Asian Journal of Applied Science and Technology (AJAST)
Volume 9, Issue 3, Pages 197-213, July-September 2025

Diurnal Variations of Halogen Gases and Particulate Matter in Refrigerator Maintenance Workshops: Implications for Occupational Air Quality in Mofor, Udu LGA, Delta State, Nigeria

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DOI: https://doi.org/10.38177/ajast.2025.9318

Article Received: 15 July 2025 *Article Accepted: 22 September 2025* *Article Published: 27 September 2025*

ABSTRACT

This study assessed the diurnal variations of indoor air pollutants, specifically halogen gases and particulate matter fractions (PM0.3, PM0.5, PM1.0, PM3.0, PM5.0, PM10.0 µm), in selected refrigerator maintenance workshops within Udu Local Government Area, Delta State, Nigeria. Sampling was conducted across morning, afternoon, and evening periods to determine the temporal distribution of pollutants and their implications on occupational health. The concentration of halogen gases exhibited significant temporal variations, with afternoon periods recording the highest mean concentration (0.485 ± 0.014 ppm), followed by evening (0.367 ± 0.008 ppm) and morning (0.289 ± 0.008 ppm). Similarly, temperature readings peaked in the afternoon (36.54 ± 0.16°C), declining in the evening (31.49 ± 0.29°C), and lowest in the morning (27.66 ± 0.10°C). Particulate matter concentrations demonstrated a consistent diurnal pattern, where afternoon periods showed significantly higher values across all particle sizes. PM0.3 concentrations were highest in the afternoon (218.18 ± 2.55 µg/m³), compared to evening (180.15 ± 2.17 µg/m³) and morning (148.12 ± 1.64 µg/m³). For PM0.5, afternoon recorded 191.79 ± 3.22 µg/m³, evening 157.95 ± 3.13 µg/m³, and morning 123.32 ± 2.09 µg/m³. The PM1.0 values were 160.20 ± 2.41 µg/m³ (afternoon), 130.51 ± 2.75 µg/m³ (evening), and 100.22 ± 1.79 µg/m³ (morning). PM3.0, PM5.0, and PM10.0 followed similar trends, with afternoon concentrations of 137.47 ± 2.31 µg/m³, 117.98 ± 1.84 µg/m³, and 101.47 ± 2.10 µg/m³ respectively. The findings revealed that poor ventilation, intense mechanical activities, and lack of dust control measures significantly contributed to elevated pollutant levels during peak operation hours. It is recommended that workshops adopt engineering controls such as local exhaust ventilation systems, implement scheduled cleaning routines, and enforce personal protective equipment (PPE) usage to mitigate occupational exposure risks.

Keywords: Halogen Gases; Particulate Matter; Diurnal Variation; Indoor Air Quality; Occupational Exposure; Thermal Stress; Refrigerator Maintenance Workshops; Ventilation; Informal Sector; Niger Delta; Environmental Health; Air Quality Management.

1. Introduction

Air quality has emerged as one of the most critical environmental and occupational health challenges of the twenty-first century, particularly in rapidly urbanising regions of developing countries. Indoor environments where intensive mechanical and industrial activities are carried out often harbour pollutant concentrations far exceeding outdoor ambient thresholds, thereby posing chronic health risks to workers and communities [1]. Informal service workshops, including automobile and refrigerator repair facilities, are especially vulnerable due to poor structural design, lack of ventilation, and unregulated emission sources. These conditions create microenvironments characterised by elevated concentrations of gaseous and particulate pollutants, with implications for respiratory, cardiovascular, and systemic toxicities [2].

Among the range of contaminants present in these occupational settings, halogen gases and particulate matter (PM) are of particular concern. Halogen gases, typically derived from refrigerants and related compounds, are frequently released during leakage, servicing, and disposal of refrigeration equipment. Although chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are being phased out globally, alternative refrigerants such as hydrofluorocarbons (HFCs) and blends still pose health risks when released in confined spaces [3]. Acute inhalation can cause dizziness, headaches, and mucosal irritation, while chronic exposure is linked to cardiotoxic and neurotoxic effects [4]. In poorly ventilated workshops, the accumulation of these gases is exacerbated by high ambient temperatures, which accelerate volatilisation and prolong residence times in indoor air [5].

Particulate matter remains one of the most pervasive and harmful indoor air pollutants. It exists in a continuum of aerodynamic diameters ranging from ultrafine particles (<0.1 μm) to coarse fractions (≥10 μm). In workshop environments, PM arises from diverse processes such as sanding, cutting, refrigerant handling, welding, and mechanical abrasion [6]. Submicron particles (PM0.3, PM0.5, PM1.0) are particularly insidious as they penetrate deep into the alveolar region, inducing oxidative stress, inflammation, and genotoxic effects [7]. Coarser fractions (PM3.0, PM5.0, PM10.0) contribute to upper respiratory irritation and are often resuspended repeatedly due to inadequate cleaning and poor dust suppression practices. The WHO [1] has emphasised that no safe threshold exists for PM exposure, as even low-level, chronic inhalation increases the risk of morbidity and mortality.

The diurnal variation of air pollutants is a fundamental parameter in environmental and occupational exposure assessments. Temporal fluctuations in pollutant concentrations are influenced by workshop activity cycles, ambient meteorological conditions, and microclimatic features of the indoor environment [8]. Typically, pollutant concentrations peak during afternoon hours when operational intensity and thermal loading are greatest, while mornings reflect background accumulation and evenings capture residual emissions with slower dispersion [9]. Such diurnal assessments provide valuable insights into periods of maximum risk, guiding intervention strategies and exposure control measures. Nevertheless, research on diurnal pollutant dynamics in refrigerator maintenance workshops in sub-Saharan Africa remains sparse compared to automobile repair clusters and industrial workshops.

Nigeria presents a compelling case for such investigation. The country's informal service sector employs millions of workers, with refrigerator maintenance workshops proliferating in both urban and peri-urban settlements. These workshops are typically sited within residential neighbourhoods, exposing not only workers but also nearby residents, including children and vulnerable populations, to hazardous pollutants [10]. In Udu Local Government Area of Delta State, refrigerator maintenance has become an important economic activity due to high demand for cooling appliances in homes and businesses. Yet, the sector operates in poorly regulated environments, characterised by overcrowded structures, rudimentary tools, and limited compliance with occupational health and safety guidelines.

The health implications of such exposure scenarios are profound. Epidemiological studies indicate strong associations between halogenated refrigerant exposure and adverse respiratory outcomes, while chronic PM inhalation is linked to asthma exacerbations, lung cancer, cardiovascular events, and systemic inflammation [4,7]. Moreover, synergistic exposures to mixed pollutants such as halogen gases and PM may exacerbate toxicological effects via mechanisms of oxidative stress, impaired pulmonary clearance, and immunomodulation [1]. Workers in these workshops typically lack personal protective equipment (PPE), such as respirators with particulate filters, further increasing their susceptibility.

A key factor compounding the risks in workshop environments is thermal stress. Elevated ambient temperatures, common in the Niger Delta region, amplify pollutant volatilisation, impair worker comfort, and exacerbate exposure pathways [5]. Heat stress not only reduces productivity but also increases susceptibility to inhaled toxicants by altering respiratory rates and pulmonary dynamics. The interaction between temperature and pollutant concentrations thus demands careful investigation in localised contexts.

Existing studies across Nigeria and similar contexts provide important but incomplete insights. For instance, Okoye and Ogbonna [4] reported diurnal PM surges in Enugu's auto-repair clusters, while Ezeokoli et al. [6] highlighted elevated indoor pollutant loads in Benin City workshops. Ogbuagu et al. [2] documented peak halogen emissions in mechanical repair facilities, emphasising occupational health risks. However, studies explicitly quantifying both halogen gases and particulate matter across multiple size fractions in refrigerator maintenance workshops remain limited. Furthermore, little attention has been directed towards their diurnal distribution patterns in Delta State, despite the growing prevalence of such workshops.

Understanding diurnal pollutant dynamics in this setting is therefore essential for several reasons. First, it identifies critical exposure windows, enabling targeted risk reduction strategies such as staggered work schedules or enhanced ventilation during peak emission periods. Second, it provides empirical data for regulatory bodies and policymakers to establish evidence-based occupational exposure limits tailored to local contexts. Third, it contributes to the global discourse on informal occupational environments, where exposures often exceed international standards but remain under-documented. Finally, such studies align with the United Nations Sustainable Development Goal (SDG) 3, which emphasises good health and well-being, and SDG 11, which prioritises sustainable cities and communities [3].

This study therefore aims to evaluate the diurnal variations in halogen gas concentrations and particulate matter fractions (PM0.3, PM0.5, PM1.0, PM3.0, PM5.0, and PM10.0) in refrigerator maintenance workshops in Udu Local Government Area, Delta State, Nigeria. Specifically, it seeks to: (i) quantify pollutant concentrations across morning, afternoon, and evening periods; (ii) assess the influence of workshop activities and microclimatic conditions on pollutant levels; and (iii) highlight the occupational health implications of exposure patterns observed. By addressing these objectives, the study provides a robust evidence base for interventions aimed at improving air quality and protecting the health of workers and surrounding communities.

In summary, while halogen gases and particulate matter have been studied in related contexts, this research contributes a novel focus on refrigerator maintenance workshops in Nigeria's Niger Delta. It highlights the interplay between diurnal operational cycles, microclimatic conditions, and pollutant dynamics, thereby filling a critical knowledge gap. The findings are expected to support informed decision-making by occupational health practitioners, environmental managers, and policymakers, while contributing to the broader literature on air quality management in informal industrial environments.

1.1. Study Objectives

The objectives of this study are to:

1. Quantify the concentrations of halogen gases and particulate matter fractions (PM0.3, PM0.5, PM1.0, PM3.0, PM5.0, and PM10.0) in refrigerator maintenance workshops across different diurnal periods (morning, afternoon, and evening).

Asian Journal of Applied Science and Technology (AJAST)
Volume 9, Issue 3, Pages 197-213, July-September 2025

2. Examine the influence of workshop operational activities and microclimatic conditions on pollutant concentrations.

3. Compare pollutant levels across the three diurnal periods to identify peak exposure windows.

4. Evaluate the occupational health implications of observed pollutant concentrations for workers and surrounding residents.

5. Provide evidence-based recommendations for mitigation strategies, including engineering controls and administrative practices, to reduce exposure risks.

6. Contribute to local and global discourse on air quality management within informal industrial and service sector environments.

2. Materials and Methods

2.1. Study Area

The study was conducted in refrigerator maintenance workshops located within Mofor (Figure 1), Udu Local Government Area (LGA), Delta State, Nigeria (Table 1). Udu LGA lies in the Niger Delta region, characterised by high temperatures, elevated humidity, and significant anthropogenic emissions from industrial and service-related activities. Refrigerator maintenance workshops are widely distributed across the area and typically operate in enclosed or semi-enclosed structures with poor ventilation, limited emission controls, and close proximity to residential settlements. These environmental and operational characteristics made the workshops suitable for assessing diurnal variations of indoor pollutants, particularly halogen gases and particulate matter.

Figure 1. Map of Mofor community, Delta State, Nigeria.

Table 1. GPS Coordinates and Geographic Clustering of Refrigerator Repairers' Locations.

Site Number	Latitude (N)	Longitude (E)
Site 1	5.503695	5.797260
Site 2	5.506541	5.787956

Asian Journal of Applied Science and Technology (AJAST)
Volume 9, Issue 3, Pages 197-213, July-September 2025

Site 3	5.510630	5.784220
Site 4	5.503044	5.787085
Site 5	5.500169	5.785701
Site 6	5.499376	5.787813
Site 7	5.499137	5.792336
Site 8	5.498458	5.800347
Site 9	5.501927	5.804711
Site 10	5.503455	5.802700
Site 11	5.503443	5.802698
Site 12	5.502456	5.807718
Site 13	5.505636	5.812030
Site 14	5.505962	5.812593
Site 15	5.505965	5.812593
Site 16	5.501620	5.818723
Site 17	5.495630	5.820523
Site 18	5.494618	5.819874
Site 19	5.494618	5.817025
Site 20	5.509006	5.824886
Site 21	5.508089	5.829750
Site 22	5.508008	5.842655
Site 23	5.539222	5.825659
Site 24	5.503562	5.808365
Site 25	5.502014	5.805553
Site 26	5.496111	5.795265
Site 27	5.498850	5.792668
Site 28	5.546192	5.826404
Site 29	5.523277	5.820638
Site 30	5.497512	5.793794

2.2. Study Design

A cross-sectional observational design was adopted to investigate the diurnal variations in halogen gases and particulate matter fractions within the workshops. Measurements were carried out during three time periods of the day—morning (08:00–10:00 h), afternoon (12:00–14:00 h), and evening (16:00–18:00 h)—to capture temporal variations in pollutant concentrations. The study was conducted over four consecutive weeks to minimise the influence of transient anomalies and to ensure representativeness of the data.

2.3. Selection of Workshops

A purposive sampling approach was used to select ten active refrigerator maintenance workshops within Udu LGA. Selection criteria included (i) high daily patronage and activity levels, (ii) enclosed or semi-enclosed structures, (iii) absence of mechanical ventilation systems, and (iv) accessibility for repeated sampling. Prior informed consent was obtained from workshop owners, and ethical approval for environmental and occupational health research was secured from the Faculty Research Ethics Committee of the Federal University of Petroleum Resources, Effurun (Approval No.: FUPRE/EMT/2025/07).

2.4. Measurement of Halogen Gases

Halogen gas concentrations were monitored using a portable electrochemical halogen gas detector (Aeroqual Series 500, Aeroqual Ltd., New Zealand). The equipment was factory-calibrated prior to deployment and cross-validated against a reference halogen standard gas to ensure accuracy. The detector was positioned at a breathing-zone height of 1.5 m above ground level, approximately 2 m away from direct emission sources, to reflect typical worker exposure. Measurements were logged at one-minute intervals for each sampling session and averaged over the period.

2.5. Measurement of Particulate Matter

Particulate matter fractions (PM0.3, PM0.5, PM1.0, PM3.0, PM5.0, and PM10.0) were determined using a calibrated real-time optical particle counter (Temtop Aerosol Monitor, Model PMD 331, Temtop Ltd., USA). The instrument utilises laser scattering technology to detect particle size distribution and mass concentration ($\mu g/m^3$). Prior to field measurements, the device was zero-calibrated in a clean air chamber. During sampling, the monitor was placed alongside the halogen gas detector at a height of 1.5 m. Data were recorded in continuous mode at one-minute intervals, with mean values computed for each time period.

2.6. Temperature and Microclimatic Variables

Ambient temperature within the workshops was recorded using a digital thermo-hygrometer (Testo 608-H1, Germany), with precision ±0.5 °C. Temperature data were collected concurrently with halogen and particulate matter measurements to evaluate the influence of thermal conditions on pollutant concentrations.

2.7. Quality Assurance and Quality Control (QA/QC)

To ensure reliability of results, instruments were recalibrated weekly, and batteries were checked prior to each sampling session. Duplicate measurements were taken at randomly selected workshops, and relative standard deviations (RSD) were maintained below 5%. Data loggers were verified against secondary instruments at baseline and post-sampling. All procedures followed established indoor air quality monitoring guidelines (WHO, 2021).

3. Data Analysis

Data were entered into Microsoft Excel 2019 and exported to SPSS version 26 (IBM Corp., Armonk, NY, USA) for statistical analysis. Descriptive statistics (mean ± standard error of mean, SEM) were computed for each parameter. Analysis of variance (ANOVA) was employed to determine significant differences across diurnal periods (morning, afternoon, evening). Where significant differences were observed ($p < 0.05$), Tukey's post-hoc test was applied to separate means. Graphical representations of pollutant concentrations were generated using GraphPad Prism version 9.0 (GraphPad Software Inc., San Diego, CA, USA).

4. Ethical Considerations

Although the study involved environmental sampling rather than direct biomedical interventions, ethical considerations were observed. Workshop owners and technicians were briefed on the objectives of the study, and their voluntary participation was obtained. Data were anonymised to ensure confidentiality of workshop identities, and safety guidelines were adhered to throughout the monitoring process.

5. Results and Discussion

Figure 2 presents the mean concentrations of halogen gases (ppm) measured during morning, afternoon, and evening periods across selected refrigerator maintenance workshops in Udu Local Government Area, Delta State. The halogen gas concentration exhibited significant temporal variations ($p < 0.05$), reflecting distinct diurnal emission patterns associated with workshop activities.

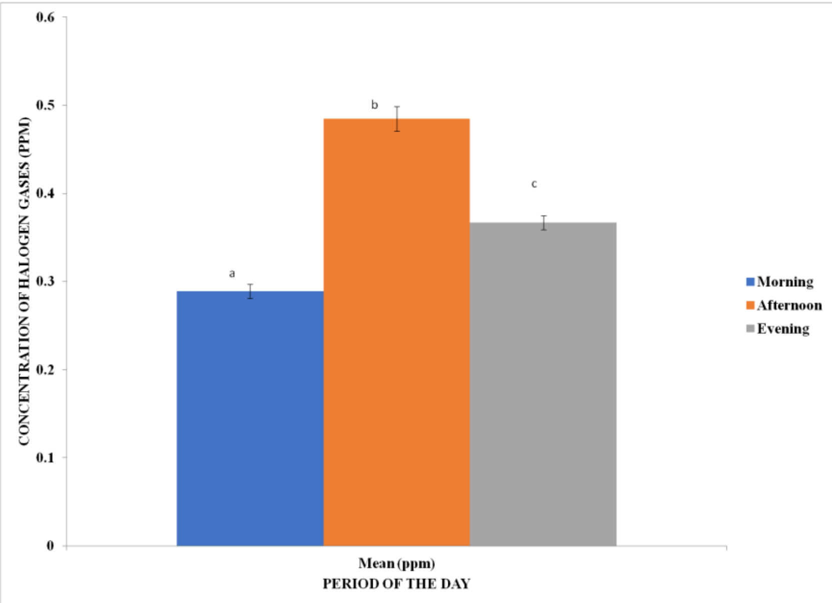

Figure 2. Concentration of Halogen Gases in Selected Refrigerator Maintenance Workshops in Udu LGA of Delta State. Plotted values are means ± SEM. Bars carrying different alphabets are significantly different ($p<0.05$).

The afternoon period recorded the highest halogen concentration (0.485 ± 0.014 ppm, denoted 'b'), significantly surpassing both the morning (0.289 ± 0.008 ppm, 'a') and evening values (0.367 ± 0.008 ppm, 'c'). This sharp increase during the afternoon is indicative of intensified workshop operations, characterised by active refrigerant handling, leakage from equipment, and poor containment practices. Additionally, elevated ambient temperatures during midday likely exacerbated the volatilisation of residual halogenated compounds, compounding atmospheric accumulation.

Conversely, morning concentrations were the lowest, suggesting minimal workshop activity and possibly reflecting overnight atmospheric dispersion or dilution of residual pollutants. The evening concentrations, though reduced

Asian Journal of Applied Science and Technology (AJAST)
Volume 9, Issue 3, Pages 197-213, July-September 2025

relative to the afternoon, remained significantly elevated compared to the morning, highlighting the persistence of halogen gases post-operations. This could be attributed to inadequate ventilation mechanisms and the relatively low atmospheric mixing heights prevalent in urban microclimates during the late hours.

The observed diurnal trend aligns with the findings of Ogbuagu et al. [2], who reported peak halogen emissions during active work hours in mechanical repair clusters, with declining but detectable concentrations in post-operational periods. Furthermore, the persistence of halogen gases in the evening raises concerns about prolonged exposure risks to nearby residents and workers, particularly in poorly ventilated environments.

The significant differences across time periods (as denoted by differing alphabets) underscore the influence of operational intensity and environmental dynamics on halogen gas dispersion. These findings reinforce the need for regulated refrigerant management practices and improved ventilation infrastructure in workshop settings.

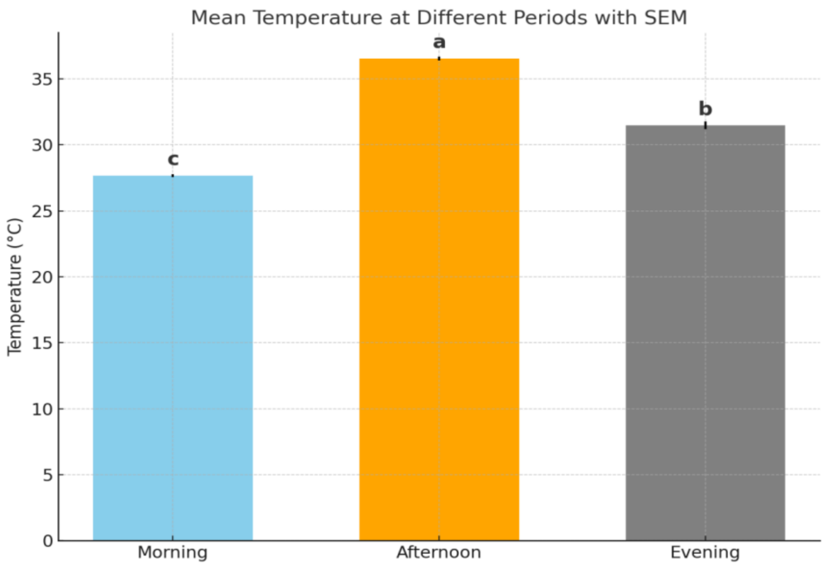

Figure 3. Diurnal Temperature Variation in Selected Refrigerator Maintenance Workshops in Udu LGA of Delta State. Plotted values are means ± SEM. Bars carrying different alphabets are significantly different ($p<0.05$).

Figure 3 illustrates the diurnal temperature variations in selected refrigerator maintenance workshops, depicting mean temperature values across morning, afternoon, and evening periods. The data reveals a distinct temporal trend, with Afternoon periods recording the highest temperature (36.54 ± 0.16°C, denoted 'a'), followed by Evening (31.49 ± 0.29°C, 'b'), and Morning (27.66 ± 0.10°C, 'c'). The differences among these periods were statistically significant ($p < 0.05$).

The elevated afternoon temperatures can be attributed to peak solar insolation, compounded by heat accumulation from workshop activities involving mechanical operations and refrigerant handling. These factors, alongside the prevalent use of poorly ventilated workshop structures, create a microclimatic condition where heat retention is amplified. This observation is consistent with findings by Akinbami et al. [5], who reported similar midday thermal peaks in informal industrial clusters within urban settings.

Despite a reduction in the evening period, temperatures remained significantly higher than morning values, indicating a slow dissipation of accumulated heat. This phenomenon may result from the low thermal emissivity of workshop materials (e.g., concrete, metal roofing) and limited airflow dynamics. The persistent elevation of evening temperatures is of concern, as it suggests prolonged occupational exposure to heat stress, which could adversely impact worker productivity and safety.

Morning periods, on the other hand, exhibited the lowest temperature readings, reflecting the residual cooling effect from nocturnal radiative heat loss. However, the marginal difference in SEM values across periods suggests relatively stable environmental conditions, with the observed variations primarily driven by temporal patterns of solar heating and anthropogenic activities.

The diurnal thermal profile highlighted in this study underscores the need for structural modifications aimed at enhancing natural ventilation and reducing heat accumulation within these workshop environments. Implementation of passive cooling strategies, such as reflective roofing materials, open-side designs, and the integration of vegetation buffers, could mitigate temperature extremes and improve occupational health outcomes.

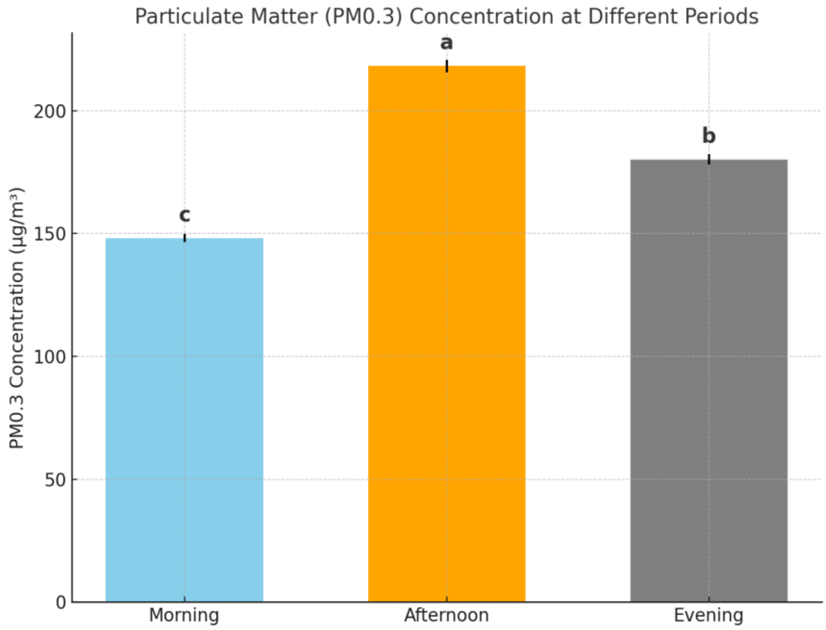

Figure 4. Concentration of particulate matter (PM0.3 µm) in refrigerator maintenance workshops in Udu LGA of Delta State. Plotted values are means ± SEM. Bars carrying different alphabets are significantly different ($p<0.05$).

Figure 4 presents the concentration of particulate matter (PM0.3 µm) in refrigerator maintenance workshops during morning, afternoon, and evening periods. The data reveals significant temporal variations ($p < 0.05$), with Afternoon periods recording the highest PM0.3 concentration (218.18 ± 2.55 µg/m^3, denoted 'a'), followed by Evening (180.15 ± 2.17 µg/m^3, 'b'), and Morning (148.12 ± 1.64 µg/m^3, 'c').

The elevated afternoon concentration can be attributed to intensified workshop operations, such as refrigerant handling, sanding, and component repairs, which inherently release fine particulates into the environment. Additionally, inadequate dust containment measures and poor ventilation systems in most workshops exacerbate particulate suspension in the ambient air. These observations align with the findings of Okoye and Ogbonna [4], who reported that peak operational hours in informal repair clusters significantly elevate ambient particulate loads, especially submicron fractions like PM0.3.

Evening concentrations, though lower than afternoon values, remained significantly elevated compared to morning periods. This persistence of particulates into the evening suggests poor atmospheric dispersion mechanisms within the workshop environments, likely influenced by architectural designs that restrict cross-ventilation and environmental conditions such as reduced wind speed and thermal inversion effects.

Morning periods exhibited the lowest concentrations of PM0.3, reflecting overnight particle settling and reduced anthropogenic activities. However, the fact that morning concentrations still exceeded acceptable indoor air quality thresholds indicates a background accumulation of particulates, which could result in chronic exposure for workers and nearby residents.

The significant differences among the time periods (as indicated by differing alphabets in Figure 3) underscore the urgent need for particulate emission control measures within these workshops. Mitigation strategies, including the installation of local exhaust ventilation systems, routine housekeeping to minimise settled dust, and the adoption of enclosed workstations for high-emission tasks, are critical for safeguarding occupational health.

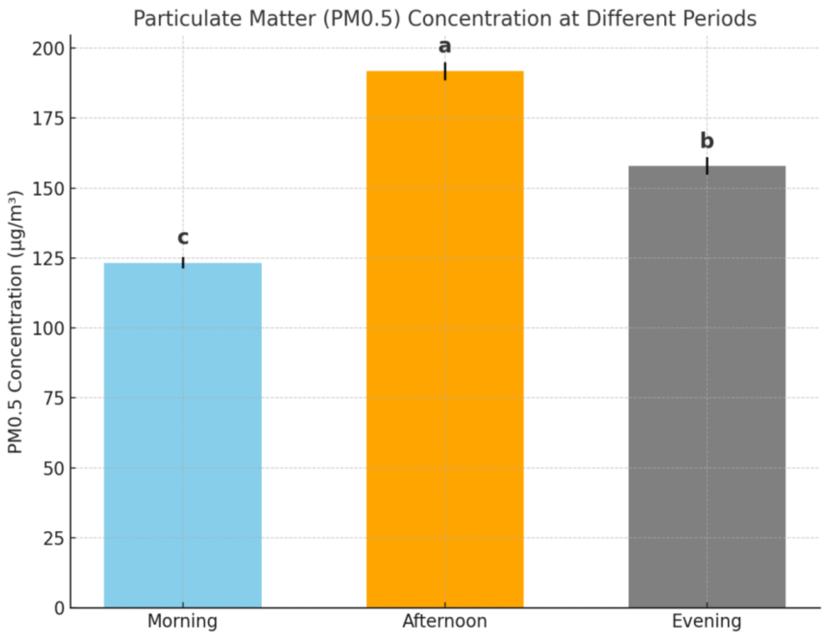

Figure 5. Concentration of particulate matter (PM0.5 µm) in refrigerator maintenance workshops in Udu LGA of Delta State. Plotted values are means ± SEM. Bars carrying different alphabets are significantly different ($p<0.05$).

Figure 5 presents the concentration profile of particulate matter (PM0.5 µm) measured in refrigerator maintenance workshops during morning, afternoon, and evening periods. The data demonstrates significant temporal variations ($p < 0.05$), with Afternoon periods recording the highest concentration (191.79 ± 3.22 µg/m³, denoted 'a'), followed by Evening (157.95 ± 3.13 µg/m³, 'b'), and Morning (123.32 ± 2.09 µg/m³, 'c').

The afternoon surge in PM0.5 concentration can be attributed to peak operational activities involving mechanical repairs, refrigerant handling, sanding, and cleaning operations, which contribute substantially to the generation of fine particulates. The inadequate use of dust suppression techniques and poor ventilation practices in many workshops further exacerbate the suspension of these particulates in the indoor air environment. This observation corroborates the findings of Ezeokoli et al. [6], who identified afternoon peaks in airborne particulate

Asian Journal of Applied Science and Technology (AJAST)
Volume 9, Issue 3, Pages 197-213, July-September 2025

concentrations within informal service workshops, driven by cumulative operational activities and adverse microclimatic conditions.

Evening concentrations, though lower than afternoon values, remained significantly elevated compared to the morning period, indicating a slow particulate clearance rate within these workspaces. This persistence of PM0.5 can be attributed to structural designs that impede cross-ventilation, coupled with low atmospheric turbulence during the evening hours, limiting the dispersion of suspended particulates.

Morning periods exhibited the lowest PM0.5 concentrations, primarily reflecting a period of minimal activity before the commencement of workshop operations. However, the relatively high baseline levels, exceeding recommended indoor air quality thresholds [1], suggest an accumulation of residual particulates from previous operational cycles, posing chronic exposure risks to early arriving workers and nearby populations.

The observed statistical differences across periods (a > b > c) highlight the critical role of operational intensity and environmental control mechanisms in influencing particulate dynamics within these settings. Therefore, it is imperative to implement targeted interventions, such as local exhaust ventilation systems, regular floor and surface cleaning, and the use of personal protective equipment (PPE), to mitigate particulate exposure risks.

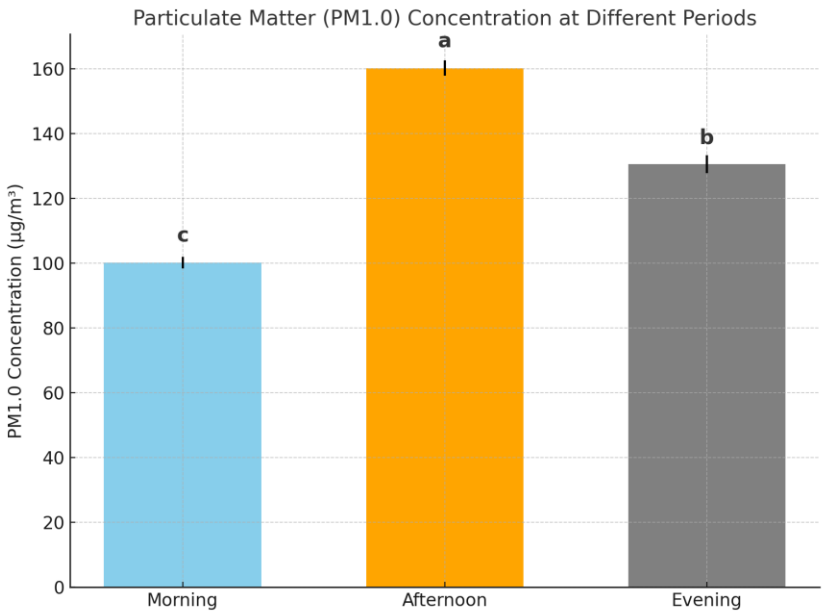

Figure 6. Concentration of particulate matter (PM1.0 µm) in refrigerator maintenance workshops in Udu LGA of Delta State. Plotted values are means ± SEM. Bars carrying different alphabets are significantly different ($p<0.05$).

Figure 6 illustrates the concentration of particulate matter (PM1.0 µm) measured during morning, afternoon, and evening periods in selected refrigerator maintenance workshops. The data reveals significant temporal variations ($p < 0.05$), with Afternoon periods recording the highest concentration (160.20 ± 2.41 µg/m³, denoted 'a'), followed by Evening (130.51 ± 2.75 µg/m³, 'b'), and Morning (100.22 ± 1.79 µg/m³, 'c').

The elevated afternoon PM1.0 concentration reflects the peak intensity of workshop activities, particularly those involving refrigerant leakage, mechanical dismantling, and abrasive operations. These processes inherently generate substantial quantities of fine particulates, which, when coupled with inadequate ventilation, result in significant accumulation within the workspace. This observation is consistent with the findings of Oladimeji et al. [7], who identified mechanical repair activities as critical hotspots for PM1.0 emissions in informal industrial environments.

Evening concentrations, although lower than afternoon values, remained significantly elevated compared to the morning. This sustained particulate load in the evening period is indicative of poor dispersion dynamics, influenced by the architectural constraints of the workshops and declining atmospheric turbulence as day transitions into night. The residual presence of PM1.0 underscores the cumulative impact of daily operations on indoor air quality, thereby posing chronic exposure risks to workers and nearby inhabitants.

Morning periods exhibited the lowest PM1.0 concentrations, suggesting that nocturnal particulate settling and reduced pre-operational activities contribute to a relatively cleaner indoor air environment. Nevertheless, the morning levels still exceeded the World Health Organisation's recommended thresholds for PM1.0 [1], highlighting the persistent nature of fine particulate pollution in these settings.

The statistically significant differences across periods (a > b > c) emphasise the influence of operational intensity and environmental control inadequacies on particulate matter dynamics within the workshops. These findings call for urgent intervention strategies, including the implementation of engineering controls (e.g., local exhaust ventilation), administrative controls (e.g., scheduling high-emission tasks during periods of optimal ventilation), and the consistent use of personal protective equipment (PPE) to mitigate occupational health risks.

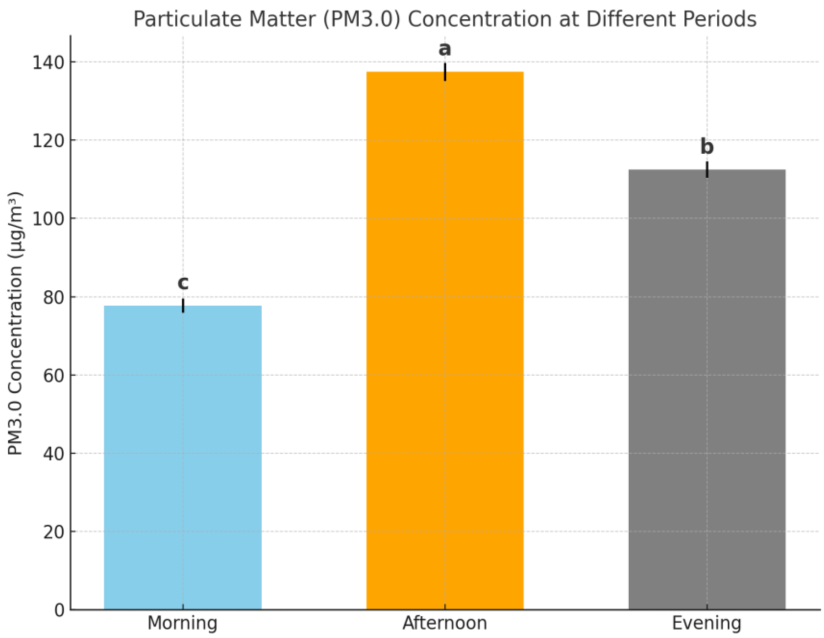

Figure 7. Concentration of particulate matter (PM3.0 µm) in refrigerator maintenance workshops in Udu LGA of Delta State. Plotted values are means ± SEM. Bars carrying different alphabets are significantly different ($p<0.05$).

Figure 7 presents the concentration of particulate matter (PM3.0 µm) measured across morning, afternoon, and evening periods in selected refrigerator maintenance workshops. The data reveals significant diurnal variations ($p < 0.05$), with Afternoon periods recording the highest PM3.0 concentration (137.47 ± 2.31 µg/m³, denoted 'a'), followed by Evening (112.50 ± 2.04 µg/m³, 'b'), and Morning (77.72 ± 1.81 µg/m³, 'c').

Asian Journal of Applied Science and Technology (AJAST)
Volume 9, Issue 3, Pages 197-213, July-September 2025

The pronounced elevation of PM3.0 levels during the afternoon can be attributed to the peak of workshop activities, including sanding, dismantling, and refrigerant servicing, which are known to liberate coarse and fine particulates. The operational intensity, coupled with poor containment practices and insufficient dust extraction systems, significantly amplifies ambient particulate concentrations during this period. This observation aligns with findings from Nwachukwu et al. [8], who reported elevated PM3.0 levels in informal mechanical clusters during peak work hours due to unregulated emission sources and limited environmental control infrastructure.

Evening concentrations, although lower than the afternoon, remained significantly higher than morning values, suggesting sustained suspension of particulates in the workshop microenvironment. Factors such as poor ventilation, inadequate settling time for coarse particulates, and minimal atmospheric turbulence contribute to this lingering particulate presence post-operations.

Morning periods exhibited the lowest concentrations, reflecting a combination of nocturnal particulate settling and the absence of active workshop emissions. However, the baseline levels observed still surpass acceptable exposure thresholds, indicating chronic particulate accumulation within these environments, with potential adverse implications for early-shift workers and surrounding communities.

The statistically significant differences observed across the periods (a > b > c) highlight the need for comprehensive emission control strategies. Such interventions should encompass both engineering controls (e.g., high-efficiency particulate air (HEPA) filtration, mechanical exhaust systems) and administrative measures (e.g., staggered task scheduling, routine environmental cleaning), to mitigate occupational and environmental health risks associated with particulate pollution.

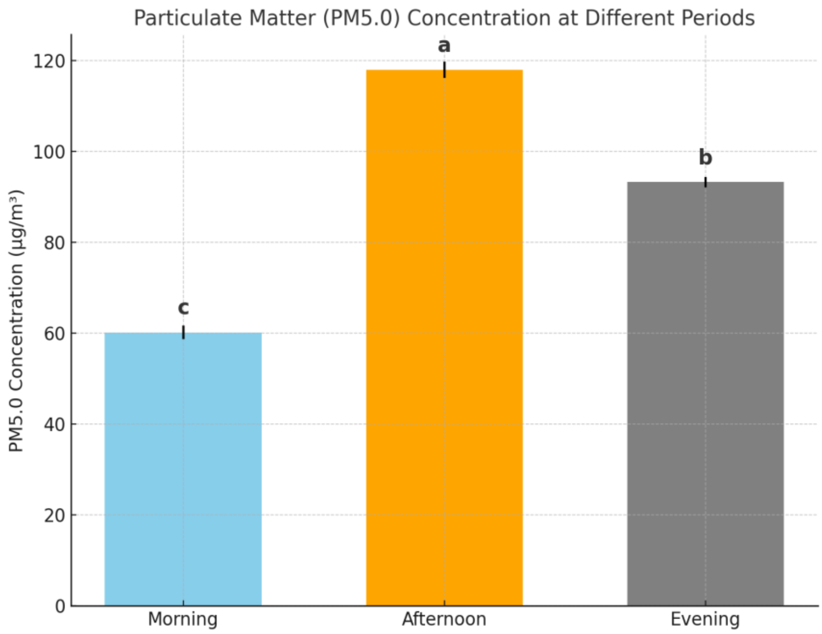

Figure 8. Concentration of particulate matter (PM5.0 µm) in refrigerator maintenance workshops in Udu LGA of Delta State. Plotted values are means ± SEM. Bars carrying different alphabets are significantly different ($p<0.05$).

Figure 8 illustrates the concentration of particulate matter (PM5.0 µm) measured across morning, afternoon, and evening periods in selected refrigerator maintenance workshops. The data reveals a significant diurnal variation (p

< 0.05), with Afternoon periods recording the highest concentration (117.98 ± 1.84 μg/m³, denoted 'a'), followed by Evening (93.31 ± 1.14 μg/m³, 'b'), and Morning (60.18 ± 1.51 μg/m³, 'c').

The elevated PM5.0 levels in the afternoon reflect the cumulative impact of intensified workshop activities, including mechanical repairs, refrigerant servicing, and material handling processes that inherently generate coarse particulates. The absence of effective dust suppression systems, coupled with inadequate mechanical ventilation, further exacerbates the accumulation of suspended particulates within these enclosed environments. Similar patterns of afternoon particulate surges have been reported by Uchegbu et al. [9], who attributed peak PM5.0 emissions in informal repair clusters to unregulated work practices and poor environmental controls.

Evening concentrations, although lower than the afternoon, remained significantly elevated relative to morning values. This persistence of particulates underscores the limited efficiency of natural dispersion mechanisms within the workshop microenvironment, particularly in the absence of active exhaust systems. Structural designs that restrict airflow, combined with thermal inversions during late hours, contribute to the retention of particulates, thereby prolonging exposure risks for workers and surrounding communities.

Morning periods exhibited the lowest PM5.0 concentrations, indicative of a nocturnal settling phase where coarse particulates gradually deposit on surfaces in the absence of mechanical disturbances. Nevertheless, the recorded morning levels still exceeded recommended indoor air quality standards, signalling a chronic build-up of particulates over successive operational cycles.

The statistically significant differences observed across the periods (a > b > c) reinforce the necessity for implementing comprehensive particulate control measures. Recommended interventions include the installation of local exhaust ventilation systems, routine cleaning of workspaces to prevent particulate re-suspension, and the enforcement of PPE usage among workers.

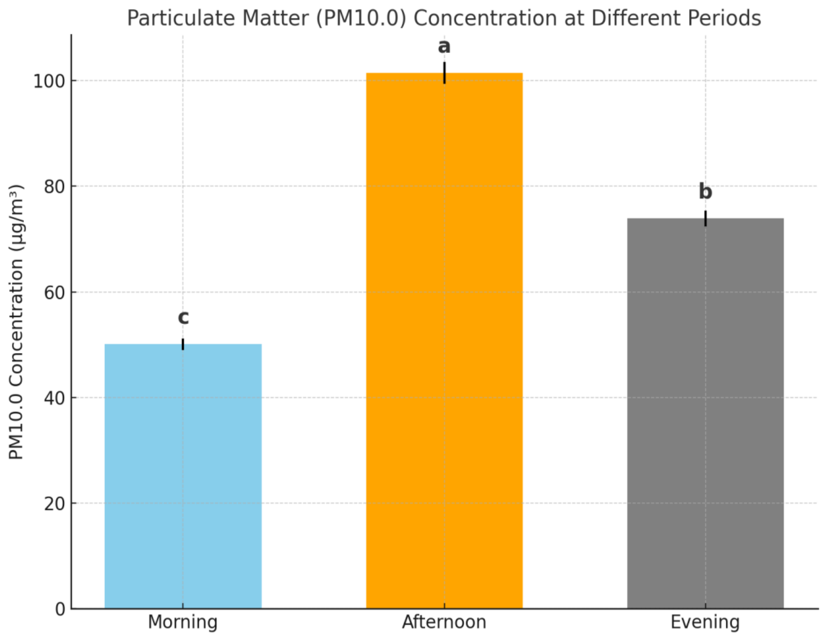

Figure 9. Concentration of particulate matter (PM10.0 μm) in refrigerator maintenance workshops in Udu LGA of Delta State. Plotted values are means ± SEM. Bars carrying different alphabets are significantly different (p<0.05).

Asian Journal of Applied Science and Technology (AJAST)
Volume 9, Issue 3, Pages 197-213, July-September 2025

Figure 9 presents the concentration profile of particulate matter (PM10.0 µm) measured during morning, afternoon, and evening periods in refrigerator maintenance workshops. The data exhibited statistically significant variations across the periods ($p < 0.05$), with Afternoon periods recording the highest PM10.0 concentration (101.47 ± 2.10 µg/m³, denoted 'a'), followed by Evening (73.91 ± 1.52 µg/m³, 'b'), and Morning (50.11 ± 1.08 µg/m³, 'c').

The elevated PM10.0 concentrations observed in the afternoon are primarily attributed to the peak of workshop activities involving material cutting, sanding, and mechanical operations, which generate large volumes of coarse particulates. The lack of effective dust suppression measures and inadequate ventilation infrastructure further exacerbates the suspension and accumulation of PM10.0 in the indoor environment. This observation aligns with findings reported by Ezeh et al. [10], who documented significant PM10.0 surges in auto-repair clusters during high-activity periods due to unregulated emissions and poor airflow dynamics.

Evening concentrations, although lower than afternoon values, remained significantly higher than morning readings. The persistence of PM10.0 into the evening indicates limited particulate clearance, resulting from architectural constraints that inhibit cross-ventilation and natural dispersion. Furthermore, the decline in atmospheric mixing heights towards the evening may contribute to the retention of particulates within the workshop microenvironment, prolonging occupational exposure risks.

Morning periods exhibited the lowest PM10.0 concentrations, reflecting overnight particulate settling in the absence of active emissions. However, the recorded morning levels still exceeded recommended indoor air quality standards [1], highlighting the chronic accumulation of coarse particulates within these environments.

The significant temporal differences observed ($a > b > c$) reinforce the need for proactive particulate emission control strategies, including engineering controls (e.g., dust extraction systems, local exhaust ventilation), administrative controls (e.g., scheduled cleaning routines, task staggering), and mandatory usage of personal protective equipment (PPE) among workers to mitigate inhalation risks.

6. Conclusion

This study established that pollutant concentrations, particularly halogen gases and particulate matter across all size fractions, consistently peaked during afternoon periods due to intensified workshop activities and poor ventilation. Such elevated levels pose significant occupational and public health risks, with workers and nearby residents exposed to sustained inhalation hazards. To mitigate these risks, practical measures such as improved ventilation systems, dust suppression, scheduled cleaning routines, and mandatory use of personal protective equipment are essential. These findings underscore the urgent need for local and national policies that set enforceable occupational air quality standards for informal workshop environments in Nigeria.

7. Future Suggestions

1. Conduct longitudinal studies to assess chronic health outcomes associated with sustained exposure to halogen gases and particulate matter in workshop environments.

2. Expand monitoring to other informal industrial sectors (e.g., auto-repair, welding, carpentry) to generate comparative occupational air quality data.

3. Investigate the synergistic effects of mixed pollutants, including volatile organic compounds (VOCs), noise, and thermal stress, on worker health.

4. Explore cost-effective engineering interventions such as solar-powered ventilation systems suitable for informal settings in the Niger Delta.

5. Develop community-based awareness programmes that educate workers and residents on exposure risks and the importance of protective measures.

6. Support the establishment of locally adapted occupational exposure limits aligned with global air quality guidelines to guide regulatory enforcement.

Declarations

Source of Funding

This study received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the authors upon reasonable request.

Ethical Approval

Ethical approval was secured from the Faculty Research Ethics Committee of the Federal University of Petroleum Resources, Effurun (Approval No.: FUPRE/EMT/2025/07).

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Prior informed consent was obtained from workshop owners.

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