Research Article

Assessment of air pollutant emission from private diesel generators in AL-Najaf city.Air pollution from diesel generators

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ABSTRACT

background: The issue of electricity supply and demand continues in Al-Najaf Al-Ashraf, Iraq, leading to the rampant proliferation of private diesel generators. They are important alternative energy resources, but are a significant environmental and public health problem in residential and commercial populations. **Aim of the study**: This study aimed to evaluate the environmental impacts of the emissions of pollutants to the atmosphere due to the use of private diesel generators in the city of Al-Najaf, and to determine the relationship between the pollutants emitted to the environment from the operators working with private diesel generators and their health condition, compared with the healthy non-exposed individuals. **Methods:** A cross-sectional comparison study was carried out involving 220 subjects who were divided into two groups, that is 110 generator operators and 110 non-operators (controls). Structured self-administered questionnaires were used to collect data on demographic characteristics and health problems. The gaseous pollutants (CO, CO2, TVOC, HCHO) and particulate matter (PM2.5, PM10) have been monitored in 110 locations located in 3 sectors (North, Centre and South). Pre- and Post level measurements were conducted at 2m, 5m and 8m from the generator inside the operator room and outdoor. IBM SPSS (v.2022) was used for statistical analysis of the experimental data with a level of significance set at $p < 0.05$. **Results:** Operators had considerable grater rate of chronic health issues compared to controls groups ($p < 0.001$ across all symptoms). Chronic coughing (53.64% vs 7.27%), shortness of breath (44.55% vs 4.55%), and nasal irritation (43.64% vs 8.18%) were among the most notable findings. The operator groups were significantly more likely to experience systemic symptoms (dizziness, 42.73%; nausea, 33.64%). Environmental data revealed significant elevation after the activation (mean PM2.5 concentration is 172.71 $\mu g/m^3$, max 2m, mean PM10 concentration is 257.04 $\mu g/m^3$, max 2m, almost 5 times of the baseline). HCHO more than doubled and CO rose by five times to 11.78 ppm at 2 m. The concentrations of all pollutants after activation were far above the WHO air quality guidelines. **Conclusions:** The emissions level of a private diesel generator is significant in Al Najaf and the impact zone is at least 200 m2/unit, with the emission of hazardous air pollutants. The high concentration of the air pollutant emissions has been correlated with adverse respiratory and toxicological health impacts in workers,

thus providing strong recommendations for adherence to regulatory standards and protective setback distances, and a transition to cleaner energy sources.

Keywords: Diesel generators, air pollution, particulate matter, environmental health, AL-Najaf city.

Introduction

In many developing countries, power generating and distribution systems remain unable to meet rapidly increasing demand, In Iraq Decades of conflict, infrastructure deterioration, population growth, urban expansion, and rising energy usage have all contributed to ongoing electrical, Private diesel generators have become an important alternative source of power in Iraqi cities, notably Al-Najaf City [1].The increasing usage of private diesel generators has helped to bridge the gap between electricity supply and demand by providing power to homes, business and public buildings during outages. However, their unregulated and dense distribution in residential and commercial area has raised serious environmental and public health concerns as large segments of the population are constantly exposed to air and noise pollution caused by diesel-powered electricity sources [2]. In most cities, diesel generators are situated residential neighborhoods, near schools, markets, mosques, hospitals, and workplaces. This close proximity of pollution sources and human settlements raises the possibility of direct exposure to harmful emissions. Unlike centralized power facilities, private generators are frequently poorly maintained, operating for long hours, and lack efficient effective emission control measures [3]. Environmental pollution caused by generators are divided into several categories, with air pollution and noise pollution emerging as the most prevalent and detrimental [4]. Air pollution is one of the most serious environmental issues linked with diesel generators. Diesel generators generate a complicate variety of air pollutants as results of fuel combustion processes that take place inside their engines. Emissions include CO, NOx, SO_2, VOCs, and tiny particles with aerodynamic dimensions less than 2.5 µm ($PM_{2.5}$) and 10 µm (PM_{10}) [5]. The composition and toxicity of these particles differ according to fuel quality, engine age and condition, operation setting and maintenance method [6].

Materials and Methods

Study settings

The research is being conducted in Al-Najaf Al-Ashraf, which is one of the most important cities in terms of religious and historical significance. The city is located on the edge of Iraq's western plateau of Iraq, at a distance of 160 kilometers from Baghdad, which is the capital of Iraq. The area has a population density that amounts to 1.950.833 residents [7].and area 28,824 km^2. The city was divided into three sectors: firstly, South Sector including the right side of Kufa-Najaf Road which extended from Najaf to Kufa, Secondly, the Central Sector includes the main urban area of Al-Najaf, encompassing the districts located around the city center and extending along the principal commercial and residential zones. And thirdly, is the north sector including the area on the left side from Kufa-Najaf Road.

Study population

The study population consisted of multiple diesel generator's location across the city, generator operators with varying level of experience and healthy individuals form diverse socioeconomic background residing in area with minimal exposure to emission from diesel generators in Iraq at Al-Najaf city.

Study design

The study objectives were attained using a cross-sectional comparative study design.

Inclusion & Exclusion Criteria for Sample

1. Inclusion criteria:

- Generators operating exclusively on diesel fuel.
- Generator operators and healthy individuals without underlying health condition and aren't smokers.

2. Exclusion criteria:

- Industrials, government and Household generators.
- Generator operators and healthy individuals those who smoke or have chronic health conditions.

Data collection

Structured self-administered questionnaires

To collect information about signs and symptoms related to air pollutants emission from diesel generator for worker and healthy individuals residing in area with minimal exposure to emission from diesel generators, the researcher used a structured self-administered questionnaire. It was subsequently modified based on feedback from the academic supervisor and a panel of experts. The questionnaire was developed following a thorough review of relevant literature and previous similar studies. It included items on respondents' sociodemographic characteristics and signs and symptoms related to air pollutants emission from diesel generator. The Questionnaire Consisted of two Parts:

Part one: Socio-Demographics Characteristics of Participants

Part two: These sections collect information about signs and symptoms related to exposure to air pollutants emission from diesel generators.

Gaseous air pollutants measurement

The gaseous air pollutants (TVOC, HCHO, PM2.5, PM10, CO, CO2,) emissions from electrical power generators was measured by (JLDG JD-3002, Temtop M2000, TOPTES -OT-139 and Jumplushion Indoor Air Quality Monitor device) in Najaf city. More than one hundred ten generating sites were evaluated in this study, which began on December 8, 2025 and ended on February 18, 2026, in north, center and south sectors in Najaf city. Several high population density quarters were selected in each sector to measure various gaseous air pollutants metrics. The studied generators were largely diesel-powered machine that operating for varying daily periods based on electricity demand and local power supply conditions. The generators average operational period during monitoring was around (12) hours per day. The equipment was positioned at about 1.5 m above ground surface and Measurement were done in both inside operators room and outside the generators before and after turning on the generators at selected distances of 2 meters as well as 5 meters and 8 meters from the generators [8].At each site, measurements were conducted in four different directions to account for spatial variation in pollutants dispersion, "Each measurement lasted 10 minutes and the mean value of the recorded data was subsequently determined. The measuring instruments was calibrated prior to each usage to guarantee that measurements were accurate.

Study Limitation

The study was limited by seasonal and environmental factors, as measurements were taken during a specific time period that may not have accurately represented extreme summer conditions in Al-Najaf and baseline air pollution from traffic and dust, may have influenced the interpretation of generator-related emissions.

Ethical Considerations During Research

1. Approval from Al-Furat Al-Awsat technical university- College of health & medical techniques/Kufa. Number/5042 Date/ 29/9/2025
2. This project has been approved by the Directorate of Private Generators in Al-Najaf Governorate Number/2547. Date/ 2/10/2025

Statistical Analysis

Data analysis in the current study was carried out using IBM SPSS Statistics (2022). The study objectives were achieved using descriptive and inferential statistics such as mean, standard deviation (SD), least significant difference (LSD), ANOVA, t-test, and logistic regression.

Result

Demographic distribution of participants

Age distribution among study participants

The demographic distribution of the surveyed population, consisting of 110 replicates per group, provides a detailed look at the age structure of both the operators and non-operators control participants. The participants were divided into five age groups: which included participants younger than 25 years and those between 25 to 35 years and those between 35 to 45 years and people aged 45 to 55 years and participants who exceeded 55 years of age. The operators group contains members from all age categories who actively work in both the younger and older age ranges. The largest group of participants belongs to the 25–35 years age range which makes up 39% of all participants, while the 35–45 years age range follows with 32% of the total. The under-25 group represents 14% of people, while the 45–55 years bracket represents 10% of people. The group which consists of people aged over 55 years makes up 5% of the total population. (Fig. 1). The non-operators group shows a demographic pattern which includes more young people who make up the majority of their population compared to their older members who are present in smaller numbers. The 25–35 years age group makes up 39% of the total population, while the 35–45 years age group comes next with 35% of the population. The 45–55 years age group makes up 14% of the total population, while the under-25 age group makes up 8% of the population. The over-55 demographic group includes 4% of the total population as their most minor segment (Fig. 1). The two groups display matching counts of young members, yet the operators group holds more people who surpass 55 years when compared to the non-operators group.

The average age of operators in the operators group reached 36.25 years with (SD = 9.42) years which exceeds the average age of 32.55 years with (SD= 7.15) years in the non-operators group. The researchers used a t-test method to assess whether the observed difference between two groups reached a level of statistical significance. The test yielded a p-value of 0.063 which exceeds the conventional cutoff value of 0.05. The statistical analysis indicates that there is no age difference between the two groups since their ages fall within equivalent ranges. The operator's group has an older age distribution than the control group ,but both populations are similar enough to meet research requirements as shown in Table1.

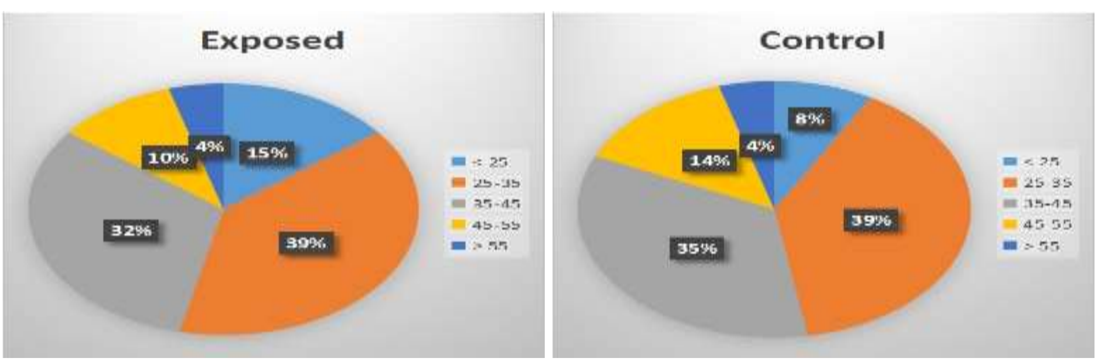

Fig.1 Age distribution among study participants in exposed and control groups

Table 1 :Comparison of mean age between operators and control groups

Age	Operators	Control
Mean	36.25	32.55
SD	9.42	7.15
T-test	0.063	

Education level distribution among study participants

The educational background of the surveyed population, which included 110 replicates per group, was evaluated to compare the formal credentials of the operators to the non-operators control group (Fig 2). The study categorized education levels into five primary tiers: Illiteracy, Elementary, middle school, High school and University. The operators group shows a distribution that leans significantly toward lower educational attainment. The largest portion of this group falls into the Illiteracy category, which represents 64 out of 110 members (58.2%) of the total group. The group distribution starts with 22 University degree holders (20.0%) followed by 12 middle school students (10.9%), 7 Elementary students (6.4%) and 5 High school students (4.5%). The Control group demonstrates superior academic achievement compared to the operators group. The largest segment of this group holds a university education, which accounts for 41 out of 110 individuals (37.3%). The group distribution starts with 36 Illiterates (32.7%) followed by 18 middle school students (16.4%), 8 Elementary students (7.3%) and 7 High school students (6.4%). The statistical analysis shows that Illiteracy and University education differences between the two Groups reach high significance at $p < 0.001$, while the middle school difference also reaches significance ($p = 0.038$). The study did not find any significant educational differences between Elementary and High school levels. (Table. 2).

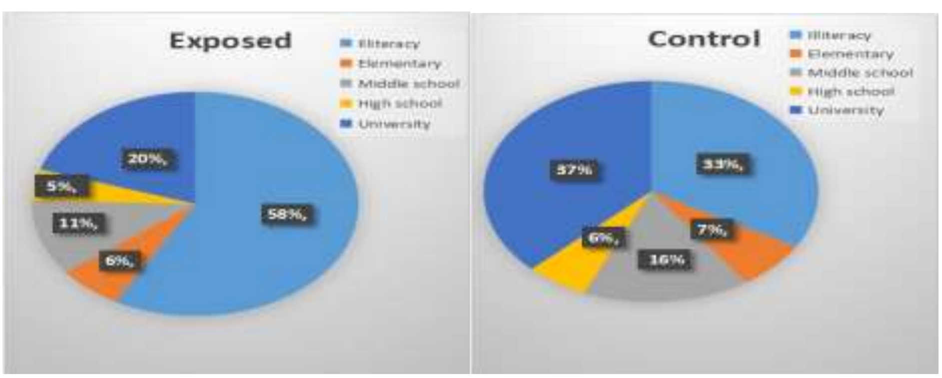

Fig.2 :Distribution of study participants by education level in exposed and control groups

Table .2: Comparison of education level between operators and control groups

Education level	operators	Control	T-test
Illiteracy	64	36	< 0.001*
Elementary	7	8	0.341
Middle school	12	18	0.038*
High school	5	7	0.188
University	22	41	< 0.001*
Total	110	110	*. Sig

Distribution of study participants by years of Experience

The study evaluated the professional history of the operator's group, which included 110 replicates, by categorizing their years of work experience into seven categories: less than < 10 years, between 10-15 years, between 15-20 years, between 20-25 years, between 25-30 years, between 30-35 years, and more than > 35 years. This data sheds insight into the duration of exposure for the workforce operating in the vicinity of the generators. The workforce shows a diverse range of experience, with the majority of workers having significant tenure. The largest segment of the population falls into less than 10 years of experience bracket, accounting for 38% of the workers, followed by those with 10–15 years of experience accounting for 25%, participants with 15–20 years of experience, representing 15% of the total. Workers with 20 to 25 years of experience account for 9% of the workforce, while workers with 25 to 30 years of experience make up 5% of the total. The least represented groups are those with 30–35 years and more than 35 years of experience, as each group makes up 4% of the sample size shown in Fig.3. The operator's population has an average experience duration of 11.51 years which corresponds to a standard deviation of 8.06 years according to statistical data shown in Table 3.

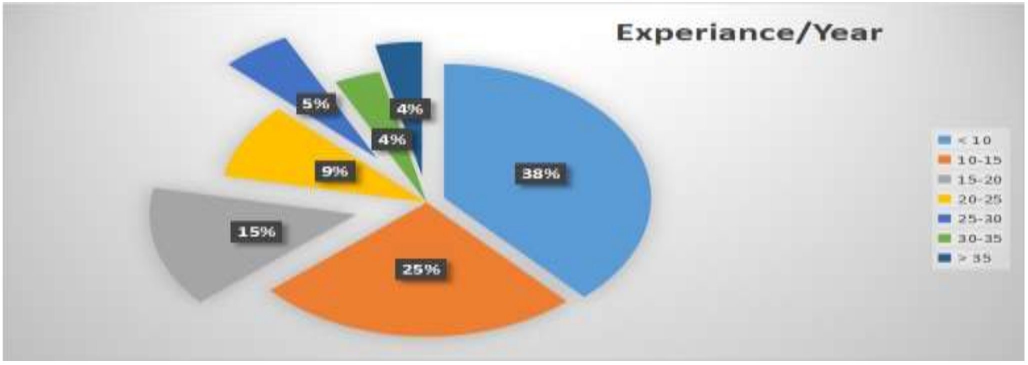

Fig. 3 :Distribution of workers by years of experience

Table 3: Comparison of the Exposed Group Based on Years of Experience

Groups of experience per year	Number of Worker	%	M±SD

< 10	42	38%	11.51 ± 8.06
10-15	28	25%	
15-20	16	15%	
20-25	10	9%	
25-30	6	5%	
30-35	4	4%	
> 35	4	4%	
Total	110	100%	

Distribution of study participants by Working Hours per day The data describe the distribution of daily working hours (Table 4) among a total of 110 workers. The workers were categorized into four groups based on the number of hours worked per day as: lower than 10 hours, 10 to 15 hours, 15 to 20 hours, and more than 20 hours. The 10–15 hours category contained 65 workers, which accounted for 59% of the entire sample according to the frequency and percentage data. The following group contained 15–20 hours, which had 26 workers (24% of the total). A smaller group of 12 workers (11% of the total) said they worked more than 20 hours daily. The lowest representation occurred in the less than 10 hours group, which had only 7 workers (6%) in total. The results show that most study participants work as operators with long working hours that mainly fall between the 10 to 15-hour period (Fig. 4). The study population worked for an average of 14.45 hours daily with a standard deviation of 3.83 hours according to (Table 4).

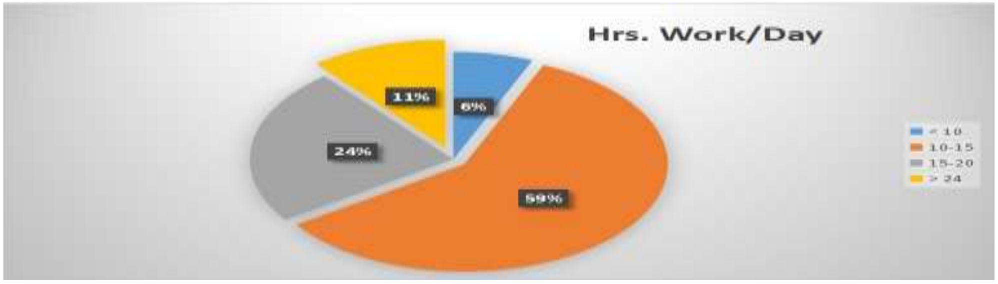

Fig .4: Distribution of workers by working per day

Table.4: Comparison of Exposed Group Based on working Hours per day

Working/ day	Number of Worker	%	M±SD
< 10	**7**	**6%**	**12.89 ± 4.05**
10-15	**65**	**59%**	
15-20	**26**	**24%**	
> 20	**12**	**11%**	
Total	**110**	100%	

Parameters		indoor±SD	2m±SD	5m±SD	8m±SD	F	Sig.	LSD
CO	Before	2.188±0.608	2.589±0.557	2.592±0.582	2.572±0.601	935.241	< 0.001*	0.299
	After	4.419±1.295	11.782±1.429	9.574±1.766	6.620±2.094			
CO2	Before	427±17.194	427±20.634	417±41.917	416±24.678	109.455	< 0.001*	16.835
	After	481±17.194	544±83.73	525±75.962	499±56.058			
TVOC	Before	0.010±0.000	0.012±0.004	0.011±0.003	0.011±0.003	264.421	< 0.001*	0.0015
	After	0.013±0.005	0.030±0.009	0.029±0.008	0.028±0.008			
HCHO	Before	0.005±0.005	0.022±0.006	0.022±0.007	0.021±0.007	179.707	< 0.001*	0.0015
	After	0.012±0.008	0.054±0.025	0.049±0.021	0.042±0.015			
PM 2.5	Before	38.289±21.998	32.165±11.600	31.787±11.511	31.152±11.800	83.623	< 0.001*	29.448
	After	123.061±71.538	172.712±147.358	126.305±56.792	91.089±31.723			
PM 10	Before	49.394±29.129	48.995±17.465	48.646±17.670	47.237±18.073	90.477	< 0.001*	23.948
	After	157.962±95.830	257.043±199.262	191.961±96.991	130.721±54.874			

***. The mean difference is significant at the 0.05 level.**

Table.5: Comparison of indoor and outdoor air pollutants at different distance before and after diesel generator operation

Air pollutants Results

Carbon monoxide (CO) Result

The research documented in Fig. 5 and table 5 shows that the highest CO levels of 11.782 emerged at a distance of 2 meters, which represents an increase of almost five times the initial value. The exhaust gases create a "sweet spot" for high concentration because they exit the system at high speeds, which leads to their initial overshooting of indoor space before they settle into concentrations at 2 meters. The concentration levels start to drop at increasing distances from the source, reaching 9.574 at 5 meters and 6.620 at 8 meters, while the 8-meter reading exceeds double the initial baseline. The standard deviation (SD) value shows a considerable increase after system startup, reaching its highest point of 2.094 at the 8 m distance. The gas concentration behavior becomes unpredictable because environmental factors such as wind currents and air mixing affect the gas movement from its source.

The ANOVA test results show a major impact with an F-value of 935.241 and a p-value < 0.001 which demonstrates that CO levels increase because of the generator running. The Least Significant Difference (LSD) is calculated at 0.299. The difference between the two states exceeds the calculated LSD of 0.299 which proves that the generator's exhaust creates major air quality problems at all distances from measurement points Table 5.

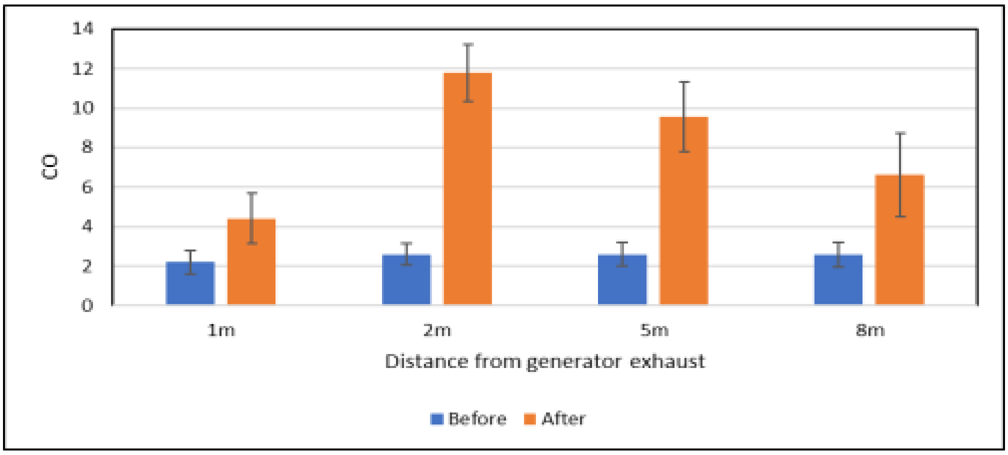

Fig .5: Shows the variation of CO concentration before and after generator operation at various distances.

Carbone dioxide (CO2) Result

The highest concentration was recorded at the 2 m mark (544 ± 83.73), rather than directly at the exhaust exit. The generator exhaust plume reaches its maximum density immediately after it exits the generator before it starts to spread into the surrounding atmosphere according to Fig. 6 and Table 5. Before the generator was turned on, the ambient CO_2 levels were relatively stable, hovering around 416–427 ppm. The levels increased substantially at all distances after the system became operational because all "After" readings were higher than "Before" readings by over the LSD threshold of 16.835. The SD shows a substantial rise after startup because it measures at 2 m and 5 m distances. The air quality becomes extremely turbulent during generator operation because exhaust forces and local air currents create turbulent conditions. The CO_2 levels at 8 m distance (499 ± 56.058) were still above the starting baseline which proves that the generator affects a wide area of its surrounding environment.

As show in Table 5, The ANOVA statistical analysis produced an F-value of 109.455 with a p-value that was less than 0.001 which demonstrated that the emission increase was statistically significant and not a random occurrence. The data-set has a Least Significant Difference (LSD) value of 16.835.

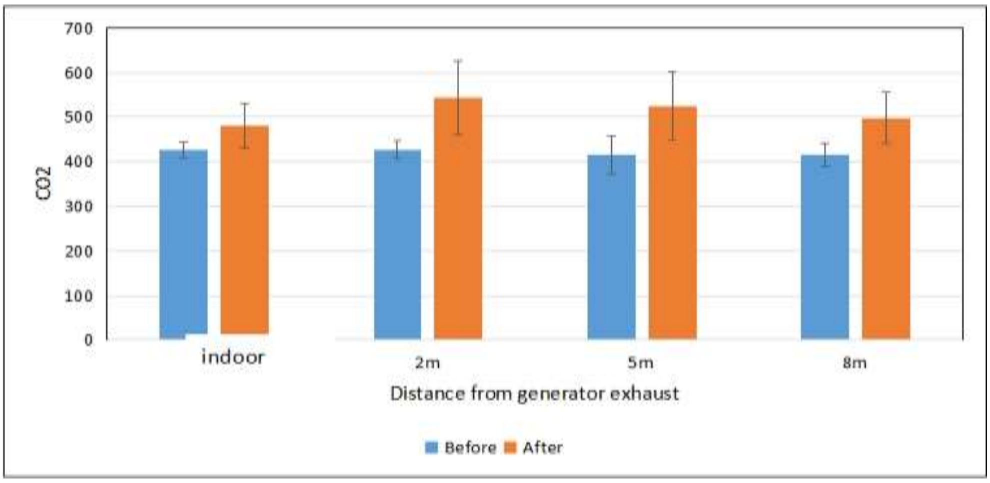

Fig .6: Shows the variation of CO_2 concentration before and after generator operation at various distances.

Total volatile organic carbon (TVOC) Result

The operation of generators caused an increase of ambient TVOC levels which had maintained their low levels prior to generator operation at all distances. The indoor environment registered a mean TVOC concentration of 0.010 ± 0.000 while the 2-meter distance showed a minor increase to 0.012 ± 0.004. The levels at 5 m and 8 m were identical, both measuring 0.011 ± 0.003 (Fig. 7, Table 5). The TVOC levels experienced a major increase after the system began its operations at all locations which scientists had previously tested. The value at indoor testing reached 0.013 ± 0.005. The highest concentration occurred at 2 m distance which showed values that increased to 0.030 ± 0.009. The measurement at 5 m distance maintained the high level at 0.029 ± 0.008 while the 8 m distance experienced a minor decrease to 0.028 ± 0.008.

The analysis of statistical data shows that the observed increases in data do not occur because of random environmental changes. The ANOVA test produced an F-value of 264.421 and a p-value below 0.001 which demonstrated that generator startup operations significantly affected TVOC levels. The researchers established the Least Significant Difference (LSD) value at 0.0015. The air quality degradation across all measured distances shows statistical significance because all distance points between "Before" and "After" times exceeded the determined LSD threshold.

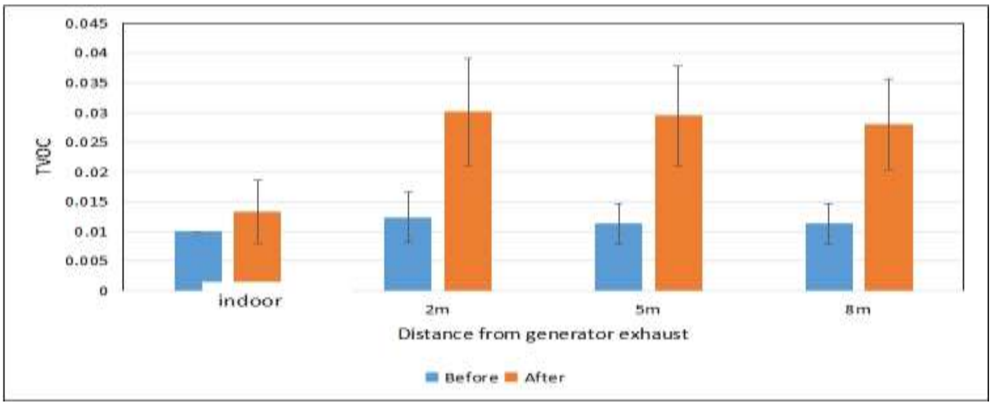

Fig .7: Shows the variation of TVOC concentration before and after generator operation at various distances.

Formaldehyde (HCHO) Result

The HCHO levels in the air stayed low when the generators had not yet begun operation. The mean concentration at the indoor location measured 0.005 ± 0.005. The baseline measurement at 2 m distance increased to 0.022 ± 0.006 and stayed mostly unchanged at 5 m (0.022 ± 0.007) and 8 m (0.021 ± 0.007) (Fig. 8, Table 5). The generator operation led to an immediate and major HCHO level increase which affected all testing locations. The mean value at indoor locations increased to 0.012 ± 0.008. The highest concentration level happened at 2 m when the readings exceeded the baseline by more than two times to reach 0.054 ± 0.025. The concentration level stayed elevated at 5 m with a mean value of 0.049 ± 0.021 which decreased slightly to 8 m with a value of 0.042 ± 0.015. The "After" results showed much greater standard deviations which reached their peak at the 2 m distance, showing that the pollutant density changed significantly after the exhaust plume became active.

The statistical data confirms that the startup of the generator has a profound impact on HCHO emissions. The ANOVA analysis showed an F-value of 179.707 which had a p-value of less than 0.001, to demonstrate that the pre-startup and post-startup periods showed extremely important differences. The LSD value was determined to be 0.0015. The actual increases in mean values (which ranged from approximately 0.007 to 0.032) exceed the LSD threshold, so we can statistically prove that the generator operation leads to air quality degradation throughout the complete 8-meter testing range (Table 5).

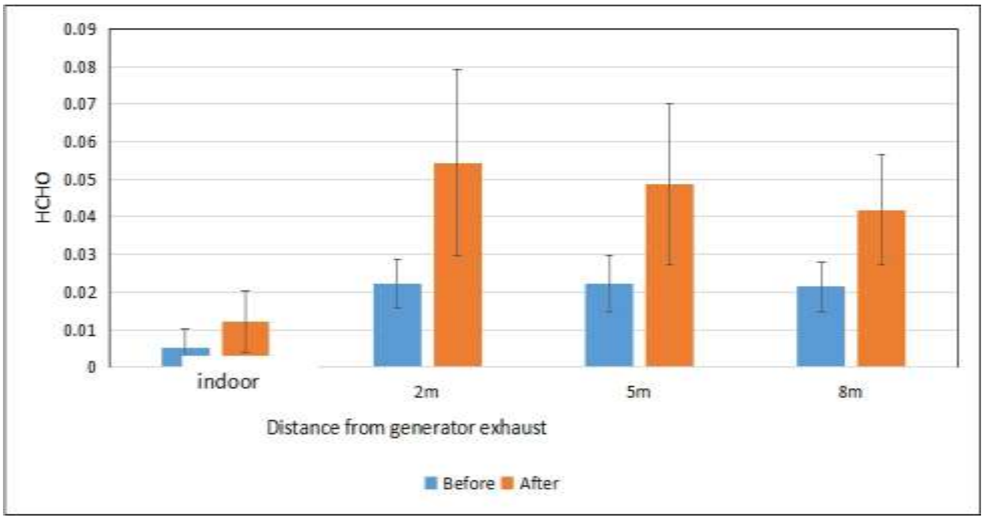

Fig .8: Shows the variation of HCHO concentration before and after generator operation at various distances.

Fine particle matters (PM2.5) Result

The ambient PM2.5 levels before startup showed low levels which remained constant throughout all testing locations. The indoor environment had a mean concentration of 38.289 ± 21.998. The measurements showed a slight decrease in baseline levels which reached stable status at 2 m with 32.165 ± 11.600, 5 m with 31.787 ± 11.511, and 8 m with 31.152 ± 11.800. The PM2.5 levels experienced a dramatic increase at all measurement locations after the generators began operation. The indoor environment showed a concentration increase to 123.061 ± 71.538. The highest pollution levels occurred at 2 m distance, where the average reached 172.712 ± 147.358. The concentration at 5 m distance stayed high, with an average of 126.305 ± 56.792, until it started to decrease at 8 m distance, which measured 91.089 ± 31.723 (Fig. 9). The 2 m measurement point shows a standard deviation which is extremely large, demonstrating that particulate matter starts to spread in unpredictable patterns with high speed and disorganized motion right after the exhaust exit from the exhaust pipe.

The statistical data demonstrates the extent of damage which the generator generates. The ANOVA test of the dataset produced an F-value of 83.623 together with a p-value of < 0.001 which demonstrated that the particulate matter level increase reached a level of significant statistical impact. The LSD was determined to be 29.448. The results show that generator startup causes air quality deterioration throughout the entire 8-meter radius area due to all distance points recording mean values which exceed the LSD threshold (Table 5).

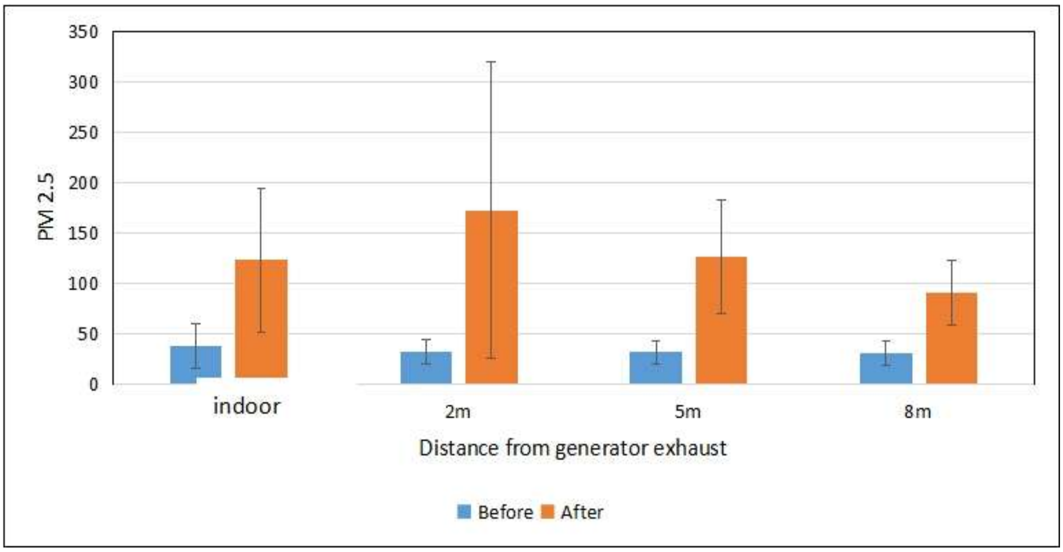

Fig.9: Shows the variation of $PM_{2.5}$ concentration before and after generator operation at various distances.

Particle matters (PM10) Result

Fig 10, showed that the prior to starting the generator, PM10 levels were relatively low and stable across all distances. Indoor spaces had an average concentration level of 49.394 ± 29.129. The recorded values remained constant with increasing distance at 48.995 ± 17.465 for 2 m, 48.646 ± 17.670 for 5 m, and 47.237 ± 18.073 for 8 m. The PM10 levels at all measurement locations showed a dramatic increase after the generator started operation. The indoor measurement showed a concentration increase to 157.962 ± 95.830. The peak concentration for this pollutant series occurred at 2 m distance, which showed a mean value of 257.043 ± 199.262 that represented an almost five times increase from the baseline level. The levels remained highly elevated at 5 m with a mean of 191.961 ± 96.991, before tapering off to 130.721 ± 54.874 at the 8 m distance. The standard deviations for the "After" group show significant widening compared to baseline results especially at the 2 m distance which indicates high turbulence and inconsistent dispersion of coarse particles near the source.

Table 5 shows that statistical analysis proves the generator startup process creates a major and definite negative impact on air quality. The ANOVA test results showed an F-value of 90.477 and a p-value of < 0.001 which demonstrated that the pre startup and post startup measurements showed highly significant differences. The LSD calculation resulted in a value of 23.948. The results show strong statistical evidence that the generator operation causes air quality deterioration across the 8-

meter testing area because every distance point showed mean value increases which exceeded the LSD threshold.

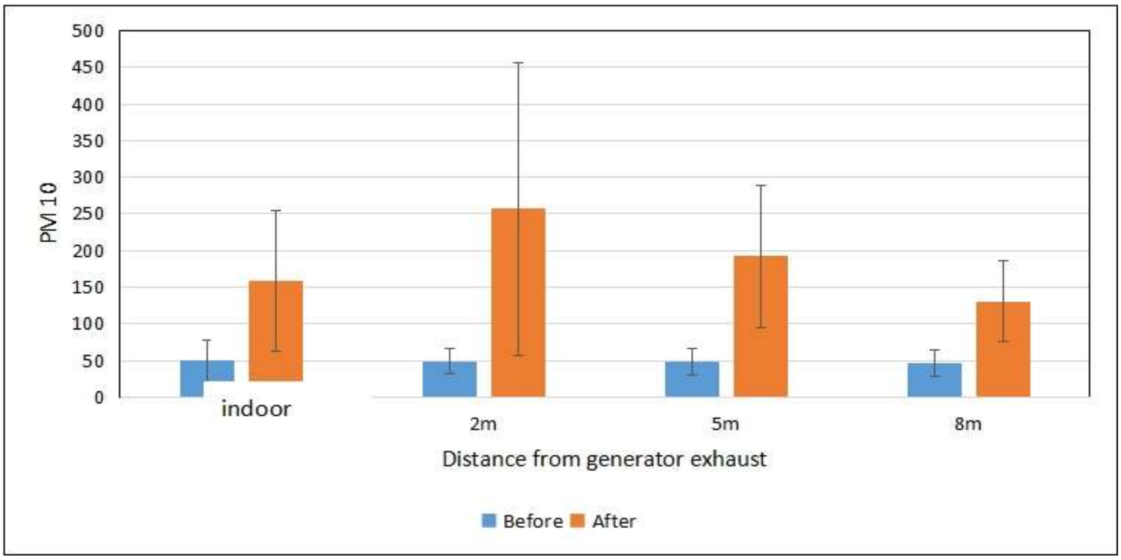

Fig .10: Shows the variation of PM_{10} concentration before and after generator operation at various distances.

Health status of participants

The findings presented in table 6 show a clear and statistically significant difference in respiratory and irritation-related complaints between the operators and control groups. Across all symptoms assessed, the operators reported a significantly higher prevalence of persistent (chronic) disorders, whereas the control group reported fewer symptoms or just occasional occurrences. The most significant differences were found in coughing and shortness of breath. In the operator's group, 53.64% experienced persistent coughing, compared to 7.27% in the control group. Similarly, 44.55% of operators reported persistent shortness of breath,compared to only 4.55% in the control group.A similar pattern was identified for nose and eye irritation, with 43.64% and 39.09% of operators reported persistent symptoms. In contrast, the control group had much lower rates of persistent irritation (8.18% for nose and 7.27% for eye irritation), with the majority of people reporting no symptoms or just occasional discomfort.

There were also significant differences in symptoms like palpitation and dizziness. Likewise, 36.36% of the operators had persistent palpitation compared to 8.18% of the control group and 42.73% of the operators had persistent dizziness in comparison to 15.45% of the control group.The nausea had also increased significantly among the operators (0.91%–33.64%). The overall percentages were higher in the "Never" and "Sometimes" categories, and there was clearly a trend of higher percentages in the "Always" category for all symptoms in the operators group.These distinctions are confirmed by a statistical study. All the symptoms had p value < 0.001 and hence they were highly significant at 0.05 level. This offers strong evidence of an association between respiratory, and irritation-related health issues, and occupational exposure among generator operators.

Table. 6: Comparison of air pollutants related symptoms between operators and control groups (Never, Sometimes, Always %).

Coughing	Control	41.82	50.91	7.27	> 0.001*
	operators	18.18	28.18	53.64	
Palpation	Control	46.36	45.45	8.18	> 0.001*
	operators	25.45	38.18	36.36	
Shortness of breath	Control	45.45	50.00	4.55	> 0.001*
	operators	16.36	39.09	44.55	
Nasal irritation	Control	42.73	49.09	8.18	> 0.001*
	operators	21.82	34.55	43.64	
Eye irritation	Control	40.91	51.82	7.27	> 0.001*
	operators	21.82	39.09	39.09	
Dizziness	Control	35.45	49.09	15.45	> 0.001*
	operators	17.27	40.00	42.73	
Nausea	Control	54.55	44.55	0.91	> 0.001*
	operators	26.36	40.00	33.64	
*. Is significant at the 0.05 level.					

Logistic regression between air pollutants and health symptoms among operators

The logistic regression analysis in Table 7 shows a pretty important part of gaseous and particle pollutants, when it comes to predicting health complaints among generator operators. Carbon monoxide (CO) was strongly linked with coughing palpitations, shortness of breath and dizziness , which suggests these influences touch both the respiratory and cardiovascular systems. Higher levels of carbon dioxide (CO_2), have been tied to palpitations and nausea, so it looks like there are broader whole body effects from exposure . Shortness of breath and nasal irritation, were predicted by volatile organic compounds (TVOC) but formaldehyde (HCHO) was much more strongly related with nose and ocular discomfort, which indicates it has irritant features.

Particulate matter also had significant effects PM2.5 was associated with coughing, shortness of breath, and dizziness, but PM10 was linked with coughing, shortness of breath, and nausea. These data demonstrate that exposure to generator emissions raises the risk of a variety health conditions, particularly respiratory and systemic issues

Table 7. Logistic regression of gaseous and particulate pollutants predicting health symptoms among operators

Predictor Variable	Coughing (OR, 95% CI, p)	Palpitations (OR, 95% CI, p)	Shortness of Breath (OR, 95% CI, p)	Irritation in Nose (OR, 95% CI, p)	Irritation in Eyes (OR, 95% CI, p)	Dizziness (OR, 95% CI, p)	Nausea (OR, 95% CI, p)
CO (per 1 ppm ↑)	1.42 (1.11–1.82, 0.006*)	1.31 (1.02–1.68, 0.033*)	1.55 (1.20–2.01, 0.001*)	–	–	1.29 (1.01–1.64, 0.041*)	–
CO2 (per 10 ppm ↑)	–	1.18 (1.03–1.36, 0.019*)	–	–	–	–	1.22 (1.07–1.40, 0.008*)
TVOC (per 0.01 mg/m³ ↑)	–	–	1.47 (1.12–1.93, 0.005*)	1.39 (1.08–1.78, 0.011*)	–	–	–
HCHO (per 0.01 mg/m³ ↑)	–	–	–	1.51 (1.17–1.95, 0.002*)	1.54 (1.18–2.01, 0.002*)	–	–
PM2.5 (per 10 µg/m³ ↑)	1.63 (1.22–2.18, 0.001*)	–	1.89 (1.33–2.69, <0.001*)	–	–	1.41 (1.09–1.83, 0.009*)	–
PM10 (per 10 µg/m³ ↑)	1.58 (1.19–2.09, 0.002*)	–	1.44 (1.11–1.87, 0.006*)	–	–	–	1.36 (1.07–1.73, 0.012*)

Note: OR > 1 indicates increased odds of symptom occurrence with higher exposure. CI = Confidence Interval.** ***p < 0.05 considered statistically significant.

Discussion

The study population included 220 participants who were divided into two groups consisting of operators who numbered 110 and non-operators who also numbered 110.The average age of the operator group was slightly greater than the non-operators. The independent-samples t-test showed a p-value of 0.063 which exceeded the standard alpha criterion of 0.05 despite the fact that the operator group was older than the non-operator group .A p-value of 0.063 indicates that the observed difference of nearly 3.7 years would occur by chance in approximately 6.3% of repeated samples, which is higher than the standard threshold for rejecting the null hypothesis. Also, the overlapping standard deviations indicate a high level of diversity within the groups, supporting the idea that the age distributions are essentially equivalent. Many occupational health studies accept such results as sufficient evidence of group comparability when age is not the primary exposure [9] [10].The studies found that operators in Iraq are slightly older than non-operators which creates a difference that fails to meet statistical significance while supporting the common observation that operating positions require workers with extensive experience who developed troubleshooting skills through their work with both aging infrastructure and fuel quality changes and inconsistent maintenance patterns [11] [12]

The educational background analysis found disparities between the two groups, providing vital insight into the workforce occupational stratification. The operators' groups had much greater rates of illiteracy than the non-operators, while the control group had higher university attainment. These findings are consistent with previous research, which indicate the lower educational attainment is typically associated with manual, physically demanding, or hazardous occupations [13]. This could be due to institutional factors, such as roles in industrial generators attracting workers with limited formal education due to barriers to white-collar employment, whereas higher education levels among non-operators may indicate more opportunities for supervisory or technical positions These findings suggests that educational inequalities might help build cumulative disadvantages in industrial contexts [14]. Given that lower education is still a well know risk factor across a range of diseases. These findings also highlight the need to examine if these gaps mediate or perhaps worsen the link between occupational exposure and health outcomes [15].

Professional experience analysis does shed light on operator group duration and the organizational stability, . The data shows a diverse range of work experience, spanning from moderately experienced to highly experienced in a way that looks pretty consistent across categories . This structural makeup is pretty typical for industrial circumstance where continuous long-term operational training is essential, to keep competence over time [16]. Also, the average experience duration of 11.51 ± 8.06 years gives a quantifiable view of this collective know-how, it demonstrates a strong base of operational familiarity among generator operators. In high-risk industrial settings, maintaining such a broad spectrum of experience is crucial for operational safety [17]. Overall, these results highlight how important it is to retain experienced employees , and they support the idea that expertise is useful in practice .

The analysis of daily labor hours gives information about the occupational demands placed on operators. The findings indicate that a high proportion of participants work long daily shifts. These findings are clinically concerning since they exceed the normal occupational limit of 8 to 9 hours, which researchers have connected to an increased risk of injury, weariness, and cardiovascular problems associated with working long shifts [18]. The average shift duration of 14.45 ± 3.83 hours highlights the high level of physical and environmental exposure experienced by generator operators. In high-risk industrial workplaces, controlling such a broad range of daily working hours is crucial for operational safety, as extended shifts have been linked to cognitive tiredness, lower situational awareness, and an increased risk of occupational accidents [19]. These findings emphasize the critical importance of monitoring labor schedules and support the notion that minimizing chronic operator fatigue can help to reduce environmental and occupational dangers.

The investigation of Carbon Monoxide (CO) concentrations gives some insight into how generator operation affects the environment. In the study , it was shown that CO levels rose quickly after startup, and the largest concentration, 11.782 ± 1.429 ppm, showed up at a distance of 2 meters not right at the exhaust exit. So, this result fits with familiar combustion engineering ideas, because internal combustion engines make CO due to incomplete combustion, and the exhaust plume has to travel a short distance before it can mix with outside air in a more complete, sort of uniform way [20]. The CO reading at 2 meters likely marks the spot where that high-velocity exhaust jet pulls in enough surrounding air so the concentration becomes clearly detectable, before extra spreading starts to dominate. Other efforts have reported comparable spatial behaviors for generator exhaust when the space is tight or restricted [21]. Also, the larger spread at 8 meters seems consistent with turbulent mixing, plus the fact that wind currents shift in real time [22]. Overall, the outcomes from these experiments basically confirm that running the generator creates major air pollution issues at every distance the researcher measured.

The evaluation of Carbon Dioxide (CO_2) concentrations revealed a spatial pattern comparable to other combustion byproducts, shedding light on the distribution of generator emission. The study found that CO_2 levels reached their highest point at a distance of 2 meters .The measurements taken after operation all above the LSD limit according to fluid dynamics principles which state that fast exhaust should first travel beyond its starting point before spreading out [23]. The study indicated that ambient levels before operation started (416–427 ppm) remained within the normal range found in indoor spaces which have proper ventilation systems. The standard deviation values at both 2- and 5-meters distance indicate significant increases which suggest that turbulent mixing occurs close to the running exhaust system. The data demonstrate that the generator produces effects which extend to an area that reaches at least 8 meters from its location. However, after operation the recorded CO2 levels which reached a maximum of 544 ppm are much lower than the occupational exposure limits set by American Conference of Governmental Industrial Hygienists which set a threshold of 5,000 ppm [24]. The observed increase from the baseline is pretty modest, like around 117 ppm at the 2 meter mark which is also lower than levels often reported in crowded indoor settings, such as classrooms [25] ; and even though the difference ends up being statistically significant, the effect on human physiology is still extremely minor

The examination of TVOC provided a statistical insight on emissions produced during operation. The examination showed a considerable increase in TVOC level after starting the generator. The observed pattern with a low baseline followed by a sudden increase and subsequent decline is consistent with recent research on generator exhaust plumes [26]. These findings are supported by the fact that diesel generators produce a wide range of TVOC including alkanes and aromatic hydrocarbons [27]. The highest measured concentration of 0.03 ppm is way lower than TVOC levels usually found in standard indoor spaces, which typically sit between 0.5 to 1.0 ppm because of everyday cleaning agent and furniture. [28]. When compared to more harmful pollutants, reported TVOC increases may have a minor environmental impact. Furthermore, the lack of speciation makes determining exact toxicity or odor thresholds challenging, as some VOCs such as benzene are carcinogenic at low concentrations while others are basically nontoxic [29].

The measured of Formaldehyde (HCHO) concentrations revealed a critical perspective on the health risk associated with generator use. This spatial pattern which reaches its highest point at 2 meters follows the behavior of other measured pollutants and matches the fluid dynamics models of exhaust plumes [23]. These finding showed that outdoor baseline measurements (0.021–0.022 ppm) correspond to urban average levels but the 2-meter post-operation concentration exceeds the WHO guideline of 0.02 ppm for 30-minute exposure [30]. The incomplete combustion of fuel together with the oxidation of unburned hydrocarbons produces formaldehyde which functions as a combustion byproduct [31]. The results demonstrate that generator operators who work near active generators face a significant danger to their health. Furthermore, the peak concentration of 0.054 ppm exceeds the WHO short-term guideline yet falls short of specific occupational limits which include the OSHA PEL of 0.75 ppm thus indicating that the levels present a risk but do not create immediate life-threatening conditions [24].

The measured of fine $PM_{2.5}$ indicated a significant environmental threat assessment, proving that generator operation creates serious air quality degradation. The study found significant increases in $PM_{2.5}$ concentrations at 2-meter height, these findings are compatible with the known emission from diesel generators, which are major sources of fine particles such as elemental carbon and metals [32]. The base air quality at testing site showed persistent problems because indoor levels between pre-operation period already reached 38.289µg/m³ which exceeded WHO 24-hour standard of 15µg/m³ [33]. The post-operation levels at 2 meters exceeded ten times the WHO guideline and stayed over national regulations, including the US EPA permitted level of 35 µg/m³ [34]. The 2-meter standard deviation shows extreme variation because active exhaust jets create unstable dispersion patterns. The PM2.5 emissions from generators contain significant amounts of black carbon and polycyclic aromatic hydrocarbons (PAHs) which are more harmful than regular ambient particulate matter [34]. These findings indicate that workers operating in this region are exposed to concentrations that offer acute and long-term health concerns, necessitating immediate engineering solutions, such as local ventilation or exhaust extensions as well as personal respiratory protection.

The analysis of coarse particulate matter PM10 showed the same patterns as PM2.5 which demonstrated how generator operations resulted in significant air quality decline. The study showed that PM10 concentrations reached their maximum at 2 meters; according to [32], diesel generators produce significant quantities of coarse particles because their combustion process produce incomplete combustion emissions which also induce dust resuspension.The study found that pre-operation baseline levels at approximately 47–49 µg/m³ exceeded the WHO 24-hour recommendation limit of 45 µg/m³ indicated poor starting air quality [33]. The post-operation peak value of 257 µg/m³ nearly reaches six times the WHO guideline while the 2-meter location shows a high standard deviation because of the exhaust source turbulence and dispersion variations. Some researchers assume that PM10 causes less serious health effects than PM2.5 because coarse particles mostly settle in upper airways rather than reaching alveoli [35] [36]. The increase in concentration exceeding 200 µg/m³ have a significant on both particle sizes. PM10 levels are a substantial impact to occupational safety because they indicate considerable deterioration in air quality.

The examination of breathing problems and irritation complaints showed that the two groups had different results which proved that operators faced serious health dangers from their work. Operators showed more chronic symptoms than all other groups who were examined and their rate of symptoms was significantly greater than 0.001 for all seven symptom categories; these clinical findings are biologically justified when compared to the high levels in environmental pollutants indicated around the generators.High quantities of PM2.5 (as much as 172.7 µg/m³) and PM10 (up to 257.0 µg/m³) can get into the respiratory system, causing inflammation plus oxidative stress [37]. Also formaldehyde, together with TVOCs, can behave like strong mucosal irritants and this sort of thing may explain the fairly elevated incidence of eye and nose irritation. And then there's The, noticeably rather frequent nausea 33.64% among operators, compared to only 0.91% in the controls could stem from systemic toxicological effects, driven by carbon monoxide along with other volatile organic chemicals [38] [39].

The logistic regression analysis in Table 7 quantifies the health hazards faced by generator operators, sort of showing robust dose dependent relationships between certain air contaminants and distinct clinical symptoms, yeah. The statistical data indicates that even incremental increases in both gaseous matter and particulate material are linked with a higher risk of respiratory, cardiovascular , and neurological problems. When you then look at the specific toxicological profiles of the substances that are emitted in close proximity to the generators, these clinical results still seem biologically reasonable.Carbon monoxide, CO exposure, was seen as a strong predictor across many physiological systems with a substantial relationship to coughing, palpitations, shortness of breath, and dizziness. In biology terms, these whole body effects seem to come from the high affinity of CO for hemoglobin, where it then makes carboxyhemoglobin, leading to systemic hypoxia plus a cellular oxygen shortage. That in turn triggers compensatory cardiovascular stress, which can show up as palpitations, and it also causes central nervous system distress, like this feeling of dizziness [39]. At the same time, higher carbon dioxide levels were strongly tied with palpitations and nausea, it kind of highlighting that notable autonomic and systemic stress that comes from not having a properly ventilated generator condition .The organic chemical components predict the localized mucosal and upper respiratory symptoms very accurately. Total volatile organic compounds (TVOCs) increased the likelihood of shortness of breath and nasal discomfort. Meanwhile, formaldehyde (HCHO) had a strong localized effect, similar to a powerful mucosal irritant, and strongly predicted both nose discomfort and ocular irritation. These findings are fairly consistent with established toxicological frameworks, which suggest that volatile aldehydes dissolve rapidly in the watery mucous membranes of the eyes and upper respiratory tract, triggering acute inflammatory cascades, sensory nerve stimulation, and tissue irritation [31]. Finally , particulate matter had really severe, size dependent effects on the operators' respiratory health and overall well-being, you know. Fine particulate matter was the strongest overall predictor for shortness of breath , and it also showed considerable risk for coughing and dizziness. Coarse particulate matter, in turn, predicted coughing , shortness of breath, and nausea too. Mechanistically, since particles have a small aerodynamic diameter, they can slip past upper airway defenses pretty easily, then reach the pulmonary alveoli deeply, which in practice triggers localized oxidative stress, stimulates alveolar macrophages, and promotes systemic inflammatory responses that show up clinically as severe dyspnea and respiratory irritation [37].

Conclusion

1. Prolonged occupational exposure to diesel generators has a substantial impact on operators' health due to continuous inhalation of air pollutants emission from diesel generators
2. 2. There is an increased environmental pollutants level across all measurement locations compared with the baseline value, which indicates that the generators are a major source of pollution and that an effective strategy to mediate their effect is required .

3. The 2 meter outdoor setting seemed to show, the zone with the highest concentrations of environmental pollutants, sort of a critical hotspot for how the exhaust plume disperses close to the generator source .

4. The study identified a strong link between generator pollution and multi-system symptoms, suggesting that chemical exposure poses a major health risk to operators.

Recommendation

1. Local authorities should enforce strict emission regulations and mandatory maintenance schedules to ensure that private generators use advanced exhaust filtration technologies for controlling air pollution.
2. Generator operators must be wearing appropriate personal protective equipment (PPE), such as high-efficiency respiratory masks and certified hearing protection devices like ear muffs or plugs.
3. Private diesel generators should be installed away from crowded populated residential areas to prevent exposure to air pollutants emission from diesel generators and to protect public health.

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