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Indoor Air Quality in Charcoal-Grilling Restaurants of Baghdad: Short-Term Monitoring of $PM_{2.5}$, PM_{10}, CO_2, and CO

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ABSTRACT

This study investigates the levels of gaseous and particulate pollutants ($PM_{2.5}$, PM_{10}, CO, and CO_2) emitted during charcoal-grilling activities in five selected restaurants in the Al-Karkh district of Baghdad, with a focus on their environmental and health implications. Developing countries, including Iraq, face severe pollution-related challenges exacerbated by inefficient combustion processes inherent to traditional cooking practices. Restaurants that rely on charcoal grilling are a significant source of both indoor and outdoor air pollution, posing acute and chronic health risks to workers and patrons. This research documented measured amounts of pollutants released from burning coal using two types of particulate matter ($PM_{2.5}$; PM_{10}) by checking each sample for the amount present during specific times (both day and night) over nine workdays in December 2024. Data indicate that very often, $PM_{2.5}$ and PM_{10} measurements are substantially greater than the 24-hour guideline values set by both the World Health Organization (WHO) and the US Environmental Protection Agency (US EPA) -- especially on evening peak hours, with maximums of 211 µg/m³ and 212.8 µg/m³, respectively. Carbon dioxide levels were found to be well over 900 parts per million (ppm) at most of the sites checked, indicating very poor air quality from insufficient ventilation, and carbon monoxide (CO) levels were consistently over 35 ppm and as high as 83.0 ppm at night -- which can lead to headaches, dizziness, problems with thinking/working, and if exposed to this for an extended time, heart disease. Temperature and relative humidity were both found to be in a thermally good zone; however, relative humidity was found to be 60 percent or more, which adds to increased health problems associated with the pollutants from burning coal, due to a much higher risk of growth of microorganisms. The researchers believe that there is a critical need to put in place effective pollution control measures; that high-efficiency exhaust systems need to be put in place; and there should be a collaborative effort by governmental bodies and restaurant owners to develop strong, enforceable policies for regulating emissions from burning coal and protecting public health in the food-service sector of Baghdad.

1. INTRODUCTION

Urban air quality is an important public health issue, with much of the literature analyzing emissions from industrial sources and vehicle exhaust. Recent literature indicates that non-traditional and often under-regulated sources of air pollution contribute significantly to the deterioration of air quality. Charcoal-grilling restaurants in the city of Baghdad illustrate one of these types of sources and produce substantial but largely unquantified emissions of gaseous and particulate pollutants, contributing to poor indoor air quality (IAQ).

Iraq is also unique in that it is a developing economy with a heavy reliance on charcoal and other solid fuels for commercial cooking and with minimal regulation of emissions from commercial cooking. Iraq has not developed a national regulatory framework related to air quality or emissions from food establishments. There are many cooking establishments in urban areas of Iraq where charcoal grilling is used, and workers at these establishments experience longer-than-average occupational exposure. Because there are no regulations governing IAQ or emissions vented through exhaust stacks, there is a very high health risk to people working in these cooking establishments, yet little evidence shows how severe these health effects will be.

Cooking-related pollution can arise for several reasons: (i) all cooking methods (gas, electric, wood, or charcoal) generate emissions through the thermal decomposition and/or combustion of organic materials; and (ii) these emissions can disperse as an aerosol plume containing both solid and liquid particulate matter (PM) as well as a large and often complex mixture of volatile organic compounds (VOCs). This PM consists largely of organic carbon (OC), elemental carbon

(EC), and complex condensed organic matter [1]. Because many cooking-generated particles have small aerodynamic diameters, they can penetrate deeply into the lungs when inhaled and pose cardiopulmonary health risks, as supported by substantial evidence [2].

The gases emitted during charcoal cooking consist of an array of chemical species, ranging from formaldehyde and acrolein (which are considered hazardous air pollutants, or HAPs) to a full range of volatile organic compounds (VOCs) such as aldehydes and polycyclic aromatic hydrocarbons (PAHs). High concentrations of carbon monoxide (CO) and carbon dioxide (CO_2) are produced by both incomplete and complete combustion of charcoal, respectively [3]. In addition to being listed in the HAPs list, VOCs from charcoal cooking play a significant role in the formation of secondary organic aerosols (SOAs) and ground-level ozone, contributing to the exacerbation of photochemical pollution formed downwind of their point of emission [4]. Charcoal broiling has been shown through numerous source apportionment studies to significantly contribute to urban $PM_{2.5}$ levels, with these emissions being comparable to or even greater than those from diesel-powered vehicles in some densely populated urban areas [5, 6]. Traditional cookstoves that are typical in many developing nations often have a lower thermal efficiency than modern gas-fired units, resulting in disproportionate emissions of these pollutants relative to those from modern gas-fired units [7]. In addition, indoor combustion emissions affect not only workers exposed to combustion-generated pollutants on the job, but also the general population in both household and business settings. Scientific evidence has shown that exposure in the home and at work can lead to significant health outcomes for all individuals who experience it [8, 9].

This growing body of work also demonstrates a clearly less strict regulatory framework in Iraq regarding emissions control from commercial cooking when compared to other industrial sources. Presently, there is no mandatory indoor air quality monitoring, emission limits, or technology standards applied to food-service facilities in Baghdad. As stated in this paper, there exists a significant lack of available quantified data on indoor air quality from charcoal-grilling establishments within this regulatory framework. This study provides the first systematic and multi-pollutant dataset for measuring indoor air quality at charcoal-grilling restaurants in the Al-Karkh district of Baghdad. The specific objectives of this study are: (1) to quantify the concentration of $PM_{2.5}$, PM_{10}, CO_2, and CO in charcoal-grilling restaurants during peak operational hours; (2) to compare the measured values to World Health Organization and U.S. Environmental Protection Agency standards; and (3) to evaluate the potential impact on worker and customer health from lack of effective emission controls.

Several international and government agencies have developed air quality standards for key pollutants. Some of these key agencies include the World Health Organization (WHO), the National Institute of Occupational Safety and Health (NIOSH), and the United States Environmental Protection Agency (US EPA). A summary of the air quality standards for each pollutant is found in Table 1. Please take note of an important discrepancy between the WHO guidelines for carbon dioxide (CO_2) and carbon monoxide (CO). In the corrected table below, it should be noted that the WHO guidelines for CO_2 are provided in parts per million (ppm) versus the previous drafts of this paper, which noted CO_2 in milligrams per cubic meter (mg/m^3); the former are the correct IAQ standards for CO, not CO_2.

Table 1. Indoor air quality standards for key pollutants according to major health organizations [10-12]

Pollutant	WHO Guideline	NIOSH Standard	US EPA Standard
CO_2	1000 ppm (ventilation threshold); no strict exposure limit at typical indoor levels	5,000 ppm (8 h TWA); 3,000 ppm (15 min STEL)	No specific standard; OSHA PEL: 5,000 ppm (8 h)
CO	100 mg/m^3 / 86 ppm (15 min); 35 mg/m^3 / 30 ppm (1 h); 10 mg/m^3 / 8.6 ppm (8 h); 7 mg/m^3 / 6 ppm (24 h)	35 ppm (8 h TWA)	35 ppm (1 h); 9 ppm (8 h)
NO_2	200 μg/m^3 (1 h); 40 μg/m^3 (annual)	1 ppm (15 min STEL)	0.053 ppm (annual mean)
SO_2	500 μg/m^3 (10 min)	2 ppm (8 h); 5 ppm (15 min)	0.5 ppm (3 h); 0.14 ppm (24 h)
$PM_{2.5}$	15 μg/m^3 (24 h); 5 μg/m^3 (annual)	No NIOSH REL established	35 μg/m^3 (24 h); 12 μg/m^3 (annual)
PM_{10}	45 μg/m^3 (24 h)	No NIOSH REL established	150 μg/m^3 (24 h)
Formaldehyde	0.1 ppm (30 min)	0.016 ppm (8 h TWA); 0.1 ppm (15 min)	920 μg/m^3 (8 h)

TWA = time-weighted average; STEL = short-term exposure limit; PEL = permissible exposure limit; REL = recommended exposure limit.

2. MATERIALS AND METHODS

2.1 Study locations

The gaseous pollutant measurements of PM, carbon monoxide (CO), carbon dioxide (CO_2) were examined and corresponding micro-climatic conditions like temperature and relative humidity were obtained from 5 different restaurants ranging from the time frames of December 03 to December 09 with approximately 3 days in between each measuring point (Table 2) located within the Al-Karkh District of Baghdad where most of the food flavourings derive from wood being used for cooking due to the large concentration of restaurants which serve foods cooked using charcoal in this densely populated urban commercial area that is reflective of what is found in most areas within Baghdad's food service industry. All five restaurants rely exclusively on charcoal as the cooking fuel and operate traditional open-flame grilling without mechanical ventilation systems.

2.2 Instrumentation

Three portable multi-sensor instruments were employed to measure the target indicators (Table 3). All instruments were manufactured in China and sourced from the same supplier batch to minimize inter-instrument calibration variability. Prior to the field campaign, the devices were checked on 2 December 2024 (one day before the first sampling event). For the CO_2 meter (KT-600), the instrument was allowed to equilibrate in outdoor ambient air (assumed near-background conditions) before each sampling session, and the zero/baseline reading was verified according to the manufacturer's instructions. For the CO monitor (GX-2009), a fresh-air zero check was performed before each sampling session; where applicable, the instrument's auto-zero function was used after warm-up. A formal span-gas calibration was not performed in the field because certified calibration gases were not available during the campaign; therefore, instrument performance relied on the manufacturer's factory calibration and pre-use verification checks. For the PM monitor (AQ-9901), zero verification was performed by operating the instrument in clean outdoor air after stabilization and confirming a stable low baseline prior to indoor measurements.

Table 2. Study sites with geographic coordinates and facility descriptions

No.	Code	Latitude	Longitude	Restaurant Name / Neighbourhood
1	S1	33°22'20.2"N	44°20'47.4"E	Zamzam Resort & Marina, Al-Kadhimiyah
2	S2	33°21'17.7"N	44°21'09.9"E	Al-Qamar Butchery and Meat Shop, Al-Shaljiya
3	S3	33°21'01.1"N	44°20'29.9"E	Al-Amir Grills and Butchery, Al-Toubji
4	S4	33°20'52.0"N	44°20'32.8"E	Ahbab Ahl Al-Bayt Kebab Restaurant, Ali Al-Saleh
5	S5	33°19'52.0"N	44°20'52.5"E	Ahmed Al-Ruba'i Kebab, Al-Washash

Table 3. Instruments used for measuring gaseous and particulate pollutants

Device Name	Origin	Detection Principle	Parameters Measured
Carbon Dioxide Meter (Model: KT-600)	China	NDIR optical sensor (CO_2); thermistor (T); capacitive (RH)	CO_2 concentration (ppm); Temperature (°C); Relative Humidity (%)
Compound Gas Monitor (Model: GX-2009)	China	Electrochemical cells (CO, H_2S, O_2); catalytic bead (LEL)	CO (ppm); LEL (%); H_2S (ppm); O_2 (%)
Multifunctional Air Quality Detector (Model: AQ-9901)	China	Laser particle counter / optical light-scattering (PM); electrochemical (HCHO); thermistor (T); capacitive (RH)	$PM_{2.5}$ and PM_{10} (µg/m^3); Formaldehyde (mg/m^3); Temperature (°C); Relative Humidity (%)

The nominal sensor specifications reported by the manufacturer were as follows: CO_2 (KT-600): range 400–5,000 ppm, accuracy ± (50 ppm + 5% of reading), response time ≤ 60 s; CO (GX-2009): range 0–500 ppm, accuracy ±5% of reading (or ± 5 ppm, whichever is greater), response time ≤ 30 s; $PM_{2.5}$/PM_{10} (AQ-9901): range 0–999 µg/m^3, resolution 1 µg/m^3, response time ≤ 10 s. The detection principles are as follows: the CO_2 sensor operates on non-dispersive infrared (NDIR) absorption; the CO sensor uses an electrochemical detection cell; and the PM sensor uses laser particle-counting (optical light-scattering). It is acknowledged that consumer-grade optical PM sensors can overestimate mass concentrations under high-humidity conditions or in the presence of cooking aerosols with high liquid-organic content; this limitation is discussed in Section 4.4.

2.3 Air quality assessment protocol

Sampling was conducted at nine measurement dates: December 3, 6, 9, 12, 15, 18, 21, 24, and 27, 2024, yielding nine discrete sampling events with approximately three-day intervals. On each date, two measurement sessions were conducted per restaurant: a morning peak session (corresponding to the busiest morning service period, approximately 09:00–11:00 h) and an evening peak session (corresponding to the busiest dinner service period, approximately 19:00–21:00 h).

Instruments were positioned at a sampling height of 1.25–1.50 m above floor level, in accordance with manufacturer guidelines, representing the breathing zone of standing adults. All instruments were powered on and allowed a stabilization period of no less than 5 minutes prior to recording data, to ensure that all sensors had reached operational equilibrium. Readings were then logged continuously for 30 minutes at each session, and both the maximum (peak) and minimum concentrations observed during that window were recorded. The reported value for each session is the arithmetic mean of the five stations' readings, and individual station values represent the range across the sensor's measurement window. Results are expressed as the mean ± standard error (SE) of the five station measurements recorded on each sampling date. Each restaurant on each sampling date and time period (morning or evening) was treated as one site-session observation; thus, the dataset consisted of repeated measurements across 5 restaurants, 9 dates, and 2 daily sampling periods.

2.4 Statistical analysis

Data were organized by sampling date, restaurant, and time period (morning and evening). Because morning and evening measurements were obtained from the same restaurants on the same sampling dates, these observations were treated as paired repeated measurements. Accordingly, morning–evening differences for each environmental parameter were evaluated using paired comparisons (paired-samples t-test when the normality assumption was considered acceptable, or the Wilcoxon signed-rank test when appropriate). Descriptive statistics, including mean, standard deviation, minimum, and maximum values, were calculated for all measured variables. Temporal and site-related variation was primarily assessed descriptively because the same restaurants were repeatedly measured across multiple dates, and the limited number of restaurants (n = 5) restricts the robustness of formal site-wise inferential comparisons. Therefore, site-level differences were interpreted cautiously, with emphasis placed on descriptive spatial and temporal patterns rather than strong inferential claims. Statistical significance was considered at $p < 0.05$. All analyses were performed using SPSS version 26 (IBM Corp., Armonk, NY, USA).

3. RESULTS

3.1 Fine particulate matter ($PM_{2.5}$)

$PM_{2.5}$ concentrations were elevated at all five stations throughout the study period (Table 4). The data represent the range of individual station readings (minimum–maximum) and the mean ± SE across the five stations for each sampling day and session. All reported ± values are SE of the mean across five stations.

$PM_{2.5}$ concentrations remained consistently elevated across all stations (Table 4). During the morning peak, mean $PM_{2.5}$ values ranged from ranged from 65.2 ± 11.4 µg/m³ (27 Dec) to 133.6 ± 6.98 µg/m³ (6 Dec). All morning values exceeded the WHO 24-h guideline of 15 µg/m³ and the US EPA standard of 35 µg/m³. Evening $PM_{2.5}$ concentrations ranged from 83.8 ± 5.73 µg/m³ (9 Dec) to 211 ± 4.61 µg/m³ (27 Dec), all exceeding both WHO and US EPA limits. The maximum instantaneous $PM_{2.5}$ concentrations recorded at each individual station are summarized in Table 5.

Table 4. Mean ± SE of $PM_{2.5}$, PM_{10}, CO_2, and CO concentrations (five stations) for each sampling day, morning, and evening peak periods

Date	Period	$PM_{2.5}$ (µg/m³)	PM_{10} (µg/m³)	CO_2 (ppm)	CO (ppm)	Temp. (°C)	RH (%)
3 Dec	Morning	90–120 111.4±5.50	153–199 173.8±8.82	845–945 904±17.77	44–51 48.8±1.24	21–22.8 22±0.30	57.8–60.2 58.80±0.43
	Evening	150–181 168.2±5.75	181–237 206.2±9.74	898–1003 959.8±20.58	56–76 70±3.64	20–21.5 20.5±0.26	60–62.6 61.12±0.47
6 Dec	Morning	116–153 133.6±6.98	153–181 167.4±5.76	860–966 925±19.70	47–59 53±2.21	21.2–22.6 21.6±0.25	58.7–60.2 59.88±0.44
	Evening	154–190 173.4±6.14	181–225 203.8±7.98	921–1070 997.4±30.94	65–85 76.2±3.61	20.5–21.3 20.8±0.14	60.4–63.1 61.62±0.47
9 Dec	Morning	63–80 71±3.37	129–155 141.6±5.49	535–810 683±55.49	12–30 20.4±3.47	18.2–19.2 18.8±0.17	60.8–62.1 61.66±0.23
	Evening	71–100 83.8±5.73	138–165 151.4±5.33	594–840 718.4±51.89	21–37 28±2.88	20.1–20.5 20.3±0.12	62.3–63.7 62.96±0.26
12 Dec	Morning	77–93 85±2.98	155–179 166±4.42	848–927 889.6±14.03	42–66 53.2±4.09	21.9–22.4 22.16±0.09	61.3–62.7 62±0.26
	Evening	89–110 99.2±4.02	168–190 177.8±4.18	922–994 964.2±12.33	51–78 62.8±4.78	20.1–20.5 20.3±0.07	62–63.6 62.82±0.29
15 Dec	Morning	76–88 80.4±2.15	152–160 155.6±1.36	835–903 877±11.54	44–59 52.6±2.73	21.2–21.8 21.4±0.10	60.3–61.9 61.18±0.30
	Evening	81–96 87±2.70	159–179 167.6±3.60	867–918 893.4±8.45	50–66 59.4±2.76	20.2–21.1 20.5±0.16	61.2–62.8 62±0.29
18 Dec	Morning	76–84 79.6±1.50	158–187 169.8±5.15	891–953 917±10.77	41–63 53±4.06	22.1–22.5 22.26±0.07	55.3–57.7 56.10±0.44
	Evening	83–106 94.8±4.56	163–194 177.2±5.50	904–982 933.4±13.26	48–69 59±4.19	21.3–22 21.6±0.13	57.1–59.3 58±0.40
21 Dec	Morning	80–85 82±0.94	154–167 160±2.12	866–933 904±11.54	29–49 36.8±3.46	21.7–22.8 22.28±0.19	60.1–61.4 60.80±0.24
	Evening	90–99 95±1.51	169–183 178±2.38	886–950 926±13.01	36–58 43.8±4.04	20.3–21 20.6±0.12	62.8–64.2 63.48±0.25
24 Dec	Morning	95–110 101.8±2.51	162–188 174.2±4.49	974–1013 993.4±6.74	52–82 67.6±3.46	22.3–22.7 22.5±0.07	58–60 59.12±0.33
	Evening	108–131 119±3.97	180–207 189.2±5.00	991–1029 1008±6.49	60–87 74.8±4.84	22–22.3 22.1±0.06	62.4–63.7 62.92±0.23
27 Dec	Morning	33–110 65.2±11.4	89–153 114.2±11.93	412–820 530.2±77.15	8–38 19±5.31	20.2–20.9 20.50±0.12	60.3–61.4 60.74±0.19
	Evening	199–225 211±4.61	187–230 212.8±7.93	1016–1092 1056±13.31	72–95 83±3.97	19–19.8 19.44±0.14	62.4–63.3 62.78±0.15

Values above each mean row show the observed station range (min–max). All ± values are standard errors (SE) of the five-station mean. WHO 24-h guideline: $PM_{2.5} \leq 15$ µg/m³; $PM_{10} \leq 45$ µg/m³. US EPA 24-h standard: $PM_{2.5} \leq 35$ µg/m³; $PM_{10} \leq 150$ µg/m³. CO WHO 1-h limit: 30 ppm. CO_2 ventilation adequacy threshold: 1000 ppm.

Table 5. Maximum instantaneous $PM_{2.5}$ concentrations (µg/m³) recorded at each station during the study period

Station	Max. Morning (µg/m³) (Date)	Max. Evening (µg/m³) (Date)
S1	153 (06 Dec)	225 (27 Dec)
S2	121 (06 Dec)	210 (27 Dec)
S3	133 (06 Dec)	210 (27 Dec)
S4	116 (06 Dec)	199 (27 Dec)
S5	145 (06 Dec)	219 (27 Dec)

3.2 Coarse particulate matter (PM_{10})

PM_{10} concentrations followed a pattern similar to $PM_{2.5}$, with consistently elevated levels across all stations (Table 4). During the morning peak, mean PM_{10} values ranged from 114.2 ± 11.93 µg/m³ (27 Dec) to 174.2 ± 4.49 µg/m³ (24 Dec). Evening PM_{10} concentrations ranged from 151.4 ± 5.33 µg/m³ (9 Dec) to 212.8 ± 7.93 µg/m³ (27 Dec), with all values exceeding both WHO and US EPA reference levels (Table 6).

Table 6. Maximum instantaneous PM_{10} concentrations (µg/m³) recorded at each station

Station	Max. Morning (µg/m³) (Date)	Max. Evening (µg/m³) (Date)
S1	199 (03 Dec)	237 (03 Dec)
S2	177 (03 Dec)	203 (27 Dec)
S3	172 (24 Dec)	210 (27 Dec)
S4	162 (24 Dec)	187 (27 Dec)
S5	185 (03 Dec)	226 (27 Dec)

3.3 Carbon dioxide (CO_2)

CO_2 concentrations exceeded the operationally recommended indoor threshold of 1,000 ppm widely used as a proxy indicator of inadequate ventilation at most stations during evening peak sessions (Table 4). Morning mean CO_2 values ranged from 530.2 ± 77.15 ppm (27 Dec) to 993.4 ± 6.74 ppm (24 Dec). Evening means ranged from 718.4 ± 51.89 ppm (9 Dec) to 1056 ± 13.31 ppm on (27 December). The highest peak concentrations were observed at all stations on 24 December (morning) and 27 December (evening), indicative of a recurring pattern of high-emission events during the busiest pre-holiday period (Table 7).

Table 7. Maximum instantaneous CO_2 concentrations (ppm) recorded at each station

Station	Max. Morning (ppm) (Date)	Max. Evening (ppm) (Date)
S1	1013 (24 Dec)	1092 (27 Dec)
S2	984 (24 Dec)	1066 (27 Dec)
S3	995 (24 Dec)	1075 (27 Dec)
S4	974 (24 Dec)	1016 (27 Dec)
S5	1001 (24 Dec)	1083 (27 Dec)

3.4 Carbon monoxide (CO)

CO concentrations exceeded the WHO 1-hour guideline of 30 ppm at the majority of stations during both morning and evening peak periods (Table 4). Morning mean CO values ranged from 19 ± 5.31 ppm (27 Dec) to 67.6 ± 3.46 ppm (24 Dec). Evening means ranged from 28 ± 2.88 ppm (9 Dec) to 83 ± 3.97 ppm (27 Dec). The morning sessions on 9 December and 27 December were the only periods where mean CO approached or briefly fell below guideline values, attributable to the lower cooking intensity and/or intermittent charcoal lighting on those days (Table 8).

Table 8. Maximum instantaneous CO concentrations (ppm) recorded at each station

Station	Max. Morning (ppm) (Date)	Max. Evening (ppm) (Date)
S1	82 (24 Dec)	95 (27 Dec)
S2	61 (24 Dec)	78 (27 Dec)
S3	64 (24 Dec)	82 (27 Dec)
S4	52 (24 Dec)	72 (27 Dec)
S5	79 (24 Dec)	88 (27 Dec)

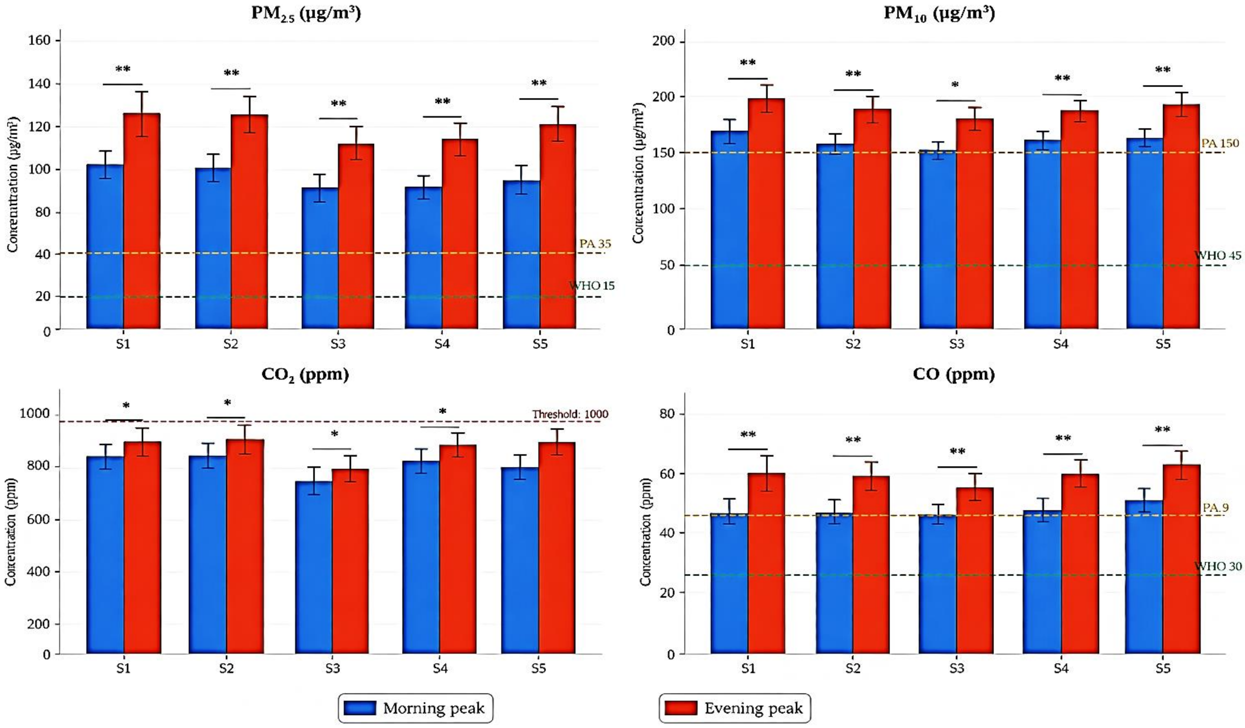

Figure 1. Average pollutant concentrations (mean ± SE) at five monitoring stations during morning and evening peak periods, December 2024

Error bars represent ± standard error (SE) across nine sampling days (3–27 December 2024). Dashed reference lines indicate WHO and US EPA guideline values. Statistical significance between morning and evening sessions was evaluated using paired comparisons based on matched site-date observations (paired-samples t-test when assumptions were met, or Wilcoxon signed-rank test when appropriate): * $p < 0.05$; ** $p < 0.01$.

3.5 Temperature and relative humidity

Temperature readings for all indoor sites throughout all sampling days (18.3 to 22.5 °C) were well within ASHRAE Standard 55's recommended range for thermal comfort (18–24 °C) [13]. The amount of variability in temperature read between day and night was small (1 to 3 °C, usually), and within-session variability was low (SE ≤ ±0.30 °C), thus indicating that temperatures remained relatively stable during the study. Temperature parameters indicate that they are conducive to providing a level of thermal comfort and will not present an additional stressor to humans' physiology above and beyond that resulting from exposure to pollutants.

Across the four sessions, the relative humidity was measured to be 56.10% through 63.48%. These values fall well within a human's thermal comfort zone. However, they are consistently at or above the upper end of the relative humidity range (30%-60%) recommended by research [13] and are also at or above the threshold level in research [14], above which the potential for microbial growth (i.e., mold) and dust mites begins to rise. The U.S. Environmental Protection Agency (EPA) also recommends that indoor RH be kept below 60% to reduce the potential for health problems associated with mold. Even though none of the RH values were particularly high, their persistent closeness to and/or exceedance of 60% RH, combined with the extremely high levels of pollution identified, creates an additive effect with regard to the indoor environmental quality and health of individuals who will be exposed to these conditions for long periods of time during a typical workday.

4. DISCUSSION

4.1 Pollution sources and combustion characteristics

The presence of CO, CO_2, $PM_{2.5}$, and PM_{10} at the same time indicates that indoor pollution is a result of combustion processes, including those that take place when cooking with charcoal. Because of this, it was expected that a strong correlation between the different types of pollution would be found; indeed, in this study, the collected source fingerprints at the various locations within this study confirm this. The solid fuel (charcoal) is not as completely burned as other fuels (like propane or natural gas), resulting in a much greater amount of emissions of both CO and PM (and also PAHs), when measured on a per-unit-basis. Charcoal grilling produces a complex aerosol plume consisting of a mixture of particle sizes from very small to much larger than would typically be found with other combustion sources (i.e., gas grilling). The largest particles found in the collection of smoke from charcoal grilling consist primarily of EC and OC, whereas the particles produced by cooking with gas consist almost exclusively of CO_2 and water vapor [1]. Charcoal-cooked fatty meats produce pyrolytic lipids from the cooking processes of frying and broiling, such as acrolein, formaldehyde, and different types of aldehydes, in addition to creating PAHs from partially burned fat drippings on the surface of the charcoal. There are differences between charcoal-cooked fatty meats and gas grills (where gas grill PM emissions are lower, but CO_2 emissions are average). Gas grills also have gases with lower PM compared to wood-burning kitchen stoves; additionally, they have higher CO_2 emission rates than conventional stovetop methods of food preparation, thereby representing combustion sources (fired through wood) of significantly higher CO_2 emissions, resulting in dissimilar PM chemical patterns due to different pyrolitic lignin-derived wood components.

Across all nine sampling days, peak pollutants observed in the evening samples were consistently higher than those observed in the morning samples. The main reasons why evening pollutants are greater than morning pollutants are: (1) increased customer traffic and, therefore, more intensive and longer grilling activity compared to dinner hours; (2) build-up of combustion pollutants in the restaurant's indoor air during the operational day, as it pertains to insufficient ventilation systems to achieve stable PM concentrations; and (3) the average amount of charcoal loaded and re-ignited is generally higher in busier evening periods. The particularly elevated concentrations recorded on 27 December evening ($PM_{2.5}$: 211 µg/m³; CO: 83 ppm) likely reflect the compounding effect of peak pre-holiday demand and sustained charcoal burning with minimal ventilation during a relatively cold December night, when windows and doors would be kept closed. These findings are consistent with Taner et al. [15], who documented similarly elevated $PM_{2.5}$ levels in 14 charcoal-grill restaurants in Turkey, and Kim et al. [16], who identified charcoal barbecue grilling as a primary source of PM_{10} in urban Korean restaurants.

4.2 Health risk implications

The pollutant concentrations documented in this study carry substantial health risk implications, particularly for kitchen staff who are occupationally exposed for six to twelve hours daily. Chronic exposure to $PM_{2.5}$ at the levels documented here—routinely 4–14 times the WHO 24-hour guideline (Figure 1)—is associated with a well-characterized exposure-response relationship for cardiopulmonary outcomes. A dose-response analysis using the WHO's published concentration-response functions for $PM_{2.5}$ suggests that sustained exposure at mean evening values of 100–211 µg/m³ corresponds to substantially elevated risk of developing chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease, and stroke compared to populations exposed at WHO guideline levels. Epidemiological evidence from biomass cooking cohorts indicates a relative risk of COPD approximately 2.4–3.5-fold higher in individuals with chronic solid-fuel cooking smoke exposure compared to those using clean fuels [17]. $PM_{2.5}$ particles—by virtue of their sub-2.5 µm aerodynamic diameter—penetrate the conducting airways and deposit in the alveolar region, where they trigger oxidative stress, pro-inflammatory cytokine release, and endothelial dysfunction [2, 18].

CO concentrations exceeding the WHO 1-hour guideline of 30 ppm were documented on the majority of sampling days at most stations (Figure 1). At the peak evening concentrations observed (83 ppm on 27 December), exposure over a 2-hour dinner service would result in carboxyhemoglobin (COHb) levels sufficient to cause headache, dizziness, fatigue, and impaired cognitive and motor function in otherwise healthy individuals [19]. For kitchen staff exposed across a full evening service, the cumulative CO dose may approach or exceed occupational threshold limit values. Differential exposure between staff—who remain in the kitchen throughout service—and customers—whose exposure duration is typically 30–90 minutes per visit—means that the occupational health risk to restaurant workers is substantially greater than that to patrons, even at identical ambient concentrations. Future studies should characterize this differential exposure using personal monitoring approaches.

The measured CO_2 concentrations in these restaurants should be interpreted primarily as an indicator of ventilation adequacy rather than as evidence of acute CO_2 toxicity at the levels observed in this study. Mean values approaching or modestly exceeding 1,000 ppm, particularly during evening peak periods, indicate insufficient air exchange relative to occupant density and combustion activity. At these concentrations, CO_2 is best viewed as a practical proxy for ventilation performance and pollutant accumulation, rather than an immediate health hazard in itself. Nevertheless, several studies suggest that indoor CO_2 concentrations in the range of approximately 1,000–2,500 ppm may be associated with reduced perceived air quality and measurable decrements in some aspects of cognitive performance in enclosed work environments [20-22]. In the present study, the elevated CO_2

levels therefore support the interpretation that ventilation was inadequate to effectively dilute co-emitted combustion pollutants such as PM and CO, thereby indirectly increasing occupational exposure risk for restaurant staff.

4.3 Thermal environment and compounding factors

All five stations had an acceptable indoor thermal rating according to ASHRAE Standard 55 (18-24 °C), with temperatures ranging from 18.3 °C to 22.5 °C. However, all five stations had a mean RH at or above 60%, creating a latent risk; according to both the US EPA [12] and the WHO [14] guidelines, this is indicative of a potential threshold for microbial proliferation (mould, dust mite activity, etc.). While the current values are not extremely high, they persistently exceed the 60% threshold and, combined with an already contaminated air environment, create conditions favourable for condensation of moisture on surfaces and the potential for biological growth on building materials and ventilation components. This will further degrade indoor air quality beyond what would be expected due to the combustion products that could be directly measured. Therefore, active humidity control measures (e.g., mechanical dehumidification, improved air exchanges) are recommended to lower the relative humidity to a range of 50-55%.

4.4 Limitations

There are a number of methodological limitations to this study that need to be recognized. First, the portable optical PM sensors used in the current study provided both high temporal resolution and practicality for operation; however, there is the potential for PM mass concentrations to be overestimated, particularly in environments with a high liquid-organic aerosol content (such as cooking oil mist). Conversely, particle density and optical properties are assumed to be standardized in the light-scattering algorithm. The absence of cross-validation with gravimetric (filter-based) reference methods was another limitation of this study, but it remains a priority for future studies. Second, the sampling period consisted of only December 2024 (a single month in the colder climate of the study area), and therefore, the possibility for seasonal variability of ventilation behaviours (such as more open-window ventilation in the summer months) could greatly affect the IAQ within the various seasons. Third, a limitation of the present study is that repeated observations were collected from a relatively small number of restaurants (n = 5) across multiple dates. Accordingly, while temporal and spatial patterns were evident, site-level inferential comparisons should be interpreted cautiously and are best considered indicative rather than definitive. Finally, personal monitoring of individual workers' exposure was not conducted. The area concentration estimates reported in this study are not equivalent to personal doses but provide an estimate of the area concentration at the worker location within the sampled area. Additionally, these limitations must also be considered before future studies can be truly robust.

5. CONCLUSIONS

This research has created a comprehensive multi-pollutant dataset regarding indoor air quality (IAQ), from charcoal-grilling restaurants located in the Al-Karkh district of Baghdad during normative peak operating hours, administering chronic and significant IAQ safety issues during operational peak hours, as well as in December 2024. In particular, the levels of PM size ≤ 2.5 and size ≤ 10 exceeded the WHO and US EPA AQI guidelines for most sampling days, and evening peak $PM_{2.5}$ concentrations reached as high as 14× the WHO 24-h contaminant for that pollutant. CO_2 levels frequently approached or modestly exceeded the commonly used 1,000 ppm ventilation indicator during peak evening periods, suggesting inadequate air exchange and poor dilution of combustion-related pollutants. Temperature levels were typically satisfactory; however, relative humidity levels consistently exceeded the comfortable limits associated with microbial risk; this serves to further degrade overall indoor environmental quality.

The results highlight that it is essential to take immediate action on both regulatory and technical levels. On the technical side, installing the proper high-efficiency mechanical exhaust ventilation systems that are appropriately sized for the combustion loads associated with charcoal grilling is the most significant action available. Additionally, air pollution control devices such as electrostatic precipitators or high-efficiency filtration hoods installed at the source should be a priority. On the regulatory side, Iraq, specifically Baghdad, needs to establish and enforce mandatory IAQ standards for commercial food establishments and conduct regular inspections of those establishments, similar to how other jurisdictions have done it. It is critical that health and environmental authorities work together with restaurant owners to create abatement pathways for compliance that are both attainable and economically feasible.

Additional research should be conducted to evaluate seasonal variations of IAQ within Baghdad restaurants, utilize gravimetric PM validation, include personal exposure monitoring of kitchen employees, and extend chemical characterization to include PAHs, VOCs, and formaldehyde. Finally, a complete health risk assessment using exposure-response functions for documented pollutants and taking into account that culinary employees have different exposure than patrons should be developed as a priority.

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