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The Health Impact of Workers' Exposure to Particulate Matter ($PM_{2.5}$, PM_{10}) and Gaseous Pollutants (CO_2, CO, NO_2, SO_2) Emitted from Barbecue Grills in Some Restaurants in Al-Rusafa District/Baghdad

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ABSTRACT

This study aimed to evaluate the health effects of exposure to particulate matter ($PM_{2.5}$ and PM_{10}) and gaseous pollutants, including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), on the hematological parameters of workers exposed to charcoal grilling emissions in restaurants. Air pollutant concentrations were measured in six barbecue restaurants located in Al-Rusafa District, Baghdad, during December 2024 and January 2025. Nine measurements were recorded monthly during morning and evening peak cooking periods. Blood samples were collected from two groups: grilling workers exposed directly to charcoal smoke (n = 30) and customers from dining areas as the control group (n = 30). Hematological analyses included white blood cells (WBC), red blood cells (RBC), hemoglobin (HGB), hematocrit (HCT), platelets (PLT), and other blood indices. Statistical analyses were performed using independent t-tests and stepwise multiple linear regression analysis. The results showed that pollutant concentrations were consistently higher in grilling areas than in dining areas, especially during evening hours, due to intensive cooking activity and insufficient ventilation. $PM_{2.5}$ and PM_{10} concentrations frequently exceeded World Health Organization (WHO) permissible limits in grilling areas, while CO, NO_2, and SO_2 also reached elevated levels. Significant increases ($p \leq 0.05$) were observed in WBC, RBC, HGB, HCT, mean corpuscular volume (MCV), and PLT among exposed workers compared with the control group. Stepwise regression analysis demonstrated that CO_2 was positively associated with WBC, HGB, RBC, MCV, and PLT, whereas PM_{10} and $PM_{2.5}$ showed negative associations with several hematological parameters after adjustment for co-pollutants. These findings suggest that chronic exposure to indoor air pollutants generated from charcoal grilling may induce systemic inflammation, oxidative stress, and physiological adaptation to hypoxic conditions among restaurant workers.

1. INTRODUCTION

The complexity of environmental issues presents a global challenge for humanity. Both developing and modern societies are increasingly concerned about global environmental problems, particularly pollution, which has become a multifaceted issue that extends beyond health implications. Grilling processes consume a significant amount of energy worldwide, especially in developing nations [1, 2]. Restaurants, as major cooking hubs, draw large crowds, increasing exposure to harmful fumes and gases emitted during cooking. These emissions pose risks to workers and contribute to outdoor air pollution [3]. Barbecue restaurants primarily use charcoal, wood, and biomass [4], which release substantial amounts of greenhouse gases daily due to incomplete combustion [5]. Charcoal is particularly popular worldwide for its cost-effectiveness, high calorific value, and ability to impart distinctive flavors [6]. Recent studies have highlighted emissions from cooking and grilling in densely populated urban areas, where many restaurants operate close to residential neighborhoods [7]. The composition and quantity of pollutants depend on cooking methods, materials, and fuel combustion [8].

The combustion of coal generates considerable amounts of particulate matter ($PM_{2.5}$, PM_{10}), carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2), with peak concentrations occurring during the addition of coal, as well as during high-power and low-power cooking phases [9]. Elevated levels of pollutants in enclosed spaces worsen air quality, often exceeding international standards and endangering both workers and patrons [10]. Gaseous pollutants such as CO_2, CO, NO_2, and SO_2 can increase blood parameters like white blood cells (WBC), red blood cells (RBC), hemoglobin (HGB), and platelets (PLT). This elevation can raise the risk of cardiovascular and hematological disorders [11]. Additionally, particulate matter ($PM_{2.5}$, PM_{10}) has a direct effect on HGB, hematocrit (HCT), mean corpuscular volume (MCV), and PLT, while decreasing

mean corpuscular hemoglobin concentration (MCHC). These changes can exacerbate respiratory and circulatory diseases [12]. Although some studies have examined the effects of cooking emissions on indoor environments in both developed and developing countries [13], there is a lack of data regarding the health impacts on exposed workers. This study aims to fill that gap by analyzing the health effects of restaurant emissions on workers in Baghdad, a densely populated city in a developing nation.

Despite increasing concerns about indoor air pollution, limited studies have investigated the hematological effects of pollutants emitted from charcoal barbecue grills on restaurant workers, particularly in developing urban environments such as Iraq. Most previous studies focused on outdoor pollution or residential biomass exposure rather than occupational exposure inside poorly ventilated restaurants. Therefore, this study aimed to evaluate the relationship between indoor air pollutants generated from charcoal grilling and hematological changes among restaurant workers in Baghdad city.

The study aimed to evaluate the impact of indoor air pollution (particularly in grilling restaurants) on workers in grilling areas compared to dining areas, while analyzing air pollutant levels and their relationship to changes in blood parameters. It also seeks to guide restaurant owners in implementing preventive measures to mitigate pollutants and reduce associated environmental risks.

2. MATERIALS AND METHODS

This current study included thirty men working in six restaurants (exposed to pollution), and thirty men who were customers (not exposed to pollution) from the same six restaurants studied (the control group) to determine the health impact of particulate matter and gaseous pollutants. All of them were from Baghdad, the Al-Rusafa side, which is characterized by a dense population and a popular character. They were divided into 6 local groups that included: 5 restaurant workers (exposed) from each of the six restaurants studied (6 sites), and 5 customers (not exposed) from the same six restaurants studied. The ages of the groups under study ranged from 30 to 40 years.

2.1 Description of study sites

The study was conducted for a period of two months, from December 1, 2024, to January 31, 2025, to study the impact of gaseous pollutants and particulate matter on workers (exposed) in restaurants. The restaurants are located in 6 sites as follows:

1. **Site (1)**: Ur neighborhood, main street, according to the following geographical coordinates: 33°24'23.01"N, 44°25'23.32"E.
2. **Site (2)**: Sadr City, main street of Sector 57, according to the following geographical coordinates: 33°22'36.87"N, 44°26'37.08"E.
3. **Site (3)**: Al-Obaidy neighborhood, near Al- Alalawy mosque, according to the following geographical coordinates: 33°22'10.09"N, 44°30'43.92" E.
4. **Site (4)**: Al-Baladiyat neighborhood, main street, according to the following geographical coordinates: 33°20'26.19"N, 44°29'1.93"E.
5. **Site (5)**: Al-Ameen neighborhood, Al-Ameen Square, according to the following geographical coordinates: 33°18'49.35"N, 44°30'6.12"E.
6. **Site (6)**: Al-Zaafaraniya neighborhood, Al-Zaafaraniya's square, according to the following geographical coordinates: 33°15'52.45"N, 44°28'55.80" E.

2.2 Scientific devices and laboratory supplies

Measuring the indicators used in the study of polluting parameters ($PM_{2.5}$, PM_{10}, CO_2, CO, NO_2, SO_2), collecting blood specimens and transporting them to the laboratory, was done using the following scientific devices and laboratory supplies, as in Table 1.

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/m³, resolution 1 μg/m³, 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.

Table 1. Scientific devices and laboratory supplies are used to measure study indicators

Devices and Supplies Name	Origin	Indication
GM8804-Particulate Matter Meter	CHINA	Measures particulate matter ($PM_{2.5}$, PM_{10}), temperature, and relative humidity, as it contains five fixed sensors
GM8802-Carbon Dioxide Meter	CHINA	Measures CO_2 concentration, temperature, and relative humidity, as it contains three fixed sensors
Compound Gas Monitor	CHINA	Measures CO concentration, as it contains four fixed sensors
Micro IV	GERMAN	Measures NO_2 and SO_2 concentrations, as it contains two non-fixed sensors
Cool Box	CHINA	Preserving blood samples when transporting them to the laboratory
Sterile Medical Syringes (5 ml)	IRAQ	To draw blood samples from people under study
Surgical Plaster	India	Sterilize the place where blood was drawn
Potassium Ethylenediaminetetraacetic Acid (K_3-EDTA) tubes (5 ml)	JORDAN	To prevent blood samples from clotting during transport to the laboratory

EDTA Tubes Rack	JORDAN	Gently shake the K_3-EDTA tubes to mix the blood with the anticoagulant
CBC Analyzer	HUNGARY	Perform a complete blood count (CBC) on the blood samples studied

Notes: CBC: complete blood count.

2.3 Description of blood sample collection

A total of 60 blood samples were collected during the study. The blood samples were divided into two groups: restaurant workers and customers from the same restaurants studied (the control group), depending on the type of test. All of them were males; workers spent 8 to 12 hours working inside restaurants. Participants included in the study were apparently healthy males aged between 30 and 40 years. Workers had occupational exposure periods ranging from 8 to 12 hours daily and had been employed in grilling restaurants for at least two years. Individuals with known chronic hematological diseases, severe respiratory disorders, or recent infectious illnesses were excluded from the study whenever possible based on self-reported medical history. Information regarding smoking habits and lifestyle factors was limited and considered one of the study's limitations.

2.4 Processing blood samples

A 5 ml blood sample was drawn from the veins of the restaurant workers included in the study and from the control group, using sterile 5 ml medical syringes. 3 ml of blood was placed in the tubes containing the anticoagulant. The tubes containing the blood were gently shaken to mix the blood with the anticoagulant. The samples were transferred to a private laboratory in a cool box to conduct a complete blood count for the samples under study using a CBC analysis device. Among the blood parameters studied were WBC count, absolute lymphocyte count, percentage lymphocyte count, absolute granulocyte count, percentage granulocyte count, RBC count, HGB concentration, HCT, MCV, mean corpuscular hemoglobin (MCH), MCHC, and PLT count.

2.5 Measuring pollution indicators

Particulate matter and gaseous pollutants ($PM_{2.5}$, PM_{10}, CO_2, CO, NO_2, and SO_2) were measured in the current study at each of the six sites (study restaurants) inside the restaurant near the barbecue grill where charcoal is burned, using the devices specific to each pollutant (Table 1). These pollutants were noticed during the afternoon hours (lunch time) and during the evening hours (dinner time), as these hours represent peak times and cooking activity, since these restaurants serve all foods cooked over charcoal. The measuring devices were placed at a height of one and a quarter meters above the ground during the measurement, and a period of 20 to 30 seconds was waited for the sensors of each device to work, according to the instructions of the manufacturing companies, and the measurement period continued at each peak for a full hour. Measurements were conducted during morning and evening peak operating periods to represent the highest expected worker exposure conditions associated with grilling and cooking activities. Pollutant concentrations presented in the study represent averaged values obtained from repeated measurements during the monitoring period. Continuous 24-hour monitoring was not feasible because of operational and equipment limitations; however, repeated measurements were performed monthly to improve exposure representation and data reliability. All monitoring devices were calibrated according to the manufacturer's instructions before field measurements. Functional checks and zero calibration procedures were periodically performed to minimize instrumental errors and improve measurement accuracy during data collection. The estimated measurement uncertainty of the devices was within the acceptable operational range specified by the manufacturers.

The investigated barbecue restaurants mainly used fixed charcoal grilling units located inside semi-closed cooking areas. Ventilation conditions varied among restaurants and included natural ventilation, wall exhaust fans, and limited local exhaust systems. In most locations, smoke generated during grilling accumulated within the cooking area before partial discharge through doors, windows, or ceiling ventilation openings. The grilling workspaces were relatively confined, which may have contributed to increased indoor pollutant concentrations during peak cooking periods.

All monitoring devices were calibrated before each sampling campaign according to the manufacturers' instructions. Functional checks and zero calibration procedures were routinely performed prior to field measurements to minimize instrumental drift and measurement bias. The estimated measurement uncertainty and operational error range for the monitoring devices were within ±5% of the recorded values, as specified by the manufacturers.

2.6 Statistical analysis

Data were processed using R statistical software (version 4.4.2) and analyzed using both descriptive and inferential statistics. One-sample t-tests were used to determine whether mean values of hematological parameters exceeded the upper limit of standard reference ranges. Independent two-sample t-tests compared means between the grilling and dining groups. To assess the independent effects of air pollutants on hematological variables, stepwise multiple linear regression analyses were performed. Each blood parameter was used as a dependent variable, while the concentrations of $PM_{2.5}$, PM_{10}, CO_2, CO, NO_2, and SO_2 served as independent variables. The final models were selected based on statistical significance and adjusted R^2. All p-values ≤ 0.05 were considered statistically significant [14].

3. RESULTS AND DISCUSSION

3.1 Demographic characteristics of participants

Table 2. Demographic characteristics of study participants

Variable	Grilling Workers (n = 30)	Dining Group (n = 30)
Age (years)	35.4 ± 3.2	34.8 ± 2.9
Employment duration (years)	6.8 ± 2.1	5.9 ± 1.8
Smoking (%)	Limited information available	Limited information available
Chronic diseases/comorbidities	No severe chronic diseases reported	No severe chronic diseases reported

Table 2 presents the demographic characteristics of the study participants from grilling and dining groups. Participants in both groups were adult males within a comparable age range. Workers in grilling areas had relatively longer occupational exposure durations because of continuous involvement in grilling and barbecue cooking activities. Information regarding smoking habits and lifestyle factors was limited because complete participant records were not available during data collection, and this limitation was considered in the interpretation of the study findings.

Detailed information regarding smoking habits and lifestyle factors was limited because complete participant records were not available during data collection. This limitation was acknowledged in the study limitations section.

3.2 Integrated assessment of indoor air pollutants in grilling and dining areas

Researchers checked six restaurants for $PM_{2.5}$, PM_{10}, CO_2, CO, NO_2, and SO_2 in the grilling areas and dining rooms. Overall, pollutant levels in grilling areas were always higher than in dining zones, and they also tended to reach their highest point in the evening, especially during January. It illustrates the effect of extra cooking and a lack of ventilation during the busiest times at the restaurants. Many times, the fine particles ($PM_{2.5}$) and coarse particles (PM_{10}) exceeded the World Health Organization's (WHO) guidelines in grilling zones, which seems to link to grilling, especially during evening hours. Evening periods in the grilling area had levels consistently above 800 ppm of CO_2, suggesting there were plenty of people and poor airflow, but the dining area always stayed below that level [15]. In many cases, CO was above the work limit of 35 ppm in the grilling areas, mostly because the campfires did not burn all their fuel [16]. In grilling zones, the SO_2 often went above 0.14 ppm, and it was most noticeable during the evening, as raw coal is the primary source of SO_2 emissions [17]. However, the dining areas never exceeded the limit.

The presence of higher NO_2 levels shows that grilling areas are still being contaminated by pollutants. In St.2, the levels of NO_2 in the air during the grilling periods were higher than usual, and the range went from 0.37 to 1.21 ppm in the morning to a maximum of 1.98 ppm in the evening. Whilst NO_2 in the air during the morning in January was lower (0.24 to 0.48 ppm) than the previous month, evening levels continued to be the same as they had been in December, as reliance on gas, fossil fuels, and coal for cooking and heating releases NO_2 [18, 19]. Conversely, the dining area had NO_2 levels that were low throughout the whole study, and they never went above or close to 0.1 ppm (Tables 3 and 4). Together, the studies show that three major factors have a strong influence on how high indoor pollutants get [20]. Places where the gathering takes place (grilling outside or inside dining), hours of the day (morning or evening), and time of year (late December or early January) are all examples. During evening grilling, NO_2 and CO showed the highest increase of all pollutants, which poses health risks. Continued high levels of these combustion-related pollutants point out how vital enhanced ventilation, proper real-time air testing, and suitable ways to protect people inside are to grilling establishments [21].

Table 3. Mean morning and evening concentrations of $PM_{2.5}$, PM_{10}, and CO_2 in grilling and dining areas across six restaurants compared with WHO guidelines

Sites	$PM_{2.5}$, µg/m³				PM_{10}, µg/m³				CO_2, ppm			
	Grilling		Dining		Grilling		Dining		Grilling		Dining	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
St.1	79.35	118.55	58.055	66.05	148.7	179.7	130.05	140.5	756	892.5	581.5	620.5
St.2	82.75	124.4	61.055	69	154.55	185.55	135.1	144	766	902.5	588	626
St.3	72.3	108.7	53.61	60	142.35	163.55	125.75	133.85	732.5	870.5	568	604
St.4	65.05	98	48.5	56.35	131.5	156.6	119.45	127	711.5	844	556	588.5
St.5	71.25	103.45	53.28	58.75	139.5	161.65	124.15	132.8	739	861.5	571	599
St.6	75.25	113.55	55.275	63.3	144.05	172	127.8	137.1	743	884.5	573.5	610.5
WHO Guideline	75 µg/m³				150 µg/m³				800 ppm			

Note: WHO: World Health Organization.

Table 4. Mean morning and evening concentrations of CO, NO_2, and SO_2 in grilling and dining areas across six restaurants compared with WHO guidelines

Sites	CO, ppm				NO_2, ppm				SO_2, ppm			
	Grilling		Dining		Grilling		Dining		Grilling		Dining	
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
St.1	35.8	55.2	17.775	22.55	0.693	1.722	0.083	0.117	0.1985	0.37	0.0778	0.1111
St.2	38.95	59.55	19.39	24.25	0.843	1.978	0.083	0.117	0.221	0.4335	0.0778	0.1111
St.3	29.15	47.4	14.17	18.15	0.5055	1.233	0.056	0.100	0.147	0.294	0.05555	0.1
St.4	22.45	39.95	8.945	14.85	0.3025	0.756	0.044	0.094	0.119	0.238	0.02775	0.0778
St.5	27.5	42.9	12.225	16.6	0.382	1.033	0.067	0.100	0.1425	0.249	0.03885	0.08335
St.6	31.95	50.85	15.11	20.8	0.6145	1.5	0.072	0.106	0.1815	0.394	0.0667	0.1
WHO Guideline	35 ppm				0.1 ppm				0.14 ppm			

Note: WHO: World Health Organization.

3.3 Assessment of hematological parameters in individuals exposed to indoor air pollutants in grilling vs. dining areas

Table 5 presents the hematological parameters (Mean ± SE) of workers exposed to grilling emissions compared with the dining group. Significant increases ($p \leq 0.05$) were observed in WBC count, lymphocyte count, HGB concentration, RBC count, granulocyte count, and lymphocyte percentage among grilling workers, indicating possible inflammatory and physiological responses associated with prolonged exposure to indoor air pollutants. The results demonstrated that workers in grilling areas exhibited higher hematological values compared

with the dining group. The mean WBC count among grilling workers (11.50 × 10^9/L) exceeded the upper normal reference limit (10 × 10^9/L), suggesting activation of inflammatory or immune responses due to exposure to combustion-related pollutants [22]. Similarly, granulocyte counts and percentages were significantly higher in grilling workers (6.69 × 10^9/L and 65.54%, respectively) compared with the dining group (3.30 × 10^9/L and 55.52%), although these values remained within the normal reference ranges. In addition, red blood cell indices, including RBC count, HGB, HCT, and MCH, were significantly elevated in grilling workers compared with the dining group. The mean HGB concentration in grilling workers (17.13 g/dL) exceeded the upper normal reference value (16 g/dL), which may indicate a compensatory physiological response to reduced oxygen availability associated with exposure to CO and NO_2 [23, 24]. Similar findings were observed for RBC count (5.72 × 10^{12}/L) and HCT values (53.65%), reflecting possible adaptation to chronic exposure conditions.

Likewise, PLT counts in grilling workers reached a mean value of 315.73 × 10^9/L, exceeding the upper normal reference limit (300 × 10^9/L) in several cases and showing significant differences compared with the dining group (160.50 × 10^9/L). These elevations may reflect inflammatory or oxidative stress responses among workers continuously exposed to grilling emissions [25, 26].

Table 5. Mean hematological parameters in grilling and dining area workers compared with reference ranges (Mean ± SE)

Parameter	Grilling Workers (Mean ± SE)	Dining Group (Mean ± SE)	Reference Range	p-Value
WBC (10^9/L)	11.50 ± 0.14	5.15 ± 0.16	4–10	<0.001
Lymph (10^9/L)	4.23 ± 0.05	1.76 ± 0.07	0.8–4	<0.001
HGB (g/dL)	17.13 ± 0.17	12.17 ± 0.08	11–16	<0.001
RBC (10^{12}/L)	5.72 ± 0.06	4.16 ± 0.05	3.5–5.5	<0.001
Gran (10^9/L)	6.69 ± 0.34	3.30 ± 0.16	2–7	<0.001
Lymph (%)	36.11 ± 0.59	27.06 ± 1.22	20–40	<0.001

Notes: WBC: white blood cells; HGB: hemoglobin; RBC: red blood cells.

Table 6 shows additional hematological indices (Mean ± SE) among grilling and dining groups. Significant increases in HCT, MCV, and PLT were detected among workers exposed to grilling emissions, whereas MCHC values showed a relative decrease compared with the dining group. These findings may be associated with oxidative stress, inflammatory responses, and compensatory physiological adaptation to combustion-related pollutants. According to the statistical analysis, exposure to indoor grilling emissions and airborne pollutants, particularly $PM_{2.5}$, CO, NO_2, and SO_2, was associated with most of the hematological differences observed between the two groups ($p \leq 0.05$). These findings suggest that continuous occupational exposure to indoor air pollutants generated during grilling activities may induce measurable biological responses among restaurant workers and may represent a potential occupational health concern [27].

Table 6. Mean hematological parameters in grilling and dining area workers compared with reference ranges (Mean ± SE)

Parameter	Grilling Workers (Mean ± SE)	Dining Group (Mean ± SE)	Reference Range	p-Value
Gran (%)	65.54 ± 2.34	55.52 ± 0.77	50–70	<0.001
HCT (%)	53.65 ± 0.42	38.98 ± 0.16	37–54	<0.001
MCV (fL)	103.25 ± 0.50	90.47 ± 0.39	80–100	<0.001
MCH (pg)	32.92 ± 0.15	30.40 ± 2.15	27–34	<0.001
MCHC (g/dL)	30.98 ± 0.24	33.33 ± 0.28	32–36	<0.001
PLT (10^9/L)	315.73 ± 3.83	160.50 ± 4.16	100–300	<0.001

Notes: HCT: hematocrit; MCV: mean corpuscular volume; MCH: mean corpuscular hemoglobin; MCHC: mean corpuscular hemoglobin concentration; PLT: platelets.

3.4 Stepwise multiple regression analysis and interpretation of hematological responses to air pollutants

Stepwise multiple linear regression analyses were done to see how each indoor air pollutant affects the blood parameters independently. While the first data set consisted of several pollutants—PM_{10}, $PM_{2.5}$, CO_2, CO, NO_2, and SO_2 —the process limited the included predictors in each model to the most significant ones found by the statistics. In all cases, CO_2 plus either PM_{10} or $PM_{2.5}$ was the greatest predictor of pollution. As a result, we think the pollutants were strongly related to the blood parameters and likely contributed greatly to the differences seen, since they may have overlapped or acted similarly with other factors (Table 7).

For the WBC count, the final model included both CO_2 and PM_{10}. CO_2 exhibited a strong positive association ($\beta = 0.033$, $p < 0.001$), while PM_{10} showed an unexpected negative association ($\beta = -0.057$, $p < 0.001$), despite both variables appearing positively associated with WBC in bivariate scatter plots. This apparent contradiction arises from the multivariable nature of the regression model, which adjusts for the shared variance between predictors. In other words, after statistically controlling for CO_2, PM_{10} showed a negative independent effect on WBC. This reversal in the direction of association is a well-known outcome in multiple regression analysis and often reflects multicollinearity or confounding [28]. It suggests that, although PM_{10} might correlate positively with WBC overall, its unique contribution after accounting for the effect of CO_2 may be inhibitory or suppressive [29] (Figure 1).

The negative associations observed for PM_{10} and $PM_{2.5}$ after adjustment for CO_2 may also reflect overlapping exposure patterns among pollutants and potential multicollinearity effects between combustion-related pollutants. Similar statistical behavior has been reported in environmental exposure studies where pollutants originate from the same combustion source. In addition, physiological adaptation, exposure variability, and individual biological responses may contribute to differences in hematological reactions among exposed workers.

Similar patterns were observed in other hematological outcomes. For instance, lymphocyte count was positively

associated with CO_2 ($\beta = 0.016$, $p \leq 0.001$) and negatively with $PM_{2.5}$ ($\beta = -0.038$, $p = 0.001$), with an R^2 of 0.883. This dual pattern suggests that fine particulate matter may suppress lymphocyte proliferation or survival, especially under co-exposure to elevated CO_2 (Figure 2) [30].

Table 7. Stepwise multiple linear regression models for predicting hematological parameters based on indoor pollutant exposure (CO_2, PM_{10}, and $PM_{2.5}$)

Dependent Variable	Indicators	β	t	Sig	R^2	R^2_{adj}
WBC 10^9/L	Constant	-6.612	-5.992	< 0.001	0.951	0.950
	CO_2	0.033	17.364	< 0.001		
	PM_{10}	-0.057	-3.842	< 0.001		
Lymph 10^9/L	(Constant)	-5.624	-10.201	< 0.001	0.883	0.879
	CO_2	0.016	8.739	< 0.001		
	$PM_{2.5}$	-0.038	-3.470	0.001		
HGB g/dL	Constant	2.063	2.521	0.015	0.956	0.955
	CO_2	0.024	17.331	< 0.001		
	PM_{10}	-0.032	-2.881	0.006		
RBC 10^{12}/L	Constant	1.516	3.507	0.001	0.884	0.880
	CO_2	0.008	11.341	< 0.001		
	PM_{10}	-0.017	-2.978	0.004		
MCV fL	Constant	58.972	30.415	< 0.001	0.871	0.869
	CO_2	0.054	19.821	< 0.001		
PLT 10^9/L	Constant	-139.254	-5.418	< 0.001	0.956	0.954
	CO_2	0.788	17.819	< 0.001		

Notes: WBC: white blood cells; HGB: hemoglobin; RBC: red blood cells; MCV: mean corpuscular volume; PLT: platelets.

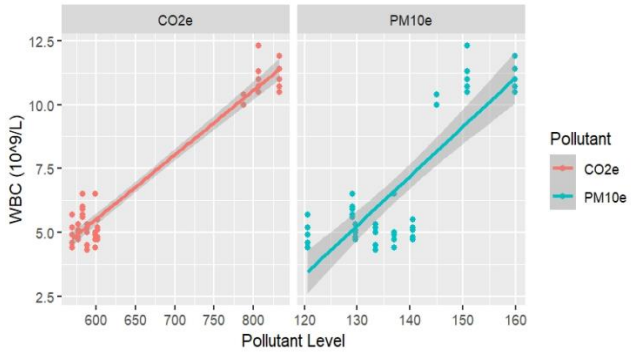

Figure 1. Bivariate relationships between CO_2 and PM_{10} levels and white blood cell (WBC) count

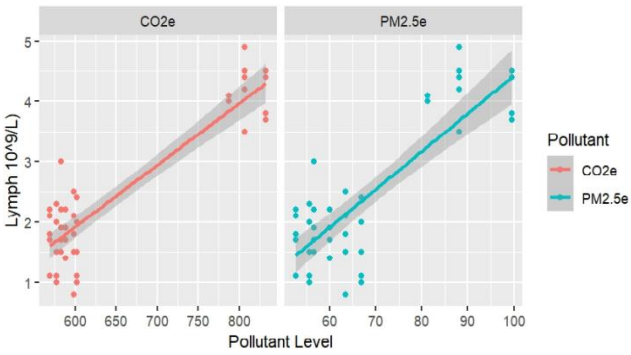

Figure 2. Bivariate relationships between CO_2 and $PM_{2.5}$ levels and white lymphocyte count

While HGB concentration and red blood cell count also demonstrated positive relationships with CO_2 and negative ones with PM_{10}. With R^2 adjusted of (0.995 and 0.880) respectively, indicating that these two pollutants have an important effect on these blood parameters (Figures 3 and 4).

In contrast, MCV was significantly associated with CO_2 only, suggesting a more direct and isolated effect (Figure 5).

PLT count showed one of the strongest relationships, with CO_2 again contributing positively and PM_{10} negatively. Across all models, the adjusted R^2 values were high, ranging from 0.869 to 0.956, indicating strong model fit and robust explanatory power. For these parts pleas discuss each dependent variable separately (Figure 6).

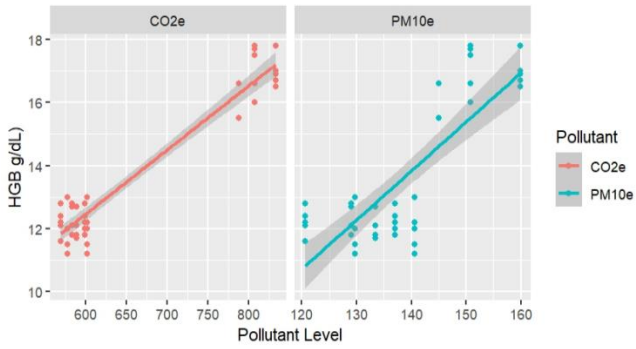

Figure 3. Bivariate relationships between CO_2 and PM_{10} levels and hemoglobin (HGB) concentration

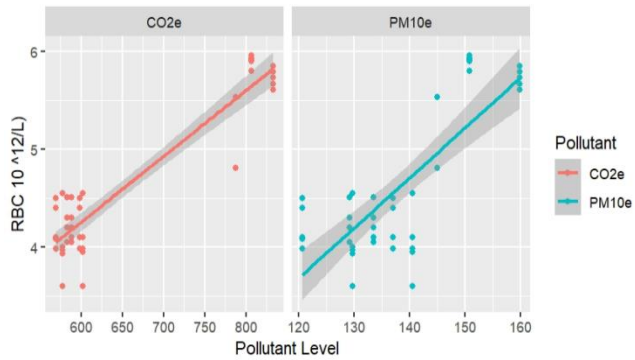

Figure 4. Bivariate relationships between CO_2 and PM_{10} levels and red blood cell (RBC) count

3.5 Study limitations

Some limitations should be considered when interpreting the findings of the present study. The sample size was

relatively limited, and continuous 24-hour pollutant monitoring was not feasible because of operational and technical constraints. In addition, detailed information regarding smoking habits, dietary factors, and lifestyle characteristics of participants was limited. Although repeated measurements were performed to improve reliability, future studies with larger sample sizes, continuous monitoring systems, and longer exposure assessment periods are recommended to further validate these findings.

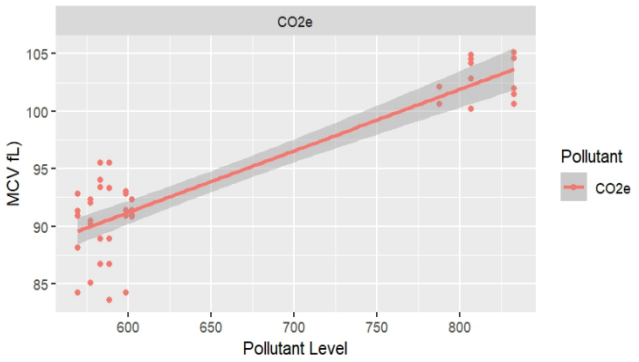

Figure 5. Relationships between CO_2 levels and mean corpuscular volume (MCV)

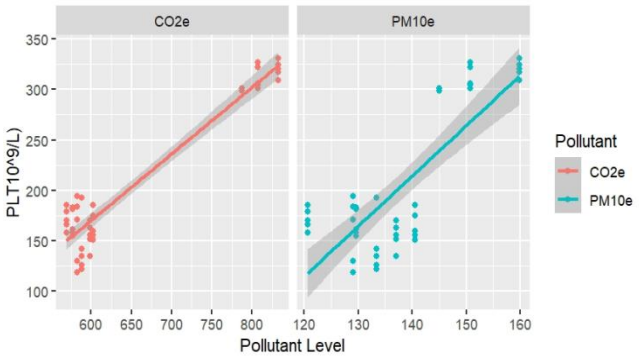

Figure 6. Bivariate relationships between CO_2 and PM_{10} levels and platelets (PLT) count

4. CONCLUSIONS

The findings of the present study indicate that prolonged occupational exposure to indoor air pollutants generated from charcoal grilling may contribute to hematological alterations associated with systemic inflammation, oxidative stress, and physiological adaptation to hypoxic conditions. Elevated concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2, and SO_2 in poorly ventilated grilling areas may increase potential long-term health risks among restaurant workers.

The study also emphasizes the importance of improving indoor air quality management in barbecue restaurants through adequate ventilation systems, local exhaust installation, periodic air quality monitoring, and the reduction of smoke accumulation in grilling areas. Regular medical examinations and occupational health surveillance for restaurant workers are also recommended to minimize adverse health effects associated with chronic exposure to combustion-related pollutants.

REFERENCES

[1] Ajayi, A.B., Abegunde, O.E. (2022). Development of a renewable energy barbecue grilling machine. Acta Technica Corviniensis-Bulletin of Engineering, 15(3): 91-98.

[2] Olorunsogo, T.O., Ogugua, J.O., Muonde, M., Maduka, C.P., Omotayo, O. (2024). Environmental factors in public health: A review of global challenges and solutions. World Journal of Advanced Research and Reviews, 21(1): 1453-1466. https://doi.org/10.30574/wjarr.2024.21.1.0176

[3] Zhang, S., Xu, X., Wang, Y., Ma, S., Meng, C., Dong, J., Cao, H. (2025). Pollutant emissions from restaurant cooking in commercial complexes: A comprehensive air quality analysis. Journal of Building Engineering, 105: 112442. https://doi.org/10.2139/ssrn.4985370

[4] Singh, A., Yadav, V.K., Shrivastava, D., Singh, M.K., Maurya, S., Vibhanshu, V., Sharma, A.K. (2021). Estimation of performance parameter of top-lit up-draft cookstove using locally available wood feedstock. International Journal of Energy for a Clean Environment, 22(6): 129-146. https://doi.org/10.1615/interjenercleanenv.2021036706

[5] Katutsi, V., Dickson, T., Migisha, A.G. (2020). Drivers of fuel choice for cooking among Uganda's households. Open Journal of Energy Efficiency, 9(3): 111-129. https://doi.org/10.4236/ojee.2020.93008

[6] Onyegirim, S.N., Nwankwo, E.I., Owuama, K.C., Madukasi, H.A. (2025). Advances in charcoal briquetting machines: A comprehensive review of technologies, performance, and sustainable applications. International Journal of Applied and Natural Sciences, 3(2): 35-49. https://doi.org/10.61424/ijans.v3i2.325

[7] Gupta, M., Dwivedi, S., Kota, S.H. (2024). From kitchen to air: Emissions from India's thriving restaurant food service sector. ACS ES&T Air, 1(6): 570-581. https://doi.org/10.1021/acsestair.4c00043

[8] da Silva, Á.M., Ucella Filho, J.G.M., da Silva, K.C.A., Oliveira, T.R., Pereira, A.K.S., Dias Júnior, A.F. (2023). Combustion equipment used in food preparation around the world: What is its influence on air pollution and how to mitigate these harmful effects? In Impacts of Using Biomass as an Energy Source in Homes, Springer, Cham, pp. 43-66. https://doi.org/10.1007/978-3-031-38824-8_3

[9] Li, X., Chen, P., Xie, Y., Wang, Z., Hopke, P.K., Xue, C. (2023). Fine particulate matter and gas emissions at different burn phases from household coal-fired heating stoves. Atmospheric Environment, 305: 119803. https://doi.org/10.1016/j.atmosenv.2023.119803

[10] Bari Fezea, M.A., Gathwan, M.A. (2023). Assessment of indoor air quality for closed cafés in Baghdad City, Iraq. Caspian Journal of Environmental Sciences, 21(5): 1279-1287. https://doi.org/10.22124/CJES.2023.7430

[11] Wang, W.Z., Chen, Q., Li, H.Y., Liu, Q.S.J., Wu, S.W. (2020). Effects of gaseous air pollutants on blood routine indicators in elders from a community in Beijing. Journal of Environmental and Occupational Medicine, 37(7): 664-671. https://doi.org/10.13213/j.cnki.jeom.2020.20029

[12] Fezea, M.A.B., Gathwan, M.A. (2024). Effect of PM2.5 and PM10 on the hematopoietic system of cafés workers in Baghdad. Ibn AL-Haitham Journal For Pure and Applied Sciences, 37(3): 88-97.

https://doi.org/10.30526/37.3.3316
[13] Akteruzzaman, M., Rahman, M.A., Rabbi, F.M., Asharof, S., Rofi, M.M., Hasan, M.K., Rahaman, M.H. (2023). The impacts of cooking and indoor air quality assessment in the southwestern region of Bangladesh. Heliyon, 9(1): e12852. https://doi.org/10.1016/j.heliyon.2023.e12852
[14] Barrett, K.C., Leech, N.L., Gloeckner, G.W., Morgan, G.A. (2019). IBM SPSS for Introductory Statistics: Use and Interpretation. Routledge.
[15] Geng, S., Dorling, K.C., Prenzel, T.M., Albrecht, S. (2024). Grill and chill: A comprehensive analysis of the environmental impacts of private household barbecuing in Germany. Sustainability, 16(3): 1041. https://doi.org/10.3390/su16031041
[16] Mencarelli, A., Greco, R., Balzan, S., Grigolato, S., Cavalli, R. (2023). Charcoal-based products combustion: Emission profiles, health exposure, and mitigation strategies. Environmental Advances, 13: 100420. https://doi.org/10.1016/j.envadv.2023.100420
[17] Usto, M.A., Solangi, Z., Shah, A.K., Qureshi, K.M., et al. (2024). Characterization and value-added addition of biomass for the reduction of emissions using coal as co-feed. Biomass Conversion and Biorefinery, 14(14): 16189-16197. https://doi.org/10.1007/s13399-022-03704-6
[18] Abulude, F.O., Oluwafemi, M.O., Arifalo, K.M., Elisha, J.J., Kenni, A.M. (2023). Assessment of indoor household air quality using SentinAir's cost-effective sensor. Tropical Aquatic and Soil Pollution, 3(1): 15-23. https://doi.org/10.53623/tasp.v3i1.131
[19] Sun, L., Héroux, M.È., Xu, X., Wheeler, A.J. (2025). Associations between residential fossil fuel combustion and indoor concentrations of nitrogen dioxide, carbon monoxide, and aldehydes in Canadian homes. Journal of Exposure Science & Environmental Epidemiology, 35(4): 649-660. https://doi.org/10.1038/s41370-025-00762-6
[20] Meo, S.A., Salih, M.A., Alkhalifah, J.M., Alsomali, A.H., Almushawah, A.A. (2024). Environmental pollutants particulate matter (PM2.5, PM10), carbon monoxide (CO), nitrogen dioxide (NO2), sulfur dioxide (SO2), and ozone (O3) impact on lung functions. Journal of King Saud University-Science, 36(7): 103280. https://doi.org/10.1016/j.jksus.2024.103280
[21] Yan, H., Koo, J., Song, D., Park, S. (2025). Real-time monitoring and control of cooking fumes: Implementation strategies for school kitchens. Environmental Pollution, 391: 127578. https://doi.org/10.1016/j.envpol.2025.127578
[22] Hazeem, S.S., Mohammed, A.B. (2024). Study of the blood characteristics of people exposed to smoke from grilled meat in some areas within Alhawija district in Kirkuk governorate, Iraq. European Journal of Research Development and Sustainability, 5(8): 8-14.
[23] Mancardi, D., Ottolenghi, S., Attanasio, U., Tocchetti, C.G., Paroni, R., Pagliaro, P., Samaja, M. (2022). Janus, or the inevitable battle between too much and too little oxygen. Antioxidants & Redox Signaling, 37(13-15): 972-989. https://doi.org/10.1089/ars.2021.0153
[24] Weaver, L.K. (2024). Carbon monoxide poisoning. Undersea & Hyperbaric Medicine, 51(3): 253-276.
[25] Nsonwu-Anyanwu, A.C., Idenyi, A.N., Offor, S.J., Thomas, C.C., Okpotu, F., Edet, C.E., Usoro, C.A.O. (2022). Association of exposure to polycyclic aromatic hydrocarbons with inflammation, oxidative DNA damage and renal-pulmonary dysfunctions in barbecue makers in Southern Nigeria. Reports of Biochemistry & Molecular Biology, 11(1): 74. https://doi.org/10.52547/rbmb.11.1.74
[26] Figueiredo, D., Vicente, E.D., Gonçalves, C., Lopes, I., Oliveira, H., Alves, C.A. (2024). Outdoor charcoal combustion in barbecue grills: Potential cytotoxic, oxidative stress and mutagenic effects. Atmospheric Environment, 322: 120383. https://doi.org/10.1016/j.atmosenv.2022.120383
[27] Biju, P., Sheta, W., Saumer, B. (2024). Towards healthier dining environments: Evaluating indoor air quality in Dubai restaurants. Journal of Building Design and Environment, 2(3): 37946-37946. https://doi.org/10.70401/jbde.2024.0006
[28] Wiedermann, W., Sebastian, J. (2020). Direction dependence analysis in the presence of confounders: Applications to linear mediation models using observational data. Multivariate Behavioral Research, 55(4): 495-515. https://doi.org/10.1080/00273171.2018.1528542
[29] Yang, Y., Wu, H., Zeng, Y., Xu, F., et al. (2024). Short-term exposure to air pollution on peripheral white blood cells and inflammation biomarkers: A cross-sectional study on rural residents. BMC Public Health, 24(1): 1702. https://doi.org/10.1186/s12889-024-19116-2
[30] He, J., Wang, T., Li, H., Zhou, Y., Liu, Y., Xu, A. (2025). Ozone aggravated the toxicity of fine particulate matter by impairing membrane stability and facilitating particle internalization. Toxics, 13(6): 446. https://doi.org/10.3390/toxics13060446