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Assessment of Particulate Matter Emissions from Corn-Milling Sites in Cape Coast Metropolitan, Southern Ghana

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Abstract

Food milling operations in informal urban markets of Sub-Saharan Africa generate substantial particulate matter (PM) emissions, yet longitudinal, size-resolved data on PM dynamics and associated occupational health risks remain scarce for Ghanaians. A 10-month longitudinal observational study (March–December 2024) was conducted at two commercial milling markets in Cape Coast, Ghana: Kotokoroba and Kingsway. IQAir AirVisual Outdoor monitors deployed at breathing height (1.5 m) recorded PM_1, $PM_{2.5}$, and PM_{10} continuously at 5-minute intervals. Data were analysed using descriptive statistics, Pearson correlations, t-tests, time-series decomposition, and occupational health risk assessment (ADD and HQ) following U.S. EPA methodology. Mean $PM_{2.5}$ were 27.0 µg/m³ (Kotokoroba) and 28.9 µg/m³ (Kingsway), exceeding the WHO 24-hour guideline (15 µg/m³) on 61% and 92% of monitored days, and the Ghana EPA standard (25 µg/m³) on 44% and 78% of days. Mean PM_{10} of 53.5 and 57.5 µg/m³ exceeded WHO limits on 50% and 43% of days. Seasonal peaks were observed during grain milling (June–August) at Kotokoroba (~ 30 µg/m³ $PM_{2.5}$) and spice milling (December) at Kingsway (~ 35 µg/m³ $PM_{2.5}$). Hazard Quotients exceeded 1.0 for $PM_{2.5}$ (1.80 and 1.93) and PM_{10} at both sites. Strong inter-fraction correlations (r = 0.82–0.95, *p-value* ≤ 0.00) confirm shared milling emission sources. PM concentrations persistently exceed national and international guidelines, posing chronic occupational health risks. Wet processing, local exhaust ventilation, and staggered milling schedules are recommended. The study highlights the need for industry-specific PM standards. Limitations include absence of chemical composition analysis, no indoor–outdoor comparison, and no humidity correction for OPC readings.

INTRODUCTION

Atmospheric particulate matter contamination constitutes a paramount environmental health crisis in contemporary society. It exerts profound influence upon metropolitan atmospheric quality, climatological processes, and human physiological well-being. This complex aerosol system comprises a diverse assemblage of suspended solid and liquid constituents within the atmospheric medium (Vellero, D. A., 2025). The environmental and health impacts of these particles are determined primarily by their morphometry, chemical composition, and source characteristics, which collectively govern their atmospheric behavior, deposition patterns, and toxicological potential.

These environmental and epidemiological consequences are predominantly determined by particle morphometry, chemical composition, and emission source characteristics. The size and shape of particles govern their atmospheric transport, residence time, and the region of the respiratory tract they deposit upon inhalation (Hinds & Yhu, 2022). Coarse particulate matter (PM_{10}; ≤10 µm) exhibits preferential deposition within upper respiratory passages through inertial impaction mechanisms, whereas fine particulate matter ($PM_{2.5}$; ≤2.5 µm) achieves deeper bronchiolar penetration via gravitational settling processes (Heyder et al., 1986). The sub-micron fine fraction (PM_1; ≤1 µm) demonstrates the capacity to circumvent mucociliary defense mechanisms, accessing alveolar regions through Brownian motion, where deposition efficiency approaches 50% (Bailey, M. R., 1994). Following

respiratory deposition, $PM_{2.5}$ and PM_1 fractions possess the capability for translocation across alveolar-capillary barriers into systemic circulation, thereby presenting health hazards extending beyond pulmonary manifestations (Oberd, 2005).

International studies show that ambient air pollution causes approximately 7 million premature deaths annually (WHO, 2016)., with developing countries bearing a disproportionate health burden. Over 70% of these deaths result from non-communicable diseases, including heart disease, chronic lung conditions, and cancer (Lelieveld et al., 2020). High-income countries have largely implemented robust air quality monitoring systems and regulatory frameworks that provide detailed, size-resolved data on particulate emissions, temporal exposure patterns, and associated health risks (Yu et al., 2024). African cities consistently exceed World Health Organization air quality standards (Yu et al., 2024), due to poorly regulated industrial activities, biomass burning, and vehicle emissions (Pope & Dockery, 2006). In West African urban areas, small-scale industrial operations, especially cereal flour processing facilities, represent a poorly understood but potentially significant source of particulate matter emissions. Flour milling processes produce substantial mechanical dust emissions containing high concentrations of starch particles, plant fibers, and biological materials (Boac et al., 2009). These activities frequently occur within inadequately ventilated indoor or semi-enclosed commercial spaces, exposing workers and proximate merchants to concentrated pollutant plumes. Mechanical grinding and sieving processes predominantly generate PM_{10} and $PM_{2.5}$ fractions, while material handling and packaging operations may facilitate additional particle fragmentation, producing $PM_{1.0}$ components (Braniš, Řezáčová, & Domasová, 2005).

From atmospheric science perspectives, PM_{10} typically undergoes deposition within minutes to hours following emission and remains localized within approximately 100 meters of source origins, whereas $PM_{2.5}$ demonstrates atmospheric persistence spanning days to weeks with transport potential across hundreds of kilometers (Seinfeld & Pandis, 2016). $PM_{1.0}$ may maintain atmospheric suspension for weeks to months, exhibiting enhanced long-range transport capacity and increased potential for deep respiratory infiltration (Zhang et al., 2017). Chemical composition profiles vary systematically across size fractions: PM_{10} demonstrates enrichment in crustal and biological constituents, while $PM_{2.5}$ and $PM_{1.0}$ exhibit elevated concentrations of combustion-derived metals, organic compounds, and secondary aerosol components (Pöschl, 2005). This compositional differentiation, combined with the elevated surface-area-to-mass ratios characteristic of finer particles, enhances the toxicological potency of smaller fractions in transporting and delivering harmful compounds to human physiological systems (Nel et al., 2006). Notwithstanding, most regional studies in Africa focus on general urban air quality rather than size-differentiated particulate matter emissions from specific industrial sources or temporal variations in exposure. Cross-sectional measurements dominate the available data, preventing an understanding of fluctuations across operational cycles, peak activity periods, and seasonal variations. These limitations create significant knowledge shortfalls regarding emission dynamics, particle size distribution, exposure levels, and health risks in workplace environments, hindering the development of targeted, evidence-based interventions.

Within the Ghanaian context, limited research has investigated size-differentiated particulate matter emissions from milling operations, despite documented evidence of occupational respiratory health impacts in comparable settings (Amoabeng et al., 2020; Bowen, J. 2025). Most existing studies employed to assess general urban air quality monitoring without separating the contributions from specific industrial sources and considering the long-term assessment impacts of these particulate matters. This limits understanding of the emission dynamics, exposure levels, and health risks associated with different-sized particles in workplace environments. In particular, cross-sectional studies fail to capture fluctuations in particulate concentrations across operational cycles, seasonal changes, and long-term exposure trends, limiting the ability to develop targeted interventions.

The purpose of the study is to generate detailed, temporally-resolved data on PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ concentrations, characterize emission sources, and evaluate associated occupational health risks at two principal Food milling centers in Cape Coast: Kotokuraba and Kingsway markets. This study, specifically seeks to (1) quantify PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ concentrations at organic food milling centres at Kotokuraba and Kingsway markets for 10 months using IQAir monitors (2) evaluates compliance with World Health Organization guideline thresholds, (3) characterizes temporal emission patterns, assesses inter-particle correlations to infer source relationships, and (4) conducts occupationally-adjusted health risk assessment utilizing Average Daily Dose (ADD) and Hazard Quotient (HQ) analytical frameworks. This detailed study approach gives practical, research-based advice to government officials, health departments, and market managers who need to cut down air pollution in Ghana's city business areas.

MATERIALS AND METHODS

Study Area and Site Selection

This investigation was executed within two principal food milling centres in the Cape Coast Metropolis, Central Region of Ghana: Kotokoroba Market (5.114°N, 1.247°W) and Kingsway Market (5.109°N, 1.247°W). The Cape Coast Metropolis is an urban district with an estimated population of approximately 169,000 (Ghana Statistical Service, 2021), serving as the regional capital of the Central Region. Both Kotokoroba and Kingsway are among the largest commercial markets in the city, each hosting over 50 small-scale milling operators serving hundreds of customers daily, and situated within 500 m of densely populated residential neighbourhoods. Both sites operate six days per week (approx. 06:00–19:00). These sites were selected based on their high concentration of milling businesses, consistent customer traffic, and proximity to residential areas.

The market environments are distinguished by semi-enclosed processing facilities where cereal grains, including maize, millet, soya bean, and cassava, alongside various spices, undergo mechanical processing utilising locally manufactured grinding equipment. These milling operations constitute significant sources of atmospheric particulate matter emissions through grain comminution processes, and dust re-entrainment mechanisms (Arku et al., 2008; Etyemezian et al., 2005). The regional climate features tropical conditions with two distinct rainy seasons: a main wet season from April to July and a

shorter wet period from September to November. Between these rainy periods is the dry Harmattan season (December to February), characterized by high dust levels carried by winds from the Sahara Desert (Breuning-Madsen & Awadzi, 2005). The careful choice of these research sites allowed for thorough assessment of both workplace exposure (affecting workers directly involved in milling operations) and general environmental exposure (affecting customers, vendors, and nearby residents). The sampling sites (Kingsway and Kotokuraba) are shown in Fig. 1.

Sampling Design and Duration

A longitudinal observational design was implemented across a and 10 months investigation period, encompassing both wet and dry seasonal cycles to comprehensively characterize seasonal fluctuations in particulate matter concentrations. Monitoring activities at Kotokuraba and Kingsway extended from March through December 2024 respectively. Continuous monitoring occurred 24 hours each day without interruption.

The investigation yielded 306 monitoring days across the 10-month period, of which 288 met the ≥ 75% daily data completeness threshold. Coverage by season was: wet season 1 (April–July): 112 of 122 days (92%); dry/Harmattan season (August–November): 104 of 122 days (85%); and short wet season/spice milling period (December): 72 of 92 days (78%). Days failing the completeness threshold were excluded from all analyses. Particle concentration data were collected every 5 minutes for all three size fractions, producing over 83,000 quality-controlled measurements per size fraction at each site. The high-frequency sampling enabled identification of short-term pollution events and diurnal patterns, in line with WHO (2021) monitoring standards.

Instrumentation and Calibration

Particulate matter quantification was accomplished utilising IQAir AirVisual Outdoor Monitor systems, representing low-cost optical particle counter (OPC) technology operating on laser light scattering principles. The instrumentation exhibits a detection range spanning 0–1000 μg/m³, with manufacturer-specified measurement accuracy of ± 10–15% for $PM_{2.5}$ and PM_{10} fractions under ambient atmospheric conditions.

Prior to field deployment, factory calibration certificates for all optical particle sensors were obtained from the manufacturer to ensure baseline accuracy. Supplementary co-location calibration was then conducted against a reference-grade Teledyne T640 analyzer at the Afri-SET (Air Quality Sensor Evaluation and Training Facility for West Africa), hosted by the University of Ghana's Physics Department. The calibration period extended over 168 continuous hours under controlled ambient conditions representative of urban Ghanaian air quality. Comparative analysis yielded strong correlation coefficients ($PM_{2.5}$: $r = 0.87$), confirming reliable instrument response within internationally accepted validation thresholds for optical particle counters. These correlation magnitudes are consistent with

previous low-cost sensor evaluation studies in developing-country contexts (Sousan et al., 2016; Jayaratne et al., 2018), thereby supporting the credibility of the field data used in subsequent analysis. However, optical particle counters are susceptible to positive measurement bias under elevated relative humidity (RH > 70%) due to hygroscopic particle growth (Jayaratne et al., 2018). Cape Coast's tropical climate regularly produces RH > 80% during wet season mornings, so a modest positive bias in PM readings during those periods cannot be excluded. No humidity correction factor was applied, as site-specific coefficients were unavailable; this constitutes a recognised measurement limitation. Future deployments should incorporate concurrent RH logging and apply empirically derived correction algorithms.

Data Collection

Air quality monitors were installed at 1.5 m height to capture measurements at human breathing level (Chakraborty & Mondal, 2021). At both Kingsway and Kotokoroba, the monitors were mounted on an exterior wall of a semi-enclosed milling shed approximately 3 m from the primary grinding equipment, in a partially roofed structure open windows on two sides (moderate ventilation). Neither site had mechanical air handling systems. Weekly cleaning and maintenance followed manufacturer guidelines. Monthly data integrity assessments identified anomalous measurements, including zero values (attributed to instrument initialisation intervals and data-download periods, excluded from health risk calculations) and implausibly elevated concentrations.

Data Processing and Statistical Analysis

Raw particulate matter concentration data were downloaded from the IQAir Cloud platform as CSV files. Quality assurance and quality control (QA/QC) procedures followed internationally recognized air quality monitoring standards (Mücke, H. G., 2008). Data completeness evaluations excluded any monitoring day exhibiting greater than 25% missing records, while outlier filtration removed values falling outside physically plausible ranges (exceeding the 99.5th percentile unless meteorologically substantiated).

Quality-controlled datasets underwent temporal aggregation into hourly and daily mean concentrations for PM_{1}, $PM_{2.5}$, and PM_{10} fractions to facilitate temporal trend characterization and comparative evaluation against World Health Organization (2021) 24-hour guideline thresholds.

A comprehensive descriptive statistical analysis was conducted for each particulate fraction and site, including:

- Minimum (min) and maximum (max) concentrations to capture the exposure range.
- Arithmetic means to represent central tendency.
- Standard deviation (stdev) to quantify dispersion.
- Sample count (n) to document data volume.

- 95% confidence intervals (CI) as in Eq. 1 for mean concentrations is calculated as:

$$CI = \bar{x} \pm t_{\alpha/2,n-1} \times \frac{s}{\sqrt{n}} \text{ (Eq. 1)}$$

where $\bar{x}$ is the sample mean, s is the sample standard deviation, and t is the Student's t-statistic for $n-1$ degrees of freedom at α = 0.05.

Coefficient of variation (CV) expressed as in Eq. 2:

$$CV\,(\%) = \frac{s}{\bar{x}} \times 100 \text{ (Eq. 2)}$$

to allow comparison of variability between pollutants and sites regardless of magnitude.

Pearson product-moment correlation coefficients were calculated to evaluate inter-relationships among PM_1, $PM_{2.5}$, and PM_{10} concentration distributions, while independent two-sample t-test procedures were employed to examine statistically significant disparities between mean concentrations observed at Kotokuraba and Kingsway monitoring locations (α = 0.05). Time-series decomposition methods were used to identify daily and seasonal patterns in the particulate matter data (Griffin & Gharabaghi, 2021). This analytical approach is consistent with current methods used in urban air quality studies across Sub-Saharan Africa (Abera et al., 2021).

Health Risk Assessment

A complete health risk analysis was performed to evaluate potential health effects from particle exposure, following the EPA's 2011 risk assessment methodology for non-cancer health impacts. The exposure was characterized in terms of the Average Daily Dose (ADD, µg/kg-day) in Eq. 3 is calculated as:

$$ADD = \frac{C \times IR \times EF}{BW \times AT} \text{ (Eq. 3)}$$

where C is the concentration of particulate matter (µg/m³), IR is the inhalation rate (m³/day), EF is the exposure frequency (days/year), BW is the body weight (kg), and AT is the averaging time (days).

For occupational scenarios, parameter values were adjusted to reflect realistic conditions of milling operators: IR = 10.4 m³/day (based on 1.3 m³/h × 8 h/day; U.S. EPA Exposure Factors Handbook), EF = 312 days/year (6 days/week × 52 weeks), BW = 70 kg (adult default), and AT = 365 days (averaging over one year for non-carcinogenic effects).

The Hazard Quotient (HQ) in Eq. 4 was then derived as:

$$HQ = \frac{ADD}{RfD} \text{ (Eq. 4)}$$

where RfD is the reference dose. Concerning $PM_{2.5}$ exposure assessment, the reference concentration threshold was established at 15 µg/m³, derived from World Health Organization interim target guidelines and corroborated by preceding risk evaluation studies (WHO, 2021). An HQ greater than 1 indicates a potential for adverse non-carcinogenic health effects. The percentage of monitoring days exceeding WHO 24-hour guidelines ($PM_{2.5}$ = 15 µg/m³; PM_{10} = 45 µg/m³) was also calculated to assess acute exposure risk.

RESULTS AND DISCUSSIONS

The comprehensive descriptive statistical evaluation (Table 1) furnishes an exhaustive quantitative characterization of particulate matter distributions (PM_1, $PM_{2.5}$, PM_{10}) across Kotokuraba and Kingsway commercial markets, encompassing maximum observed values, arithmetic means, standard deviations, sample populations, 95% confidence intervals (CIs), and coefficients of variation (CV).

At the Kotokuraba monitoring location, arithmetic mean concentrations were determined as 17.2 µg/m³ for PM_1, 27.0 µg/m³ for $PM_{2.5}$, and 53.5 µg/m³ for PM_{10}, each exhibiting pronounced variability (CV > 80%) and substantial upper confidence interval boundaries (18.9, 30.1, and 59.0 µg/m³, respectively). The high coefficient of variation values suggests that short-term emission bursts, likely linked to intensive milling operations and mechanical handling of materials, are the main causes of significant swings in ambient particulate matter concentrations. Peak concentrations reached 70.0 µg/m³ (PM_1), 101 µg/m³ ($PM_{2.5}$), and 255 µg/m³ (PM_{10}), showing levels that were several times higher than World Health Organization (WHO, 2021) 24-hour guidelines for $PM_{2.5}$ (15.0 µg/m³) and PM_{10} (45.0 µg/m³).

At the Kingsway monitoring station, arithmetic mean concentrations (µg/m³) were established as 17.0 (PM_1), 28.9 ($PM_{2.5}$), and 57.5 (PM_{10}). Concentration variability demonstrated marginally reduced values for PM_1 (CV = 44.7%) relative to Kotokuraba, while maintaining considerable dispersion for $PM_{2.5}$ and PM_{10} fractions (CV = 66.3% and 93.4%, respectively). Maximum concentration episodes achieved 66.3 µg/m³ for PM_1, 187 µg/m³ for $PM_{2.5}$, and an extraordinary 565 µg/m³ for PM_{10}, with the latter exceeding World Health Organization daily guidelines by more than twelve-fold.

The diminished coefficient of variation for PM_1 at Kingsway may signify more consistent ultrafine particle emission patterns relative to coarse fraction variability, potentially reflecting continuous yet moderate-intensity sources including background urban aerosol contributions (Flores et al., 2007) and persistent mechanical abrasion processes associated with grain processing activities. Conversely, the exceptionally elevated $PM_{2.5}$ and PM_{10} concentration peaks indicate intermittent, high-intensity dust generation events, consistent with observations documented by Amegah & Agyei-Mensah (2017) and Amato et al., (2012) within analogous open-market and informal food processing environments.

From an epidemiological perspective, the persistently elevated $PM_{2.5}$ and PM_{10} mean concentrations exceeding World Health Organization threshold values, coupled with frequent episodic concentration spikes, demonstrate substantial potential for both acute and chronic respiratory health impacts (Lelieveld et al., 2005; Schraufnagel et al., 2019). Although international regulatory guidelines remain

absent for PM_1 fractions, their demonstrated capacity for deep alveolar penetration and systemic translocation via bloodstream pathways emphasizes the imperative for incorporating this size fraction within market-based atmospheric quality surveillance protocols (Oberdörster et al., 2005).

Table 1
Comprehensive descriptive statistical characterization of PM_1, $PM_{2.5}$, and PM_{10} concentration distributions observed at Kotokuraba and Kingsway markets within the Cape Coast Metropolis, Southern Ghana.

Site	Pollutant	Min (µg/m³)	Max (µg/m³)	Mean (µg/m³)	Stdev	95% CI Lower	95% CI Upper	CV (%)
Kotokuraba	PM_1	0.00	70.0	17.2	14.1	15.5	18.9	82.3
	$PM_{2.5}$	0.00	101	**27.0**	25.6	23.9	30.1	94.8
	PM_{10}	0.00	255	**53.5**	45.5	48.0	59.0	85.0
Kingsway	PM_1	0.00	66.3	17.0	7.62	16.2	17.9	44.7
	$PM_{2.5}$	0.00	187	**28.9**	19.2	26.7	31.1	66.3
	PM_{10}	0.00	565	**57.5**	53.6	51.3	63.6	93.4

Bold-formatted values denote exceedances of WHO 2021 24-hour guidelines ($PM_{2.5}$: 15 µg/m³; PM_{10}: 45 µg/m³) and Ghana EPA national standards ($PM_{2.5}$: 25 µg/m³; PM_{10}: 70 µg/m³). WHO has not established regulatory guidelines for PM_1. Minimum values of 0.00 µg/m³ reflect isolated instrument initialisation intervals and connectivity gaps; these were flagged during QA/QC and excluded from health risk calculations, and do not represent true environmental minima.

Temporal Variability and WHO Guideline Exceedance

The comprehensive exceedance evaluation (Fig. 2) demonstrates systematic violations of both WHO (2021) 24-hour guidelines and Ghana EPA national ambient air quality standards ($PM_{2.5}$: 25 µg/m³; PM_{10}: 70 µg/m³) at both sites. Against WHO guidelines, $PM_{2.5}$ exceeded 15 µg/m³ on 60% of days at Kotokoroba and 92% at Kingsway; against the Ghana EPA standard of 25 µg/m³, exceedances occurred on 44% and 78% of days, respectively. PM_{10} exceeded the WHO limit (45 µg/m³) on 50% and 42% of days; against the Ghana EPA limit (70 µg/m³), on 28% and 34% of days. These patterns indicate that elevated PM is a consistent, chronic feature of these environments, not isolated episodic events. This sustained exposure is driven by regular operational activities such as cereal processing, dust being stirred up again, and nearby vehicle emissions.

Although World Health Organization regulatory thresholds remain absent for PM_1 fractions, the observed mean and maximum values documented in this investigation warrant clinical consideration. Concentrations frequently surpassed 60.0 µg/m³ during peak exposure periods, a concentration range previously correlated with elevated risks of cardiovascular incidents, respiratory inflammatory responses,

and mortality outcomes in epidemiological investigations (Stanek et al., 2011; Schikowski et al., 2014). Additionally, ultrafine particulate matter such as PM_{1} demonstrates enhanced capability for deep alveolar penetration relative to $PM_{2.5}$ fractions, and has been associated with systemic oxidative stress mechanisms and inflammatory cascade pathways (Lelieveld et al., 2020).

The integrated exceedance patterns observed across particulate matter size fractions suggest that health risks within these occupational environments are characterized by chronic and cumulative exposure profiles. This phenomenon presents particular concern for milling facility workers subjected to 8–12 hour daily exposures, as well as for residential populations and commercial vendors maintaining prolonged proximity to emission sources. Sustained exposure to above-guideline $PM_{2.5}$ concentrations has been epidemiologically linked to accelerated pulmonary function decline (Schikowski et al., 2014), increased hospital admission rates for asthma and chronic obstructive pulmonary disease (COPD) manifestations and elevated incidence of ischemic cardiac pathology (Brook et al., 2010).

Because pollution limits were frequently exceeded, emission control plans must focus on both short-term spike reduction (using dust suppression and improved ventilation) and long-term reduction of ongoing baseline pollution. Regulatory authorities should consider incorporating these empirical findings into occupational health surveillance frameworks and market-specific environmental hygiene policy development initiatives.

Diurnal Patterns of PM Concentrations

The diurnal fluctuation profiles (Fig. 3) demonstrated a remarkably consistent temporal signature across both Kotokuraba and Kingsway commercial markets, characterized by distinct morning and afternoon concentration maxima separated by a relative midday plateau phase. Particulate matter concentrations showed a marked increase after 7:00 AM, which coincided with the start of milling operations and increased human activity. The initial concentration peak, manifesting between 09:00–11:00 hours, presumably reflects the cumulative influence of sustained milling processes since operational commencement, particulate matter resuspension resulting from material handling activities, and emissions originating from auxiliary operations, including transport vehicle exhaust and biomass combustion systems utilized for supplementary food preparation activities.

A secondary pronounced concentration maximum occurring between 14:00–16:00 hours corresponds with post-meridian milling operations as clientele return for afternoon grain processing services. This bimodal peak configuration demonstrates consistency with investigations conducted within other sub-Saharan African market environments, wherein milling and mechanical processing activities are concentrated within discrete, high-intensity operational periods (Amegah & Agyei-Mensah, 2017; Ezeh et al., 2020).

Notably, Kingsway exhibited a secondary concentration peak around 17:00 hours less pronounced at Kotokoroba, likely attributable to late-afternoon milling activity serving post-work customers, evening peak traffic emissions on adjacent roads, and reduced ventilation as stall operators partially close

market openings toward end of business. A day/night analysis (06:00–18:00 vs. 18:00–06:00) confirmed that daytime mean $PM_{2.5}$ was approximately 2.3-fold higher than nighttime at both sites (~ 32 vs. ~14 µg/m³), consistent with activity-driven emission. The general decline in concentrations after 19:00 can be explained by both operational and meteorological perspective, this decline aligns with the development and stabilization of the atmospheric boundary layer, which promotes better vertical mixing and helps disperse pollutants more effectively (Seinfeld & Pandis, 2016). Analogous diurnal concentration decay patterns have been documented in tropical urban atmospheric quality investigations, wherein afternoon convective mixing processes significantly reduce ground-level particulate matter concentrations (Kinney et al., 2011).

The synchronized timing of pollution peaks across PM_1, $PM_{2.5}$, and PM_{10} fractions confirms that milling activity is the dominant shared source across all size ranges, corroborating the inter-fraction correlations. A milling vs. non-milling hour comparison (06:00–19:00 vs. 19:00–06:00) showed mean $PM_{2.5}$ of 33.4 µg/m³ (Kotokoroba) and 35.7 µg/m³ (Kingsway) during operating hours, versus 12.1 and 14.3 µg/m³ during non-operating hours – a 2.5 to 2.8-fold elevation directly attributable to milling. These contrasts provide strong evidence that targeted interventions during active milling hours including local exhaust ventilation, aqueous spray dust suppression, and staggered processing schedules would yield disproportionate exposure reductions.

Strong and statistically significant positive correlations were found between different particulate matter size fractions at both monitoring sites (Fig. 4). At the Kotokuraba site, PM_1 and $PM_{2.5}$ fractions demonstrated exceptionally strong correlation coefficients ($r = 0.93$, $p < 0.001$), paralleled by $PM_{2.5}$ and PM_{10} associations ($r = 0.91$, $p < 0.001$). This elevated coherence across fine and coarse particle distributions indicates predominant influence from shared emission sources, including mechanical grain processing and material handling operations, which simultaneously release both respirable (< 2.5 µm) and inhalable (< 10 µm) particulate matter into the identical microenvironmental space (Lelieveld et al., 2015; Lelieveld et al., 2020). The near-perfect correlation between PM_1 and $PM_{2.5}$ fractions signifies that a considerable proportion of the fine particulate burden at Kotokuraba exists within the ultrafine-to-fine size range, characterized by enhanced deposition efficiency within alveolar lung regions (Oberdörster et al., 2005).

Conversely, the Kingsway monitoring location exhibited strong correlation between $PM_{2.5}$ and PM_{10} fractions ($r = 0.91$, $p < 0.001$) while demonstrating only moderate correlation between PM_1 and $PM_{2.5}$ components ($r = 0.69$, $p < 0.001$). This attenuated PM_1–$PM_{2.5}$ association indicates that although coarse and fine particles maintain substantial co-emission patterns, the ultrafine particle contribution at Kingsway demonstrates greater variability and potential influence from supplementary intermittent emission sources, including vehicular exhaust, proximate combustion activities, or aeolian dust entrainment from open commercial stalls. Such heterogeneity in ultrafine particle source contributions has been documented within other open-air urban market environments throughout West Africa (Amegah & Agyei-Mensah, 2017; Ezeh et al., 2020).

From an emission control strategy perspective, the enhanced PM_1–$PM_{2.5}$ coupling observed at Kotokuraba implies that interventions targeting fine particle reduction (including improved milling enclosure systems and dust extraction technologies) would presumably generate concurrent reductions in ultrafine particle exposure. At Kingsway, however, the diminished ultrafine–fine particle linkage indicates that targeted mitigation measures may require addressing specific PM_1 emission sources in addition to comprehensive particulate matter control strategies. This differentiation assumes particular importance, considering that PM_1 fractions are increasingly recognized for their contributions to oxidative stress mechanisms and systemic inflammatory responses (Stanek et al., 2011; Schraufnagel et al., 2019), despite remaining unregulated within current World Health Organization guideline frameworks (WHO, 2021).

Health Risk Assessment

The occupational exposure evaluation (Table 2) demonstrates that workers within both commercial markets experience persistent exposure to considerable particulate matter doses across all particle size classifications. At the Kotokuraba facility, mean Average Daily Dose (ADD) values were quantified as 3.43 μg/kg-day for $PM_{2.5}$ and 6.80 μg/kg-day for PM_{10} fractions. Marginally elevated values were documented at Kingsway (3.67 and 7.30 μg/kg-day, respectively). These measurements capture continuous breathing exposure during typical 8-hour work shifts, six days a week, which reflects the working conditions commonly found in cereal milling operations.

The computed Hazard Quotient (HQ) values provide comprehensive insight into potential non-carcinogenic health risks. Regarding $PM_{2.5}$ exposure, arithmetic mean HQ values attained 1.80 at Kotokuraba and 1.93 at Kingsway, both substantially exceeding the United States Environmental Protection Agency reference threshold of unity. PM_{10} Hazard Quotients similarly surpassed the acceptable limit (1.19 and 1.28, respectively). PM_1 fractions, despite remaining unregulated by current standards, generated HQ values approximating 1.14 at both monitoring locations, emphasizing concerns regarding ultrafine particle exposure scenarios. Values exceeding unity indicate that chronic adverse health effects cannot be definitively excluded, particularly among workers experiencing repeated long-term occupational exposure.

This risk characterization receives confirmation through the exceedance evaluation (Fig. 2). $PM_{2.5}$ daily mean concentrations surpassed World Health Organization regulatory limits on 60.6% of monitoring days at Kotokuraba and 94.2% of observation periods at Kingsway. PM_{10} threshold violations occurred on approximately half of the monitored temporal periods at Kotokuraba and 43.3% at Kingsway. The convergence of frequent guideline exceedances and Hazard Quotient values exceeding unity indicates a bifurcated risk profile: episodic acute exposure events coupled with chronic cumulative health impacts.

Table 2
Summary of Occupationally Adjusted Average Daily Dose (ADD) and Hazard Quotient (HQ) Estimates for Fine and Coarse Particulate Matter ($PM_{2.5}$ and PM_{10}) at Kotokuraba and Kingsway Markets, Cape Coast, Ghana

Site	Pollutant	Mean ADD (µg/kg-day)	95% CI (ADD)	Mean HQ	95% CI (HQ)
Kotokoraba	$PM_{2.5}$	3.43	3.04–3.82	1.80	1.59–2.01
	PM_{10}	6.80	6.10–7.49	1.19	1.07–1.31
Kingsway	$PM_{2.5}$	3.67	3.39–3.95	1.93	1.78–2.07
	PM_{10}	7.30	6.51–8.08	1.28	1.14–1.41

The confidence interval parameters provide additional substantiation for these conclusions. Specifically, Kotokuraba $PM_{2.5}$ Hazard Quotient values ranged from 1.59 to 2.01, while Kingsway demonstrated ranges from 1.78 to 2.07 (95% CI), indicating that the empirical findings are not influenced by statistical outliers but rather represent systematic exposure patterns. Elevated standard deviation values, exemplified by ± 3.25 µg/kg-day for $PM_{2.5}$ Average Daily Dose at Kotokuraba reflect the manifestation of high-intensity exposure episodes associated with operational activity intensification during milling processes.

Epidemiological investigations demonstrate that chronic $PM_{2.5}$ exposure within African urban environments is correlated with increased incidence of chronic bronchitis, asthma pathology, and diminished pulmonary function parameters (Brauer et al., 2012; Amegah & Agyei-Mensah, 2017). The results additionally reinforce occupational health studies documenting elevated prevalence rates of respiratory pathology among cereal processing facility workers (Rana et al., 2018).

From a regulatory policy perspective, the empirical evidence indicates the necessity for immediate intervention measures. Although Hazard Quotient values below 2.0 suggest that acute toxicological effects may be improbable, the convergence of guideline exceedances and HQ values exceeding unity strongly implies substantial risk of chronic respiratory impairment should current exposure concentrations persist. Mitigation measures including local exhaust ventilation systems, enhanced particulate matter control practices (such as wet sweeping methodologies), staggered milling operational schedules, and implementation of protective respiratory equipment should be prioritized to safeguard both occupational workers and proximate residential populations.

The longitudinal analysis of monthly Mean Average Daily Dose (ADD) for $PM_{2.5}$ and PM_{10} at Kotokuraba and Kingsway (Fig. 5) shows that the exposure to particulate matter was always high over the monitored ten months from March to December. The PM_{10} fraction showed higher ADD values than $PM_{2.5}$ in both sites, indicating coarse particles formed through milling, handling, and packaging processes. Specifically, at Kotokuraba, the $PM_{2.5}$ ADD varied from 3.30 to 3.48 µg/kg-day and PM_{10} from 6.70 to 6.85 µg/kg-day, while at Kingsway, it was slightly higher: $PM_{2.5}$, between 3.55 and 3.68 µg/kg-day; and PM_{10}, between 7.10 and 7.31 µg/kg-day. This result shows that Kingsway sees more intensive operation or

higher particle resuspension, in agreement with previous studies that show site-specific differences in exposures related to variation in ventilation, worker crowding, and milling equipment efficiencies (Braniš, 2005; Boac et al., 2009). The relatively small variation in these monthly averages suggests that the exposure pattern may be systematic rather than incidental, implying the chronic nature of the particulate matter pollution in such occupational settings.

Temporal trends in exposure provide additional insight into occupational health risks. Incremental increases in $PM_{2.5}$ and PM_{10} ADD were observed in the months of peak milling, namely June and July, probably reflecting periods of higher throughput and intensified grinding operations. These results are in agreement with the well-understood principles of atmospheric and particle deposition, that the coarse particles (PM_{10}) would mostly remain localized and the fine particles ($PM_{2.5}$) would tend to have a larger potential for deeper respiratory infiltration and long-range dispersal (Seinfeld & Pandis, 2016; Hinds & Yhu, 2022).

Limitations

Several limitations were acknowledged. First, the IQAir AirVisual monitors are low-cost OPCs with ± 10–15% accuracy; measurements reflect fixed-location ambient levels rather than individual worker inhalation doses. Second, no chemical composition analysis (e.g., OC/EC, metals, endotoxins, bioaerosols) was performed; the observed PM fractions cannot be attributed to specific source types beyond grain and spice dust from milling. Third, no indoor–outdoor concentration gradient was measured. Fourth, OPC sensors are susceptible to positive bias under elevated RH (> 70%), common in Cape Coast's tropical climate; no humidity correction was applied due to absence of site-specific coefficients, potentially causing modest PM overestimation during wet season mornings. Fifth, the HQ framework assumes steady-state exposure and does not capture peak short-duration inhalation events. Finally, data coverage varied by season (78–92%), and results were interpreted accordingly.

Conclusions

This study provides longitudinal, size-resolved data on PM_1, $PM_{2.5}$, and PM_{10} from two commercial food milling markets in Cape Coast, Ghana, contributing to the limited evidence base on occupational PM exposure in informal urban industries in Sub-Saharan Africa. Mean $PM_{2.5}$ of 27.0 μg/m³ (Kotokoroba) and 28.9 μg/m³ (Kingsway) exceeded WHO guidelines on 61% and 92% of monitored days, and Ghana EPA standards on 44% and 78% of days. PM_{10} means of 53.5 and 57.5 μg/m³ exceeded regulatory thresholds at both sites. Hazard Quotient values above 1.0 for $PM_{2.5}$ (1.80 and 1.93) and PM_{10} at both locations indicate potential chronic non-carcinogenic health effects under current exposure conditions.

Diurnal patterns at both sites showed bimodal PM peaks aligned with morning and afternoon milling activity (2.3-fold higher daytime vs. nighttime concentrations). Strong inter-fraction correlations (r = 0.82–0.95) confirm that milling is the dominant shared source across all PM size fractions. The inclusion of PM_1 is particularly noteworthy: despite lacking regulatory thresholds, it constitutes a

substantial share of total exposure and, given its alveolar penetration capacity and systemic translocation potential, warrants incorporation into future occupational health frameworks.

The findings support prioritising local ventilation, staggered milling schedules, and mandatory use of particulate-filtering respirators. At the policy level, these results call for incorporating small-scale milling into Ghana's occupational health regulatory frameworks, developing industry-specific PM exposure limits, and establishing routine PM monitoring in informal commercial food processing environments. Future research should characterise the chemical composition of milling-generated PM, conduct indoor–outdoor gradient measurements, apply humidity corrections to OPC data, and assess long-term respiratory health outcomes in exposed worker cohorts.

From public health and regulatory policy perspectives, these results indicate an immediate necessity for targeted intervention measures within Ghana's urban commercial markets and analogous small-scale industrial environments. Practical mitigation measures including enhanced stall ventilation systems, localized exhaust technologies, periodic particulate matter suppression methodologies (such as wet cleaning protocols), and mandatory implementation of particulate-filtering respiratory protection could substantially reduce occupational exposure burdens. Administrative strategies, including temporal scheduling of milling operations to circumvent cumulative peak concentration periods, may additionally contribute to health risk reduction. At broader implementation scales, incorporating small-scale milling operations into urban atmospheric quality management and occupational health policy frameworks would enhance worker safety protocols, protect vulnerable population demographics, and reduce background ambient PM concentrations within densely populated community environments.

This investigation serves as a methodological guide for assessing PM exposure in similar developing-country settings and underscores the need to expand regulatory frameworks beyond $PM_{2.5}$ and PM_{10} to explicitly incorporate fine sub-micron PM_1, particularly within informal industrial sectors where exposure is frequent, prolonged, and under-recognised.

Declarations

Conflict of Interest

The contact author has declared that none of the authors has any competing interests.

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Data Availability Statement

The data used in this study are available upon request from corresponding author

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Figures

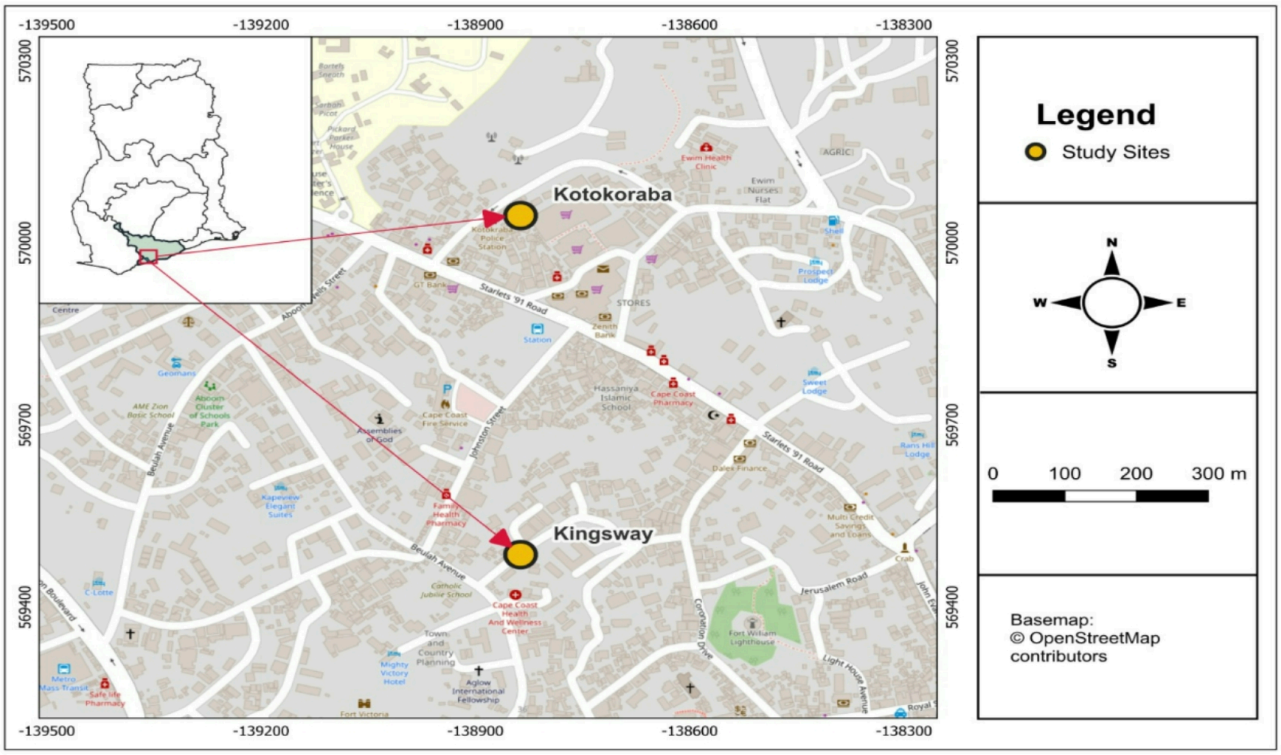


Figure 1

A map showing Kingsway Market in the Cape Coast metropolis, Ghana (map content by Alexander B. Marful). [Authors' note: Redraw using a GIS tool with scale bar, north arrow, labelled monitoring site, and surrounding landmarks.])

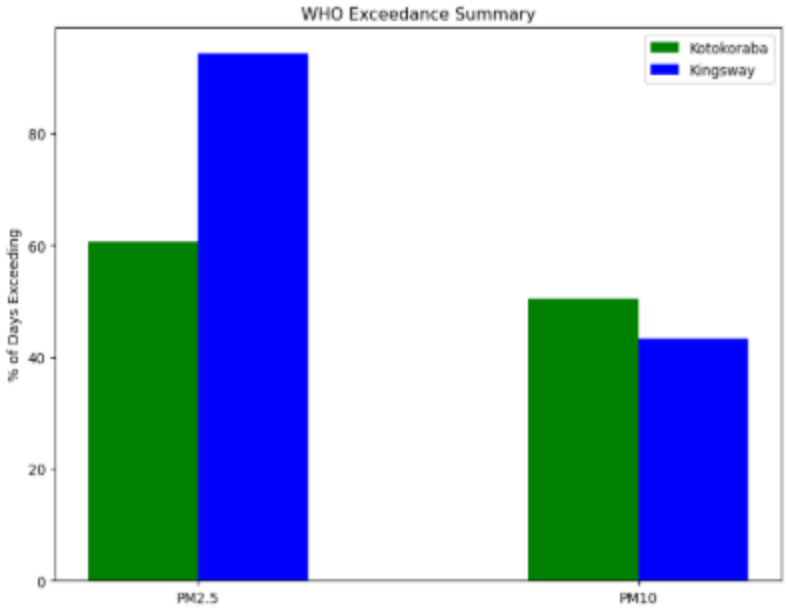


Figure 2

Exceedance frequencies of WHO 24-hour air quality guidelines for $PM_{2.5}$ (15 µg/m³) and PM_{10} (45 µg/m³) at Kotokuraba and Kingsway markets. Bars represent the percentage of monitored days exceeding guideline values.

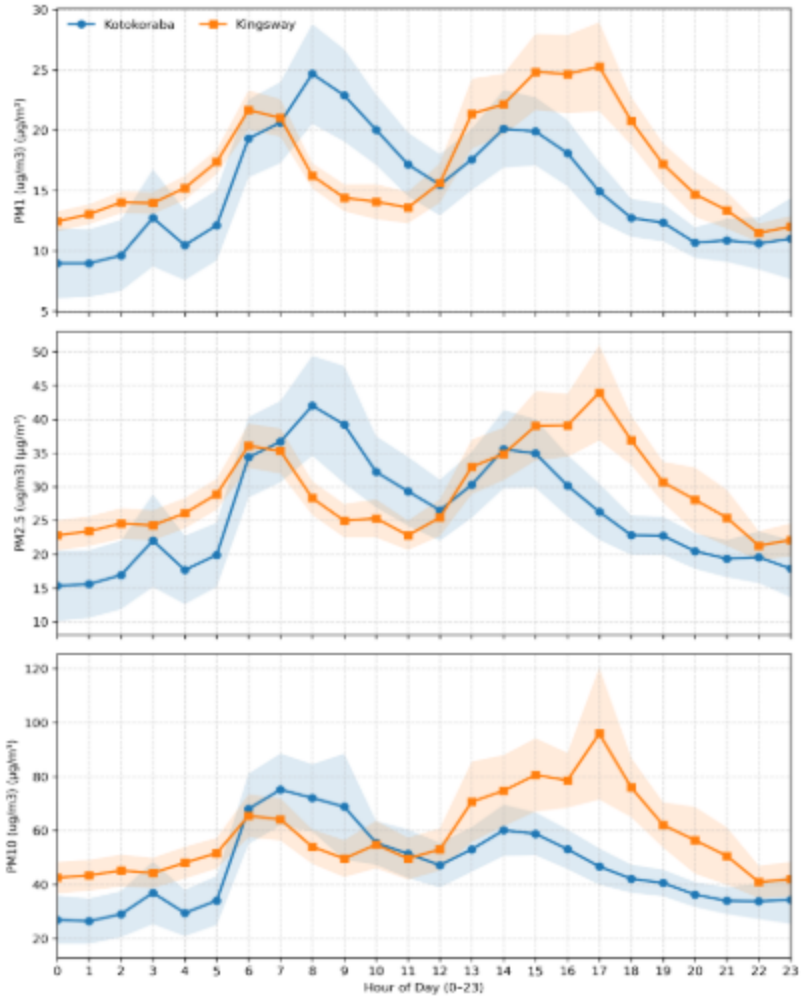


Figure 3

Diurnal variation of PM_1, $PM_{2.5}$, and PM_{10} concentrations at Kotokuraba and Kingsway markets, averaged across the full monitoring period. Solid lines display hourly average values, with shaded regions showing the statistical 95% confidence range for these measurements.

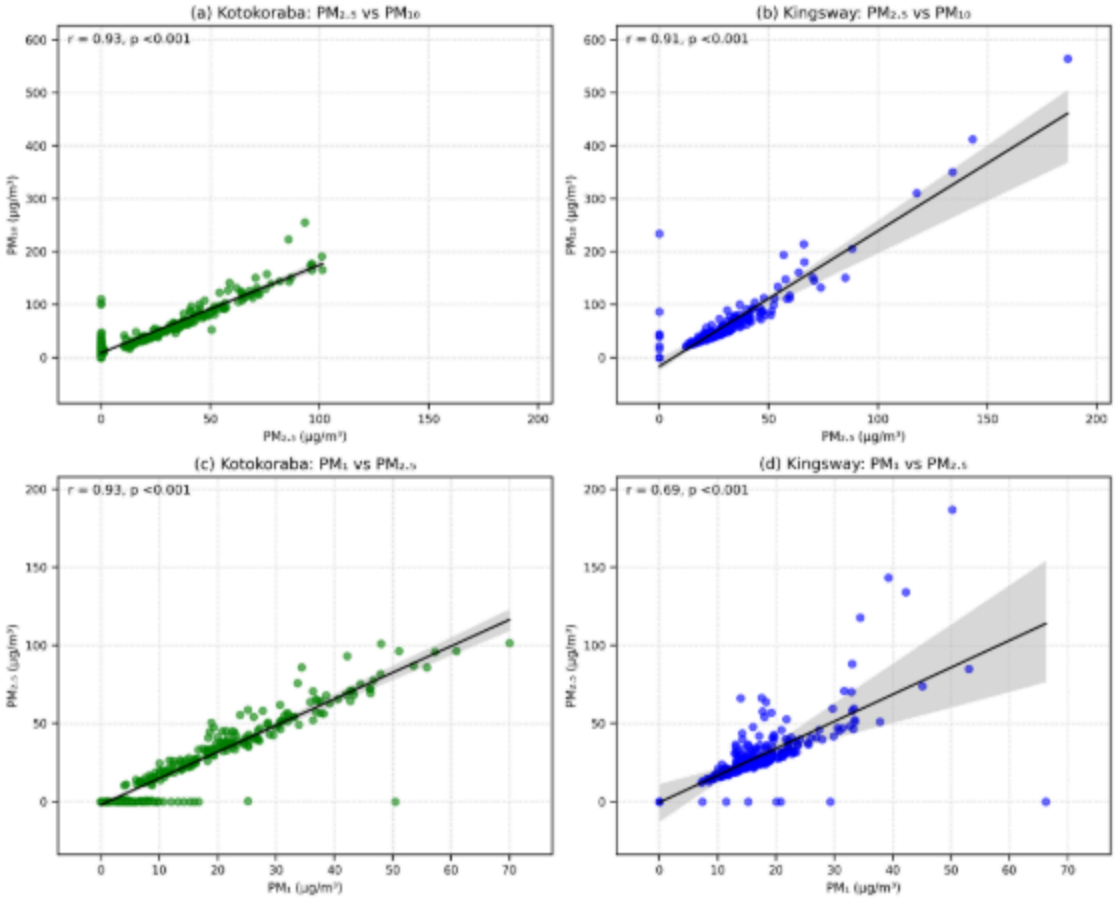


Figure 4

Scatterplots showing inter-particle relationships between $PM_{2.5}$ and PM_{10} concentrations at (a) Kotokuraba Market and (b) Kingsway Market, and PM_1 and $PM_{2.5}$ concentrations at (c) Kotokuraba Market and (d) Kingsway Market, based on daily mean values over the monitoring period. The chart displays daily average values as individual points, along with trend lines in black and shaded 95% confidence bands. Data from Kotokuraba appears in green, and Kingsway data in blue. Statistical measures showing relationship strength and reliability are included in each section.

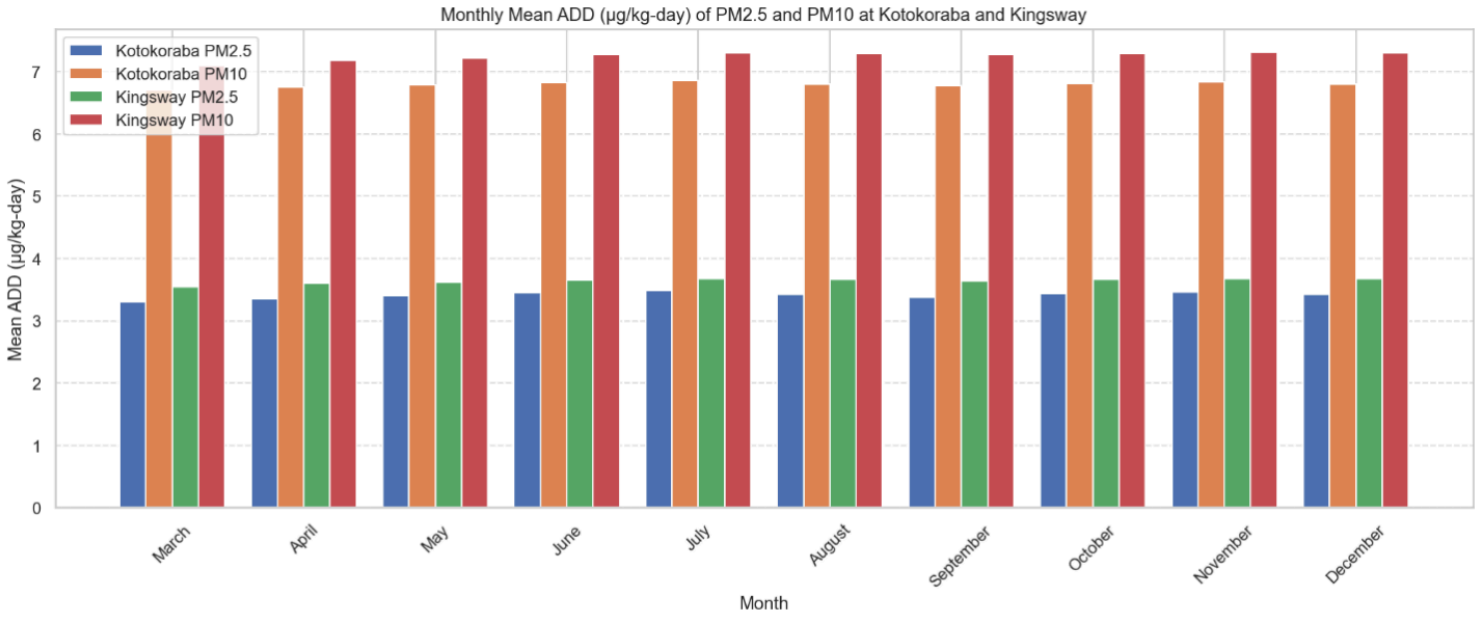


Figure 5

The longitudinal analysis of monthly Mean Average Daily Dose (ADD) for $PM_{2.5}$ and PM_{10} at Kotokuraba and Kingsway within the Cape Coast Metroplis, Southern Ghana.