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Co-Contamination of Air Conditioning Filter Dust: Assessing Microbial and Heavy Metal Loads and Their Implications for Indoor Air Quality in Basra Technical Engineering College (BTEC), Iraq

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ABSTRACT

Air conditioning (AC) systems are commonly used for obtaining comfort and raising the efficiency of humans in workplaces and educational buildings. Nevertheless, accumulation of dust on the AC may have diverse effects on human health. This research aimed to assess indoor air quality (IAQ) by collecting dust samples from AC filters at six locations in Basra Technical Engineering College (BTEC) through two sampling periods. Microorganisms, heavy metals, and IAQ parameters such as CO_2, $PM_{2.5}$, PM_{10}, and Air Quality Index (AQI) were measured and evaluated. Analysis of results revealed the presence of several bacterial and fungal genera, like *Staphylococcus, Streptococcus, Klebsiella*, and *Aspergillus.* High levels of heavy metal concentrations were recorded: Pb (2.5 µg/g), Hg (1.3 µg/g), and Cu (2.5 µg/g) at locations 4, 1, and 4, respectively, exceeded permissible limits established by the WHO. IAQ assessment highlighted significant differences ($p < 0.05$) at locations 2 and 6 for CO_2, $PM_{2.5}$, and PM_{10} levels, while IAQ assessments were generally good for indoor air conditions across all locations, except location 6. Overall, the outcomes illustrate that AC filters could serve as reservoir points for heavy metals and potentially pathogenic microbes that adversely affect human health. So that maintenance and further research of AC systems are necessary to limit and reduce indoor air pollutants.

1. INTRODUCTION

Indoor air quality (IAQ) has a significant effect on public health, particularly in regions with harsh weather where people spend most of their time indoors. So, due to exceeding safe limits of temperature limits, air conditioning (AC) systems are seriously relied upon for current comfort and ventilation in places like Iraq and other Middle Eastern countries. Generally, 70% of daily human activity takes place indoors, which possibly increases the exposure to airborne pollutants. Therefore, AC systems are crucial for controlling indoor heat, ventilation, and air quality. AC filters serve as key barriers to prevent dust, suspended particulate matter (PM), pollen, and microbes from circulating all over interior spaces. Nevertheless, filters might serve as sinks and reservoirs for lethal chemical and biological contaminants in favorable environmental conditions, like high humidity and prolonged operating times. As a result, the growth of microbial colonization and particle accumulation perhaps helps secondary pollutants to survive and continually spread through indoor air circulation. Previous studies declared the connection between pollution and negative health impacts, such as general declines in IAQ, respiratory infections, and allergic reactions [1, 2].

In parallel, increased urbanization, traffic density, and closeness to industrial operation areas led to an increase in heavy metal emissions in Middle East countries, specifically Basra city in Iraq. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), and zinc (Zn) are found in indoor dust because of emissions from building materials and household substances, as well as penetration from outdoor sources. The effectiveness of AC filters became more broadly acknowledged as an integrative sample media for determining indoor exposure to these pollutants, even at low concentrations. However, long-term exposure to heavy metals could have serious health impacts, such as neurotoxicity, respiratory conditions, and even cancer [3, 4]. Latest studies in Gulf nations, such as Saudi Arabia and Kuwait, have shown that AC filters in commercial, industrial, and residential settings contain elevated levels of heavy metals and microorganisms, sometimes exceeding global health recommendations. Moreover, research indicates that the existence of heavy metals may affect the configuration of microbial communities by favoring pathogenic or metal-tolerant species [3, 5].

Nevertheless, previous research has investigated heavy metal build-up and microbial contamination separately, with a few methodological integrations and investigations of their mechanistic or interaction links. However, these studies have not been able to link microorganisms and the existence of

heavy metals in AC systems. Therefore, this study assumes that campus buildings located near major traffic roads, the concentrations of heavy metals (e.g., Pb, Cu), and the abundance of certain microorganisms (e.g. *Staphylococcus, Streptococcus, Klebsiella*, and *Aspergillus*) on air-conditioning filters are significantly higher than in buildings located farther from the roads, and highlighting possible health risks under urban and climatic settings.

2. MATERIALS AND METHODS

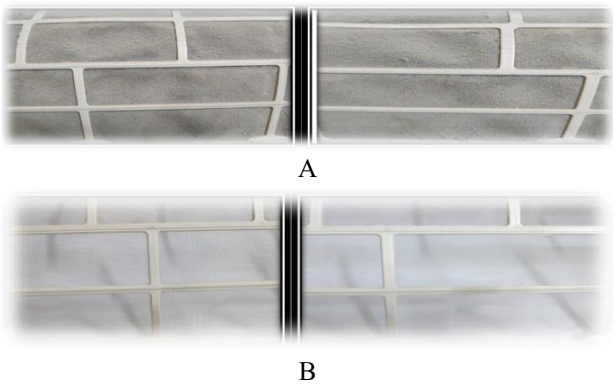
2.1 Sites of collected samples and experimental design

From Basra Technical Engineering College (BTEC)/Southern Technical University/Basra/Iraq, dust samples from AC systems were collected from three buildings of the campus. Forty-eight (48) dust samples from filters were gathered from six different indoor environments, which represent various occupancy and activity patterns. At each location, twenty-four samples were collected per sampling period, resulting in forty-eight samples per site across the study duration. These samples represent unique collections obtained from different AC units within the same location. Administrative offices were among these settings, as shown in Figure 1. Each location had (1-3) different types of air conditioners; also, four samples of each location were taken at two periods, in October 2023 and April 2024, to evaluate temporal variance.

Figure 1. Sites of samples
Department name (Fuel and Energy, Petrochemical, Environ and Pollution, Thermal mechanical, Electrical power, and Automotive), sites (1, 2, 3, 4, 5, and 6) respectively.

For analytical clarity and to assess the influence of traffic-related emissions, the sampling locations were classified into two groups:

- Near-road group, comprising Buildings 3, 4, and 5, which are located in close proximity to traffic roads; and
- Far-from-road (control) group, comprising Buildings 1, 2, and 6, which are situated farther from direct traffic influence.



A

B

Figure 2. Dust samples collected from air-conditioning system filters: (A) before use and (B) after use

A sterile soft brush was used to thoroughly remove all dust from both sides of the AC filters during the first sample session. Then, they were cleaned with distilled water and dried at room temperature before being returned to their original units until the second sampling period, as shown in Figure 2(A and B).

Importantly, all filters were in regular use before the first measurement, which assures that the collected dust was reflective of actual indoor exposure circumstances. Furthermore, the filters were not replaced during the two periods of sampling.

The dust samples were placed in sterile polypropylene containers, size 25 mL, and kept at room temperature for physicochemical and microbiological analysis.

2.2 Preparation and identification of microbial species

One gram of dust was taken from each chosen location and aseptically suspended in 100 milliliters of sterile distilled water to create a stock homogenized suspension. Sterile distilled water was used to prepare a series of ten-fold serial dilutions (10^{-1} – 10^{-7}) to spread on Petri dishes with 0.1 mL aliquots from the appropriate dilutions containing various culture media. For total bacteria, nutrient agar was used, while for gram-negative bacteria, MacConkey agar and blood agar were used for fastidious and hemolytic bacteria. For fungal isolation, a potato dextrose agar supplemented with antibiotics was used.

Bacterial plates were incubated aerobically at 30°C for 24 to 48 hours, while fungal plates took 3 to 5 days. Pure isolates

were obtained by separating colonies and subcultured after incubation. According to Bergey's Manual of Systematic Bacteriology [6], the isolated bacteria were identified through the morphology of the colony, Gram staining, and biochemical traits. For isolated fungi, two ways were used: firstly, macroscopic colony features and secondly, microscopic analysis of lactophenol cotton blue-stained samples, focusing on the structure of spores and morphology of hyphae to identify fungi species [7].

2.3 Preparation and measurement of heavy metals

The presence of heavy metals in the collected dust samples was determined via a conventional acid digestion process. Briefly, 0.5 g of oven-dried dust sample was digested by a mixed acid system (HNO_3–$HClO_4$) until the formation of a clear solution, which was cooled and filtered before diluting with distilled water to a determined final volume. An Atomic Absorption Spectrophotometer (AAS, AA-7000, Shimadzu, Japan) was used to measure lead (Pb) and copper (Cu) concentrations (μg/g). Additionally, concentrations of mercury (Hg) (μg/g) were determined by using an Atomic Absorption/Flame Emission Spectrophotometer (AA-630-12, Shimadzu, Japan) [8].

2.4 Health risk assessment

To evaluate the potential health risks associated with exposure to heavy metals in indoor dust, a human health risk assessment was conducted following the methodology recommended by the United States Environmental Protection Agency (USEPA) [9]. Both non-carcinogenic and carcinogenic risks resulting from exposure to heavy metals via dust ingestion and inhalation pathways were assessed.

2.4.1 Exposure assessment

The average daily dose (ADD) for each heavy metal was calculated for ingestion and inhalation exposure routes using standard USEPA equations:

Dust ingestion:

$$ADDing = \frac{\mathrm{C} * \mathrm{IngR} * \mathrm{EF} * \mathrm{ED}}{\mathrm{BW} * \mathrm{AT}} \quad (1)$$

Dust inhalation:

$$ADDinh = \frac{\mathrm{C} * \mathrm{InhR} * \mathrm{EF} * \mathrm{ED}}{\mathrm{PEF} * \mathrm{BW} * \mathrm{AT}} \quad (2)$$

where:

C = heavy metal concentration in dust (mg/kg)
IngR = ingestion rate (mg/day)
InhR = inhalation rate (m^3/day)
EF = exposure frequency (days/year)
ED = exposure duration (years)
BW = body weight (kg)
AT = averaging time (days)
PEF = particle emission factor (m^3/kg)

2.4.2 Non-carcinogenic risk

The non-carcinogenic risk posed by individual heavy metals was evaluated using the hazard quotient (HQ):

$$HQ = \frac{ADD}{RfD} \quad (3)$$

where, *RfD* is the reference dose (mg/kg/day). The hazard index (HI), representing the cumulative non-carcinogenic risk from multiple metals, was calculated as the sum of individual HQs:

$$HI = \sum HQ \quad (4)$$

An HQ or HI value less than 1 indicates no significant non-carcinogenic risk, while values greater than 1 suggest potential adverse health effects.

2.4.3 Carcinogenic risk

The lifetime carcinogenic risk (CR) was estimated using the following equation:

$$CR = ADD \times SF \quad (5)$$

where, *SF* is the cancer slope factor ($(mg/kg/day)^{-1}$). The total carcinogenic risk (TCR) was obtained by summing the CR values for all carcinogenic metals.

According to USEPA guidelines, carcinogenic risk values between 10^{-6} and 10^{-4} are considered acceptable, whereas values above 10^{-4} indicate a potential cancer risk.

2.5 Evaluation of air quality

Assessment of IAQ for chosen sites was done by a PTH-9A Air Quality Detector (INKBIRD PLUS) to monitor particulate matter ($PM_{2.5}$ and PM_{10}), carbon dioxide (CO_2), and overall air quality index (AQI). According to the manufacturer's standards, the instrument is calibrated before use, with measurement accuracy of ± 10 μg/m^3 for particulate matter and ± 50 ppm for CO_2. Measurements were scheduled between 9:00 and 11:00 a.m. for one hour of continuous monitoring at each location. The AC systems were operating normally during the time of the sampling period; also, the number of occupants varied from 3 to 6 people.

Based on measured airflow rates expressed in cubic feet per minute (CFM), air changes per hour (ACH) were monitored for three different-sized rooms (offices): office 1 (2.5 × 4 × 3 m), office 2 (4 × 6 × 3 m), and office 3 (5 × 9 × 3.5 m). ACH was calculated by converting room volumes to cubic feet, and to evaluate the ventilation efficiency of air purifiers, measurements of the CFM of each device and installation of the air filters were done and compared with the room volume.

Then, to calculate ACH [10], use the following formula:

$$ACH = \frac{CFM * 60}{V} \quad (6)$$

where:

CFM = Cubic feet per minute of airflow (from the ventilation system)
V = Volume of the space in cubic feet (length × width × height)
60 = Converts minutes to hours

To determine the ventilation system's airflow capacity (CFM) for the AC unit, it should list the airflow rate in CFM (cubic feet per minute) or m^3/h (cubic meters per hour) by:

$$CFM = \frac{\frac{m3}{h}}{1.7} \quad (7)$$

Then the air supplies indoor calculate from:

$$\text{Air supply (m}^3\text{/h)} = \text{Room Volume (m}^3\text{)} \times \text{ACH} \quad (8)$$

2.6 Statistical analysis

The results were analyzed with the SPSS program using the ANOVA test [11]. The statistical examination of microorganisms in dust from six locations revealed significant differences ($p < 0.05$) in the presence of *Staphylococcus* and *Aspergillus* compared to other species of microorganisms. *Streptococcus* demonstrated significant differences ($p < 0.05$) in locations 2, 4, and 5 compared to other locations. Furthermore, locations 2 and 6 showed significant differences ($p < 0.05$) in air quality pollutants (CO_2, $PM_{2.5}$, and PM_{10}), while locations 4 and 5 showed significant differences ($p < 0.05$) in comparison to the other locations. The IAQ indicates that all locations appear to be in good condition, with the exception of location 6.

3. RESULTS

3.1 Microbial contamination levels and distribution

The results of microbial pollutants in the first collection period showed three suspected genera, such as *Staphylococcus* cf., *Streptococcus* cf., *Klebsiella* cf., and *Aspergillus* cf., as declared in Table 1 and Figure 3. *Streptococcus, Staphylococcus*, and *Aspergillus* showed the highest average contamination level, with a mean value of 620 CFU/g, 450 CFU/g, and 430 CFU/g, respectively, across all locations. However, *Klebsiella* cf. was only detected at location 6, with an average concentration of 470 CFU/g.

In the second collection period, a general reduction in bacterial and fungal loads was observed. *Streptococcus* continued to be the dominant genus, but with a lower average value of 470 CFU/g at locations 2, 3, and 5. Meanwhile, *Staphylococcus* cf. showed a further decrease in value to 350 CFU/g at locations 1, 3, 4, and 6. *Klebsiella* cf. was recorded to be 380 CFU/g at locations 1 and 4, confirming its sporadic distribution. The final suspected fungi, *Aspergillus*, were consistently detected at all locations in both periods with an average value that slightly decreased to 400 CFU/g, as shown in Table 1.

Table 1. Microbial detection status table

Microorganisms	Locations	Average Colony Forming Units (CFU/g)
1st Collection		
Staphylococcus	1-6	450
Streptococcus	1-6	620
Klebsiella	6	470
Aspergillus	1-6	430
2nd Collection		
Staphylococcus	1, 3, 4, and 6	350
Streptococcus.	2, 3, and 5	470
Klebsiella	1 and 4	380
Aspergillus	1-6	400

To enable clearer comparison between building locations, the microbial results were regrouped according to proximity to the main road. Sampling sites were classified as near-road buildings (Sites 3, 4, and 5) and far-road buildings (Sites 1, 2, and 6). Differences in microbial composition and abundance between these two groups are summarized based on the data presented in Table 1.

Near-road buildings showed a higher overall abundance of bacterial genera, particularly *Staphylococcus* and *Klebsiella*, compared with far-road buildings. In contrast, far-road buildings exhibited relatively lower bacterial counts but a more consistent presence of fungal genera, especially *Aspergillus*. Across all sampling periods, bacterial genera were dominant in both building groups; however, their abundance was more pronounced in near-road environments.

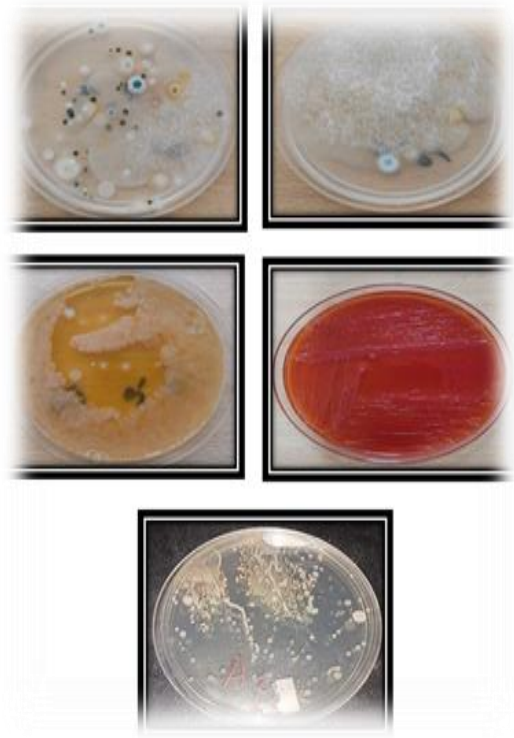


Figure 3. Growth of various bacterial colonies and fungi on different media (Nutrient, MacConkey, blood, and potato dextrose agar)

3.2 Heavy metal concentration profiles

The concentrations of Pb, Cu, and Hg measured across the six locations showed relatively narrow ranges, with noticeable spatial variations between roadside-facing and non-roadside sites.

Lead (Pb) concentrations ranged from 2.3 to 2.6 µg/g across all sites and sampling periods. During the first collection, the highest Pb level was recorded at site 5 (2.6 µg/g), followed by site 4 (2.5 µg/g), both of which are roadside-facing locations. In contrast, non-roadside sites (1, 2, and 6) showed slightly lower and more uniform values (≈ 2.4 µg/g). A similar but slightly reduced pattern was observed in the second collection, where roadside sites still exhibited marginally higher Pb concentrations compared to indoor or less traffic-exposed locations.

Copper (Cu) concentrations exhibited a wider range than Pb, varying from 2 to 2.5 µg/g. In the first collection period, elevated Cu levels were observed at sites 3 and 4 (2.4–2.5 µg/g), while site 5 also showed moderate enrichment. During the second collection, the highest Cu concentration was detected at site 5 (2.5 µg/g), followed by sites 3 and 4 (2.3–2.4 µg/g). Non-roadside locations consistently recorded lower Cu values, indicating a stronger association between Cu

accumulation and roadside exposure.

Mercury (Hg) concentrations ranged from 0.8 to 1.3 µg/g. In the first collection, roadside sites (2 and 5) exhibited slightly higher Hg levels (≈ 1.1–1.2 µg/g) compared with other locations. This trend became more pronounced in the second collection, where site 1 showed the highest Hg value (1.3 µg/g); however, roadside sites (3, 4, and 5) maintained moderate Hg levels relative to non-roadside sites, suggesting both traffic and indoor sources may contribute to Hg presence, as shown in Figure 4.

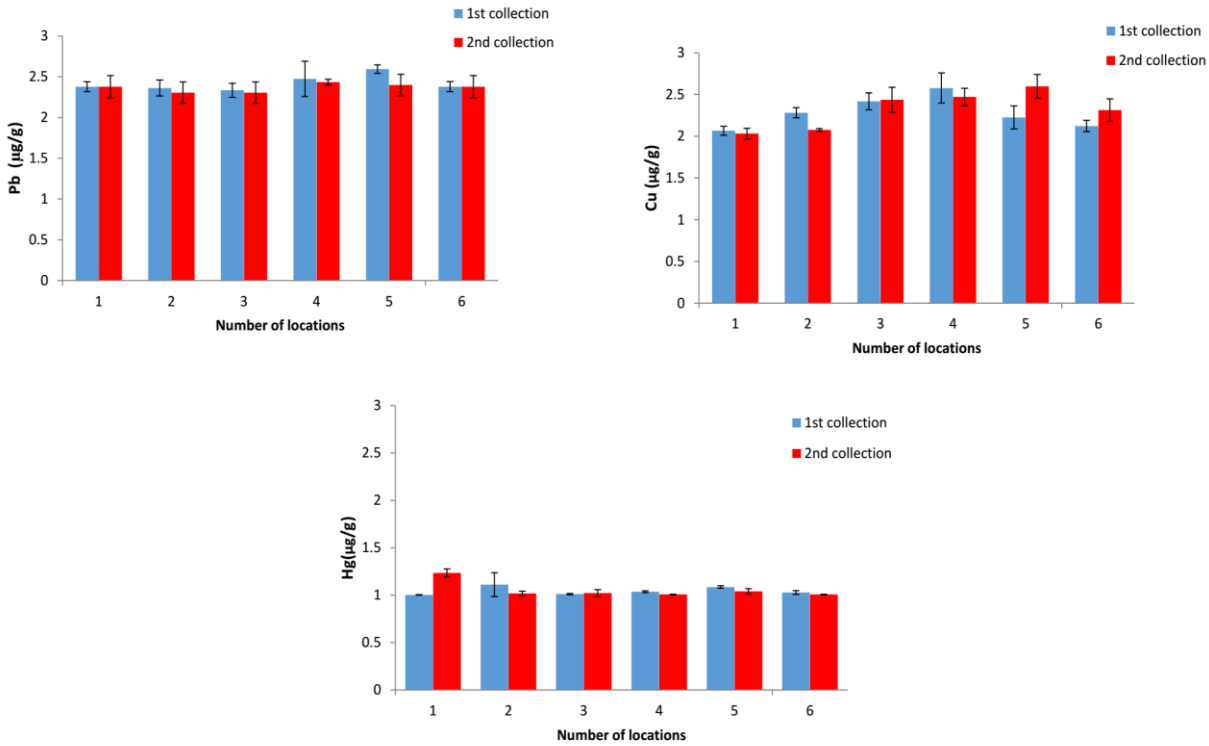


Figure 4. Measurement of heavy metals, Pb, Cu, and Hg in dust

3.3 Health risk assessment

For both collection periods, the HQ values of Pb, Cu, and Hg at all locations were well below unity, indicating no significant non-carcinogenic health risk. The calculated HI values ranged from 3.34×10^{-3} to 4.96×10^{-3}, remaining substantially lower than the safety threshold of 1. Mercury contributed the highest proportion to the HI due to its lower reference dose. The estimated carcinogenic risk (CR) for Pb ranged from 1.91×10^{-8} to 2.16×10^{-8}, which is below the acceptable risk range (10^{-6} – 10^{-4}), suggesting negligible lifetime cancer risk for adult occupants, as shown in Tables 2 and 3.

3.4 Co-occurrence patterns of microbes and heavy metals

The heat map revealed positive co-occurrence patterns between heavy metals such as Pb and Cu and most microbial genera, particularly *Klebsiella* at location 6, whereas Hg exhibited weak and negative associations, indicating a stronger inhibitory effect on microbial distribution in Figure 5.

Table 2. First collection period – HQ, HI, and CR

Loc.	HQ (Pb)	HQ (Cu)	HQ (Hg)	HI	CR (Pb)
1	6.71×10^{-4}	5.10×10^{-5}	2.94×10^{-3}	3.66×10^{-3}	2.00×10^{-8}
2	6.71×10^{-4}	5.60×10^{-5}	3.91×10^{-3}	4.64×10^{-3}	2.00×10^{-8}
3	6.71×10^{-4}	5.90×10^{-5}	2.94×10^{-3}	3.67×10^{-3}	2.00×10^{-8}
4	6.99×10^{-4}	6.10×10^{-5}	2.94×10^{-3}	3.70×10^{-3}	2.08×10^{-8}
5	7.27×10^{-4}	5.40×10^{-5}	3.59×10^{-3}	4.37×10^{-3}	2.16×10^{-8}
6	6.71×10^{-4}	5.10×10^{-5}	2.94×10^{-3}	3.66×10^{-3}	2.00×10^{-8}

Table 3. Second collection period – HQ, HI, and CR

Loc.	HQ (Pb)	HQ (Cu)	HQ (Hg)	HI	*CR (Pb)
1	6.71×10^{-4}	4.60×10^{-5}	4.24×10^{-3}	4.96×10^{-3}	2.00×10^{-8}
2	6.43×10^{-4}	4.20×10^{-5}	2.94×10^{-3}	3.62×10^{-3}	1.91×10^{-8}
3	6.43×10^{-4}	5.90×10^{-5}	2.94×10^{-3}	3.64×10^{-3}	1.91×10^{-8}
4	6.71×10^{-4}	5.60×10^{-5}	2.61×10^{-3}	3.34×10^{-3}	2.00×10^{-8}
5	6.43×10^{-4}	6.10×10^{-5}	2.94×10^{-3}	3.64×10^{-3}	1.91×10^{-8}
6	6.71×10^{-4}	5.40×10^{-5}	2.94×10^{-3}	3.66×10^{-3}	2.00×10^{-8}

Carcinogenic risk (CR) was estimated exclusively for Pb because cancer slope factors are not available for Cu and Hg. Therefore, the total carcinogenic risk represents Pb exposure only, whereas the hazard index (HI) accounts for the combined non-carcinogenic risks of Pb, Cu, and Hg.

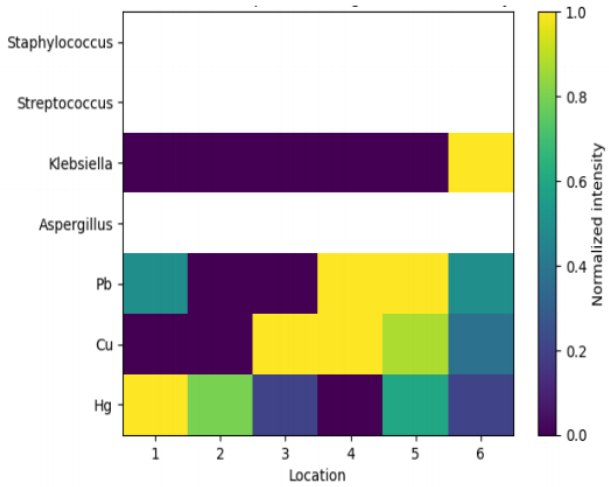


Figure 5. Co-occurrence heat map of microorganisms and heavy metals

3.5 Box plots: Indoor air quality parameters ($PM_{2.5}$, PM_{10}, CO_2)

Particulate matters: $PM_{2.5}$, PM_{10}, and CO_2 concentrations across six indoor locations. CO_2 exhibited the greatest variability, reflecting differences in occupancy and ventilation efficiency, while particulate matter concentrations frequently exceeded WHO guideline limits (Table 4), as illustrates at box plots in Figure 6 and Table 5.

Table 4. WHO air quality guidelines [12]

Air Pollutants	Average Period	AQG (µg/m³)
CO_2 ppm	24 hours	1,000
$PM_{2.5}$ µg/m³	24 hours	15
PM_{10} µg/m³	24 hours	45
Air Pollutants	**Grad**	**Remark**
IAQ	0-50	Good
	51-100	Moderate
	101-150	Unhealthy for sensitive groups
	151-200	Unhealthy
	201-300	Very unhealthy
	301-500	Hazards

Table 5. The average value of CO_2, $PM_{2.5}$, PM_{10} and IAQ in six locations

Locations	CO_2 (ppm)	$PM_{2.5}$ (µg/m³)	PM_{10} (µg/m³)	IAQ
1st Collection				
1	619	27	35	40
2	1368	27	35	38
3	814	24	27	35
4	1181	23	25	31
5	1164	29	36	41
6	2144	28	44	66
2nd Collection				
1	568	16	21	22
2	1126	29	40	38
3	778	26	34	34
4	1120	21	24	30
5	899	25	33	35
6	955	28	38	38

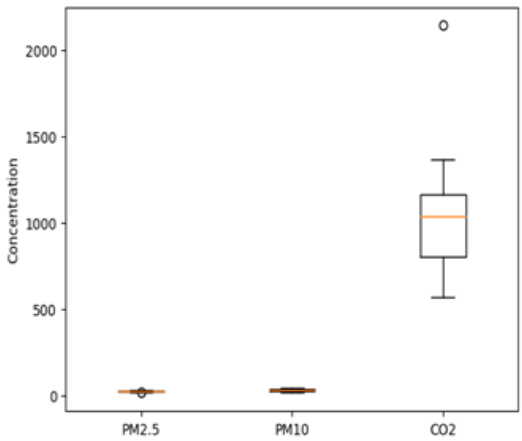


Figure 6. Distribution of indoor air quality (IAQ) parameters (all locations)

3.6 Real-time air quality parameters

The measured concentrations of $PM_{2.5}$, PM_{10}, and CO_2 for all six locations showed a noticeable spatial and temporal variability during both sampling periods. CO_2 levels ranged from 568 to 2144 ppm. Several locations, particularly locations 2, 4, 5, and 6 during the first collection, exceeded the WHO recommended limit of 1000 ppm, with location 6 recording the highest concentration (2144 ppm). In the second collection period, CO_2 concentrations generally decreased; however, locations 2, 4, and 6 still exceeded or approached the guideline value, indicating insufficient ventilation in these indoor environments.

$PM_{2.5}$ concentrations varied between 16 and 29 µg/m³ across all sites. Most locations exceeded the WHO 24-hour guideline value of 15 µg/m³, particularly during the first collection period, where all sites recorded values above the recommended limit. Although a slight reduction was observed in the second collection, $PM_{2.5}$ levels at several locations (notably 2, 3, 5, and 6) remained above WHO guidelines, suggesting persistent fine particulate pollution indoors.

Similarly, PM_{10} concentrations ranged from 21 to 44 µg/m³. During the first collection, PM_{10} levels at locations 1, 2, 5, and 6 approached or exceeded the WHO guideline value of 45 µg/m³, with location 6 showing the highest concentration. In the second collection period, PM_{10} concentrations generally declined but remained elevated at several locations, particularly 2, 5, and 6, indicating continued exposure to coarse particulate matter, as shown in Tables 4 and 5.

3.7 Ventilation efficiency assessment

Calculated air supply with fixed target 8 ACH values for the six investigated locations equipped with split air-conditioning systems. Measurements were conducted for three different office sizes as presented in Table 6:

- The first office size: (2.5 × 4 × 3 m³), air supply values 240 m³/h.
- The second office size: (4 × 6 × 3 m³), air supply values 576 m³/h.
- The third office size: (5 × 9 × 3.5 m), the air supply values 1260 m³/h.

Across all locations and room sizes, measurable air supply values were registered, with higher required values observed in larger rooms and lower values in smaller rooms.

Table 6. The air supply in six locations

Office Size (m^3)	ACH	Required Air Supply (m^3/h)
30	8	240
72	8	576
157.5	8	1260

First office size (2.5 × 4 × 3), second office size (4 × 6 × 3), and third office size (5 × 9 × 3.5).

4. DISCUSSION

4.1 Effect of sampling location and floor level

The dust samples, as mentioned before, were obtained from several sites at different locations (ground, first, and second floors), as indicated in Figure 1. Early research pointed out that several factors might affect results, such as the building's architecture [13], or human occupancy capacity and ventilation, which may be crucial factors in micro-organism growth [14] Another investigation explored how the built environment influences the composition of microbial community patterns by using a database platform termed "meta-analysis" that incorporated all potential sources of airborne microorganisms entering the interior environment, such as geography [15].

Furthermore, as stated by Mohammed and Abdulrazzaq [16], certain types of HVAC systems, such as central systems, may act as a contamination accelerator during the COVID-19 pandemic when compared to systems that simply use fan coil units. As a result of temperature changes and humidity differences, heat and ventilation air-conditioning systems are regarded as one of the encouraging elements that contribute to the formation of a suitable habitat for the growth of bacterial and fungal communities [17].

Additional research indicated that outside elements, such as landscape and building design, had a direct impact on the structure of the indoor microbial community [18]. Consequently, measuring the presence of microbial communities in the indoor environment may indicate people's health status and the stability of their communities (Figure 7).

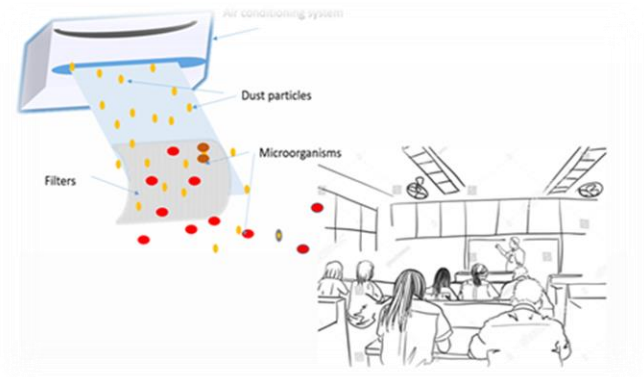


Figure 7. Illustration of an air conditioning (AC) system spreading dust and microorganisms in the indoor environment [19]

4.2 Microbial community composition in AC filter dust

Analysis of results of samples from all six locations for microbial community species revealed that the most common genera in the dust of AC filters were Streptococcus, Staphylococcus, and *Klebsiella* as bacterial species and *Aspergillus* as a fungal species, as shown in Table 1 and Figure 3.

Bacterial genera are more frequent than fungal species on the dust of air conditioner filters, as shown in Figures 3, 4, 5, and 6. These findings highlighted that bacteria prefer high temperatures and low humidity in contrast to the presence of fungi, according to Lv et al. [20]. Identification of microorganisms on dust samples was analyzed; four major microbe genera were identified as *Aspergillus*, a fungal species, and *Streptococcus*, *Staphylococcus*, and *Klebsiella* as bacterial species. The analysis results for the 1st period collection showed that *Staphylococcus* and *Streptococcus* were both found in most locations, except for *Klebsiella,* which was only present in location number 6.

In the 2nd period collection of samples, *Staphylococcus* was not identified in locations 2 and 5, while *Streptococcus* was not identified in locations 1, 4, and 6. Furthermore, *Klebsiella* was only recognized in two locations, 1 and 4, because these species are considered common microbial communities found in indoor environments [21, 22]. Furthermore, Staphylococcus and Streptococcus were spread in most locations due to their existence on and transmission to the surfaces of the indoor environment, in addition to their presence in the nasal cavity [21]. And according to Liang et al. [23], although it is found in various environments of water, soil, and wood dust, it infects humans and animals with a significant pathogen, with particular populations like the elderly, newborns, and people with low immune responses being more susceptible to its infections. Plus, woodworkers who are exposed to wood dust contaminated with *Klebsiella* may experience allergic or immune-toxic symptoms [24]. Also, this study's findings are consistent with Liu et al. [25]. Meanwhile, the *Aspergillus* genus was found in all locations for both collections, as shown in Table 1 and Figure 3.

Because of the climate during the collection period, suitable humidity and temperature. These findings are similar to the results of Allen and Ibrahim [17], who reported that *Aspergillus* appeared in the most samples. So, the distribution of the *Aspergillus* genus in all collected samples indicates biological pollution, which may induce chronic allergy and fatal infection of the upper respiratory system, as mentioned by Eidem et al. [26]. Therefore, the presence of these microorganisms on AC filters could be harmful to the health of the room's occupants [25, 27].

Other researchers claimed various reasons for the appearance and increase in the population of microorganisms. For instance, it increases them during summer and autumn seasons, particularly in outdoor air, due to a variety of conditions that influence their survival, including humidity, the presence of carbon monoxide (CO), and ozone gas [16], while Prussin and Marr [28] admitted that eight sources, including humans, pets, plants, plumbing systems, heating, ventilation, and air-conditioning (HVAC) systems, mold, resuspension of settled dust, and outdoor air, affect airborne microorganisms. Humans are considered to be the main source of bioaerosols in the built environment, carrying between 10^{12} and 10^{14} microorganisms on their skin and in their digestive tract [28]. Specifically, in heavily occupied and poorly ventilated areas [18].

4.3 Heavy metal concentrations in filter dust

Heavy metals play a key role in the environment because of their toxicity, long-term presence in the atmosphere, and

capacity to accumulate in organisms and humans. According to the United States Environmental Protection Agency (USEPA) and the International Agency for Research on Cancer (IARC), stated that heavy metals are also classified as probable elements or compounds included in carcinogenic agents to humans based on experimental studies that demonstrated a link between exposure and cancer occurrence in humans and animals [9]. Also, merging the heavy metals with other components in the environment, such as water, soil, and air, will be more hazardous or lethal to living organisms when immediately exposed via skin or inhaling them to enter the respiratory system or by the digestive system through the food chain [29, 30].

In the 1st collection, concentrations of lead (Pb) were the lowest in location 3 and the highest value in location 5. Meanwhile, in the 2nd collection, the minimum concentration was in location 2, and the highest concentration was recorded at locations 4 and 5.

Copper measurement findings revealed that the lowest concentrations (2 µg/g) were found in location 1 at the 1st and 2nd collection, and the highest value (2.6 and 2.7 µg/g) was found in both positions 4 and 5, respectively, at the 1st and 2nd collection. Mercury concentrations recorded the lowest value in site 1 and the highest in location 2 at 1st collection. Whereas, in the 2nd collection, most concentrations were lowered, except location 1, which was increased and recorded the highest concentration (1.3 µg/g) due to the location of the building.

The two buildings with numbers (1, 2, and 6) have sideways entrances, therefore most of the lower concentrations were indicated in theses building. Therefore, location and design had a significant impact on increasing pollution inside the building environment [31]. However, according to the data above, the buildings with numbers (3, 4, and 5) in Figure 1 had the highest concentrations, most likely because their entrance location faces Al-Zubair Street, which is considered a main street in the city and has numerous vehicles daily. Additionally, the discharge of the Oil Refinery Company into the air in the south of Basra is the main contributor of air pollutants such as heavy metals and particle matter that can travel over large distances. However, the values of this study were much lower compared with the study by Dahlawi et al. [32].

Therefore, IAQ can be assessed by collecting dust samples, and several procedures (such as settled dust and short-term air sampling) [33, 34]. Consequently, the efficiency and flow air rate considered primary elements of spreading "bio-aerosols" (microbes and dust) downstream of the filter to settle in the space of rooms, besides the fraction of dust particles that pass through filters, have significantly modified the number of bio-aerosols [35]. Likewise, other researchers demonstrated that smaller particles of dust have a larger active area and are more effective at attracting trace metals [26]. All of these variables should be considered when examining the impact of microbes and heavy metals on health issues.

4.4 Health risk assessment of heavy metals (HQ and HI)

The calculated HQ and HI values for Pb, Cu, and Hg across all locations were significantly lower than unity, indicating negligible non-carcinogenic health risk for adult occupants. These results are in agreement with recent assessments of indoor and urban dust exposure, which similarly reported low HI values under standard USEPA exposure assumptions [9]. Although Pb exhibited higher mass concentrations, Hg accounted for the dominant contribution to the total HI due to its lower reference dose, consistent with findings reported by Hammood et al. [36]. Furthermore, the calculated carcinogenic risk for Pb remained well below the acceptable risk range recommended by USEPA, confirming minimal lifetime cancer risk. These findings demonstrate that, while heavy metals are detectable in indoor dust, their associated health risks in office environments remain low when evaluated using conservative exposure parameters.

4.5 The potential interactions between microorganisms and heavy metals

The co-existence of heavy metals and particular microbial taxa indicates a potential relationship, as illustrated in Figure 5; further investigation is definitely required about metal resistance genes or microbial adaptation mechanisms. However, metal-resistant bacteria or fungi might be favored through increasing concentrations of heavy metals such as Cu and Hg, which may put indoor microbial communities under selective pressure [37]. According to Zhao et al. [38], a number of bacterial taxa, such as *Staphylococcus* and *Klebsiella*, have resistance mechanisms like forming biofilm and detoxifying enzymes, enabling their persistence in environments contaminated with metals. Another research states that these bacteria are commonly found in areas with high concentrations of heavy metals, which could be indicated as a response of adaptation to environmental stress [39]. In contrast, sensitive microbial species may be inhibited or modify the community structure under such circumstances [40].

4.6 Potential exposure pathways from contaminated AC filters

Indoor residents could be exposed to contaminants such as heavy metals and microbes by AC filters due to accumulated dust particles and related pollutants, or perhaps by being re-suspended and carried into indoor air to be breathed and deposited in the respiratory system during the operation of the system [41]. Furthermore, the increase in the concentration of CO_2 fine dust particles ($PM_{2.5}$ and PM_{10}), in Figure 6, is dangerous because they can carry both heavy metals and germs to enter deeply into the lungs; with long-term exposure, health hazards will be raised, especially in crowded or ineffectively ventilated indoor spaces. For instance, students, employees, the elderly, and people with debilitated immune systems, who spend most of their time indoors, are examples of vulnerable groups that may be more susceptible to respiratory infections or harmful effects [42].

4.7 Indoor air quality implications and ventilation requirements

The results were compared with the WHO air quality guidelines, as shown in Tables 4 and 5, and the calculation of air supply in different locations is shown in Table 6. The air supply values vary between locations because of the different of rooms size in all locations. Select three types of office sizes first (2.5 × 4 × 3), second (4 × 6 × 3), and third (5 × 9 × 3.5) with a stable of ACH. An air change rate of 8 ACH was selected to represent enhanced ventilation conditions suitable for office environments with prolonged occupancy. This

ventilation level is effective in diluting metabolically generated carbon dioxide (CO_2), maintaining indoor concentrations below commonly recommended thresholds (≤ 1000 ppm), which are associated with improved occupant comfort, cognitive performance, and reduced health complaints. Since split air-conditioning systems primarily recirculate indoor air and do not supply outdoor air, the calculated air supply values represent the required fresh air ventilation rates needed to achieve adequate CO_2 control. Higher room volumes necessitate substantially greater ventilation rates to prevent CO_2 accumulation, particularly in larger offices with continuous occupancy [43].

5. CONCLUSIONS AND RECOMMENDATIONS

Detection of microorganisms and heavy metals in accumulated dust on AC filters highlights how these elements work together to influence the quality of indoor air and possibly pose human health risks. As markers of indoor air hygiene, the indoor environmental conditions may contain species with pathogenic or allergic potential. At the same time, recorded levels of heavy metals like Pb, Cu, and Hg in dust on AC filter systems are capable of collecting metal-containing particulate matter from both interior activities and exterior penetration. The simultaneous presence of both contaminants in AC filter dust indicates a potential relationship between microbial abundance and heavy metal concentrations. Variance in pollutant levels among locations is due to several conditions, such as air change rates, occupancy density, filter condition, and ventilation performance. Plus, microbial activity is able to change metal speciation and retention on particles that affect microbial viability.

Therefore, their integrated co-occurrence should be taken into account for IAQ assessments. Increasing ventilation efficiency, specifically the air supply, plays a crucial role in decreasing the accumulation of pollutants. Insufficient air supply loads higher pollutants on filters and increases the risk of exposure, particularly in crowded, unventilated spaces. Consequently, accurate and regular calculations to verify air supply based on room volume, occupancy patterns, and system capacity are necessary. Also, filters with higher particulate capture efficiency and elevated microbial counts or heavy metal levels (e.g., appropriate MERV ratings) should be used for crowded room occupants. Following these recommendations may enhance the health assessment and elevate the comfort of occupancy in mechanically unventilated areas.

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