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Article

Evaluation of the microbiological indoor air quality at a commercial building in Muscat, Oman, utilizing an all-air multi-zone HVAC system

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Abstract: This study evaluates the microbiological indoor air quality (IAQ) of a commercial office building in Muscat, Oman, equipped with an all-air multi-zone heating, ventilation, and air-conditioning (HVAC) system operating under hot-arid climatic conditions. Active air sampling was conducted at multiple locations, including open-plan offices, outdoor air intake, supply air diffusers, fan coil units, and the humidification water tank of the air handling unit (AHU), across different seasons. Airborne bacteria were analyzed using incubation at 22 ℃ and 37 ℃ to distinguish environmental and human-associated microbial populations, while fungal concentrations were assessed at 25 ℃, with results expressed as colony-forming units per cubic meter (CFU/m^3). For analytical consistency, data from the three office spaces investigated were aggregated and evaluated as seasonal averages. Bacterial concentrations in indoor air generally ranged from 32 to 496 CFU/m^3 at 37 ℃ and 4 to 500 CFU/m^3 at 22 ℃, indicating low to moderate contamination levels under normal operating conditions. In contrast, a pronounced increase in fungal concentrations was observed during the initial winter sampling, exceeding 2000 CFU/m^3, which was attributed to an exceptional flooding event. Comparative analysis of outdoor air, AHU-treated air, and indoor air demonstrated that the HVAC system effectively reduced microbial loads during standard climatic conditions. The findings provide region-specific baseline data on microbiological IAQ and highlight the influence of HVAC operation, seasonal variation, and extreme environmental events on indoor bioaerosol levels in commercial buildings located in hot-arid climates.

Keywords: bacteria; fungi; indoor air quality; HVAC device; commercial building

1. Introduction

An increasing array of critical issues with indoor air quality (IAQ) endangers public and occupational health. Enhanced sealing, air recirculation, and the progression of HVAC systems illustrate energy conservation measures adopted in homes, potentially alleviating the negative health effects of poor indoor air quality (IAQ). This issue is exacerbated by multiple factors, including an aging population, an increase in individuals sensitive to environmental stimuli, and a propensity to spend the majority of life indoors. The health consequences of inhaled biological particles must not be disregarded, since they constitute a significant category of organic matter found in indoor environments, despite the primary emphasis on chemical contaminants in discussions about indoor air quality.

Indoor Air Quality (IAQ) is a vital factor influencing occupant health, comfort, and productivity in commercial structures. In hot-arid climates like Muscat, Oman, structures rely significantly on central HVAC systems, especially all-air multi-zone systems, which regulate and distribute air to various thermal zones. Although these systems effectively regulate temperature and humidity, they may also affect the occurrence and dissemination of microbiological pollutants (bacteria, fungi, mold spores, Actinomycetes, etc.).

Factors influencing microbial growth and movement encompass:

- Elevated humidity levels in cooling coils and drain pans.
- Insufficient fresh air uptake rates.
- Ineffective filtering or filter circumvention.
- Neglected ducts or air handling units (AHUs).
- Population density and activities.

Considering that individuals in Oman spend about 85–90% of their time indoors, assessing microbiological indoor air quality in business edifices is crucial for adherence to international standards, including ASHRAE 62.1, WHO, and EPA guidelines. Despite numerous ventilation studies worldwide, microbiological indoor air quality data in commercial buildings within the Gulf area is scarce, necessitating region-specific evaluation [1].

Bioaerosols are airborne particulate matter that may be either living (e.g., bacteria, fungi) or produced from living creatures. They can originate from Natural or artificial sources and exhibit remarkable variety and complexity. In recent years, there has been an increased interest in the collection and assessment of airborne microbes in indoor settings [2–4]. Bioaerosols account for five to thirty-four percent of indoor air pollution [5]. Furniture, construction materials, and microbiological contamination within wall, ceiling, and floor cavities all contribute to the prevalence of bioaerosols in interior environments. Humans substantially facilitate the spread of pathogens in enclosed settings [6]. Doors, windows, and other openings in the building's exterior act as common pathways for external bioaerosols to enter the interior. Heating, ventilation, and air conditioning (HVAC) systems are often integrated into a single unit for indoor air quality (IAQ), especially in commercial buildings. While HVAC systems can efficiently eliminate and/or dilute over 80% of external aerosols, they may also serve as favorable settings for the proliferation of bioaerosols [7]. Factors that promote microbial growth in HVAC systems encompass low-efficiency filters, water-recycling humidifiers, and humid conditions marked by significant air recirculation [8, 9]. Consequently, HVAC systems may enable the transmission of infections throughout a building, permitting inhalation by occupants [10].

In the last ten to fifteen years, various research has been published that offers substantial scientific evidence linking indoor aerosol particles, especially in the optimal range, to fitness outcomes. Viruses, bacteria, and fungi exemplify viable bioaerosol particles associated with respiratory allergies and bronchial asthma, as well as the airborne transmission of various infections termed building-associated ailments, including Legionnaires' disease and aspergillosis [11, 12]. Sick Building

Syndrome (SBS) is a generic sickness that may be induced by airborne germs and fungus. Even in structures devoid of substantial health litigation, Sick Building Syndrome (SBS) has been demonstrated to be highly widespread, as evidenced by many medical investigations [13]. Epidemiological studies demonstrate a common correlation between Sick Building Syndrome (SBS) and hypersensitivity illnesses, including humidifier fever and bronchial asthma, linked to increased airborne microbial exposure [14, 15]. This research, conducted in an office building in Muscat, Oman, equipped with an HVAC system, evaluates the extent and composition of bacterial and fungal contamination in indoor air during different seasons to improve the understanding of indoor air quality (IAQ). Researchers investigated the impact of HVAC factors and human actions on indoor air quality.

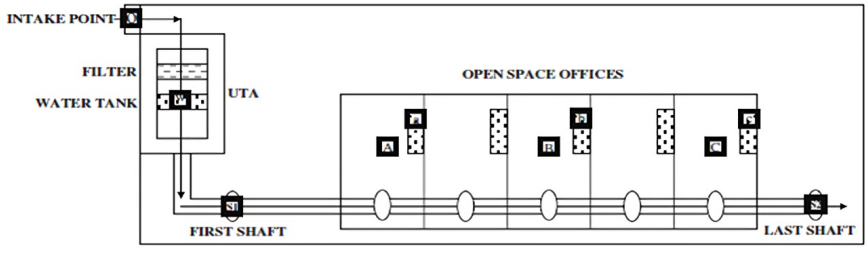
Despite the growing body of international literature on microbiological indoor air quality (IAQ) in office buildings, data from hot-arid regions of the Gulf, particularly commercial buildings in Oman, remain extremely limited. Most existing studies focus on temperate or cold climates and do not adequately account for the continuous year-round operation of all-air HVAC systems, high dust loads, and extreme climatic events characteristic of the region. The present study addresses this gap by providing a comprehensive seasonal evaluation of airborne bacterial and fungal contamination in a commercial office building in Muscat equipped with an all-air multi-zone HVAC system, with particular emphasis on the role of individual HVAC components (air handling unit, supply diffusers, fan coil units, and humidification water tank).A further novel aspect of this work is the assessment of microbiological IAQ under exceptional environmental conditions, namely a winter flooding event, allowing the investigation of its short-term impact on indoor bioaerosol levels. In addition, the use of dual bacterial incubation temperatures (22 ℃ and 37 ℃) enables improved interpretation of microbial origin and potential indoor versus occupant-related contributions. The findings provide region-specific baseline data and practical insights for HVAC operation, maintenance strategies, and preventive IAQ management in commercial buildings located in hot-arid climates.

2. Materials and methodologies

The research was conducted in a 15-year-old commercial edifice situated in Muscat, Oman, including an appropriate HVAC system and open-plan workspaces. The existence of desks, computers, and printers suggests that two or three individuals once utilized the space. The heating, ventilation, and air conditioning system comprises an outside air intake on the building's roof, vent ducts in the ceiling for air expulsion, and a duct connecting the outdoor air intake to the air treatment unit (AHU, 4 years old). The AHU introduced fresh air (a mandatory minimum of 50%) and recirculated air, amalgamated them, filtered them (utilizing a bag-style filter with 85% efficiency for 3 m debris per ASHRAE 52-76), thermally conditioned them, adjusted humidity levels (employing an air humidification tank), and ultimately disseminated them through a duct system to vent ducts in the false ceiling. Heating and cooling systems, specifically fan coil units, have been installed in open areas to regulate the Temperature of the recycled air. The windows are secured, and the optimal method for the occupants to

regulate the building's Temperature is by utilizing the fan coil units.

Figure 1 is a demonstrative figure illustrating the positions of the samples. A, B, and C are three open-concept workspaces situated at the points where the ductwork for filtered air enters and exits the structure, respectively. The air in the center of each open office is tested bi-daily (at 9 AM and 4:30 PM), three times weekly (on Sunday, Tuesday, and Thursday), and once weekly throughout distinct seasons for microbiological analysis (winter, spring, summer). Due to the atypical flood that transpired during winter, every future winter sampling was conducted again. Supplementary evaluations were conducted weekly (on Wednesdays) during each season to analyze the impact of HVAC on the dissemination of microbiological infections within the building. Bacterial and fungal concentrations in the interior air were quantified at the intake factor of the AHU device (**Figure 1**) and at the two ventilation shafts (the initial and ultimate air flow shafts post-AHU system). The humidification water tank at the AHU has also been subjected to microbiological testing. Airflow samples from fan coil units were collected from the same workplaces where indoor air quality assessments were conducted. A total of 240 samples were collected for the examination of bacteria and fungi: two daily samples (one in the morning and one in the afternoon); three offices: (A, B, and C); three temperature ranges: (22 °C, 37 °C, and 25 °C); three occurrences per week (Monday, Wednesday, and Friday); and one outdoor sample, two ventilation ducts, and three fan coil units across 4 seasons (winter, spring, summer, winter). Airborne bacteria and fungus were collected at a flow rate of 180 L/min using a calibrated impactor sampler (SAS Super 180TM, International PBI, Milan), with sampling durations of 1.10 min for fungi and 1.20 min for bacteria. To evaluate the specific microbiological parameters and the quality assurance/control component, three plates were obtained for each sample factor. Field blank plates were employed during shipping and airborne tracking to maintain stringent quality control standards. The processing and analysis of these field blanks are commensurate with those of the pertinent plates. Occupancy during working hours typically ranged between 2–3 occupants per office zone, with standard office activities including computer use, printing, and desk work. Occupancy followed a regular weekday schedule from 08:00 to 16:30, with no night-time occupancy. No indoor plants were present in the monitored areas. Floor finishes consisted primarily of hard tiles, while office furniture was composed of laminated wood and plastic materials.



O: outdoor air;
S_1: first ventilation shaft;
S_2: last ventilation shaft;
W: humidification water tank;
A,B,C: offices;
a,b,c: fan coil units.

Figure 1. Office building with HVAC-AHU.

Precise architectural data on floor area and air volume were not available for this building; therefore, this study represents a limitation in terms of exact air volume normalization. However, consistent sampling locations and repeated seasonal measurements ensured reliable comparative analysis across time.

Commercial buildings in Muscat are fully dependent on all-air HVAC systems throughout the year due to extreme outdoor temperatures. These systems, if not properly maintained or operated, may become reservoirs and pathways for microbial contamination.

- The extent of bacterial and fungal contamination inside commercial buildings.
- How HVAC operational parameters influence microbial distribution.
- Whether IAQ meets recommended international limits.
- Spatial differences in microbial concentration across HVAC zones.

Therefore, a systematic microbiological IAQ evaluation is required to identify contamination sources, assess occupant exposure, and recommend HVAC improvements.

Continuous monitoring of indoor temperature and relative humidity was not performed during the sampling periods, which represents a limitation for detailed interpretation of microbial growth mechanisms; however, HVAC operation maintained thermal comfort conditions consistent with typical commercial office environments in Muscat throughout the study.

Method: Active air sampling using an air sampler (e.g., SAS, Merck MAS-100, or equivalent).

Sampling volume: 100–250 L/min for 1–5 min.

Media plates:

- Nutrient Agar (Total Bacteria).
- Sabouraud Dextrose Agar (Fungi/Mold).

Microbiological air sampling was conducted across three open-plan office zones (A, B, and C) and at key HVAC-related locations, including:

- Outdoor air intake.
- AHU supply air.
- Supply air diffusers.
- Fan coil unit outlets.
- AHU humidification water tank.

Sampling was performed during different seasons (winter, spring, summer, and repeated winter) to capture seasonal variability. Air samples were collected twice daily (09:00 and 16:30), three times per week, using an active air sampling approach. Incubation:

- Bacteria: 35–37 ℃ for 24–48 h;
- Fungi: 25–28 ℃ for 3–5 days.

Units: CFU/m^3 = Number of colonies × 1000/Sampling volume (L)

The building is fully dependent on a central all-air HVAC system throughout the year. The system comprises an outdoor air intake, an air handling unit (AHU) equipped

with bag-type filters (nominal efficiency approximately 85% for 3 μm particles), cooling coils, a humidification water tank, and a duct network distributing conditioned air to multiple zones. Fresh air accounted for a minimum of 50% of the supply air, mixed with recirculated indoor air before filtration and conditioning. Fan coil units installed in the open office areas were used to regulate the temperature of recirculated air based on occupant preferences. Windows remained closed during operation, and indoor thermal comfort was achieved exclusively through mechanical ventilation and air conditioning.

2.1. Microbiological examinations

The total bacterial count was assessed on Rose-Bengal Agar augmented with chloramphenicol (100 g/L), whereas the total fungal count was evaluated on trypticase soy agar containing cycloheximide (100 g/L). Petri plates for bacterial counts were incubated at 37 ℃ for 24 h, at 22 ℃ for 48 h, and at room Temperature for 4 to 8 days. Results were expressed as colony-forming units per cubic meter (CFU/m^3), and the proposed cost of the triplicate samples was calculated according to the manufacturer's correction guidelines for the sampler. To ascertain the legitimacy of the mean price from the three measures, the consistency of triplicate counts was examined using a 2 index. The most prominent bacterial and fungal colonies were identified and isolated from both indoor and outdoor air samples based on their shape, total bacterial counts (22 ℃ and 37 ℃ counts; EN ISO 1999) were examined in water samples obtained from the air humidification tank of the AHU.

2.2. Microbial identity

The biology device initially designed for the identification of soil and water microorganisms, was utilized to conduct metabolic fingerprinting study and identify bacteria [16]. This method assesses a microbe's capacity to utilize or oxidize diverse carbon substrates. Tetrazolium violet is extensively utilized as a redox dye. Microbes were cultivated on Biology Universal Growth agar at 37 ℃ for 24 h or at 22 ℃ for 48 h. To attain the specified turbidity range, inoculum density was adjusted, and colonies were suspended in a 0.4% saline solution. Airborne bacterial and fungal concentrations were quantified as colony-forming units per cubic meter (CFU/m^3). Bacterial samples were cultured using Rose-Bengal Agar supplemented with chloramphenicol, while fungal samples were cultured on Sabouraud Dextrose Agar.

To improve source interpretation:

- Bacterial samples were incubated at 22 ℃ (environmental bacteria) and 37 ℃ (human-associated bacteria).
- Fungal samples were incubated at 25 ℃ for 3–5 days.

Triplicate plates were used for each sampling point to ensure analytical reliability. Field blank plates were included for quality assurance. Bacterial identification was performed using the Biolog Microbial Identification System, based on metabolic fingerprinting of carbon substrate utilization. Fungal genera were identified through microscopic examination and comparison with standard taxonomic keys.

Following the inoculation of a Biology GP Microplate with bacterial suspensions, the plates were incubated at 37 or 22 ℃ for 24 h prior to visual examination. The purple well sample was analyzed using Biology Micro log. Microscopic analysis of fungal colonies and the application of contemporary taxonomic keys to classify them into their corresponding families [17].

2.3. Statistical examination

The release of version 8.0 of the statistical analysis tool SYSTAT for Windows was implemented. Indoor levels of microorganisms (counts at 22 ℃ and 37 ℃) and fungi have undergone analysis of variance (ANOVA), utilizing season, working weekday, and time of day as independent variables. A multitude of microbiological factors were examined, and their interrelationship was assessed utilizing Pearson's correlation coefficient. Statistical analysis was conducted using SYSTAT version 8.0. Analysis of variance (ANOVA) was applied to assess the influence of season, sampling location, day of the week, and time of day on bacterial and fungal concentrations. Pearson correlation analysis was used to examine relationships between bacterial and fungal counts.

3. Results and analysis

Enhanced Microbiological Quality of Indoor Air

Table 1 summarizes the levels of bacterial and fungal contamination in indoor environments throughout different periods of seasonal monitoring. Bacterial and fungal counts from the three workplaces (A, B, and C) were aggregated and shown as a weekly average, along with the minimum and maximum values for each season. The identified figures were subsequently contrasted with the infection classifications outlined in the recommendations of the Commission of European Communities. Indoor fungal levels were discovered to be excessively elevated following the initial cold sampling. All offices exhibited significant fungal contamination, with office C recording the highest concentration (>2000 CFU/m^3) (**Table 1**). **Table 1** is situated here. Seasonal assessment of bacterial and fungal counts in indoor air (in CFU/m^3) at ambient Temperature of 22 and 37 ℃. The mean quantity of microorganisms detected in samples collected on Sundays, Tuesdays, and Thursdays from each of the three offices (A, B, and C) weekly. Although minor spatial variability was observed, statistical analysis (ANOVA, $p > 0.05$) indicated no significant differences among offices, justifying the subsequent use of aggregated values for seasonal trend analysis. This finding suggests that the HVAC air distribution and open-space configuration promoted relatively uniform microbial dispersion within the occupied zones. density of mixed microbial and fungal populations (CFU/m^3) in non-commercial buildings, categorized by **Table 2**.

Unlike a health risk assessment potentially associated with a flood near the sampled building in Turin, these groupings are predominantly found on the values derived from inside environments. Extensive mold proliferation was also proposed in various investigations concerning flood-affected residences [18,19]. Consequently, the subsequent winter experienced a reiteration of all prior sampling. values below

500 CFU/m^3 (medium-low infection levels in spring) and 100 CFU/m^3 (very low-low infection levels in summer and winter) have been established in the other seasonal samples (spring, summer, and winter). The low infection rate throughout winter further substantiates that the very elevated fungal levels observed in the initial winter sampling were affected by the flood and do not reflect a typical winter infection rate [20,21].

Table 1. Indoor air bacterial (22 ℃ and 37 ℃) and fungal concentrations (CFU/m^3) during seasonal samplings.

Parameter (CFU/m^3)	Time	Winter (n = 18) mean	Min	Max	Spring (n = 18) mean	Min	Max	Summer (n = 18) mean	Min	Max	Winter 2 (n = 18) mean	Min	Max
Bacteria 37 ℃	m	102	32	248	97	36	256	198	120	368	253	116	496
	a	76	44	128	65	32	96	136	68	324	158	84	268
Bacteria 22 ℃	m	72	32	200	120	56	320	176	112	240	271	128	500
	a	28	4	56	129	40	308	134	52	368	160	72	304
Fungi 24 ℃	m	514	50	1528	321	55	465	44	25	90	49	10	100
	a	872	30	2315	43	25	100	44	10	75	39	10	70

Table 2. Categories of CFU/m^3 (mixed population of bacteria and fungi) for non-industrial indoor environments (CEC, 1993).

Category	Bacteria (CFU/m^3)	Fungi (CFU/m^3)
Very low	<50	<25
Low	<100	<100
Intermediate	<500	<500
High	<2000	<2000
Very high	>2000	>2000

Bacterial concentrations at 37 ℃ were below 500 CFU/m^3, indicating low to moderate infection levels, with values between 32 and 496 CFU/m^3. At 22 ℃, microorganisms exhibited a comparable trend, with a median concentration of 136 CFU/m^3 (range, 4–500 CFU/m^3) identified. except for the core winter sampling, an ANOVA conducted on the raw data indicated substantial seasonal variations in bacterial (at 22 and 37 ℃) and fungal (at both Temperatures) infection rates indoors (**Table 3**). Spring exhibited a rise in bacterial counts at both 22 and 37 ℃, but summer and winter showed an increase in fungal prevalence. Additional research has identified consistent trends analogous to this study. Bacterial and fungal contamination rates, at both 22 and 37 ℃, were observed to be highest in the morning and lowest in the afternoon (**Table 3**). The ANOVA revealed a significant trend in bacterial indoor contamination at 22 ℃, with the order of prevalence being Friday > Wednesday > Monday. Pearson's correlation analysis did not identify a significant link between bacterial loads at 22 ℃ and 37 ℃ and fungal burdens.

Table 3. Analysis of variance (ANOVA) on bacterial and fungal counts with respect to season, sampling point (office), day of working week, and sampling hour.

Factor	Bacteria 22 ℃	Bacteria 37 ℃	Fungi 24 ℃
Season	$p < 0.001$ (Sp > Su > W2)	$p < 0.001$ (Sp > Su > W2)	$p < 0.001$ (W2 ≈ Su > Sp)
Office	Not significant (n.s)	n.s.	n.s.
Days of working week	$p < 0.05$ (F > W > M)	n.s.	n.s.
Hour	$p < 0.05$ (m > a)	$p < 0.05$ (m > a)	$p < 0.05$ (m > a)

3.1. HVAC—Air handling unit (AHU)

The microbial contamination of outdoor and interior air measured near supply air diffusers was assessed to evaluate the impact of the AHU device on indoor air quality (**Table 4**). Temperatures conducive to the proliferation of fungus and bacteria outdoors were observed to increase from winter to summer, except for the fungal airborne concentration recorded during the flood, which surged unexpectedly. Elevated seasonal Temperature and humidity can enhance microbiological activity, resulting in increased bacterial and fungal populations, as documented by many authors [21,22,24]. Fungal counts exceeding 3000 CFU/m^3 were detected in both outdoor and indoor air diffusers during the preliminary winter monitoring, indicating a strong likelihood that the AHU was not the source of contamination. **Table 3** presents season, sampling location (office), workday, and sampling time as variables in an ANOVA for microbial load. Periodic sampling of air and ventilation shafts for bacterial and fungal concentrations (CFU/m^3) was conducted at room temperature (22 ℃) and at 37 ℃ post-AHU system, as well as indoor air at the height of the remaining shaft following the AHU device (**Table 4**).

Table 4. Bacterial (22 ℃ and 37 ℃) and fungal concentrations (CFU/m^3) in outdoor air and at the ventilation shafts during seasonal samplings.

Parameter	Location	Winter (mean ± SD)	Spring (mean ± SD)	Summer (mean ± SD)
Bacteria 37 ℃	O	114 ± 62	96 ± 17	284 ± 86
Bacteria 22 ℃	O	189 ± 17	352 ± 57	600 ± 127
Fungi 24 ℃	O	> 3268[b]	145 ± 15	695 ± 145
Bacteria 37 ℃	S1	20 ± 4	44 ± 5	84 ± 11
Bacteria 22 ℃	S1	4 ± 2	144 ± 39	120 ± 30
Fungi 24 ℃	S1	> 3268[b]	60 ± 10	70 ± 4
Bacteria 37 ℃	S2	48 ± 5	48 ± 20	76 ± 38
Bacteria 22 ℃	S2	16 ± 1	104 ± 2	60 ± 28
Fungi 24 ℃	S2	> 3268[b]	30 ± 3	50 ± 18

Note: b: High values.

The mean upper detection limit of the three measurements, as reported by the manufacturer, was calculated by aggregating the total number of colonies on Petri dishes utilizing the SAS Super 180. Eliminate the elevated fungal contamination from the outdoor air. In contrast, fungal counts exceeded outdoor bacterial levels (22 ℃ and 37 ℃) during this sampling, and the AHU effectively eliminated most of the fungal contamination. microbial contamination of the air at the AHU air diffusers was consistently measured below 500 or 100 CFU/m^3 throughout various samplings, which is lower than the values detected outdoors. Air samples from fan coil units typically vary with the seasons. Both indoor and outdoor air exhibited elevated fungal counts, with the initial cold air sample obtained from a fan coil unit indicating a significant fungal presence (range 500–2000 CFU/m^3).

Additional samplings have indicated bacterial and fungal quantities comparable to those present in indoor air, ranging from medium-low to extremely low levels (500 or 50 CFU/m^3). Ratio of Indoor to Outdoor The indoor microbial counts (recommended values derived from open-area workplaces on Wednesday) and outdoor

microbial counts were utilized to calculate the indoor/outdoor ratio (I/O; **Table 5**). Consistent with prior research in office buildings, I/O ratios indicated that fungal counts and bacterial concentrations at 22 ℃ were consistently superior outside compared to indoors [3]. Nevertheless, I/O values approaching one for 37 ℃ bacterial populations suggested an increase, as shouwn in **Table 6**. The quantity of bacteria (at 22 and 37 ℃) and mold spores (in CFU/m^3) in the air moving through the fan coil unit is presented for different periods of the year.

Table 5. Indoor/outdoor ratios calculated for bacterial and fungal loads in seasonal samplings.

Season	Bacteria 22 ℃ (I/O)	Bacteria 37 ℃ (I/O)	Fungi 24 ℃ (I/O)
Winter	0.63	0.82	0.34
Spring	0.39	1.08	0.80
Summer	0.80	1.06	0.38
Winter 2	0.70	1.13	0.28

Table 6. Bacterial (22 ℃ and 37 ℃) and fungal concentrations (CFU/m^3) in the fan coil unit air flow during seasonal samplings.

Parameter (CFU/m^3)	Winter (n = 3) mean	Min	Max	Spring (n = 3) mean	Min	Max	Summer (n = 3) mean	Min	Max
Bacteria 37 ℃	82	60	113	52	36	80	128	32	200
Bacteria 22 ℃	36	20	47	71	44	116	95	32	128
Fungi 24 ℃	935	560	1465	15	10	20	50	30	65

Seasonal monitoring revealed pronounced temporal variability in microbial concentrations. Under normal climatic conditions, indoor bacterial concentrations remained within low to moderate levels, with values ranging from 32 to 496 CFU/m^3 at 37 ℃ and 4 to 500 CFU/m^3 at 22 ℃. Fungal concentrations during spring and summer generally remain below 500 CFU/m^3, consistent with values reported for well-maintained office buildings. A marked increase in fungal concentrations (>2000 CFU/m^3) was observed during the initial winter sampling. This peak coincided with an exceptional flooding event, suggesting that elevated indoor humidity and moisture ingress promoted short-term fungal proliferation. Subsequent winter monitoring, conducted after remediation and drying, showed fungal concentrations below 100 CFU/m^3, confirming that the initial winter peak was not representative of typical seasonal conditions.

Sample sizes for each investigated parameter the average microbiological count obtained from the air circulating through the building's three fan coils exceeded the count outside the building in all three offices (A, B, and C).

3.2. Microbiological analysis of the humidification water reservoir

Table 7 indicates that with rising Temperature, the total bacterial count in the humidification water tank increased consistently from a baseline of 1103 CFU per 100 mL to 150,000 CFU per 100 mL during spring and summer. The predominant genera identified among the most numerous gigantic microorganisms in indoor air were Micrococcus (32% of species) and Staphylococcus (44% of species). These data

support the idea that micrococci and staphylococci are the predominant microorganisms present in house dust.

Table 7. Microbiological contamination of humidification water tank.

Parameter	Winter	Spring	Summer
Bacteria at 37 ℃ (CFU/100 mL)	1900	29,200	43,000
Bacteria at 22 ℃ (CFU/100 mL)	1100	150,000	136,000
Legionella spp. (CFU/L)	<100[a]	<100[a]	<100[a]

Note: a: CFU/L.

Every indoor air sample contained either Micrococcus luteus or Staphylococcus hemolytic. Common skin bacteria, including Micrococcus Lyle and Staphylococcus saprophyticus, as well as ear canal bacteria Staphylococcus auricularis and scalp bacteria Staphylococcus capitis, were identified. Certain identified bacteria can be categorized as opportunistic pathogens whereas others are predominantly located in environmental samples. The bacterial species present in the fan coil air flow closely resembled those detected in the inside air of the building. Aero coccus and viridians are two prevalent environmental organisms located in the atmosphere.

This is the inaugural use of the Biolog system for airborne bacterial identification, yielding promising results, with 94.3% of the studied colonies accurately recognized. Microbial concentrations measured in air discharged from fan coil units exhibited seasonal variability but generally remained within low to medium contamination levels (≤500 CFU/m^3). During the initial winter sampling, fungal concentrations from fan coil airflow reached 500–2000 CFU/m^3, consistent with elevated indoor fungal levels observed during the flooding period. Outside this exceptional condition, bacterial and fungal concentrations in fan coil airflow were comparable to or lower than indoor background levels, indicating that fan coil units primarily facilitated air circulation rather than acting as amplification sources of microbial contamination.

3.3. Fungal identity

Figure 2 illustrates the seasonal change of fungal genera in indoor air. Numerous investigations have identified that the predominant big fungal genera in indoor air include *Penicillium* spp., *Aspergillus* spp., and *Cladosporium cladosporioides* and *C. sphaerospermum*. Penicillium was the predominant genus in indoor air throughout winter (68% of the time) and spring (60% of the time), but Cladosporium emerged as the most prevalent genus in summer. This tendency reflected what was extensively documented in public media [20]. Penicillium, Aspergillus, and Cladosporium are three prevalent fungal species identified in buildings, all acknowledged as possible triggers of respiratory hypersensitivity reactions [25]. Indoor-to-outdoor ratios (I/O) were calculated to assess potential indoor microbial sources. Fungal I/O ratios remained consistently below unity (0.28–0.80), indicating a dominant outdoor origin and limited indoor amplification under normal conditions. In contrast, bacterial I/O ratios at 37 ℃ approached unity (0.82–1.13), suggesting a greater contribution from occupant-related sources. These findings align with the predominance of Micrococcus and Staphylococcus species identified in indoor air samples.

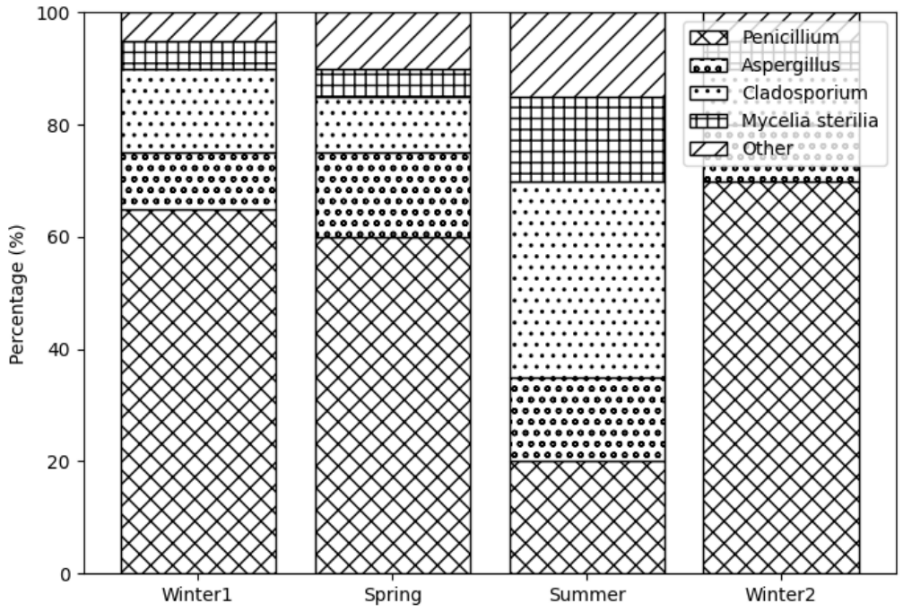


Figure 2. Distribution of fungal genera in indoor air during different seasons.

4. Discussion

This study provides a comprehensive evaluation of microbiological indoor air quality (IAQ) in a commercial office building in Muscat, Oman, operating under hot-arid climatic conditions and relying on an all-air multi-zone HVAC system. The results demonstrate that, under normal operating and climatic conditions, airborne bacterial and fungal concentrations remained within ranges commonly reported for well-maintained office buildings in international literature observed dominance of Micrococcus and Staphylococcus species in indoor air samples is consistent with previous studies identifying human occupancy as a primary contributor to indoor bacterial populations. This interpretation is further supported by indoor-to-outdoor (I/O) ratios approaching unity for bacteria incubated at 37 °C, indicating a stronger association with occupant activity rather than outdoor sources. In contrast, fungal I/O ratios consistently below one suggests that fungal spores primarily originated from outdoor air and were introduced through ventilation rather than amplified indoors. Seasonal analysis revealed relatively stable bacterial concentrations throughout the year, while fungal concentrations exhibited greater variability. The exceptionally high fungal levels recorded during the initial winter sampling were temporally associated with a flooding event, likely resulting in elevated indoor humidity and favorable growth conditions. The return of fungal concentrations to low levels during the subsequent winter sampling supports the interpretation that this peak was event-driven rather than seasonal, in agreement with findings reported for flood-affected buildings in other climatic contexts. Quantitative comparison of microbial concentrations upstream and downstream of the air handling unit (AHU) indicates that the HVAC system was effective in reducing airborne microbial loads under standard operating conditions. Lower concentrations measured at supply air diffusers compared to outdoor air suggest that filtration, dilution, and conditioning processes contributed to microbial control. However, this effectiveness was reduced during extreme environmental

conditions, highlighting the importance of HVAC operation and maintenance in mitigating short-term contamination events. fan coil unit measurements showed microbial concentrations comparable to or lower than indoor background levels for most of the monitoring period, indicating that these units primarily facilitated air circulation rather than acting as independent sources of contamination. The absence of a significant correlation between bacterial and fungal concentrations further suggests that these microbial groups were influenced by different source mechanisms and environmental drivers. While the measured microbial concentrations did not indicate abnormal contamination under typical conditions, interpretation of potential health implications must be made with caution. This study did not include personal exposure assessment, clinical data, or epidemiological evaluation. Consequently, conclusions are limited to comparative assessment against published IAQ benchmarks rather than direct inference of health risk.

Several limitations should be acknowledged. The study was conducted in a single commercial building, which may limit broader generalization. Although multiple sampling locations were monitored, results were aggregated after statistical evaluation confirmed limited spatial variability. In addition, building-specific factors such as occupancy density, cleaning practices, and material characteristics may have influenced microbial levels alongside HVAC operation. This was undertaken not in response to tenant concerns, but to illustrate the improvement of the building's air quality over time. Our data suggested that the bacterial and fungal loads in all workplaces were below 105 CFU/m^3, implying a modest level of infection.

The observed pricing range corresponds with research on high-quality office buildings that have received little to no negative tenant feedback [22, 23]. A notable fungal infection (between 500 and 2000 CFU/m^3) in indoor air was recorded during the preliminary winter assessment. This discovery is likely linked to the flood that occurred during that time, leading to water stagnation and, consequently, conditions (such as relative humidity and nutrients) favorable for fungal proliferation. The microbial air contamination levels in the three offices were relatively similar, perhaps due to their position in an open area, away from concentrated sources of microbial infection. A multitude of studies commenced to examine the analogous distribution of bacterial and fungal populations [24].

ANOVA results demonstrated statistically significant effects of season and sampling time on both bacterial and fungal concentrations ($p < 0.05$), while spatial differences among offices were not significant. Microbial concentrations were generally higher during morning sampling compared to afternoon measurements, likely reflecting overnight stagnation followed by resuspension during HVAC system startup. Pearson correlation analysis showed no significant correlation between bacterial and fungal concentrations, indicating distinct sources and influencing mechanisms.

Humans may contribute to the prevalence of Micrococcus and Staphylococcus among the detected bacterial species in indoor air. The indoor/outdoor ratio's closeness to 1 at 37 ℃ (0.82 I/O 1.13) corroborates this assumption. The indoor bacterial population surpasses that of the outdoors, a disparity perhaps ascribed to multiple factors, including human activity. A fungal I/O ratio of 1 (0.28 I/O 0.8) indicated the

absence of an indoor air contamination source. The seasonal distribution of fungal species in indoor air revealed the impact of outdoor air. The analysis of records revealed no correlation between bacterial and fungal counts, suggesting they originate from separate sources. While specific bacteria found in indoor air (*S. haemolyticus*, *S. epidermidis*, and *S. hominis*) can be categorized as opportunistic pathogens, their varied presence and minimal concentrations do not pose a substantial risk to occupant health. Evaluation reveals a possible fitness hazard in that context due to increased fungal contamination and the identification of clearly allergenic species (Penicillium) during the initial winter sampling (linked to the flood). The investigation of bacterial and fungal counts can provide substantial data on the impact of HVAC characteristics (such as AHU, fan coil, and water) on indoor air quality. The notable daily fluctuation in indoor air bacterial (22 ℃ and 37 ℃) and fungal contamination may correlate with airflow resulting from the daily activation and deactivation of HVAC systems.

In this design, bacteria and fungi within the AHU and vent ducts should flourish when the HVAC system is dormant. Upon activation of the HVAC system, the microbes are anticipated to disperse throughout the area. Multiple studies have measured the concentrations of bacteria and fungi released into the air following overnight incubation with the HVAC system turned off. Various factors, including indoor air circulation and the intermittent functioning of HVAC systems, may account for the seasonal fluctuations of microbial levels in indoor air, in contrast to outdoor air. Thus, in the case of a moderate microbial infection, indoor microbial counts do not correspond with outside levels [26]. The results of the AHU investigation confirmed the unit's maximum effectiveness in preventing microbiological contamination. The AHU appears to have eradicated airborne microbial illness in standard climatic circumstances, with the exception of the initial cold weather sampling [27, 28]. The operation of fan coil units markedly affects air circulation, since it depends on the preferences of the building's occupants. The microbial infection levels in the airflow from the fan coil unit were significantly lower than those in the indoor air. The water analysis indicated a substantial presence of microorganisms in the humidification water tank, signifying microbial proliferation, particularly during the warmer months [29,30].

- Provides baseline IAQ microbial data specific to Muscat climatic conditions.
- Supports Ministry of Health & Municipality IAQ policy development.
- Help commercial facilities improve building health and sustainability.
- Highlights importance of maintenance in dust-heavy hot climates.
- Supports design optimization of multi-zone HVAC systems.
- Reduces risk of Sick Building Syndrome (SBS).

This study has certain limitations. It was conducted in a single commercial building, which may limit broader generalization of the findings. In addition, the absence of continuous indoor temperature and relative humidity monitoring restricts detailed assessment of environmental drivers influencing microbial growth. Nevertheless, the use of repeated seasonal measurements and consistent HVAC operating conditions provides robust comparative insights into microbiological indoor air quality in a hot-arid climate.

5. Conclusion

This study presents region-specific baseline data on microbiological indoor air quality in a commercial office building in Muscat, Oman, contributing to the limited body of IAQ research available for hot-arid climates. The findings demonstrate that, under standard operating conditions, the all-air multi-zone HVAC system effectively maintained bacterial and fungal concentrations within ranges typical of well-managed office environments. Seasonal monitoring revealed that extreme environmental events, such as flooding, can temporarily disrupt indoor microbiological balance and lead to elevated fungal concentrations, even in mechanically ventilated buildings. Quantitative analysis confirmed that HVAC components, particularly the air handling unit, played a critical role in controlling microbial loads through filtration and air treatment, although their effectiveness may be challenged during atypical climatic conditions.

Based on the results, preventive IAQ management strategies—such as regular HVAC inspection, timely filter replacement, drain pan and coil cleaning, and careful monitoring of humidification systems—are essential to minimize microbial proliferation. Recommendations for enhanced filtration efficiencies (e.g., MERV 11–13 or HEPA filtration in sensitive zones) are supported by existing literature and should be considered as precautionary measures rather than direct outcomes of the present study. Overall, the study highlights the importance of integrating HVAC operation, maintenance practices, and environmental monitoring to ensure acceptable microbiological IAQ in commercial buildings located in hot-arid regions. Future research should include multi-building investigations, detailed occupant exposure assessment, and continuous monitoring to further elucidate the interaction between building systems, climate, and indoor bioaerosol dynamics.

Microbial IAQ profile for a commercial building in Muscat:

- Identification of critical HVAC components contributing to contamination.
- Correlation between HVAC operation and microbial levels.

Recommendations for:

- Filter upgrades (MERV 11–13 or HEPA for critical zones).
- Increased outdoor air ratio.
- Coil/drain pan cleaning frequency.
- Humidity control improvements.

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