Indoor Air Quality Assessment in Heritage Adaptive Reuse: A Case Study of Cagayan de Oro City Museum

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Abstract

This study addresses a critical research gap in assessing indoor air quality (IAQ) in adaptively reused heritage structures. IAQ assessment measured chemical and biological air pollution parameters in the century-old Cagayan Waterworks Tank, repurposed as the Cagayan de Oro City Museum. Using standardized air sampling methodologies, the proponent measured the Air Quality Index (AQI), the Index of Microbial Air Contamination (IMA), and bacterial pollution levels. Results revealed a dichotomy in pollution parameters: chemical pollutants showed favorable conditions, with an average AQI of 12 (categorized as "GOOD"), while biological parameters suggested concerning levels, with an average IMA of 51 (classified as "POOR", since it falls at the lower boundary of the 51–75 range) and bacterial contamination at 728 CFU/m³ (indicating a "HIGH" degree of bacterial pollution). Statistical analysis, including Spearman's correlation tests, observed an exploratory positive monotonic trend between microbial contamination indices and bacterial pollution levels, suggesting an association with ventilation and HVAC system deficiencies in the adaptively reused heritage building. The findings provide preliminary evidence supporting targeted intervention strategies to reduce biological pollutants, including the implementation of indoor air quality (IAQ) monitoring systems, enhancements to sanitation protocols, HVAC system rehabilitation, and spatial reorganization. This research contributes valuable insights into sustainable heritage preservation by identifying the specific indoor air quality challenges in adaptively reused heritage structures.

***Keywords**:* adaptive reuse, heritage conservation, indoor air quality, microbial contamination, sustainable development

1. Introduction

Indoor Air Quality (IAQ) in heritage buildings that have undergone adaptive reuse has emerged as a critical concern, particularly as these structures are increasingly repurposed for uses such as museums, offices, and community centers. Preserving cultural heritage must now be balanced with the health and comfort of building occupants, making IAQ assessment an essential component of sustainable heritage management (Megahed & Ghoneim, 2021). This dual imperative is especially pressing in tropical urban environments, where environmental conditions and building modifications can exacerbate indoor pollution.

According to the City Information Office (CIO) Admin (2025), the Cagayan Waterworks Tank, an early 20th-century structure, stands as a significant example of industrial heritage in Cagayan de Oro. Its transformation into the City Museum illustrates the challenges and opportunities of preserving historical architecture while adapting it for contemporary cultural use. Adaptive reuse has emerged as a critical strategy for preserving heritage structures while meeting modern needs. This approach involves repurposing historical buildings to extend their lifespan, though it introduces challenges such as maintaining indoor environmental quality. Studies emphasize the need for frameworks that evaluate both cultural significance and technical feasibility during reuse planning, ensuring compliance with conservation principles and occupant safety standards (Mısırlısoy & Günçe, 2016).

IAQ is a crucial consideration in the evaluation of repurposed heritage buildings, as these spaces must meet existing IAQ standards, which vary internationally and are often embedded within broader Indoor Environmental Quality (IEQ) frameworks that also address thermal comfort, noise, and lighting (Paleologos *et al.*, 2021). According to Settimo *et al.* (2023), each country's IAQ standards differ in their focus: United Kingdom (UK) emphasizes ventilation rates, the World Health Organization (WHO) focuses on pollutant concentrations, and the United States of America (USA) includes acceptable Carbon Dioxide (CO_2) concentrations. In contrast to the Philippines, regulations such as the Philippine Green Building Code (Department of Public Works and Highways [DPWH], 2015) and Republic Act 8749, the Philippine Clean Air Act of 1999 (Environmental Management Bureau [EMB], 2021), primarily address ventilation and outdoor air quality, leaving gaps in comprehensive indoor guidelines.

According to Spengler *et al*. (2001), IAQ problems are commonly associated with old and poorly maintained buildings, but new buildings can also exhibit these issues, which affect human comfort, health, and productivity, with key influences including temperature, humidity, pollutant sources, and ventilation systems. As stated by Prihatmanti (2015), acceptable IAQ is achieved when harmful pollutants are absent, and at least 80% of occupants are satisfied with the indoor environment. Settimo *et al* (2023) further states that indoor air pollutants are diverse, with sources ranging from building materials and furnishings to human activity and outdoor infiltration, and the total number of potential indoor pollutants may be larger than previously recognized, as reflected in expanded lists by the WHO Regional Office for Europe (2010). To achieve good IAQ, Nazaroff (2013) recommends minimizing indoor emissions, maintaining dry indoor conditions, ensuring adequate ventilation, and protecting indoor spaces from outdoor pollution, as excessive indoor emissions or dampness can pose health risks, including respiratory diseases.

Air pollution in indoor environments is primarily caused by chemical and biological pollutants, which can significantly degrade air quality and affect occupant health (Prihatmanti, 2015). Chemical pollutants arise from human metabolism and combustion processes, with common examples including carbon monoxide (CO), carbon dioxide (CO_2), and volatile organic compounds (VOCs). High concentrations of these chemicals can cause adverse health effects or even immediate death, as outlined by the Department of Occupational Safety and Health [DOSH], (2010), Malaysia’s Industry Code of Practice on Indoor Air Quality [ICOP IAQ 2010] remains the current and unrevised standard in Malaysia to date, sets acceptable limits for indoor air contaminants. Among VOCs, formaldehyde is particularly notable for its persistence and potential health risks, especially as its levels increase with temperature (Prihatmanti, 2015; United States Environmental Protection Agency [US EPA], 2025b). The World Health Organization recommends a maximum average concentration of 0.1 mg/m^3 for formaldehyde over a 30-minute period (WHO Regional Office for Europe, 2010).

Particulate matter, specifically PM_{10} and $PM_{2.5}$, represents another significant category of indoor air pollutants, as these inhalable particles can penetrate the respiratory system and cause health issues (United States Environmental Protection Agency [US EPA], 2025a). The World Health Organization (WHO) has established guidelines for 24-hour concentrations of particulate matter to protect public health (WHO, 2006). In addition to chemical and particulate pollutants, bio-aerosols—such as bacteria, fungi, viruses, pollen, and animal dander—are also prevalent and can contribute to various health problems (Prihatmanti, 2015).

To communicate air quality to the public, government agencies use the Air Quality Index (AQI), which reflects the potential health risks associated with current air pollution levels. Each country has its own AQI standards, and the Philippines has developed specific protocols and indices for different pollutants and their exposure durations, following methodologies from the US EPA (Clean Air Asia, 2020; Department of Environment and Natural Resources [DENR, 2021]; US EPA, 2018). The AQI calculation involves identifying the highest pollutant concentration and determining the critical pollutant, which guides public health advisories.

For biological contaminants, the Aerobic Plate Count (APC) is a standard method for quantifying airborne microorganisms, using settle plates to capture and incubate airborne microbes (Napoli *et al*., 2012). The Index of Microbial Air Contamination (IMA) assesses microbial fallout and uses specific measurement protocols and contamination classes (Pasquarella *et al*., 2000). Microbial assessments can also be expressed as colony-forming units per cubic meter (CFU/m^3), with classification criteria for pollution levels (Stanley *et al*., 2019).

In the Philippines, studies on IAQ over the past two decades have been limited but cover a range of building types, including transportation vehicles, institutional and commercial buildings, and hospitals (Demetrio, 2025). These studies have primarily focused on chemical pollutants, with fewer investigations into biological contaminants. Recent research post-2011 has included assessments of modernized jeepneys, multipurpose buildings, communities near coal-fired power plants, and hospitals, addressing both chemical and particulate pollutants (Ayala *et al*., 2021; Cordon *et al*., 2019; Quizon *et al*., 2016; Sakilan & Demayo, 2015; Lomboy *et al*., 2015; Vergeire-Dalmacion *et al*., 2016).

This study aims to address this gap by conducting a thorough assessment of both chemical and biological IAQ parameters in the Cagayan de Oro City Museum, a century-old waterworks tank repurposed as a public museum. By employing standardized air sampling methodologies and correlating IAQ data with observed building adaptations, the research seeks to provide evidence-based recommendations for improving IAQ in heritage adaptive reuse projects. In doing so, it contributes to the broader discourse on sustainable heritage preservation, emphasizing the importance of holistic IAQ management for the continued use and enjoyment of historic spaces.

2. Methodology

2.1 Research Design and Ethical Considerations

This study employed a mixed-methods approach, combining qualitative documentation of the city museum's technical drawings (i.e., floor plans) with quantitative measurement of indoor air quality (IAQ) parameters. Although measurements were collected from three floor levels, these observations are not statistically independent because they come from a single building; therefore, the effective sample size is n = 1, and the floor-level comparisons and correlation results should be interpreted as exploratory. The study did not involve human or animal subjects.

2.2 Data Collection Instruments and Equipment

For the chemical parameters monitoring, an air quality monitor was used (uHoo Smart Air Monitor, uHoo Pte Ltd, Singapore). The uHoo Smart Air Monitor, which offers real-time multi-pollutant data (TVOC, $PM_{2.5}$, etc.) validated against Environmental Protection Agency (EPA) / WELL benchmarks in accordance with manufacturer specifications, has not been linked to any peer-reviewed studies for heritage IAQ. For the biological parameters, air sampling and analysis were provided independently by the third-party laboratory.

2.3 Research Procedures

2.3.1 Chemical Parameters for Gauging Indoor Air Pollution

Adaptive reuse of old buildings aims to extend their lifespan with minimal intervention while maintaining their economic, social, and environmental viability (Foster, 2020). However, repurposing heritage structures often involves modifications, such as installing HVAC systems to accommodate new occupants' needs. These changes can inadvertently trap indoor pollutants, leading to higher indoor air pollution levels than in outdoor environments (Foster, 2020).

The WELL Performance Verification Guidebook (International WELL Building Institute, 2021), which offers globally accepted benchmarks for indoor pollutants and thermal conditions to supplement current Philippine IAQ regulations, was followed in the chemical parameter measurements. Getty (2021), who used the WELL Building Standard for the adaptive reuse of the historic Engel Stadium during the COVID-19 pandemic, provides an example of a relevant application. Getty's study indicates how heritage building retrofits can successfully incorporate WELL's comprehensive IAQ criteria, which include ventilation, air filtration, and pollutant thresholds, to improve occupant health and safety while maintaining the building's historic character. By placing the current study within a global framework, the incorporation of WELL criteria guarantees the applicability and comparability of IAQ evaluations in adaptively reused heritage spaces.

To assess the extent of chemical indoor air pollution, several key pollutants were measured. Carbon monoxide (CO) is emitted from the combustion of fossil fuels, tobacco, and automobiles, and CO levels tend to be higher in old buildings due to inadequate ventilation (Nnaji *et al*., 2023). Particulate matter (PM2.5) consists of fine particles less than 2.5 microns in diameter that are hazardous when inhaled and can originate from furniture, finishes, molds, and office supplies; older buildings are particularly prone to higher PM2.5 levels (Bekierski & Kostyrko, 2021). Because it affects occupant comfort and can be an indoor pollutant, carbon dioxide (CO_2) is a crucial indicator of occupancy and ventilation efficiency (US EPA, 2025a). The term "*total volatile organic compounds*" (TVOCs) refers to a broad category of chemical emissions from building materials and occupant activities that are known to have negative health effects and affect indoor chemistry (US EPA, 2025b). Asthma flare-ups and respiratory irritation have been linked to nitrogen dioxide (NO_2), which is mostly produced by combustion processes (US EPA, 2025a). As a reactive oxidant produced by both indoor and outdoor sources, ground-level ozone (O_3) contributes to the formation of secondary pollutants and can affect the lungs (WHO, 2021).

2.3.2 Biological Parameters for Gauging Indoor Air Pollution

Biological indoor air pollutants, particularly bacteria, pose significant risks in tropical heritage buildings. Bacterial growth is closely linked to moisture, which is a common issue in historic structures. High moisture levels can lead to microbial contamination, resulting in damp stains, mold growth, and potential health hazards such as allergic reactions and infectious diseases.

Even low levels of moisture can support the proliferation of harmful bacteria (Baldan *et al*, 2021).

2.4 Test Locations and Procedures

2.4.1 Chemical Parameters

The chemical parameters for thermal condition and pollutant testing were based on the WELL Performance Verification Guidebook for testing air parameters. The testing was conducted under the regular museum operations conditions during the weekdays.

Testing Duration and Restrictions: Although monitoring was scheduled for weekdays (Monday through Friday) during regular museum operations, political and administrative restrictions, such as restricted access permissions and equipment availability, limited the actual data collection to 24-hour continuous periods per parameter. In particular: Eight-hour measurements of CO and O_3, 24-hour measurements of TVOC, CO_2, and $PM_{2.5}$, and NO_2: 1-hour measurements. Although typical daily patterns were captured by this short-term monitoring, multi-day time series analysis was not possible. While intra-day trends could be identified thanks to hourly real-time readings, weekly and seasonal variations could not. Extended monitoring (≥7 days) should be used in future research to identify peak contamination events and perform reliable temporal analysis.

Testing was done with the usual schedule of the air conditioning units' (ACUs) and air coolers' operation during data gathering. The sampling locations were in areas frequently occupied by employees or visitors. The sampling zone and air-quality measurement tool were located within the breathing zone of the building's occupants. The sampling point were above one (1) meter or 3.3 feet from the finished floor line to replicate the height of occupants within the building. The sampling zone contained the locations of the sampling points. These points were approximately 1 meter (3.3 feet) away from any openings or ventilation walls (e.g., doors, windows, exhaust, etc.). Data collection was conducted on each floor of the building. There was one sampling point on each floor according to each floor's area ($43.96m^2$) as indicated in Figure 1. Because the floor-level data come from one building, the observations are not independent and should not be treated as separate replicates.

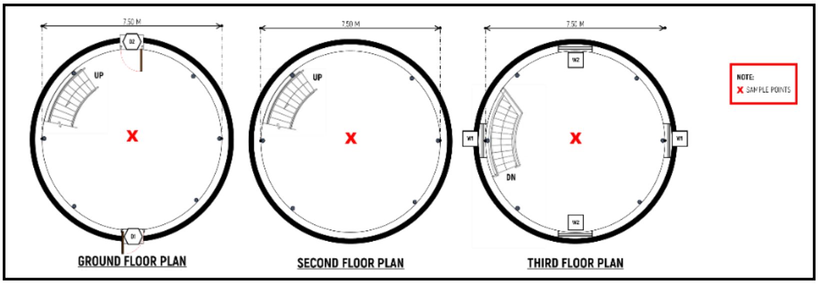

Figure 1. City Museum's sample points for the chemical parameters per floor

2.4.2 Biological Parameters

The biological pollutant testing used the sedimentation test method with settle plates or Plate Count Agar (PCA) to determine the Aerobic Plate Count (APC) through passive air sampling. The testing was conducted under regular museum operating conditions, Monday through Friday. Testing was done with the usual schedule of the air conditioning units' (ACUs) and air coolers' operation during data gathering. The sampling locations were in areas frequently occupied by employees or visitors, such as display areas. The sampling points were above one (1) meter, at least one (1) meter or 3.3 feet away from any openings or ventilation walls (e.g., doors, windows, exhaust, etc.), and were tested for 15 minutes of exposure. Data collection was conducted on each floor of the building. The settle plates were located within the breathing zone of the building's occupants, such as on top of displays, as shown in Figure 2. Because the floor-level data come from one building, the observations are not independent and should not be treated as separate replicates.

Settle plate exposure (15 minutes per floor) represents an instantaneous microbial snapshot under operational conditions. Combined with 24-hour chemical data, this provides a cross-sectional IAQ profile rather than a longitudinal time series. Longer-term monitoring recommended for future validation (Pasquarella *et al*., 2000).

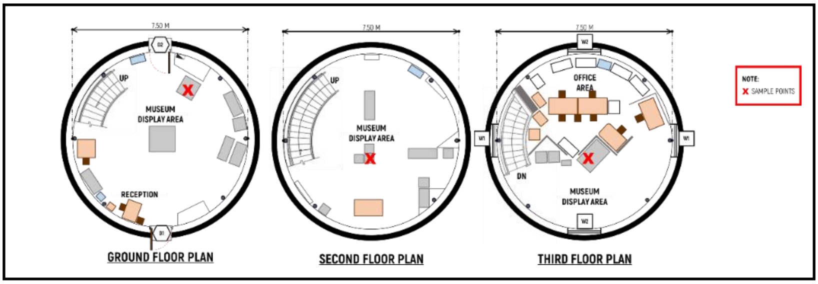

Figure 2. City Museum's sample points for the biological parameters per floor

2.5 Test Methods

2.5.1 Chemical Parameter

The Philippines' Air Quality Index was a useful tool for assessing indoor pollutant concentrations. The index produced a value that quantifies and presents the level of chemical pollution within the City Museum. To use the Air Quality Index (AQI), these steps were followed:

a. Prepared the Smart air monitor on the sample points of each floor level as shown in Figure 1, with at least 1 hour of acclimation.
b. Measured the Real-Time Environment Reading of the indoor contaminants: TVOC (ppm), NO_2 (ppb), CO_2 (ppm), CO (ppm), O_3 (ppm), and $PM_{2.5}$ (µg/m^3) using the smart air monitor.
c. Measured CO (ppm) and O_3 (ppm) for 8 hours, while measuring TVOC, CO_2, and $PM_{2.5}$ (µg/m^3) for 24 hours, and NO_2 for an hour.
d. Recorded the Real-Time Environment Measurements every hour while the NO_2 per minute.
e. Calculated the average of Real-Time Environment Measurements of each pollutant.
f. Compared the average Real-Time Environment Measurements of TVOC, NO_2, and CO_2 to benchmarks from Industry Code of Practice on Indoor Air Quality (ICOP IAQ 2010) form Malaysia and WELL Building Standard, as neither existing Philippine accepted criteria nor these pollutants were used to calculate the AQI (Philippines).
g. Used Tables 1, 2, and 3 and input the following into the AQI formula (Equation 1):

$$I_p = \frac{I_{HI} - I_{LO}}{BP_{HI} - BP_{LO}} * \left(C_p - BP_{LO}\right) + I_{LO} \tag{1}$$

Where I_p is the index for pollutant p; C_p is the truncated concentration of pollutant p; BP_{HI} is the concentration breakpoint that is greater than or equal to C_p; BP_{LO} is the concentration breakpoint that is less than or equal to C_p; I_{HI} is the AQI value corresponding to BP_{HI}; and I_{LO} is the AQI value corresponding to BP_{LO}.

Table 1. Carbon monoxide (CO) AQI breakpoints (8-hr Average)

CO (ppm)	AQI Category	I_{LO}	I_{HI}	BP_{LO}	BP_{HI}
0–4.4	Good	0	50	0	4.4
4.5–9.4	Fair	51	100	4.5	9.4
9.5–12.4	Unhealthy for Sensitive Groups	101	150	9.5	12.4
12.5–15.4	Very Unhealthy	151	200	12.5	15.4
15.5–30.4	Acutely Unhealthy	201	300	15.5	30.4
30.5–40.4	Emergency	301	500	30.5	40.4

Note: Adapted from DENR (2021)

Table 2. Ozone (O_3) AQI breakpoints (8-hr Average)

O_3 (ppm)	AQI Category	I_{LO}	I_{HI}	BP_{LO}	BP_{HI}
0–0.064	Good	0	50	0	0.064
0.065–0.084	Fair	51	100	0.065	0.084
0.085–0.104	Unhealthy for Sensitive Groups	101	150	0.085	0.104
0.105–0.124	Very Unhealthy	151	200	0.105	0.124
0.125–0.374	Acutely Unhealthy	201	300	0.125	0.374
≥0.375	Emergency	301	500	0.375	Above

Note: Adapted from DENR (2021)

Table 3. $PM_{2.5}$ AQI breakpoints (24-hr Average)

$PM_{2.5}$ (μg/m^3)	AQI Category	I_{LO}	I_{HI}	BP_{LO}	BP_{HI}
0–25	Good	0	50	0	25
25.1–35.0	Fair	51	100	25.1	35.0
35.1–45.0	Unhealthy for Sensitive Groups	101	150	35.1	45.0
45.1–55.0	Very Unhealthy	151	200	45.1	55.0
55.1–90.0	Acutely Unhealthy	201	300	55.1	90.0
≥91.0	Emergency	301	500	91.0	Above

h. The pollutant with the highest AQI shall be the critical pollutant and will be referred to as the AQI.

i. Interpreted the AQI value according to Table 4.

Table 4. Air Quality Index (AQI PH) and its categories

AQI PH	Category
0-50	Good
51-100	Fair
101-150	Unhealthy For Sensitive Groups
151-200	Very Unhealthy
201-300	Acutely Unhealthy
301-500	Emergency

2.5.2 Biological Parameter

The Aerobic Plate Count (APC) was a common technique for assessing the total number of viable bacteria by air-exposure sampling using the sedimentation test method. To quantify microbial air contamination, the Index of Microbial Air Contamination (IMA) was a useful tool for assessing air quality in indoor environments. The index was converted using Omeliansky's formula, which produced a value that quantifies and presents the level of bacterial pollution within the City Museum. To test the level of bacterial pollution, the following steps were followed.

a. The laboratory technician prepared the agar plate on a new paper towel on a flat surface at least 1 meter or 3.3 feet above the floor, 1 meter or 3.3 feet away from the wall, windows, and door on the sample locations shown in Figure 2 on each floor level.
b. The laboratory technician opened the agar plate and exposed the medium for 15 minutes.
c. The laboratory technician placed the cover after the duration of the exposure and placed it in a secondary container before placing it in an ice bucket.
d. The agar plates were analyzed in the laboratory, and the estimated Colony-forming Units (cfu) were counted on the plate.
e. Determined the Index of Microbial Air Contamination (IMA) per Pasquarella *et al*. (2000) using Omeliansky's formula (15-min exposure ×4 for 1-hour equivalent).
f. Interpreted the IMA value according to Table 5.

Table 5. Index of Microbial Air Contamination (IMA) values

IMA Value	Performance
0-5	Very Good
6-25	Good
26-50	Fair
51-75	Poor
≥ 76	Very Poor

g. Calculated the Bacterial Degree of Pollution by using Omelianky's Formula (Equation 2) (Stanley *et al.*, 2019):

$$N = 5a\ x\ 10^4\ (bt)^{-1} \tag{2}$$

Where N *is* the microbial CFU/m³ of indoor air; a is the number of colonies per Petri dish; b is the dish surface cm²; and t is the exposure time in minutes.

h. Interpreted the Pollution Degree according to Table 6:

Table 6. Bacterial Pollution Degree and its range of values (Stanley *et al.*, 2019)

Group of Microbes	Range of Values (CFU/m^3)	Pollution Degree
Bacteria	< 50	Very Small
	50 – 100	Small
	100 – 500	Medium
	500 – 2000	High
	> 2000	Very High

3. Results and Discussion

3.1 Indoor Air Quality Parameters by Floor

The IAQ of the Cagayan de Oro City Museum's three floors is compiled in Table 7. All floors were categorized in the "Good" category (AQI values 10–12), indicating effective control of particulate matter levels indoors despite limited natural ventilation. The $PM_{2.5}$ Air Quality Index (AQI) showed consistently low levels of chemical air pollutants. This suggests that existing structural modifications, such as building envelope features and air conditioner operation, may be helping prevent the intrusion of chemical pollutants.

Table 7. Indoor air quality summary by floor level

Floor	Para-meter	Measured Average (Units)	Standard/ Benchmark	Status	Remarks
Ground	AQI ($PM_{2.5}$)	12	DENR AQI (0-50 = Good)	🟢Good	Lowest chemical pollution
Ground	IMA	80	Pasquarella (51-75 = Poor)	🔴Very Poor	RH 70.1%, Temp 24.3°C - Highest microbial
Ground	CFU/m³	1149	Stanley (500-2000 = High)	🔴High	Poor HVAC, high occupancy
Second	AQI ($PM_{2.5}$)	10	DENR AQI (0-50 = Good)	🟢Good	Consistent chemical compliance
Second	IMA	32	Pasquarella (26-50 = Fair)	🟡Fair	RH 64.8%, Temp 27.8°C - Medium bacterial
Second	CFU/m³	460	Stanley (100-500 = Medium)	🟡Medium	Better than ground floor
Third	AQI ($PM_{2.5}$)	10	DENR AQI (0-50 = Good)	🟢Good	Minimal chemical pollutants
Third	IMA	40	Pasquarella (26-50 = Fair)	🟡Fair	RH 57.8%, Temp 27.0°C - High bacterial
Third	CFU/m³	575	Stanley (500-2000 = High)	🔴High	Ventilation limitations evident
Overall	AQI	12 (Good)	DENR AQI	🟢Good	Chemical pollutants controlled
Overall	IMA	51 (Poor)	Pasquarella	🔴Poor	Avg RH 64.2%, Temp 26.3°C - Biological contamination primary concern
Overall	CFU/m³	728 (High)	Stanley	🔴High	Urgent HVAC/sanitation needed

Note: Color coding; 🟢 Green = Good/Favorable; 🟡 Yellow = Fair/Medium; 🔴 Red = Poor/High concern. AQI based on $PM_{2.5}$ as critical pollutant (Tables 1-3). IMA per Pasquarella et al. (2000); CFU/m³ per Stanley et al. (2019).

Biological contamination, on the other hand, was highly variable and concerning. The Ground Floor had the highest index value of 80, classified as "Very Poor," and corresponding bacterial colony-forming units per cubic meter (CFU/m³), classified as "High" at 1149 CFU/m³. The Index of Microbial Air Contamination (IMA) varied from fair to poor across floors. This increased microbial load may be associated with issues frequently encountered in heritage adaptive reuse projects, such as poor HVAC maintenance, spatial overcrowding, and lax janitorial procedures. Although there was some bacterial contamination on the second and third floors, the microbial air quality standards were still exceeded.

3.2 Correlation Analysis of Biological and Chemical Parameters

Because the floor-level observations come from a single building, they are not statistically independent; therefore, the correlation analysis should be interpreted as exploratory rather than inferential.

Due to the small sample size ($n = 3$) and non-normal data distribution, Spearman's rank correlation coefficients (ρ) were computed to explore monotonic trends between indoor biological contamination and chemical pollutants across the three floors of the Cagayan de Oro City Museum. A strong positive monotonic trend was observed between the Index of Microbial Air Contamination (IMA) and estimated bacterial pollution (CFU/m³), suggesting an exploratory association between higher microbial air contamination and higher bacterial counts. IMA showed a strong positive trend with CFU/m³ ($\rho = 0.95$) and a moderate positive trend with RH ($\rho = 0.85$), indicating that moisture may be an important contributing factor (Ground Floor RH 70.1% corresponded to an IMA of 80, classified as Very Poor). IMA-$PM_{2.5}$ was lower ($\rho = 0.45$, ns). Temperature showed an inverse trend with IMA ($\rho = -0.60$), which may reflect the influence of ACU operation on microbial conditions.

CO_2-APC Theory: In contrast to the theory that elevated CO_2 (>1000 ppm) inhibits APC/bacterial growth through pH shifts, museum CO_2 (avg 604 ppm) showed no suppression; instead, poor maintenance and high RH (64.2%) predominated (Spengler *et al*., 2001).

Table 8. Correlation matrix (Spearman's ρ)

Metric	IMA	CFU/m³	$PM_{2.5}$	CO_2	RH	Temp
IMA	1	0.95*	0.45	0.20	0.85†	-0.60
CFU/m³	0.95*	1	0.30	0.10	0.75	-0.50
$PM_{2.5}$	0.45	0.30	1	-0.10	0.25	0.10

*Note. *p<0.05, †p<0.10. n=3 floors*

3.3 Implications for Heritage Adaptation and IAQ Management

The contrast between problematic biological contamination and favorable chemical IAQ suggests the need for thorough indoor air strategies in heritage adaptive reuse. The biological pollutants appear to reflect issues related to internal environmental conditions and building system performance, whereas the chemical pollutants seem to be sufficiently controlled, possibly because of limited outdoor air exchange through minimal fenestrations. Table 7 suggests the RH-temperature-microbial nexus: Ground Floor (RH 70.1%), worst IMA despite the lowest Temp (24.3°C); upper showed signs of ACU underuse. Favorable chemical IAQ (limited fenestration) contrasts poor biological performance, and supports targeted HVAC rehab, dehumidification, and sanitation which are critical for health and artifact preservation in tropical heritage reuse.

Effective HVAC system rehabilitation, sanitation reinforcement, and spatial reorganization should be prioritized, as these biological agents pose health risks and potential biodeterioration threats.

These findings broadly consistent with related IAQ studies of heritage buildings, underscoring the need for continuous monitoring and flexible environmental management techniques tailored to the specific limitations of heritage buildings to balance conservation and occupant health.

4. Conclusion and Recommendation

The assessment of chemical and biological indoor air pollution at the adaptively reused Cagayan de Oro City Museum revealed a complex picture of IAQ. The study found that while the average Air Quality Index for chemical pollutants was "GOOD," the biological parameters, specifically the Index of Microbial Air Contamination and bacterial pollution levels, indicated “POOR” and “HIGH” degrees of contamination, respectively. These findings highlight that, despite favorable chemical air quality, the museum's indoor environment is affected by substandard upkeep, inadequate ventilation, a malfunctioning HVAC system, and overcrowded, dusty, and disorganized office spaces. Such conditions not only diminish comfort but also pose significant health risks to occupants.

The results underscore the importance of regular, comprehensive IAQ assessments in adaptively reused heritage structures. The lack of consistent janitorial and custodial maintenance, coupled with insufficient building adaptation to new uses, can lead to elevated levels of biological pollutants that threaten both occupant health and the preservation of the historic structure. Exploratory analysis suggested monotonic relationships between microbial indicators and environmental conditions, but these patterns should be interpreted cautiously because the sample size was very limited. This study suggests that adaptive reuse projects must go beyond structural conservation to address the day-to-day environmental quality experienced by users, ensuring both the longevity of heritage buildings and the well-being of their occupants.

Future studies should broaden the scope of evaluation to include additional indoor environmental quality parameters, the structure's airtightness, and the impact of nearby buildings and outdoor conditions. A more comprehensive understanding of IAQ challenges in heritage adaptive reuse projects would be possible by incorporating staff and visitor feedback, measuring air velocity and pressure, monitoring the condition of artifacts and building fabric, and conducting more thorough analyses of chemical and biological pollutants over extended periods of time and across seasons. Future work: To enable ventilation rate calculations in accordance with ASHRAE 62.1, conduct timed occupancy counts per floor (e.g., visitors/hour) during sampling to correlate with CO_2 rises. Such all-encompassing approaches will influence better management, policy, and design choices for sustainable heritage preservation.

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