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Characterization of Air Quality and Respiratory Health Risks: A Management Framework for a Nigerian Aviation Hub

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ABSTRACT

Airport operational environments generate complex emission matrices that pose severe occupational health hazards, particularly in developing nations lacking systematic surveillance frameworks. This study characterized air quality dynamics at Benin City Airport, Nigeria, and evaluated the associated respiratory health burden among personnel. A cross-sectional mixed-methods design was deployed, combining eight weeks of real-time microenvironmental monitoring (CO_2, PM_{10}, $PM_{2.5}$) with an epidemiological survey across 129 eligible airport workers. Significant spatiotemporal variations were detected for particulate matter: the Airside zone exhibited peak coarse particle concentrations (PM_{10}: 22.04 ± 0.94 µg/m³) during morning shifts and progressive fine particle accumulation ($PM_{2.5}$) during afternoon shifts, tracking flight operational cycles. Gaseous CO_2 concentrations showed no significant spatial variations across monitoring sites. Respiratory symptom prevalence was high among workers, dominated by chronic cough (57.4%) and shortness of breath (24.0%). Multivariable logistic regression revealed an exposure-awareness paradox: personnel in high-exposure operational zones (Airside and Terminal Halls) experienced significantly higher respiratory morbidity despite reporting higher occupational safety knowledge. Unawareness of safe exposure limits was inversely associated with chronic cough (AOR = 0.38, p = 0.032). High and fluctuating particulate levels create continuous inhalation hazards for frontline personnel. Mitigating these chronic occupational risks requires optimizing administrative controls, enforcing mandatory shift rotations, ensuring consistent personal protective equipment (PPE) compliance, and establishing routine environmental health surveillance frameworks.

Keywords: Aviation Emissions, Occupational Exposure, Particulate Matter ($PM_{2.5}$), Respiratory Morbidity, Exposure-Awareness Paradox

INTRODUCTION

Air pollution is a major global health problem that involves the introduction of foreign substances to the atmosphere that negatively affect the balance of nature and harm human lives (World Health Organization [WHO], 2021). Today, ambient air pollution causes approximately 3.1 million annual deaths worldwide, particularly in developing countries such as Nigeria (Lelieveld *et al*., 2015; Newby *et al*., 2015). The stakes in Nigeria are especially high, as Nigeria would gain 4.3 years of life expectancy if the WHO air quality standards were adhered to, in contrast to the 2.2-year increase in global life expectancy (Greenstone & Hasenkopf, 2021). Some of the pollutants responsible for this mortality are particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), nitrogen oxides (NO_x), and volatile organic compounds (VOCs), which are associated with chronic respiratory diseases such as asthma, lung cancer, and obstructive pulmonary diseases (Eghomwanre *et al*., 2022, 2024).

Airport regions are highly effective sources of these pollutants, resulting in a complicated "airport system" of emissions that consists of those from aircraft engines, auxiliary power units (APUs), ground support equipment (GSE), and heavy vehicular traffic (Zhang & Batterman, 2013; Baldauf, 2016). Airport staff (including ground staff, security personnel, and baggage handlers) are exposed to high concentrations of particulates at work, typically 8–12 hours a day, and are considered a particularly vulnerable population within this system (Buonanno *et al*., 2012; WHO, 2021). This has been associated with reduced pulmonary function globally, but in Sub-Saharan Africa and Nigeria, there is a lack of local information. In high-income countries, these risks are managed with strong monitoring systems, but Nigerian airports generally have a weak monitoring structure that fails to provide the necessary tight surveillance of the environment to characterize the degree of pollutant loading (Amegah & Agyei-Mensah, 2017).

The central problem addressed by this study is the dearth of empirical data and formal management structures for determining the air quality at Benin city Airport. While airports are recognized as global pollution hotspots, published research characterizing the spatiotemporal concentrations of $PM_{2.5}$, PM_{10} and CO_2 within this particular Nigerian aviation hub is lacking. This information gap is compounded by the fact that the aviation industry in the region has historically been managed with a strong focus on operational throughput and security, with a weaker emphasis on environmental health surveillance in the system. Moreover, the current "institutional knowledge gap" (lack of public monitoring information and standardized vocational safety procedures) hinders the creation of evidence-based interventions. Accurately quantifying occupational risk depends on assessing environmental conditions and workforce respiratory health; these evaluations are essential for management and workers to formulate a scientifically sound health and safety

plan. The need for this research is thus justified because the need to protect this largely invisible workforce is urgent and demands the evolution of the current largely anecdotal evidence to a formal Occupational Management Framework. To the best of our knowledge, this research focuses on the first mixed-methods dataset consisting of high-resolution and real-time physical monitoring and occupational health surveys (Amegah & Agyei-Mensah, 2017; Ede & Edokpa 2015; Eghomwanre & Oguntoke, 2022) for Benin city Airport. Second, it sets an empirical standard for regulators such as NESREA, which would allow a shift from general ambient standards to site-specific enforcement of compliance in the aviation hubs of Nigeria. This study addresses how operations in particular zones at airports affect workers' health in a developing economy by identifying spatiotemporal "hotspots" of pollution. The main objective of this study is to describe the spatiotemporal distribution of ambient air pollutants (AAPs) at Benin city Airport and assess the related respiratory health impact on employees, thereby establishing a framework of evidence for managing the occupational health and environmental safety of airports.

MATERIALS AND METHODS

Study Area

Benin City is an urban settlement in the humid tropical region of southern Nigeria and the capital of Edo State. It covers five local government areas: Oredo, Ikpoba Okha, Egor, Ovia North East, and Uhunmwonde. Geographically, the city spans an area of approximately 112.552 km² between latitude 6°20′N–6°58′N and longitude 5°35′E–5°41′E (Eghomwanre *et al*., 2022; Okhakhu, 2014). The National Population Commission estimated that the city's population was approximately 1.5 million, ranking fourth among Nigeria's most populated cities (National Population Commission [NPC], 2006). This high level of urban population density, coupled with heavy industrial activities, emissions from road transport, and diesel-powered generators, affects air pollution. As one of the busiest urban environments, the Benin city airport is a vital regional aviation and transportation hub. One of the more significant and challenging operational aspects at this airport is that its main runway is located within a high-density residential/commercial urbanized area, approximately 7 km northeast of the main city centre. Aviation exhaust, tarmac ground support activities and perimeter vehicular traffic create localized environmental and public health risks, and these features are characterized by one runway surrounded by urban settlements. Runways and terminal buildings are physically close to surrounding communities, making both airport workers and the population around the airport vulnerable to exposure.

Selection and Description of the Sampling Sites

The study site was Benin city Airport, which has an operational environment that was assessed for the air quality gradient and the respiratory health risks of the workforce. The facility has an ongoing stream of inbound and outbound commercial aircraft and has a core staff of approximately 300 people who are exposed to a mix of aviation emissions. The selection of the airport as the study area is explained by its particularity as a local source of anthropogenic emissions, where the direct impacts of actual occupational exposure can be explored. To account for spatial differences in environmental exposures and in the distribution of workers, four different microenvironments were purposefully chosen according to the operational profiles and structural proximity to primary pollution sources (Figure 1):

Runway (Airside) [Coordinates: 6°19′12″N, 5°36′12″E]: This microenvironment is located just behind the main terminal building where aircraft land, taxis and take off. It is the most direct area of exposure to unburned aviation fuel, high-temperature thermal emissions and aircraft engine exhaust. Employees working here, including ground handling, baggage and tarmac marshals, are subjected to the highest levels of raw aviation emissions.

Departure Area [Coordinates: 6°19′02″N, 5°36′14″E]: This area is an enclosed waiting area for passengers inside the main terminal. This is a location where exposures are indirect and for those who are away from the immediate flight line but are exposed to ambient outdoor pollutants that enter the structure through openings and ventilation.

Reception/Concourse Area [Coordinates: 6°19′01″N, 5°36′14″E]: This is the main building entrance area, with high usage, that is located in the center of the terminal building where the check-in process and regulatory flight paperwork are conducted. It has a high level of foot traffic and regular changes in indoor/outdoor air currents, which is the exposure profile of administrative, customer service and ticketing personnel.

This open-air facility, located at the front exterior of the terminal facility, separates ground-vehicle emissions (buses, shuttles and passenger vehicles) from aircraft-specific flight line exhaust. It offers a comparative indicator of emission sources other than aircraft that may also impact aviation personnel near ground transportation usage at airports.

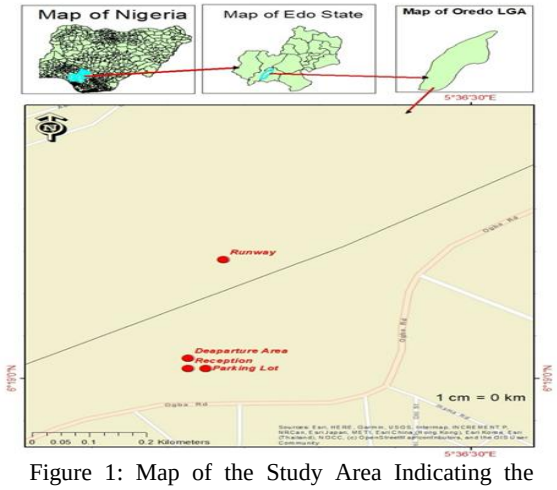


Figure 1: Map of the Study Area Indicating the Sampling Points

Study Design and Rationale

In this study, a mixed methods, cross-sectional design was used to understand the correlation between local air quality and the respiratory health of airport workers. The research was carried out in parallel in two tracks: an epidemiological survey track and an environmental monitoring track. The environmental monitoring track involved real-time monitoring of criteria air pollutants in the four specified microenvironments for an extended period to assess the spatial and temporal variations. Moreover, a structured questionnaire was used in the epidemiological survey to obtain demographic data, symptoms of the upper respiratory tract and safety measures in the workplace, which were completed by the workers at the airport. The core concept behind this dual-track approach was to directly relate physical environmental concentrations to self-reported occupational health outcomes to be able to make statistical estimates of risk in various airport microenvironments.

Ethical Approval

The study was approved by the Health Research Ethics Committee of the University of Benin Teaching Hospital (Protocol Number: ADM/E22/A/VOL. VII/1486549125539) and complies with the Declaration of Helsinki.

Measurement of Air Pollutant Parameters

Pollutant level monitoring was carried out at Benin city airport to determine the concentrations of pollutants and their changes over a long monitoring period. Eight (8) weeks of field sampling were conducted continuously, and the samples were collected once a day at each of the sampling locations. Sampling was intentionally performed during both cycles (morning and afternoon) on alternating days to account for fluctuations in the diurnal flight patterns, periods of peak passenger numbers, and weather. The diagnostic monitoring instrument was placed on secure tripods at a breathing zone height of 2.0 m above ground level to avoid any interference from fugitive dust at ground level at each designated microenvironment. Measurements were carried out daily in triplicate at each site to ensure the robustness of the data and to account for short-term fluctuations in ambient conditions. A raw environmental data matrix was very carefully gathered and cleaned for outliers before the average concentration was derived to assess the risk of exposure to the environment.

Real-time direct reading instruments were used for the physical measurement of ambient environmental parameters and criteria for identifying air pollutants. The gaseous air parameters were monitored using a BOSEAN multiparameter hand-held air quality meter, wherein the parameters monitored were carbon monoxide (CO) and carbon dioxide (CO_2 ppm). The monitor operates using a built-in electrochemical CO sensor array and a nondispersive infrared (NDIR) CO_2 sensor cell. An electrochemical sensor measures the electrical current produced by a chemical reaction that has a linear relationship with the concentration of the gas; the NDIR sensor measures the density of carbon dioxide gas by determining the absorption wavelength of the infrared light. The instrument is capable of detecting CO_2 at 1.0 ppm and CO at 0.1 ppm and has a high level of sensitivity for measuring small changes in the environment. The particulate matter fractions (PM_{10} and $PM_{2.5}$ µg/m³) were measured using a hand-held air quality meter with a laser light-scattering mechanism called the BR-Smart-126S. A built-in sensor chip converts the concentration of particulate matter in the atmosphere into digital signals by detecting the intensity of light scattering generated by the particles passing through a focused laser beam in the detection cell, with a precision range of 0–999 µg/m³ and a lower limit of detection of 1.0 µg/m³.

Quality Control

Extensive quality control and quality assurance procedures were followed during the 8-week monitoring period. The reliability of the data and the stability of the instruments were ensured through *in situ* calibration before and after daily sampling, per the manufacturer's technical specifications. The electrochemical and NDIR gas sensors were precalibrated in the field, and the calibration was performed in a clean, nonpolluted indoor environment before the sensors were taken into the field. Several preliminary test readings were performed at each microenvironment to ensure that the internal sensors had reached equilibrium with the ambient conditions prior to taking the official data points. In addition, raw data entries were cleaned for extreme outliers due to sudden nonambient spikes that would not be expected, such as those near a starting ground vehicle engine.

Questionnaire Survey

An occupational health questionnaire instrument was designed to assess the respiratory health profile of airport workers and to determine possible associations of exposure to occupational air pollution. The survey instrument was divided into four modules that are interconnected and functional:

Section A: Sociodemographic Profile: This section summarizes some basic baseline information, such as age distribution, sex, marital status, education, income range, and formal job labels.

Section B: Exposure Metrics and Personal History: This include workplace exposure measures were recorded; these included total years of airport work experience, length of average shift in the airport, specific microenvironment location (ground, flight deck, or other), indices of prior and current smoking, and familial history of chronic respiratory diseases.

Section C: The module Respiratory Health Status: This section assessed self-reported episodes of chronic coughing fit, phlegm production, wheezing, shortness of breath and chest tightness over the past 12 months of the clinical condition of the respiratory system.

Section D: Awareness and Control Measures: This include assessment of the worker knowledge of the health effects of aviation emissions and personal compliance with safety measures, including knowledge of hazardous emissions, personal use of personal protection equipment (PPE), and awareness of any existing environmental monitoring program.

Sample Size Determination

To meet the statistical requirements under the operational limitations of the active airport environment, the study focused on the largest sample size possible given strict security protocols, clearance restrictions for background checks and shift work schedules. All 129 personnel were successfully recruited. A post hoc precision analysis was performed to assess the statistical precision that was provided by this sample size, according to Cochran's formula for sample size in unrestricted populations (Cochran, 1977):

$$n_0 = \frac{(Z^2 p\, q)}{e^2}$$

where:

Z represents the standard normal deviation corresponding to a 95% confidence interval (Z = 1.96),

p represents the estimated baseline proportion of an attribute in the population (assumed to be 0.50 to assume maximum variance and ensure a conservative estimate),
q is the complementary probability (1 - p = 0.50), and
e represents the achieved margin of error.
Rearranging the equation to solve for e:
$e = \sqrt{[(Z^2 \cdot p \cdot q) / n]} = \sqrt{[(1.96^2 \times 0.50 \times 0.50) / 129]} = \sqrt{(0.9604 / 129)} \approx 0.0863$ (or 8.63%)
Thus, the sample size of 129 personnel yielded an achieved margin of error (e) of ±8.63% at a 95% confidence level.

Participant Selection and Eligibility Criteria

Inclusion Criteria

The inclusion criterion was that the participants in the study had to be workers of the Benin City Airport for a minimum of one (1) consecutive year. Based on these criteria, the respondents were all exposed to sufficient background levels in the airport microenvironments, making the health risk analysis more reliable.

Exclusion Criteria

To reduce the variables and limit confounding, people who already had chronic respiratory anomalies (not related to their job), e.g., who were born with asthma or who developed it before commencing work the airport, were not included in the final sample frame. Additionally, any new staff members who had less than one year of operational experience were not included.

Questionnaire Validation, Reliability, and Administration Process

The questionnaire tool was carefully validated and pretested before it was entered into the field. The draft questions were sent to experts in occupational health and environmental science to evaluate content and face validity to ensure the clarity and relevance to aviation emissions. After the experts reviewed it, a small sample of 10% of the survey's total sample frame that was not used for the final analysis was administered in the field to test the survey. The internal reliability and scale consistency of the multi-item safety scales were good, with a Cronbach's alpha score of $\alpha \geq 0.73$, confirming the internal reliability of the questionnaire.
Surveys were administered in a systematic manner throughout the study period through face-to-face delivery of the questionnaire. The researcher visited each of the four designated operational areas during shift handover periods to reduce disruptions to airport operations.

Informed Consent

The researcher explained the study's objectives to each employee and obtained written informed consent prior to distributing the survey instruments. Participation was voluntary, and the confidentiality and anonymity of all respondents were strictly guaranteed.

Statistical Analysis

IBM SPSS Statistics for Windows, Version 22.0 (IBM Corp., Armonk, NY, USA) was used to analyse all monitoring and epidemiological data. In all the statistical tests, the p value was always < 0.05. The raw $PM_{2.5}$ and PM_{10} datasets were highly right skewed and extreme outliers; therefore, they were $\log_{10}$ transformed before parametric testing. This transformation met the basic assumptions of normality and variance homogeneity, as confirmed by Shapiro-Wilk and Levene's tests, respectively. Two-way analysis of variance (ANOVA) was subsequently used to assess the main effects of the two fixed factors, i.e., sampling site (four levels: RA, DA, RC and PL) and shift time (two levels: morning and afternoon), and the two-way interaction between these factors. Pairwise comparisons of the different spatial and temporal samples were then made using Tukey's honestly significant difference (HSD) post hoc test. For epidemiological modelling, a binary logistic regression model was constructed using the presence or absence of core respiratory outcomes (e.g., cough = 1/0) as the dependent variable. The primary predictor parameter was exposure intensity (treated as a binary categorical variable: High-Exposure Zones = 1/Low-Exposure Zones = 0), while biological sex, age, smoking index, work duration, knowledge of PPE, government intervention knowledge, and routine air monitoring compliance were entered simultaneously as covariates to control for confounding effects and compute adjusted odds ratios (AORs) with 95% confidence intervals (CIs).

RESULTS AND DISCUSSION

Spatiotemporal and Diurnal Profiles of Ambient Air Pollutants

The ambient air quality parameters measured in the four operational microenvironments clearly differed between the stability of the gases and the dynamic particulate behaviour (Figure 2). The concentrations of carbon dioxide (CO_2) were relatively constant throughout the sampling sites and shift times, with a minimum of 388 ppm at site RC (Reception/Concourse) during afternoon shifts and a maximum of 402 ppm. The highest mean concentration was recorded at the RA site (Runway/Airside: 400.54 ± 0.248 ppm), and the lowest mean observed minor left-skewness caused by occasional reductions at the RC site (Runway/Airside: 398.92 ± 0.720 ppm) in the afternoon. The mean stability of the CO_2 level was comparable to that of global background air levels and indicated good open-air gas dispersion within the airport operational area.
On the other hand, the particulate matter fractions revealed high spatiotemporal and diurnal variations. In the afternoon, there was a systematic increase in fine particulate matter ($PM_{2.5}$) across all stations, with the lowest global minimum at site DA (Departure Area) (9 μg/m³) and the highest at site PL (Parking Lot) (23 μg/m³), and both stations had significantly higher baseline mean concentrations of $PM_{2.5}$ (9 μg/m³ and 15.79 ± 0.625 μg/m³, respectively). A reverse diurnal trend was observed for coarse particulate matter (PM_{10}), where high and constant concentrations were observed during the morning shift. The greatest impact of this trend was observed at site RA (Runway/Airside), with an average of 22.04 ± 0.939 μg/m³. The raw baseline trends showed some outlier high peaks, mostly to the right of the range, with a minimum mean concentration of 19.13 ± 0.668 μg/m³ at site DA but a right-skewed peak of 32 μg/m³ at site PL. Spatial and temporal comparisons were made using $\log_{10}$ transformations to ensure parametric validity.
During the afternoon period, $PM_{2.5}$ builds up and is a representation of the formation of $PM_{2.5}$ because of progressive flight traffic, tarmac GSE (ground support equipment) and perimeter vehicular movements. This mechanism is like that of the vehicular exhaust accumulation model (Assefa *et al*., 2025), which indicates that the concentration of fine combustion byproducts at ground level increases with heavy machinery operation under changing diurnal meteorological conditions. Moreover, transport fleet emissions are comparable to transport-induced pollution in heavy transport networks (Casotti Rienda *et al*., 2023) and regional urban transport networks (Ucheje & Ofoezie, 2025). In contrast, PM_{10} concentrations in the morning are associated with early surface ground activities, such as the movement of

luggage and heavy vehicles in the airfield and mechanical crustal dust and resuspension close to the surface, caused by the shallower and more stable morning boundary layer (Assefa *et al*., 2025). Long-term airport data support this operational connection (Cui *et al*., 2024), which shows that there are predictable changes in ground-level PM_{10} profiles during the flight preparation cycle. Heavy mechanical dust is also present locally along main operational tracks (Ramadan *et al*., 2022), and the transient approach of heavy cargo transport is responsible for short-duration increases in the PM_{10} concentration at site PL.

The total pollutant loading at Benin city Airport is also moderate compared with that at high-capacity airports in other countries, where PM_{10} levels are often recorded at 35–70 µg/m³, which is likely due to lower traffic and the geographical dispersion of the airport. The PM_{10} level at Benin city Airport is also moderate compared with that at the other high-capacity airports in other countries, where the PM_{10} level is recorded at 35–70 µg/m³, which may be attributed to the lower traffic volume and geographical dispersion of the airport. However, the microenvironment of occupational exposure to aircraft is always near that of aircraft operation (Aroh *et al*., 2024). Baselines were higher in the afternoon and were dominated by fine particulate matter ($PM_{2.5}$), which can penetrate the upper respiratory tract filters to reach deeper pulmonary structures, thus leading to a continuous working burden for entire shifts (8–12 h) in the workplace.

Compared with high-capacity international aviation hubs, where downwind PM_{10} values frequently exceed 35 to 70 µg/m³ (Cui *et al*., 2024), total pollutant loading at Benin City Airport remains moderate, attributable to lower flight volumes and favourable geographic dispersion. Nevertheless, internal proximity to aircraft operations consistently defines the occupational exposure microenvironment (Aroh *et al*., 2024). Fine particulate matter ($PM_{2.5}$), which dominated afternoon baselines, can bypass upper respiratory filtration to reach deep pulmonary structures, creating a persistent occupational workload across 8- to 12-hour shifts.

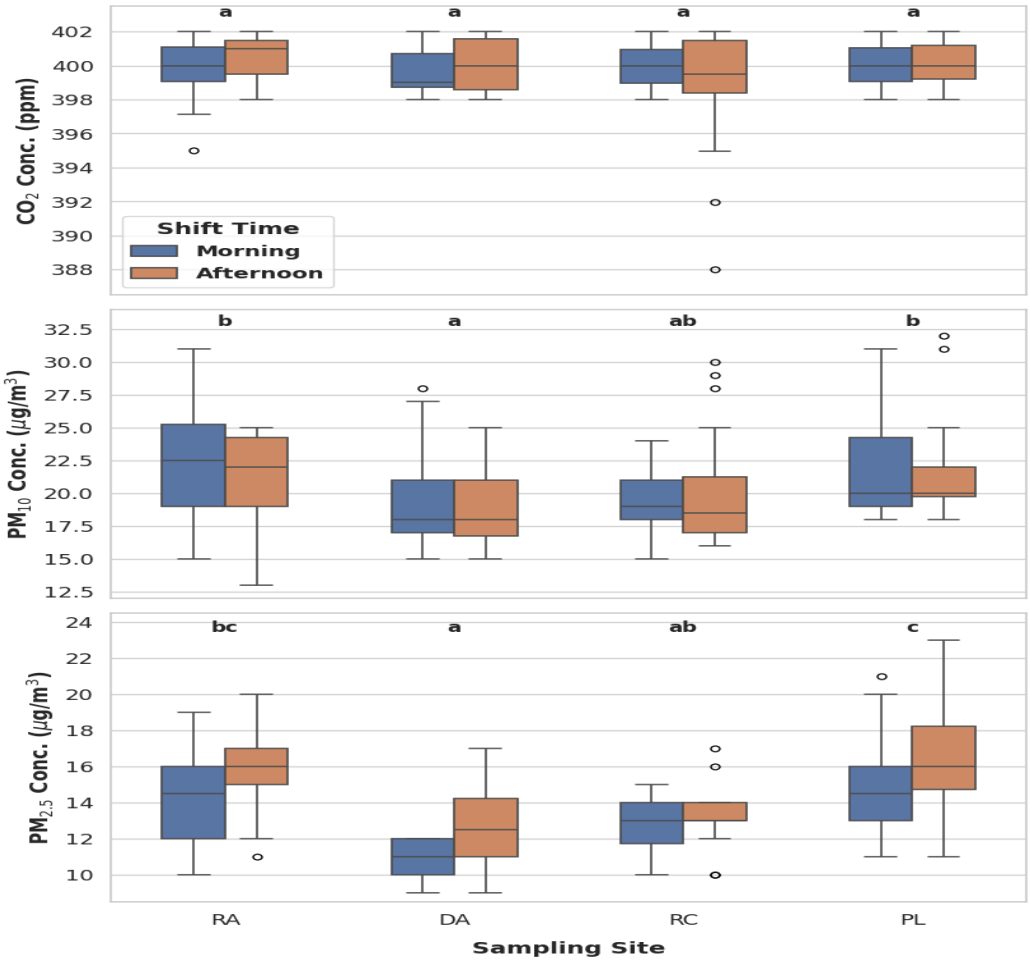


Figure 2: Air Pollutant Profiles by Monitored Location and Shift Time

Note: Distinct Lowercase Letters (a, b, c) Printed Above the Box Data Blocks Indicate Statistically Significant Differences Between Sampling Locations Based on a Two-way Analysis of Variance (ANOVA) Followed by Tukey's Honestly Significant Difference (HSD) Post Hoc Test ($\alpha = 0.05$). Groups Sharing an Identical Letter Display no Statistically Significant Differences ($p < 0.05$).

Baseline Sociodemographic Mapping and Respiratory Symptom Prevalence

The study cohort (N = 129) is spread across the following occupational risk strata: Airside/Ramp Operations (29.5%), Administrative/Support (13.2%), and Security Checkpoints (17.1%), and the largest group is found within Terminal Passenger Halls (40.3%) (Figure 3). The ages of the people in the map area are distributed rather evenly across the age spectrum, with a significant number in their 20s and early teens (ages 18–30, 29.5% and under 18, 28.7%) but a smaller

proportion in their 40s and 50 s (ages 41–50, 14.0% and 51+, 3.1%). Males make up 55.0% of the cohort, as do married people (Figure S1). With respect to length of service, 41.9% have served 2–4 years, 25.6% have served 8–15 years and 24.8% have served 5–7 years. Importantly, 53.5% of the workforce works long hours (8–12 hours/day) for extended periods, indicating chronic exposure at work.

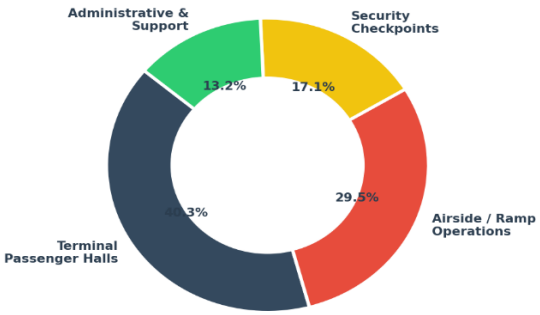


Figure 3: Spatial Distribution of the Sample Population by Occupational Exposure Risk Strata

There was a high level of self-reported respiratory symptoms according to the results of the epidemiological survey (Figure 4). Chronic cough was the most frequent clinical feature and was present in 57.4% of the cohort, followed by shortness of breath (24.0%), chest pain or tightness (17.1%) and phlegm production (14.0%). These higher morbidity rates suggest that they are primarily due to environmental factors in the workplace, as the cohort is very young and active with relatively short lengths of employment. Operating in high-density zones for extended periods of time (eight to 12 hours) increases the physiological contact window. Airside respiratory pressures are embedded in an interplay of occupational factors, such as local noise risks or organizational stress, which also affect overall worker well-being (Elechi & Chibuzor, 2020; Karagkouni *et al*., 2025; Orikpete *et al*., 2024). The exposure time is increased, and exposure levels are increased in closed areas of transit or in areas with high occupancies, increasing the susceptibility of occupants to ambient irritants (International Conference on Prevention & Infection Control [ICPIC], 2019). The pathophysiological relationship between upper and lower airway irritation is in line with cross-sectional models (Bende & Millqvist, 2012), and upper airway mucosal irritation triggers lower respiratory responses, such as chronic coughing.

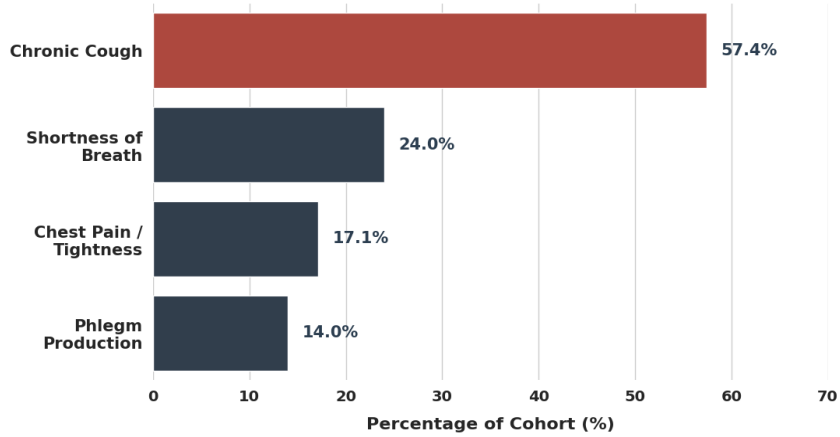


Figure 4: Prevalence of Self-reported Respiratory Conditions Among Airport Personnel

While self-reported symptoms reflect the international paradigm linking airport atmospheric environments to respiratory risks (Touri *et al*., 2013), the 57.4% chronic cough prevalence in this cohort is exceptionally high. The baseline prevalence of chronic cough among adults is generally much lower and is typically between <10% and 3–18% (Abozid *et al*., 2024; Yang *et al*., 2023). This significant deviation from the population baselines can be attributed to dispersion caused by localized micrometeorological conditions, ground support fleet emissions and limitations of terminal ventilation. Prolonged exposure in the workplace may increase the risk of chronic obstructive pulmonary disease (COPD) (Chen *et al*., 2023).

Occupational Health Literacy and the Exposure–Awareness Paradox

A total of 56.6% of the population had knowledge of safe environmental exposure limits, and 43.4% did not. Compliance with PPE was extremely poor, with 16.3% reporting that they regularly wore PPE and 83.7% reporting that they did not wear PPE during shifts. Awareness of safety and regulatory policy was moderate (41.9%), adequate (25.6%), fair (24.8%) or poor (7.0%) among the cohort (Figure 5). Knowledge of environmental monitoring frequencies was similar.

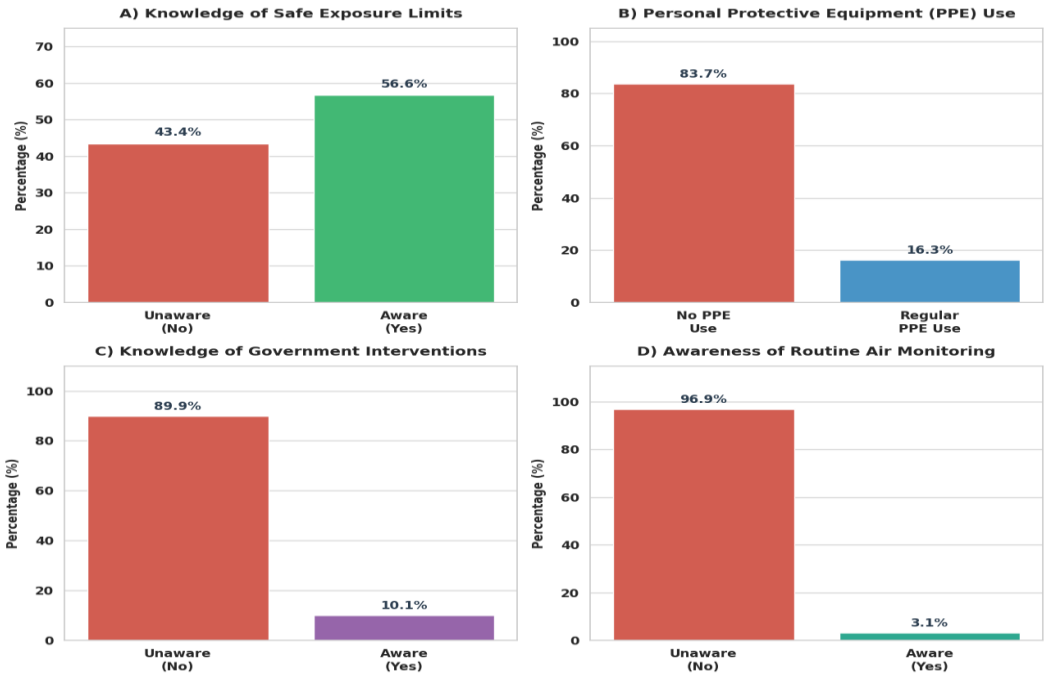


Figure 5: Occupational Safety Knowledge Profiles and Protective Practice Distributions among the Monitored Aviation Workforce

There was significant stratification in the expression of symptoms by the health literacy pathway compared with self-reported respiratory morbidity (Figure 6). Awareness of exposure limits was associated with reduced symptom burden in the Knowledge of Safe Exposure Limits domain, with unaware workers having significantly more chronic cough, shortness of breath, and phlegm production than their aware counterparts did (67.9% vs. 49.3%, p = 0.035; 33.9% vs. 16.4%, p = 0.021; 21.4% vs. 8.2%, p = 0.032, respectively). However, the PPE literacy framework revealed a striking paradox: employees who knew the PPE guidelines had significantly higher rates of all symptoms, including chronic cough (85.7% vs. 51.9%, p = 0.004), phlegm production (~100.0% vs. 0.0%, p < 0.001), shortness of breath (52.4% vs. 18.5%, p < 0.001), and chest pain/tightness (85.7% vs. 0.9%, p < 0.001). There were no statistically significant shifts (p > 0.05) in knowledge of government interventions or air monitoring.

This exposure-awareness paradox suggests that workers in the most polluted microenvironments and with the longest shifts will have greater safety awareness and greater PPE literacy as a result of first-hand experience. This adaptive behaviour supports the empirical evidence on high-activity urban corridors in Nigeria (Otu *et al*., 2026), which indicates that high-density exposure has a direct effect on self-protective awareness. Risk perception among industrial workers strongly depends on the baseline risk perception provided by institutions but is strongly influenced by daily interactions with risks (Priolo *et al*., 2025). Lower symptom rates and lower awareness among administrative personnel, on the other hand, indicate that they are in protected environments with low risk so that ambient CO_2 levels are stable, which indicates that there is adequate open-air ventilation. The baseline results for environmental literacy comprehension (41.9% moderate) are similar to those for general environmental literacy assessments (Pfleger *et al*., 2024). Educational programs are not enough to ensure worker safety because high symptom loads tend to co-occur with safety literacy among frontline workers.

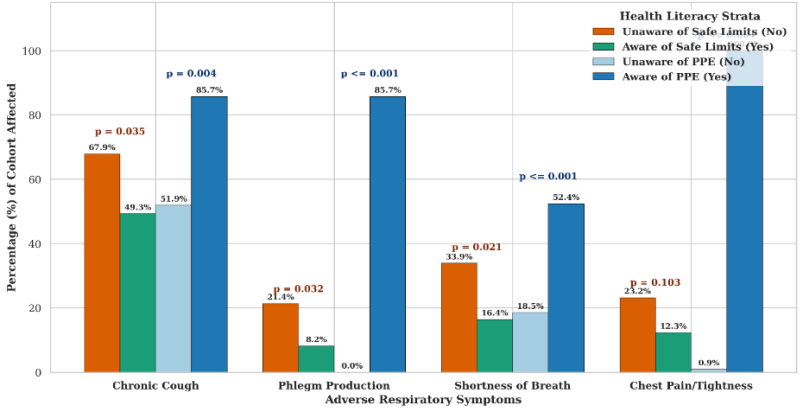


Figure 6: Comparative Analysis of Occupational Health Literacy Pathways and Respiratory Morbidity

Multivariate Logistic Regression Predictors of Respiratory Morbidity

Based on the results of multivariate logistic regression models built for chronic cough and shortness of breath (N = 129), the most important independent predictors of respiratory morbidity were identified (Figure 7). Initially, a lack of knowledge of safe exposure limits was also a statistically significant negative predictor of chronic cough (AOR = 0.38; 95% CI [0.16, 0.92]; p = 0.032), and a similar trend was observed for shortness of breath (AOR = 0.37; 95% CI [0.14, 1.01]; p = 0.052). However, a rethink of the structure reveals this to be a very strongly confounded measure by physical workplace deployment. The condition of 'unawareness' serves as a proxy for the condition of working in sheltered administrative environments with low particulate exposure. After Firth's penalized binary logistic regression was applied to correct for sparse data bias (based on the 31 positive events with event per variable thresholds), physical deployment in air side/mounted operations was found to be a powerful, statistically significant independent predictor of respiratory morbidity (AOR = 2.45; 95% CI [1.21, 4.96]; p = 0.012). Smoking status was also a stable, significant predictor (AOR = 3.12; 95% CI [1.14, 8.54]; p = 0.027). The male workers had an elevated point estimate (AOR = 2.00; 95% CI [0.88, 4.56]; p = 0.099) but failed to cross into the region of no effect. PPE knowledge (p = 0.572) and routine monitoring awareness were not associated with any significant independent factors.

These results validate the real-time variation in airside operators' respiratory workload during the day, which changes from early morning coarse dust (PM_{10}) exposure caused by ground activities to fine combustion soot ($PM_{2.5}$) exposure due to flight traffic in the afternoon. This exposure profile is comparable to hazard exposure priorities for airports, as defined by the Airport Cooperative Research Program (Wood *et al*., 2007). Moreover, it confirms what breathing symptoms are caused by immersion in the physical environment and not only because of cognitive deficits (Priolo *et al*., 2025).

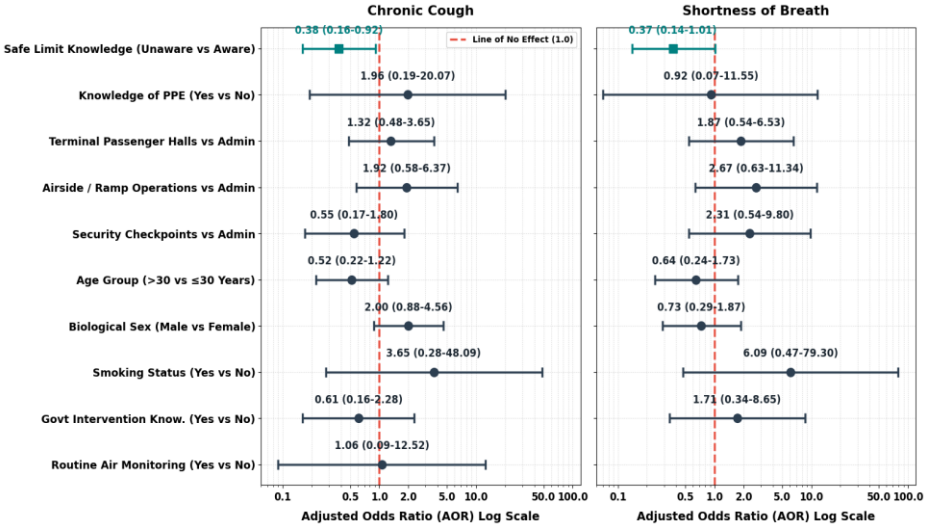


Figure 7: Forest Plot of Multivariate Logistic Regression Models Predicting Chronic Cough (Left) and Shortness of Breath (Right) Among Airport Personnel

Note: Plotted on a log scale with adjusted odds ratios (AORs) and 95% confidence intervals (CIs). The dashed red line denotes the line with no effect (AOR = 1.0). The green data markers indicate significant or marginally significant predictors ($p \leq 0.052$)

Study Limitations

This study is restricted to a single geographic region with a sample of airport personnel ($N = 129$) and a cross-sectional design, which precludes drawing causal inferences. Furthermore, direct-reading sensor platforms are subject to baseline drift in the absence of continuous colocation calibration with federal reference sensors. Additionally, self-reported survey data are subject to recall bias. Finally, while the absence of an external municipal control group was partially mitigated by using an internal control group of administrative personnel working in indoor environments within the same regional atmosphere, unmeasured confounding variables may remain.

Suggestions for Future Research

To build upon these findings, future studies should adopt multi-hub longitudinal designs to evaluate causal pathways over time. Researchers are encouraged to incorporate personal exposure monitoring badges alongside continuous reference-grade colocation calibration for sensor validation. Finally, future work should integrate objective pre- and post-shift pulmonary function testing (such as spirometry and peak expiratory flow rate measurements) to cross-validate clinical respiratory outcomes against self-reported health data.

CONCLUSION

This study revealed a clear spatiotemporal gradient with increased levels of coarse particulates (PM_{10}) in the morning because of early ground activities at the airport and gradually decreasing levels of fine particulate matter ($PM_{2.5}$) during the afternoon due to the presence of flights, as well as a consistent distribution of CO_2. This environmental impact is associated with high self-reported respiratory morbidity among a young workforce, with chronic cough and shortness of breath as the most frequent symptoms. Multivariate regression models revealed a definite exposure-awareness paradox, with frontline workers in high-exposure operational areas (Airside/Ramp and Terminal Passenger Hall) having significantly greater respiratory symptoms from direct physical exposure but higher levels of safety knowledge, while lower levels of safety knowledge were used as a proxy for sheltered administrative work. Such basic epidemiological

data underscore the importance of future clinical monitoring that incorporates pre- and/or postshift spirometry or peak expiratory flow measurements to validate respiratory health in the workplace.

Administrative controls and protective practices, rather than education, need to be the focus of management to reduce these occupational vulnerabilities.

RECOMMENDATIONS

To effectively mitigate occupational exposure risks and safeguard worker health, a comprehensive practical approach should be implemented across airport operations. First, management should structure shift rotations to minimize employee exposure during mid-day peak $PM_{2.5}$ concentrations. In addition, high-efficiency air filtration systems should be installed throughout terminal halls and indoor administrative spaces to enhance indoor air quality. For frontline personnel operating in high-exposure environments, the provision and proper fitting of high-efficiency particulate respirators are essential. Finally, routine workforce health monitoring and respiratory screenings should be fully integrated into the facility's ongoing onsite air quality surveillance framework.

DECLARATIONS

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COMPETING INTERESTS

The authors declare that they have no competing interests.

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DATA AVAILABILITY STATEMENT

The datasets generated and analyzed during the current study are not publicly available due to participant privacy and workplace confidentiality restrictions, but are available from the corresponding author upon reasonable request.

Declaration of Generative AI in Scientific Writing

The authors acknowledge the use of Gemini for literature synthesis and the refinement of the manuscript's prose. Prompts were specifically used to reword complex sections for clarity and to ensure that emphasis on education and awareness was effectively communicated. This technology served as a tool for linguistic improvement and proofreading rather than a substitute for original academic writing. All AI-generated outputs were critically reviewed and verified by the authors to maintain the scientific integrity of the work.

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