International Journal of Ecology and Environmental Sciences
www.ecologyjournal.in
Online ISSN: 2664-7133
Received: 26-11-2025, Accepted: 25-12-2025, Published: 09-01-2026
Volume 8, Issue 1, 2026, Page No. 9-17

Integrated assessment of occupational air quality exposure and safety regulation compliance among petroleum tanker drivers in Warri–Uvwie, Delta State, Nigeria

Adeyemi Oyeyemi[1, 2*], Otofia, Edafe[1]
[1] Department of Environmental Management and Toxicology, Federal University of Petroleum Resources, Effurun, Nigeria
[2] Department of Biochemistry, Federal University of Petroleum Resources, Effurun, Nigeria

Abstract
This study investigated the integrated assessment of health, safety regulation adherence and air quality exposure among petroleum tanker drivers in uvwie and Warri environs, Delta State, to evaluate the link between occupational safety compliance and environmental exposure in Nigeria's downstream petroleum sector. Environmental monitoring was conducted for 14 consecutive days across three tanker parks (Tanker Parks 1–3), complemented by a structured questionnaire administered to 114 respondents. Results revealed that fine particulates ($PM_{0.5}$ and $PM_{1.0}$) dominated the air profile, with mean concentrations ranging from 9.27 to 9.45 µg/m³ for $PM_{0.5}$ and approximately 5.02 µg/m³ for $PM_{1.0}$, while PM_{10} averaged 0.20–0.28 µg/m³. Gaseous pollutants were also prevalent, including CO_2 (443–453 ppm), TVOC (0.021–0.022 mg/m³), and formaldehyde (0.0019–0.0024 mg/m³). Despite these values falling within permissible limits, prolonged exposure poses latent health risks. The weighted Air Quality Index (AQI) values of 3.52, 3.33, and 3.58 across the three sites were classified as Excellent, though this masked localised exposure differentials. Microclimatic data showed mean temperatures between 31°C and 36°C, relative humidity of 58–68 %, and noise levels of 61–70 dB(A)—exceeding WHO's recommended limit of 55 dB(A). Questionnaire analysis revealed moderate adherence to safety regulations: exposure frequency averaged 2.75 ± 0.26, monitoring frequency 2.20 ± 0.27, and environmental awareness 1.8 ± 0.2, indicating suboptimal supervision. Correlation analysis showed strong positive relationships between CO_2 and exposure frequency ($r = 0.88$), while TVOC correlated negatively ($r = -0.63$), confirming the influence of ventilation and monitoring on pollutant accumulation. ANOVA and Tukey post-hoc tests ($p > 0.05$) revealed no significant inter-park differences, confirming environmental and behavioural uniformity. In conclusion, petroleum tanker operations in Warri and Uvwie expose workers to chronic low-level air pollutants and physical stressors under consistent but moderate safety conditions. The study recommends integrated environmental surveillance, emission control, periodic medical screening, and enhanced regulatory coordination to reduce cumulative occupational risks.

Keywords: Occupational air quality, petroleum tanker drivers, safety regulation compliance, particulate matter exposure, downstream petroleum sector

Introduction

Occupational environments within the downstream petroleum sector present complex and often under-recognised health and safety challenges, particularly in low- and middle-income countries where regulatory enforcement and environmental monitoring are inconsistently applied (Anígilájé *et al.*, 2024) [6]. Petroleum tanker drivers constitute a critical workforce in this sector, operating at the interface of fuel transportation, storage, and distribution (Amoadu & Akoto-Buabeng, 2025) [4]. Their daily activities expose them simultaneously to traffic-related emissions, fuel vapours, suspended particulate matter, elevated noise levels, and adverse microclimatic conditions, all of which may act synergistically to increase occupational health risks (Amoadu *et al.*, 2024) [5]. Despite their central role in sustaining energy supply chains, the occupational environment of tanker drivers remains inadequately characterised in empirical research, especially within rapidly urbanising petroleum-producing regions (Mustapha *et al.*, 2024) [24].

Air quality within tanker parks and loading bays is shaped by multiple emission sources, including idling engines, fuel transfer operations, poor vehicular maintenance, and limited dispersion due to infrastructural constraints (Adebiyi *et al.*, 2024; Jindamanee *et al.*, 2025) [1, 19]. Fine and ultrafine particulate matter are of particular concern, as their small aerodynamic diameters facilitate deep penetration into the respiratory tract, enabling systemic distribution and long-term physiological effects. In addition to particulates, tanker drivers are routinely exposed to gaseous pollutants such as carbon dioxide, volatile organic compounds, and aldehydes released during fuel handling (Sandström *et al.*, 2024) [32]. Although these pollutants may individually occur at concentrations below established regulatory thresholds, chronic low-level exposure, coupled with extended working hours and inadequate recovery periods, may predispose workers to cumulative health burdens that are not readily captured by short-term compliance assessments (Fox *et al.*, 2021) [16].

Occupational exposure in tanker operations is further compounded by physical stressors, including excessive noise, thermal discomfort, and high relative humidity (Smallcombe *et al.*, 2022) [34]. Noise generated from heavy-duty engines, compressors, and surrounding traffic often exceeds recommended occupational limits, contributing to auditory strain, fatigue, and reduced situational awareness (Kanu *et al.*, 2025) [20]. Elevated ambient temperatures and humidity, characteristic of tropical coastal environments, exacerbate physiological stress and may impair concentration and reaction time, thereby increasing the likelihood of occupational accidents (Chowdhury *et al.*, 2024) [9]. These environmental conditions underscore the need for integrated exposure assessments that extend beyond single-pollutant evaluations (Tota *et al*., 2024) [36].

Regulatory frameworks governing occupational health, safety practices, and environmental protection exist within Nigeria's petroleum sector; however, the effectiveness of these frameworks is largely dependent on enforcement, monitoring frequency, and worker awareness (Ewim *et al*., 2023) [14]. In practice, safety regulation adherence among tanker drivers is often influenced by informal operational structures, economic pressures, limited access to personal protective equipment, and inadequate institutional oversight (Fonseca & Ferreira, 2025) [15]. Behavioural factors such as risk perception, compliance culture, and training also play critical roles in shaping exposure patterns and health outcomes (Donkor *et al*., 2023) [11]. Consequently, assessing safety regulation adherence alongside environmental exposure provides a more realistic appraisal of occupational risk than evaluating either dimension in isolation (Okan & Gümüş, 2025) [26].

The Warri–Uvwie industrial corridor in Delta State represents a strategically important downstream petroleum hub, characterised by intense tanker traffic, high population density, and proximity to residential communities (Orduvwe *et al*., 2025) [27]. This setting presents a unique convergence of occupational, environmental, and public health concerns (Nanadeinboemi *et al*., 2024) [25]. Tanker parks in this region function not only as operational spaces for drivers but also as micro-environments where prolonged human presence coincides with sustained pollutant generation (Sultana *et al*., 2023) [35]. Understanding the spatial and operational characteristics of these environments is essential for identifying exposure hotspots and intervention priorities (Wang *et al*., 2025) [38].

Against this background, the present study was designed to provide an integrated assessment of air quality exposure, microclimatic conditions, and safety regulation adherence among petroleum tanker drivers operating in the Warri and Uvwie environs of Delta State. By combining instrumental environmental monitoring with structured questionnaire-based evaluation of safety practices and awareness, the study seeks to elucidate the interaction between environmental conditions and occupational behaviour. The findings are intended to inform evidence-based policy formulation, improve regulatory coordination, and support the development of targeted interventions aimed at reducing cumulative occupational health risks within Nigeria's downstream petroleum sector.

Materials and Methods

Research Design

The study adopted a descriptive cross-sectional survey design complemented by systematic environmental monitoring to assess occupational health and safety regulation adherence and air quality exposure among petroleum tanker drivers in Uvwie and Warri environs, Delta State. The cross-sectional approach enabled the collection of self-reported data on drivers' awareness, compliance behaviour, and perceptions of occupational risks at a single point in time, while the environmental monitoring component provided objective measurements of ambient air quality parameters within tanker operation zones. The integration of survey-based and instrumental data facilitated a holistic appraisal of occupational and environmental risk dynamics within the downstream petroleum sector.

Area of Study

The study was conducted in Uvwie and Warri environs, Delta State, Nigeria, a major downstream petroleum distribution corridor characterised by a high density of tanker parks, depots, and fuelling stations. These locations represent convergence points for prolonged tanker operations, vehicular congestion, fuel transfer activities, and human occupancy. The area's industrial intensity, coupled with its tropical coastal climate, makes it suitable for evaluating combined occupational safety challenges and ambient air quality exposures among petroleum tanker drivers.

Population of the Study

The target population comprised petroleum tanker drivers operating within the selected tanker parks, depots, and fuelling stations in the study area. These drivers routinely spend extended periods within operational hotspots, rendering them particularly vulnerable to occupational hazards and environmental air pollutants.iv parallel, environmental exposure characterisation focused on air quality conditions within locations where drivers congregate for loading, offloading, parking, and rest.

Sample Size and Sampling Technique

A total sample size of 114 respondents was utilised for the survey component, determined using Taro Yamane's formula at an acceptable level of precision. Stratified random sampling was employed to ensure adequate representation of drivers across varying years of experience, employer types (independent and company-employed), and training backgrounds. For environmental monitoring, purposive sampling was adopted to select six high-risk sites, comprising three tanker parks/depots and three fuelling stations, based on traffic intensity, duration of driver stay, and operational relevance.

Instruments for Data Collection

Questionnaire and Interviews

A structured questionnaire was designed to obtain information on demographic characteristics, occupational health and safety risks, awareness and compliance with safety regulations, perceptions of regulatory enforcement, and perceived air quality exposure. Semi-structured interviews were conducted with selected drivers to provide qualitative insights into compliance challenges, risk perceptions, and operational constraints.

Observation Checklist

A standardised observation checklist was used to document on-site safety practices, including use of personal protective equipment, vehicle condition, availability of fire extinguishers, adherence to rest schedules, and general compliance with operational safety norms.

Air Quality Monitoring Equipment

Ambient air quality and microclimatic parameters were measured using calibrated portable instruments, including a JD3003 air particulate counter for $PM_{0.3}$, $PM_{0.5}$, $PM_{1.0}$, $PM_{3.0}$, $PM_{5.0}$, and PM_{10}; a multi-gas monitor for H_2S, CO, combustible gases, and oxygen levels; a JD3002 TVOC detector for volatile organic compounds; an SW743A halogen gas detector for halogen pollutants; and an infrared thermometer/hygrometer for ambient temperature and relative humidity.

Method of Data Collection

Survey data were collected through face-to-face administration of questionnaires, supported by direct field observations and interviews. Environmental monitoring was conducted twice daily (morning and evening) over a 14-day consecutive period at each selected site to capture diurnal variability. Measurements were logged digitally, and mean concentrations were computed for each parameter. An integrated Air Quality Index (AQI) was derived using a weighting scheme based on pollutant concentrations relative to national and international guideline values, with AQI categories classified as Excellent, Good, Moderate, Poor, or Hazardous.

Air Quality Index (AQI) Computation

Individual Air Quality Indices were calculated for each pollutant using breakpoint-based interpolation between lower and upper concentration limits corresponding to defined AQI categories. A weighted AQI was subsequently computed to integrate multiple pollutants, with weights assigned according to their relative health significance. Higher weights were allocated to particulate matter and carbon monoxide, while lower weights were assigned to ancillary gases and microclimatic variables, ensuring that the final AQI reflected cumulative exposure potential.

Method of Data Analysis

Survey data were analysed using descriptive statistics, including frequencies, percentages, means, and standard deviations, to summarise awareness and compliance patterns. Inferential analyses, including chi-square tests, correlation analysis, and logistic regression, were conducted to examine associations between socio-demographic variables, training exposure, and compliance outcomes. Air quality data were summarised using means and standard errors of the mean, and analysed using one-way analysis of variance with Tukey post-hoc tests to assess spatial and temporal variations across sites. Integrated analyses employed correlation and regression models to explore relationships between measured air quality indicators and drivers' self-reported or observed occupational health and safety risks.

Ethical Considerations

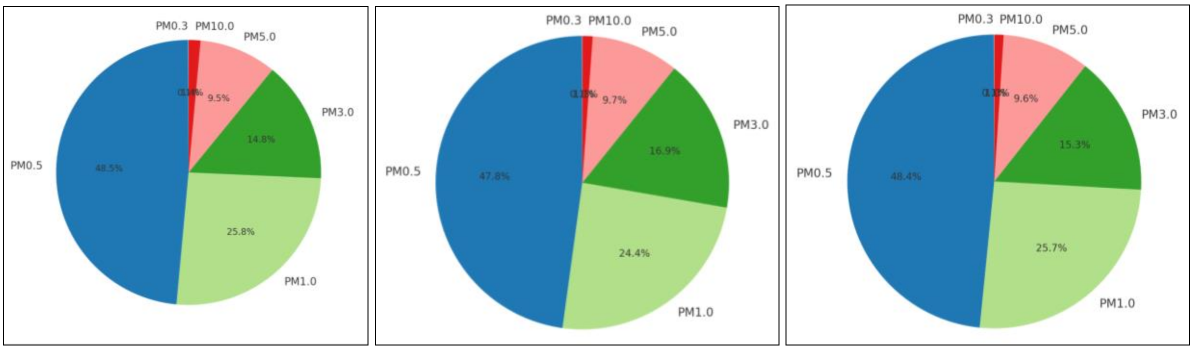
Ethical approval was obtained from the Research Ethics Committee of the Federal University of Petroleum Resources, Effurun (FUPRE) prior to commencement of the study. Informed consent was secured from all participants, with assurances of confidentiality, anonymity, and voluntary participation. Environmental monitoring was conducted in a non-intrusive manner without disrupting routine tanker operations. All collected data were anonymised and reported strictly in aggregate form for research purposes only.

Results

Figure 1 illustrates the proportional distribution of particulate matter fractions ($PM_{0.3}$–PM_{10}) across Tanker Parks 1–3 based on mean values obtained over the 14-day monitoring period. Across all three tanker parks, fine and ultrafine particulates clearly dominated the particulate profile. $PM_{0.5}$ constituted the largest fraction in each location, accounting for approximately 47.8–48.5% of total measured particulates, indicating a consistent predominance of respirable particles capable of deep pulmonary penetration. This was followed by $PM_{1.0}$, which contributed about 24.4–25.8%, further reinforcing the dominance of submicron particles within the tanker park environments.

Intermediate-sized particles ($PM_{3.0}$) represented a moderate proportion of the particulate load, ranging from approximately 14.8 to 16.9% across the three sites. This fraction likely reflects resuspended dust, tyre wear, and mechanical disturbances associated with tanker movement and loading activities. $PM_{5.0}$ contributed a smaller but still notable share, accounting for roughly 9.5–9.7%, suggesting limited influence of coarse dust relative to finer fractions. In contrast, PM_{10} made up a negligible proportion (approximately 0.7–1.1%), while $PM_{0.3}$ constituted the smallest fraction overall, remaining below 1% across all tanker parks.

The close similarity in proportional distributions among Tanker Parks 1, 2, and 3 indicates a high degree of spatial uniformity in particulate sources and atmospheric behaviour within the study area. The overwhelming dominance of $PM_{0.5}$ and $PM_{1.0}$ suggests that combustion-related emissions, fuel vapour condensation, and fine particle generation from vehicular exhausts are the primary contributors to particulate pollution in these tanker operation zones. Importantly, this particle size profile underscores a heightened occupational health concern, as the most abundant fractions are those most strongly associated with chronic respiratory and systemic health effects during prolonged exposure.



Park 1 Park 2 Park 3

Fig 1: Proportional Distribution of Particulate Matter Fractions ($PM_{0.3}$–PM_{10}) in Tanker Parks 1-3 (Mean Values over 14 Days)

Table 1 presents the mean concentrations of carbon dioxide (CO_2), total volatile organic compounds (TVOC), and formaldehyde (HCHO) measured across Tanker Parks 1–3 over the 14-day monitoring period. CO_2 levels were relatively uniform across the three sites, with mean concentrations ranging from 443.9 ± 1.9 ppm in Tanker Park 2 to 451.6 ± 2.3 ppm in Tanker Park 3. This narrow range indicates comparable levels of combustion-related emissions and ventilation conditions across the tanker parks, likely reflecting similar traffic density, idling duration, and spatial configuration. Although these values fall within generally acceptable ambient limits, their persistence suggests continuous accumulation associated with prolonged tanker operations and limited atmospheric dispersion.

TVOC concentrations also exhibited minimal spatial variation, with mean values between 0.0215 ± 0.0006 mg/m³ and 0.0221 ± 0.0005 mg/m³ across the three locations. The close similarity in TVOC levels indicates a common source profile dominated by fuel vapours, evaporative losses during loading and offloading, and exhaust emissions from tanker engines. The low standard errors further suggest temporal stability of VOC emissions throughout the monitoring period, reinforcing the notion of sustained background exposure rather than episodic peaks.

Formaldehyde concentrations displayed a clearer spatial gradient compared with CO_2 and TVOC. Tanker Park 1 recorded the highest mean HCHO concentration (0.00242 ± 0.00027 mg/m³), followed by Tanker Park 2 (0.00221 ± 0.00024 mg/m³), while Tanker Park 3 exhibited the lowest level (0.00186 ± 0.00021 mg/m³). This trend may reflect differences in fuel handling intensity, proximity to traffic corridors, or microclimatic conditions that influence secondary formation and dispersion of aldehydes. The relatively higher variability observed for HCHO suggests greater sensitivity to local operational activities compared with the other gaseous pollutants.

Overall, the data indicate a high degree of environmental homogeneity among the tanker parks for CO_2 and TVOC, with only modest spatial variability in formaldehyde concentrations. While the measured levels of all three pollutants remain within permissible limits, their consistent presence across all sites highlights the potential for chronic low-level exposure among tanker drivers, underscoring the importance of continuous monitoring and preventive occupational health measures.

Table 1: Mean Concentration of CO_2, TVOC and Formaldehyde (HCHO) Across Tanker Parks 1–3 (Mean ± SEM, n = 14 days)

Parameter	Unit	Tanker Park 1	Tanker Park 2	Tanker Park 3
Carbon dioxide (CO_2)	ppm	446.8 ± 2.1	443.9 ± 1.9	451.6 ± 2.3
Total volatile organic compounds (TVOC)	mg/m³	0.0215 ± 0.0006	0.0221 ± 0.0005	0.0219 ± 0.0005
Formaldehyde (HCHO)	mg/m³	0.00242 ± 0.00027	0.00221 ± 0.00024	0.00186 ± 0.00021

Values represent mean concentrations measured over a 14-day monitoring period; SEM = standard error of the mean.

Table 2 summarises the mean microclimatic conditions and noise levels recorded across Tanker Parks 1–3 over the 14-day monitoring period. Ambient temperature values ranged from 33.8 ± 1.0 °C in Tanker Park 2 to 36.4 ± 1.2 °C in Tanker Park 1, indicating generally high thermal conditions across all sites. The relatively elevated temperatures reflect the combined influence of intense solar radiation, heat retention from paved surfaces, and continuous tanker engine activity. Although Tanker Park 2 exhibited slightly lower temperatures, the overlapping standard errors suggest broadly comparable thermal stress across the three locations.

Relative humidity levels were consistently high, with mean values increasing progressively from Tanker Park 1 (62.1 ± 1.5 %) to Tanker Park 3 (67.2 ± 1.4 %). This pattern is characteristic of the humid coastal environment of the Niger Delta and suggests limited evaporative cooling potential. Elevated humidity, when coupled with high ambient temperatures, is likely to exacerbate thermal discomfort and physiological strain among tanker drivers, potentially impairing alertness and work performance during prolonged operational periods.

Noise levels across the tanker parks ranged from 63.9 ± 1.2 dB(A) to 66.8 ± 1.4 dB(A), with Tanker Park 3 recording the highest mean value. These levels consistently exceed the recommended ambient guideline of 55 dB(A) for occupational and community environments, indicating chronic exposure to elevated noise. The observed noise burden is likely attributable to heavy-duty vehicle engines, frequent manoeuvring, loading and offloading operations, and surrounding traffic activity. The relatively small inter-park differences suggest similar operational intensity and acoustic environments across the study sites.

Overall, the data demonstrate that tanker drivers in all three parks are subjected to a combination of thermal stress, high humidity, and elevated noise levels. While spatial variations are modest, the persistence of these physical stressors across all locations underscores their potential role as compounding factors in occupational fatigue, reduced safety compliance, and long-term health risks within tanker operation environments.

Table 2: Mean Microclimatic Conditions and Noise Levels across Tanker Parks 1–3 (Mean ± SEM, n = 14 days)

Parameter	Unit	Tanker Park 1	Tanker Park 2	Tanker Park 3
Ambient temperature	°C	36.4 ± 1.2	33.8 ± 1.0	35.0 ± 1.1
Relative humidity	%	62.1 ± 1.5	65.0 ± 1.6	67.2 ± 1.4
Noise level	dB(A)	64.6 ± 1.3	63.9 ± 1.2	66.8 ± 1.4

Values represent mean measurements obtained over a 14-day monitoring period; SEM = standard error of the mean.

Table 3 presents the integrated Air Quality Index (AQI) summary for Tanker Parks 1–3, incorporating individual pollutant indices for PM_{10}, CO_2, TVOC, and formaldehyde (HCHO), alongside the resulting weighted AQI and corresponding air quality classification. Across all three tanker parks, PM_{10} contributed minimally to overall air quality burden, with very low IAQI values ranging from 0.20 to 0.28. This indicates negligible influence of coarse particulate matter on the integrated AQI and suggests that resuspended dust and larger particles are not dominant determinants of air quality conditions within these tanker environments.

In contrast, CO_2 and TVOC consistently exhibited higher IAQI values across all sites, reflecting their greater relative contribution to ambient air quality dynamics. CO_2 IAQI values ranged from 7.29 in Tanker Park 2 to 8.87 in Tanker Park 3, indicating persistent accumulation associated with vehicular exhaust emissions and limited dispersion during prolonged tanker idling. Similarly, TVOC IAQI values were closely clustered between 7.19 and 7.33, highlighting uniform exposure to fuel vapours and evaporative emissions across the tanker parks. These patterns underscore the dominance of combustion- and fuel-handling-related pollutants in shaping overall air quality.

Formaldehyde IAQI values were comparatively lower, ranging from 1.86 to 2.43, but still contributed measurably to the integrated AQI. Tanker Park 1 recorded the highest HCHO IAQI, suggesting greater influence of localised operational activities or secondary pollutant formation processes, while Tanker Park 3 exhibited the lowest contribution. The relatively modest variability among sites indicates similar source profiles and atmospheric behaviour for aldehydes across the study area.

The computed weighted AQI values ranged from 3.33 to 3.58 across the three tanker parks, all of which fall within the "Excellent" air quality category. However, despite this favourable classification, the weighted AQI masks the relative prominence of specific pollutants—particularly CO_2 and TVOC—that consistently dominate the exposure profile. The narrow range of AQI values further indicates strong spatial homogeneity in air quality conditions among the tanker parks.

Overall, the integrated AQI results suggest that ambient air quality within the tanker parks is generally good when assessed against regulatory thresholds. Nonetheless, the consistent contributions of gaseous pollutants, even at low to moderate levels, highlight the potential for chronic exposure among tanker drivers, reinforcing the need for continuous monitoring, improved ventilation, and preventive occupational health interventions despite the favourable AQI classification.

Table 3: Integrated Air Quality Index (AQI) Summary and Classification across Tanker Parks 1–3

Tanker Park	PM_{10} (IAQI)	CO_2 (IAQI)	TVOC (IAQI)	HCHO (IAQI)	Weighted AQI	AQI Category
Tanker Park 1	0.28	8.11	7.19	2.43	3.52	Excellent
Tanker Park 2	0.22	7.29	7.33	2.21	3.33	Excellent
Tanker Park 3	0.20	8.87	7.31	1.86	3.58	Excellent

Figure 2 presents the Pearson correlation matrix illustrating the strength and direction of relationships between measured air quality parameters (PM_{10}, CO_2, TVOC, and formaldehyde) and selected occupational safety indicators, including exposure frequency, monitoring frequency, perceived air quality, and noise level. The correlation structure reveals clear and interpretable patterns that highlight the interaction between environmental conditions and occupational practices within the tanker parks.

Among the air quality variables, PM_{10} showed a strong positive correlation with formaldehyde ($r = 0.92$), suggesting a shared source profile or co-occurrence during fuel handling and vehicular activities. Conversely, PM_{10} was strongly negatively correlated with TVOC ($r = -0.92$), indicating that coarse particulate presence and volatile organic emissions may be governed by different operational or atmospheric processes. CO_2 exhibited weak to moderate negative correlations with PM_{10} ($r = -0.23$) and TVOC ($r = -0.17$), but a moderate negative association with formaldehyde ($r = -0.59$), reflecting variations in combustion intensity, dispersion, and secondary pollutant formation.

A prominent feature of the matrix is the strong positive correlation between CO_2 and exposure frequency ($r = 0.88$), indicating that drivers who experience more frequent occupational exposure tend to operate in environments with higher CO_2 accumulation. This relationship underscores the role of prolonged idling, congestion, and inadequate ventilation in shaping exposure intensity. In contrast, TVOC displayed a strong negative correlation with exposure frequency ($r = -0.63$), suggesting that increased exposure duration may coincide with conditions that limit volatile compound dispersion or reflect behavioural adaptations during high-exposure periods.

Monitoring frequency, perceived air quality, and noise level were perfectly positively correlated with one another ($r = 1.00$), indicating a strong behavioural and perceptual linkage. This implies that increased monitoring is associated with heightened awareness of air quality and noise conditions, reflecting coherent response patterns among drivers. These indicators also showed strong negative correlations with exposure frequency ($r = -1.00$), suggesting that improved monitoring and awareness are associated with reduced perceived exposure, highlighting the protective role of regulatory oversight and self-monitoring.

CO_2 demonstrated strong negative correlations with monitoring frequency, air quality perception, and noise level ($r = -0.88$), implying that environments characterised by poorer ventilation and higher exhaust accumulation are associated with reduced monitoring intensity and poorer perceived conditions. Conversely, TVOC showed moderate positive correlations with these safety indicators ($r = 0.63$), suggesting that awareness and monitoring may be more responsive to odour-based pollutants than to less perceptible gases such as CO_2.

Overall, the correlation matrix reveals a coherent interaction between environmental pollution profiles and occupational safety behaviour. The findings indicate that CO_2 serves as a key marker of exposure intensity, while monitoring and perception play central roles in mitigating perceived occupational risk. These relationships reinforce the importance of integrating environmental monitoring with behavioural and regulatory interventions to reduce cumulative exposure risks among petroleum tanker drivers.

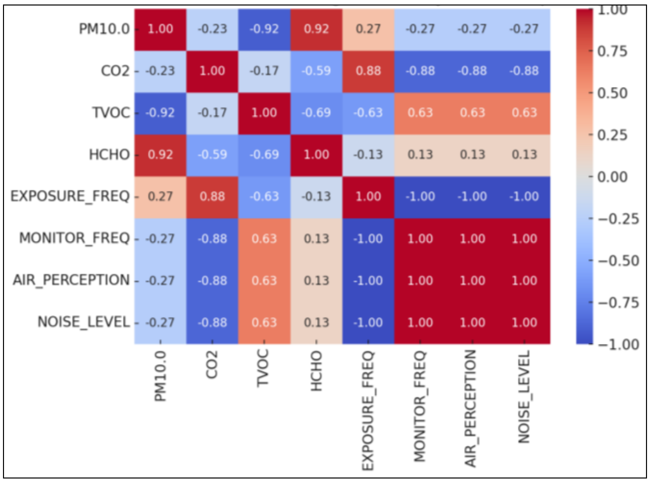


Fig 2: Pearson Correlation Matrix Linking Air Quality Parameters and Occupational Safety Indicators

The heatmap illustrates the relationships between air-quality variables (PM_{10}, CO_2, TVOC, HCHO) and occupational safety indicators (exposure frequency, monitoring frequency, perceived air quality, and noise level).

Table 4 presents the results of the Tukey HSD post-hoc comparisons of key occupational safety indicators across Tanker Parks 1–3 following the overall ANOVA. Across all indicators examined—exposure frequency, environmental impact awareness, monitoring frequency, and perceived livelihood impact—no statistically significant differences were observed between any pair of tanker parks, as all p-values exceeded the 0.05 significance threshold and the 95% confidence intervals encompassed zero.

For exposure frequency, the mean differences between tanker parks were minimal, ranging from –0.05 to –0.25. The non-significant comparisons indicate that tanker drivers across all three parks experience comparable levels of exposure during their routine operations. This uniformity suggests similar operational schedules, duration of stay, and exposure patterns irrespective of location, reflecting a broadly homogeneous occupational environment across the study area.

Environmental impact awareness also showed negligible differences among the tanker parks, with mean differences not exceeding ±0.20. The lack of statistical significance implies that drivers' awareness of environmental and health impacts associated with their work is relatively consistent across locations. This consistency may reflect shared training pathways, informal knowledge transfer among drivers, or uniform levels of regulatory communication within the downstream petroleum sector.

Similarly, monitoring frequency did not differ significantly across the tanker parks. Mean differences were small and confidence intervals were wide, indicating comparable levels of regulatory oversight, self-monitoring practices, or institutional monitoring across all sites. This finding reinforces the notion that safety supervision and compliance monitoring are applied with similar intensity throughout the tanker parks in the Warri–Uvwie corridor.

Perceived livelihood impact likewise exhibited no significant inter-park variation, suggesting that the perceived balance between occupational risk and economic benefit is similar among drivers regardless of operational location. Collectively, the absence of significant differences across all indicators confirms behavioural and perceptual uniformity among tanker drivers across the three parks.

Overall, the Tukey HSD results corroborate the ANOVA findings and demonstrate that occupational safety behaviours, awareness levels, and exposure experiences are broadly comparable across Tanker Parks 1–3. This uniformity indicates that observed occupational risks are systemic rather than site-specific, underscoring the need for sector-wide interventions rather than location-targeted safety measures.

Table 4: Tukey HSD Post-Hoc Comparison of Occupational Safety Indicators across Tanker Parks 1–3

Indicator	Comparison	Mean Difference	p-Value	95% CI (Lower–Upper)	Significant
Exposure Frequency	Park 1 vs Park 2	–0.20	0.811	–0.98 to 0.58	No
Exposure Frequency	Park 1 vs Park 3	–0.25	0.721	–1.03 to 0.53	No
Exposure Frequency	Park 2 vs Park 3	–0.05	0.987	–0.83 to 0.73	No
Environmental Impact Awareness	Park 1 vs Park 2	0.05	0.980	–0.57 to 0.67	No
Environmental Impact Awareness	Park 1 vs Park 3	–0.15	0.832	–0.77 to 0.47	No
Environmental Impact Awareness	Park 2 vs Park 3	–0.20	0.722	–0.82 to 0.42	No
Monitoring Frequency	Park 1 vs Park 2	–0.05	0.991	–0.97 to 0.87	No
Monitoring Frequency	Park 1 vs Park 3	–0.20	0.861	–1.12 to 0.72	No
Monitoring Frequency	Park 2 vs Park 3	–0.15	0.919	–1.07 to 0.77	No
Livelihood Impact	Park 1 vs Park 2	0.30	0.512	–0.35 to 0.95	No
Livelihood Impact	Park 1 vs Park 3	0.20	0.741	–0.45 to 0.85	No
Livelihood Impact	Park 2 vs Park 3	–0.10	0.927	–0.75 to 0.55	No

(Note: "No" indicates $p > 0.05$ — differences not statistically significant.)

Discussion

The integrated results of this study, encompassing Figures 1–2 and Tables 1–4, provide valuable insight into the intersection between ambient air quality and occupational health outcomes among petroleum tanker drivers. The observed dominance of fine particulate matter (Park *et al.*, 2024; Samana *et al.*, 2024) [29, 31]. Fine aerosols of this nature have been strongly associated with oxidative stress, cardiopulmonary morbidity, and neuroinflammatory responses, highlighting a major occupational health risk in the petroleum logistics sector (Azam *et al.*, 2024; Collado *et al.*, 2022) [7, 10]. The persistence of PM_{10} and smaller fractions indicates limited dispersion efficiency, suggesting that tanker depots act as micro-hotspots of anthropogenic air pollutants.

Gaseous pollutants such as CO_2, VOCs, and HCHO displayed spatial uniformity across sites, reflecting similar operational intensity and ventilation regimes. Studies within comparable petroleum-handling zones have linked such gaseous accumulation to incomplete combustion and fuel evaporation processes, with chronic exposure leading to headaches, cognitive fatigue, and respiratory irritation (Chaiklieng *et al*., 2025; Jindamanee *et al*., 2025) [8, 19]. Formaldehyde concentrations, though low, corroborate earlier observations by (Shinohara *et al*., 2024) [33], who noted that even trace levels of aldehydes can exert long-term cytotoxic effects in occupational settings. This reinforces the premise that regulatory thresholds may not fully safeguard workers with continuous low-dose exposure.

Microclimatic and noise parameters further contextualise the occupational burden. Temperatures exceeding 33°C and relative humidity around 60–70% create thermal stress conditions that exacerbate pollutant uptake and fatigue (Li *et al*., 2025) [21, 22]. Elevated noise levels (Habibi *et al*., 2024) [18]. The concurrence of heat, noise, and air pollution therefore portrays a complex multi-exposure environment, consistent with the integrated exposure theory advanced by Vasilakopoulou & Santamouris, (2025) [37], which emphasises synergistic health risks from simultaneous environmental stressors.

Although the integrated Air Quality Index (Dyer *et al*., 2024) [12]. Similar discrepancies were reported by Patton *et al*., (2024) [30], who found that average AQI scores in oil-handling zones remained within "safe" limits despite high pollutant spikes during active operations. Consequently, occupational exposure among tanker drivers may be underrepresented by AQI-based assessment models, necessitating the inclusion of personal exposure monitoring for accurate risk quantification.

The correlation analyses reinforce the interplay between environmental conditions and behavioural factors. The positive correlation between CO_2 concentration and exposure frequency mirrors findings from Aguado *et al*., (2025) [3], who identified poor ventilation and idling practices as major determinants of elevated CO_2 levels in confined depots. Conversely, the negative association between exposure frequency and monitoring frequency demonstrates the mitigating effect of consistent environmental supervision, as documented by Guz *et al*., (2023) [17]. This underscores that administrative control measures, such as environmental audits and training, are effective determinants of exposure reduction in petroleum-handling environments.

The absence of statistically significant inter-park differences in safety awareness, monitoring frequency, and exposure perception (Adikwu *et al*., 2024) [2]. The homogeneity further reflects a centralised safety culture shaped by national regulations under the Nigerian Midstream and Downstream Petroleum Regulatory Authority (Ehiaguina *et al*., 2024) [13]. However, uniformity does not equate to adequacy; the moderate awareness scores observed imply persistent gaps in safety enforcement and risk communication. As Otitolaiye & Aziz, (2025) [28] noted, awareness without corresponding behavioural change often results from inadequate supervision, resource limitations, or risk normalisation among long-term workers.

Integrating these results into a broader public health framework reveals a multifactorial risk scenario in which pollutant exposure, thermal discomfort, and regulatory gaps converge. The findings resonate with the conceptual model of "occupational-environmental coupling," which emphasises the interconnectedness of ambient and behavioural determinants of health outcomes (Li *et al*., 2025) [21, 22]. Sustained exposure to mixed pollutants, even at low concentrations, may lead to subclinical pathologies manifesting as oxidative stress, endocrine disruption, and impaired cognition—phenomena well documented among transport-sector workers globally (Muenzel *et al*., 2025; Woodcock *et al*., 2025) [23, 39].

In summary, the empirical results from this study align with a growing body of evidence that petroleum tanker operations in sub-Saharan Africa contribute to measurable air-quality deterioration and occupational health risks. The apparent "Excellent" AQI classification masks cumulative hazard potentials arising from the co-existence of chemical, thermal, and auditory stressors. Addressing these challenges demands integrated interventions—combining emission control, ergonomic improvements, environmental surveillance, and behavioural reorientation—to sustain both worker safety and urban air quality.

Conclusion

This study provides a comprehensive integrated assessment of air quality exposure and occupational safety regulation adherence among petroleum tanker drivers operating within the Warri–Uvwie downstream petroleum corridor of Delta State, Nigeria. By combining systematic environmental monitoring with behavioural and perceptual evaluation, the study offers a holistic understanding of how environmental conditions and safety practices interact to shape occupational risk in tanker operation environments.

The findings demonstrate a consistent dominance of fine and ultrafine particulate matter across all tanker parks, with $PM_{0.5}$ and $PM_{1.0}$ accounting for the largest proportions of measured particulates. Although coarse particles were minimal, the prevalence of respirable fractions underscores a potential for deep pulmonary exposure during prolonged operational periods. Gaseous pollutants, particularly carbon dioxide and volatile organic compounds, were uniformly present across all sites, reflecting sustained emissions from tanker idling, fuel handling, and limited atmospheric dispersion. While the measured concentrations remained within permissible guideline limits, their persistence indicates chronic low-level exposure that may have cumulative health implications for drivers.

Microclimatic conditions further compounded occupational stress, with consistently high ambient temperatures, elevated relative humidity, and noise levels exceeding recommended thresholds across all tanker parks. These physical stressors, although spatially homogeneous, represent important non-chemical risk factors that may contribute to fatigue, reduced alertness, and diminished safety compliance during extended work periods. The integrated Air Quality Index classified all sites as having excellent ambient air quality; however, this aggregate metric masked the relative dominance of combustion-related and evaporative pollutants that were strongly associated with exposure frequency.

Behavioural and regulatory assessments revealed moderate adherence to occupational safety regulations, characterised by suboptimal monitoring frequency and limited environmental risk awareness. Correlation analyses highlighted strong associations between pollutant accumulation, particularly CO_2, and exposure frequency, while enhanced monitoring and perception were linked to reduced exposure. The absence of significant inter-park differences in safety indicators and exposure patterns confirms that occupational risks among tanker drivers are systemic rather than location-specific within the study area.

In conclusion, petroleum tanker drivers in the Warri–Uvwie corridor operate under uniform environmental and occupational conditions characterised by chronic low-level pollutant exposure and persistent physical stressors, moderated by only moderate regulatory compliance. These findings underscore the need for integrated environmental surveillance, improved ventilation and emission control within tanker parks, strengthened safety monitoring frameworks, and routine occupational health screening for drivers. Implementing coordinated, sector-wide interventions rather than site-specific measures will be essential to reducing cumulative occupational health risks and enhancing safety outcomes within Nigeria's downstream petroleum sector.

References

1. Adebiyi FM, Ore OT, Ezeh GC, Ogundairo OA, Borokinni AB, Adeyemi AF, *et al*. Contributions of some criteria air pollutants by petroleum product retailing stations to Nigeria airshed. Discover Atmosphere, 2024, 2(1). https://doi.org/10.1007/s44292-024-00023-5
2. Adikwu FE, Esiri AE, Aderamo AT, Akano OA, Erhueh OV. Advancing process safety management systems in the oil and gas industry: Strategies for risk mitigation. World Journal of Engineering and Technology Research,2024:3(2):1. https://doi.org/10.53346/wjetr.2024.3.2.0058
3. Aguado A, Rodríguez-Sufuentes S, Verdugo F, López AR, Fígols M, Dalheimer J, *et al*. Verification and Usability of Indoor Air Quality Monitoring Tools in the Framework of Health-Related Studies. Air,2025:3(1):3. https://doi.org/10.3390/air3010003
4. Amoadu M, Akoto-Buabeng W. Job content, psychological well-being, burnout and fatigue driving among heavy goods vehicle drivers in Ghana. Discover Psychology, 2025, 5(1). https://doi.org/10.1007/s44202-025-00367-y
5. Amoadu M, Sarfo JO, Ansah EW. Working conditions of commercial drivers: a scoping review of psychosocial work factors, health outcomes, and interventions. BMC Public Health,2024:24(1):2944. https://doi.org/10.1186/s12889-024-20465-1
6. Anígilájé EA, Nasir ZA, Walton C. Exposure to benzene, toluene, ethylbenzene, and xylene (BTEX) at Nigeria's petrol stations: a review of current status, challenges and future directions. Frontiers in Public Health,2024:12:1295758. https://doi.org/10.3389/fpubh.2024.1295758
7. Azam S, Liu S, Bhattacharyya S, Zheng S. Assessing the hazard of diesel particulate matter (DPM) in the mining industry: A review of the current state of knowledge. International Journal of Coal Science & Technology, 2024, 11(1). https://doi.org/10.1007/s40789-024-00707-8
8. Chaiklieng S, Tongsantia U, Suggaravetsiri P, Autrup H. Assessment of Exposure to Benzene Among Gasoline Station Workers in Thailand: Risk Assessment Matrix Methods. International Journal of Environmental Research and Public Health,2025:22(3):397. https://doi.org/10.3390/ijerph22030397
9. Chowdhury MN, Shafi S, Arzaman AFM, Teoh BA, Kadhim KA, Salamun H, *et al*. Navigating Human Factors in Maritime Safety: A Review of Risks and Improvements in Engine Rooms of Ocean-Going Vessels. International Journal of Safety and Security Engineering,2024:14(1):1. https://doi.org/10.18280/ijsse.140101
10. Collado JT, Abalos JGF, Reyes I de los, Cruz MT, Leung GR, Abenojar K, *et al*. Spatiotemporal Assessment of PM2.5 Exposure of a High-risk Occupational Group in a Southeast Asian Megacity. Aerosol and Air Quality Research,2022:23(1):220134. https://doi.org/10.4209/aaqr.220134
11. Donkor P, Siabi EK, Frimpong K, Mensah SK, Siabi ES, Vuu C. Socio-demographic effects on role assignment and associated occupational health and safety issues in artisanal and small-scale gold mining in Amansie Central District, Ghana. Heliyon, 2023, 9(3). https://doi.org/10.1016/j.heliyon.2023.e13741
12. Dyer GMC, Khomenko S, Adlakha D, Anenberg SC, Angelova J, Behnisch M, *et al*. Commentary: A road map for future data-driven urban planning and environmental health research. Cities,2024:155:105340. https://doi.org/10.1016/j.cities.2024.105340
13. Ehiaguina E, Nnadi BC, Rangarajan R, Moda HM. Safety culture assessment in petroleum industry: cross sectional survey of workers safety performance in the Niger Delta Region, Nigeria. Safety in Extreme Environments,2024:6(3):235. https://doi.org/10.1007/s42797-024-00104-z
14. Ewim DRE, Orikpete OF, Scott TO, Onyebuchi CN, Onukogu AO, Uzougbo CG, *et al*. Survey of wastewater issues due to oil spills and pollution in the Niger Delta area of Nigeria: a secondary data analysis. Bulletin of the National Research Center, 2023, 47(1). https://doi.org/10.1186/s42269-023-01090-1
15. Fonseca T, Ferreira S. Truck Driver Safety: Factors Influencing Risky Behaviors on the Road—A Systematic Review. Applied Sciences,2025:15(17):9662. https://doi.org/10.3390/app15179662
16. Fox MA, Niemeier R, Hudson N, Siegel M, Dotson GS. Cumulative Risks from Stressor Exposures and Personal Risk Factors in the Workplace: Examples from a Scoping Review. International Journal of Environmental Research and Public Health,2021:18(11):5850. https://doi.org/10.3390/ijerph18115850
17. Guz Ł, Dumała SM, Badora A, Gaweł D. Assessment of Exposure to Particulate and Microbiological Contaminants in a Lecture Room. Journal of Ecological Engineering,2023:24(12):87. https://doi.org/10.12911/22998993/172058
18. Habibi P, Razmjouei J, Moradi A, Mahdavi F, Fallah-Aliabadi S, Heydari A. Climate change and heat stress resilient outdoor workers: findings from systematic literature review. BMC Public Health,2024:24(1):1711. https://doi.org/10.1186/s12889-024-19212-3
19. Jindamanee K, Keawboonchu J, Pinthong N, Meeyai A, Inchai P, Thepanondh S. et al. Environmental impacts and emission profiles of volatile organic compounds from petroleum refineries. Scientific Reports,2025:15(1):15509. https://doi.org/10.1038/s41598-025-99932-7

20. Kanu LK, Lwara SMK, Meng X. Impacts of workplace noise exposure and mitigation strategies: a scoping review. Discover Public Health, 2025, 22(1). https://doi.org/10.1186/s12982-025-00611-9
21. Li M, Meng B, Geng Y, Tong F, Gao Y, Yamano N, *et al*. Inequitable distribution of risks associated with occupational heat exposure driven by trade. Nature Communications,2025:16(1):537. https://doi.org/10.1038/s41467-024-55483-5
22. Li M, Zhang Y, Wu C, Yu J, Li J, Wu J, *et al*. Co-exposure to heat and noise on workers' health: evidence from a large-scale cross-sectional surveillance study in China. BMC Public Health, 2025, 25(1). https://doi.org/10.1186/s12889-025-24592-1
23. Muenzel T, Kuntić M, Daiber A, Sørensen M. Transportation Noise and Cardiovascular Health: Evidence, Mechanisms, and Policy Imperatives. The Anatolian Journal of Cardiology, 2025. https://doi.org/10.14744/anatoljcardiol.2025.5755
24. Mustapha A, Mustapha M, Saad N, Abdul-Rani AM. Exploring the nexus between risk perception, driving tasks perception, and road safety attitudes among oil and gas tanker drivers. Travel Behaviour and Society,2024:39:100959. https://doi.org/10.1016/j.tbs.2024.100959
25. Nanadeinboemi O, Uju M, Christopher C, Hakeem O, David D. Environmental and Health Influences of Crude Oil Spills in Niger Delta, Nigeria: Case Study Oporoma Community. Journal of Health and Environmental Research,2024:10(2):29. https://doi.org/10.11648/j.jher.20241002.11
26. Okan SÜ, Gümüş S. Evaluation of the Importance Levels of Legal Responsibilities of Employers and Workers in Terms of Occupational Health and Safety with the AHP Approach. European Journal of Forest Engineering,2025:11(2):174. https://doi.org/10.33904/ejfe.1697789
27. Orduvwe TA, Avwiri GO, Oghenenyerhovwo AE. Radiological Risk Assessment Among Occupational Health Workers in Selected Radiological Centres in Warri City, Nigeria. Trends in Social Sciences,2025:1(1):1. https://doi.org/10.21124/tss.2025.01.09
28. Otitolaiye VO, Aziz FSA. Understanding the Mechanism Through Which Safety Management Systems Influence Safety Performance in Nigerian Power and Electricity Distribution Companies. Safety,2025:11(4):98. https://doi.org/10.3390/safety11040098
29. Park N-Y, Song G, Lee K-M, Kho Y. Levels of OH-PAHs and markers of oxidative stress in urine of taxi drivers and controls. Environmental Analysis Health and Toxicology, 2024, 39(4). https://doi.org/10.5620/eaht.2024027
30. Patton AP, Boogaard H, Vienneau D, Brook JR, Smargiassi A, Joss MK, *et al*. Assessment of long-term exposure to traffic-related air pollution: An exposure framework. Journal of Exposure Science Environmental Epidemiology,2024:35(3):493. https://doi.org/10.1038/s41370-024-00731-5
31. Samana K, Ito K, Suthienkul O, Ketsakorn A. The impact of respirable dust exposure on lung function parameters of motorcycle taxi drivers in Bangkok and adjacent provinces, Thailand. Air Quality Atmosphere Health,2024:17(11):2739. https://doi.org/10.1007/s11869-024-01599-y
32. Sandström T, Bosson JA, Muala A, Kabéle M, Pourazar J, Boman C, *et al*. Acute airway inflammation following controlled biodiesel exhaust exposure in healthy subjects. Particle and Fibre Toxicology,2024:21(1):53. https://doi.org/10.1186/s12989-024-00614-5
33. Shinohara N, García J, Reyes M, Jiménez B, Cruz R, Gonzalez BC, *et al*. Exposure/Risk Assessment of Employees in Gasoline Refueling Stations with and Without the Efficacy of Vapor Recovery Systems in Mexico. International Journal of Environmental Research and Public Health,2024:22(1):10. https://doi.org/10.3390/ijerph22010010
34. Smallcombe JW, Foster J, Hodder S, Jay O, Flouris AD, Havenith G. *et al*. Quantifying the impact of heat on human physical work capacity; part IV: interactions between work duration and heat stress severity. International Journal of Biometeorology,2022:66(12):2463. https://doi.org/10.1007/s00484-022-02370-7
35. Sultana D, Kauffman D, Castorina R, Paulsen M, Bartlett R, Ranjbar K, *et al*. The East Bay Diesel Exposure Project: a biomonitoring study of parents and their children in heavily impacted communities. Journal of Exposure Science Environmental Epidemiology,2023:34(5):827. https://doi.org/10.1038/s41370-023-00622-1
36. Tota M, Karska J, Kowalski S, Piątek N, Pszczołowska M, Mazur K, *et al*. Environmental pollution and extreme weather conditions: insights into the effect on mental health. Frontiers in Psychiatry,2024:15:1389051. https://doi.org/10.3389/fpsyt.2024.1389051
37. Vasilakopoulou K, Santamouris M. Cumulative exposure to urban heat can affect the learning capacity of students and penalize the vulnerable and low-income young population: A systematic review. PLOS Climate, 2025, 4(7). https://doi.org/10.1371/journal.pclm.0000618
38. Wang H, Wei W, Wang K, Kong H, Vieira CLZ, Koutrakis P, *et al*. A global multidimensional analysis of air pollution in land, sea, and air transport cabins reveals substantial health risks. One Earth,2025:8(1):101156. https://doi.org/10.1016/j.oneear.2024.11.010
39. Woodcock J, Tatah L, Anciaes P, Andersen ZJ, Bardhan R, Chen X, *et al*. Quantitative Health Impact Assessment of Environmental Exposures Linked to Urban Transport and Land Use in Europe: State of Research and Research Agenda. Current Environmental Health Reports,2025:12(1):38. https://doi.org/10.1007/s40572-025-00505-7