric mean concentration of bioaerosols at SYM was 311 CFU/m^3. The other three fresh markets had values exceeding the MOPH guidelines of 500 CFU/m^3, with OTK at 520 CFU/m^3, KUA at 2165 CFU/m^3, and YPM at 3895 CFU/m^3.

Table 9. The descriptive statistical analysis of bioaerosol concentrations in four fresh markets.

Case Study	N	Units	TLVs[1/]	Maximum	Minimum	Mean[2/]	SD
OTK	5	CFU/m^3	500	905	259	521	242
SYM	7	CFU/m^3	500	1,078	86	311	342
YPM	6	CFU/m^3	500	15,948	1,250	3,895	6,022
KUA	5	CFU/m^3	500	38,578	431	2,165	14,916

[1/] The Department of Health, Ministry of Public Health Thailand (MOPH).
[2/] Geometric mean
[3/] The red colored number represents the value that exceeds the TVLs.

The Mann–Whitney U test was used to compare bioaerosol concentrations (CFU/m^3) among four case studies: KUA, OTK, SYM, and YPM. The results showed no statistically significant differences between most pairs: KUA vs OTK (p = 0.173), KUA vs SYM (p = 0.061), KUA vs YPM (p = 0.662), and OTK vs SYM (p = 0.462). However, YPM was found to have significantly higher CFU/m^3 concentrations compared to both OTK (p = 0.004) and SYM (p = 0.003). These findings suggest that while bacterial levels were relatively similar across KUA, OTK, and SYM.

The YPM is well-known for wholesale flowers. During field observation, wet floors were visible due to water coming from the stall and dripping from the carts onto the walkway while transporting goods. The cleaning team used coconut brooms to clear the waste. In KUA, the fresh products available for sale were fresh fruits and flowers, and there were no issues with water stagnation along the walkway. KUA does not have any floor drains for excess water. The cleaning teams focus on floor sweeping and wiping the table surfaces with a cloth. It was observed that the SYM and OTK markets have a drainage system around the rental space. Both markets had some visible wet spots on the floor, but there were no issues with water stagnating in the walkways. During the operation, the SYM cleaning team swept the garbage from the walkways. After operating hours, the walkways were cleaned daily with a water hose. OTK provides one aisle for fresh meat and seafood that uses water for food preservation and preparation. The cleaning team operates during business hours, and weekly drainage cleaning is conducted to ensure optimal sanitation.

Inadequate cleaning methods may cause excessive residue. In related research, it was found that a cleaning process involving the use of an agitated waterspout decreased the concentration of bacterial bioaerosols (BBs) by an average of 64% while increasing the concentration of fungal bioaerosols (FBs) by about 2.4-fold. A chemical sanitization process brought about an average decrease of 30.8% in BBs and 19.2% in FBs (Wei et al., 2021). Bioaerosols can threaten food safety and hygiene standards, especially in fresh markets where food handling and preparation are regular activities.

4. Discussion of a Zoning-based Approach in Fresh Market Architectural Design

This research reveals that the source of air contaminants varies by the types of products available in the stalls and cooking activities. To clarify the air contamination problem in the fresh markets, the samples were divided into three categories: Fresh Food (FF), Dry Food (DF), and Cooking Food (CF), based on the products and services provided by the food retailers. The average values of meteorological parameters are shown in Table 10. The descriptive statistics showed that the FF group had the highest RH at 66.4%. ASHRAE

Standard 62.1 recommends that relative humidity in occupied spaces be controlled to less than 65% to reduce the likelihood of conditions that can lead to microbial growth (ASHRAE, 2022). The six air contaminant parameters are shown in Table 11. The CF groups had the greatest value of IAQ issues, with all six air contaminants being the highest among the three groups. Regardless of the role fresh markets might play in future respiratory virus epidemics, traditional fresh markets pose zoonotic health risks that global health researchers and policymakers must prioritize. Using monitoring data for hygiene and sanitation infrastructure management while protecting these marketplaces as vibrant, affordable community spaces should be the global public health community's next major focus (Nadimpalli & Pickering, 2020).

Table 10. The average indoor meteorological parameters among the three categories: fresh d, dry food, and cooking food.

Parameters	Units	Fresh Food	Dry Food	Cooking Food
Temperature	°C	30.0	27.9	27.8
RH	%	66.4	56.6	57.7
Air Velocity	m/s	0.25	0.24	0.30

Table 11 The average indoor air quality parameters among three categories: fresh food, dry food, and cooking food.

Parameters	Units	TLVs	Fresh Food	Dry Food	Cooking Food
CO_2	ppm	1,100[1/]	308	390	503
HCHO	μg/m^3	33[1/]	23	150	216
TVOC	μg/m^3	500[1/]	455	986	922
$PM_{2.5}$	μg/m^3	25[1/]	15	19	51
PM_{10}	μg/m^3	50[1/]	18	11	80
Bioaerosol	CFU/m^3	500[2/]	1,346	217	1,154

[1/] The SOOK Building Standards V1.0, 2021

[2/] Department of Health, Ministry of Public Health Thailand (MOPH)

[3/] The red colored number represents the value that exceeds the TVLs.

This research proposes a zoning-based approach as a key strategy to improve IAQ in fresh markets. The zoning-based approach divides the usable area into three zones: Fresh Food (FF), Dry Food (DF), and Cooking Food (CF), considering the source of air contaminants, wastewater release behavior, and food cooking behavior. Each zone has different air quality issues that require specific facility management as follows:

(1) The FF zone includes stalls where water is used to keep the products fresh and for product preparation. The FF group has relative humidity and bioaerosol problems. High RH was found in flower shops (Yd) at 79.7% RH, vegetable stalls (Yc) at 75.1% RH, seafood stalls (Og) at 70.8% RH, and pork stalls (Sn) at 69.7% RH. Flowers and seafood use water or ice to preserve their freshness and the excess water was visible on the floor, as shown in Figure 11. Thailand's fresh markets often present live seafood slaughtered on customer demand. Fresh markets with live domesticated animals elevate health risks to animal handlers and marketgoers at all points along the supply chain, as live animals are prime channels for pathogens (Lin et al., 2021). Providing customers with animals or animal sourced foods undoubtedly acts as an interface for virus exchange with a high risk of cross species transmission to humans (Naguib et al., 2021). Slaughterhouse biowastes are a source of biohazards that pose a high risk of environmental contamination, outbreak of disease, and reduce the security of food safety (Al-Gheethi et al., 2023) . The FF area should be separated into a wet area of the fresh market.

A drainage system should be designed and connected to each rental space with accessibility for maintenance. The different cleaning processes, including water with a hose and chemical sanitization, appear to affect the levels of bioaerosols present in these traditional fresh markets (Wei et al., 2021).

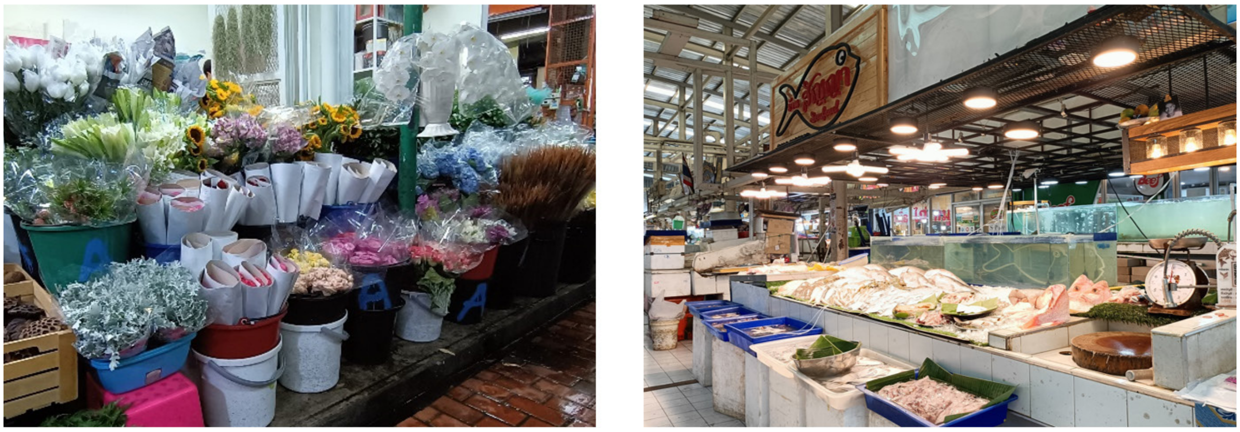


Figure 10 Flower stall (Yb) and seafood stall (Ob) have a relative humidity of over 70%, which could be caused by the water and ice used to keep the products fresh at the store display.

(2) The DF zone consists of the retailers that store dry goods such as rice, dry seafood, eggs, and cleaning and personal care products. In the DF group, the average TVOC contamination was 986 $\mu g/m^3$, which exceeds the health and well-being building standards. Grocery stalls provide household cleaning products (HCPs), including bleach, dish soap, disinfectants, dry laundry detergents, oven cleaners, and fabric softeners. HCPs are used for dirt and contamination removal, surface maintenance, sanitization, and antimicrobial purposes. The HCPs intentionally introduce substances to support the cleaning function that may contain various hazardous compounds. In the studies of HCPs, 73 products were analyzed for 23 volatile organic compounds (VOCs), with 1–17 VOCs per product being detected (Kim et al., 2024). The spray-type products exhibited the highest number of detected VOCs, with 21 out of 23 products having contaminants. In today's world, non-toxic or free from harmful chemicals cleaning products have created a market category of "green" products. The "green" cleaning products and 30 products were tested for emission factors of VOCs in an air chamber; a total of 530 unique VOCs were quantified with 205 additional VOCs detected below the limits of quantification (Temkin et al., 2023). The analysis further suggested that the use of "green" cleaning products, especially fragrance-free products, may reduce exposure to VOC emissions. The other hotspot for our study was found in pharmacies, with TVOC reaching 1,837 $\mu g/m^3$. Research on IAQ in hospitals found the highest levels of average TVOC in the pharmacy departments with a range of 1,149 to 1,500 $\mu g/m^3$ (Jung et al., 2015). Introducing fresh air into this area could dilute the concentration of TVOC.

(3) The CF zone offers ready-to-eat meal services, including restaurants, cafés, and food courts. The CF group reveals the most severe IAQ problems. The results found that the averages of the four parameters, HCHO of 216 $\mu g/m^3$, TVOC of 922 $\mu g/m^3$, $PM_{2.5}$ of 51 $\mu g/m^3$, and PM_{10} of 80 $\mu g/m^3$, exceeded the TLVs of the SOOK standards. The average bioaerosol concentration was 8,129 CFU/m^3, which also exceeded the MOPH standard. A commercial extraction hood is required to mitigate air contamination from cooking activities. The cleaning period and the number of burners can be major influencing factors in the indoor environment (Zhang et al., 2020). Ventilation patterns or the operation mode of range hoods could control indoor pollution levels (Zhao & Zhao, 2018).

5. Conclusions

Creating a clean and safe fresh market is crucial for ensuring food safety and human health. Underscoring the customer's value in food safety, IAQ improvement in fresh markets could make a better customer experience, increase value, and provide a competitive advantage. Monitoring IAQ using real-time equipment can provide data that will help optimize ventilation and detect potential issues promptly. $PM_{2.5}$, HCHO, TVOC, and bioaerosols are the air contaminants that must be mitigated in the fresh market facilities. These are influenced by the type of products, the cooking methods, and facility management. Closed spaces for cooling with air conditioning could increase airborne concentration to a hazardous level for human health. Fresh Food (FF), Dry Food (DF), and Cooking Food (CF) zoning was proposed for a zoning-based design strategy to improve IAQ and create a healthy environment within market spaces. The layout of each zone should be carefully designed to prevent a mixture of air contaminants and the recirculation of polluted air into the building.

This study did have some limitations. Ambient air quality collected from the nearest weather stations might not represent the outdoor air quality data since the data for the study monitoring IAQ inside the building were collected over a short period in the day. Additionally, it is essential to note that the surrounding air quality and wind direction can impact indoor air parameters. Therefore, future research should monitor outdoor air quality to identify local contaminants from surrounding spaces that will be of concern if allowed to enter the building.

This research was conducted during the rainy season when the ambient air quality was considered acceptable based on the Thai National Ambient Air Quality Standards (NAAQSs). Future studies should conduct long-term monitoring to assess how seasonal variations impact IAQ and thermal comfort in fresh markets. This would provide valuable data on the efficacy of ventilation systems year-round and could lead to more dynamic design solutions.

Different cleaning methods, chemical products, and floor materials may affect the bioaerosol levels in an indoor environment. The surface material and cleaning methods should be assessed more thoroughly in future research.

Author Contributions

Conceptualization, P.J; Methodology, P.J; Formal analysis, P.J; Investigation, P.J; Data curation, P.J; Writing – original draft preparation, P.J; Writing – review and editing, P.J, C.Y; Supervision, C.Y; Project administration, P.J; Funding acquisition, P.J. All authors have read and agreed to the published version of the manuscript.

Human Subjects

N/A

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Data Availability

The data supporting the findings of this study are available freely and transparently.

Use of AI

During the preparation of this manuscript, generative AI (Grammarly) was used solely for grammar correction and language refinement. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix A. The average concentrations of six IAQ parameters ($PM_{2.5}$ PM_{10}, C_{O2}, HCHO, TVOC, and Bioaerosol) were measured at 33 observation locations.

Code	Product/ Service	Zone	Ventilation System	$PM_{2.5}$ ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)	CO_2 (ppm)	HCHO ($\mu g/m^3$)	TVOC ($\mu g/m^3$)	Bioaerosol (CFU/m^3)
C01	Café	CF	AC	2	3	781	597	1,298	55,959
C02	Café	CF	AC	4	5	781	616	1,990	85,787
C03	Café	CF	NV	2	2	392	259	910	N/A
C04	Café	CF	AC	8	8	582	144	1,070	N/A
D01	Egg	DF	NV	2	2	256	1	530	N/A
D02	Grocery	DF	AC	9	13	384	1	519	N/A
D03	Rice	DF	NV	61	0	320	41	859	37,026
D04	Grocery	DF	AC	20	33	590	115	852	N/A
D05	Pharmacy	DF	AC	2	1	420	362	1,706	73,534
D06	Grocery	DF	NV	6	7	236	232	992	42,748
F01	Flower	FF	NV	12	17	308	247	492	21,185
F02	Fruit	FF	NV	2	1	259	9	17	733
F03	Fruit	FF	NV	61	13	22	179	597	25,711
F04	Seafood	FF	NV	22	32	502	1	625	26,950
F05	Pork	FF	NV	8	10	308	1	492	21,185
F06	Pork	FF	NV	2	2	239	15.5	86.3	3,718
F07	Flower	FF	NV	17	27	320	4	681	29,332
F08	Vegetable	FF	NV	16	22	346	11	514	22,134
F09	Poultry	FF	NV	1	2	270	4	552	23,782
F10	Pork	FF	NV	1	2	330	2	630	N/A
F11	Seafood	FF	NV	33	70	366	24	75	3,222
F12	Flower	FF	NV	18	26	308	57	302	13,006
F13	Flower	FF	NV	16	25	402	5	17	744
F14	Vegetable	FF	NV	15	22	252	13	693	29,860
F15	Flower	FF	AC	13	18	505	1	582	25,086
F16	Pork	FF	NV	11	18	342	1	24	1,034
R01	Restaurant	CF	AC	2	2	835	713	1,611	69,450
R02	Food court	CF	NV	2	1	259	9	17	733
R03	Food court	CF	NV	2	3	281	11	560	24,116
R04	Restaurant	CF	NV	241	379	366	1	1,220	N/A

Code	Product/ Service	Zone	Ventilation System	$PM_{2.5}$ (µg/m³)	PM_{10} (µg/m³)	CO_2 (ppm)	HCHO (µg/m³)	TVOC (µg/m³)	Bioaerosol (CFU/m³)
R05	Restaurant	CF	AC	227	351	884	218	378	N/A
R06	Restaurant	CF	AC	148	245	366	82	1,124	N/A
R07	Restaurant	CF	AC	33	59	462	118	2,194	N/A

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