

Assessment of Spatial Distribution of Ambient Particulate Matter Pollutants and Potential Health Risk Surrounding a Cement Plant in North-Central Nigeria

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Abstract

This study characterised and determined the concentrations of PM₁, PM_{2.5}, PM₄, PM₇ and PM₁₀ pollutants surrounding a cement plant in North-Central Nigeria. It also assessed the spatial distribution of the pollutants and evaluated the effects of wind speed and direction on the spatial dispersion of the PM pollutants in the study area. These were with a view to providing information on the spatial distribution of the PM pollutants in the study area.

In-situ measurements of the PM pollutants were carried out both in the study area and the control site using pre-calibrated direct reading instruments such as Met-One (AEROCET-model 531S) and hand-held environmental meter (KESTREL-model 5500). A total of 12 sampling points were set up in the study area. Four sampling points were considered at the four cardinal points (i.e. North, East, South and West) each at three varying distances, buffer of 0, 250 and 500 m in the study area. Similarly, the same technique was undertaken at the control points. Data from all the sampling points were collected three times in a day between June and August, 2023. Meteorological parameters such as wind speed and direction were measured at all the sampling points along with the PM pollutants.

The study established that the mean values of the PM pollutants PM: PM₁, PM_{2.5}, PM₄, PM₇ and PM₁₀ were 59.02 ± 4.15 , 60.20 ± 4.15 , 64.56 ± 4.18 , 64.83 ± 4.18 , 64.97 ± 4.18 $\mu\text{g}/\text{m}^3$ respectively in the study area. The spatial analysis showed that the concentrations of all the pollutants were generally highest at 0-metre (i.e. the nearest point to the emission source), and in the East direction but decreased with distance away from the cement plant. The results therefore indicated the concentrations of the PM pollutants in the study area were higher than the WHO standards, signaling both short-term and long-term health risks to residents in the vicinity of the cement plant. The level of the pollutants' concentrations also indicated occupational health risks.

1. Introduction

Human activities including industrialisation in general terms and cement production to be precise have compounded environmental crises, including air quality deterioration thereby exposing hundreds of millions of people to lack of access to a safe and clean air environment, leading to respiratory and cardiovascular issues, and loss of millions of lives yearly. The global air quality guidelines as stipulated by the WHO (2021) has therefore designated air pollution as the foremost environmental risk to health and further stated that about 99% of the world population do not breathe the air conforming with its Air Quality Guideline.

The WHO further reported that one among the basic human rights is access to clean air. Similarly, Bakke (2021) opined that clean air is fundamental to health and essential to human life. Thus, an average adult human for example, breathes about 15 kg of air per day, consumes averagely 1.5 litres of water and eats about 0.75 kg of solid food per day. This implies the quantity of air breathe by human is 20 times that of solid food consumption per day. Perhaps, given the deteriorating ambient air quality due to industrialisation such as cement production as illustrated in (Fig. 1), pyramid of impacts arising due to air pollution, there is high potential risk of exposure by majority of the human population. Amongst the population exposed to the unclean air with strong immunity only suffer physiological changes and sub-clinical effects. Some experience symptoms of illness and use medications, while others may need at least primary healthcare and medical attention. While severe cases such as high level of exposure may need the services of ambulance to be transported to emergence units, leading to hospital admissions and in worst case scenario, deaths may occur (Melody and Johnston, 2015; Dutta, 2020).

Different sizes of Particulate Matter (PM) pollutants are discharged into the atmosphere by which activities such as cement production processes constitute the major sources thereby deteriorating the air quality, which poses risk to human health and the environment (Etim *et al.*, 2021).

In line with this, the WHO (2021) and Kumar et al. (2023) similarly revealed that exposure to PM pollutants increases the incidence of acute and chronic health risks. Adding that acute health impact may include; headache, nose, throat and eye irritations, coughing, sneezing, skin infection, bronchitis, pneumonia etc. While chronic health risks include; cardiovascular diseases, asthma, lung cancer, heart diseases, stroke, wheezing and even death.

Ambient Pollution from Cement Production

The manufacturing of cement is a complex and energy-intensive procedure involving numerous key processes, beginning with raw materials extraction such as limestone, chalk, shale, clay, and sand, where raw materials are quarried, crushed, finely processed, and mixed to obtain the right chemical composition. Thereafter, calcination process is introduced when the raw materials have been mined, ground, and blended. This creates clinker where the raw materials are further ground or milled along with additional ingredients (such as gypsum, slag, etc.) to produce cement, involving burning of calcium oxide, ferrous oxide, silica, and alumina, at high temperatures. This entire process of cement production releases various particulate matter pollutants (PM₁, PM_{2.5}, PM₄, PM₇ and PM₁₀) into the surrounding air. (Venkata et al., 2023; Alobaydy, 2024; Nwogu et al., 2025).

Ambient particulate matter pollutants are a mixture of tiny solid particles and liquid droplets suspended in the outdoor air, released from both natural sources and anthropogenic activities like those of cement production, particularly during quarrying, crushing, grinding, clinker production, and material handling, emitting large quantities of particulates of varying sizes (Njagi, 2021; Venkata and Reddy, 2023). These PM are however classified based on their aerodynamic diameter, depending on their depth of penetration into the human respiratory system and the severity of associated health risks (Rajput et al., 2019).

PM₁ (Ultrafine Particles $\leq 1 \mu\text{m}$)

PM₁ comprises extremely fine particles with diameters less than or equal to 1 micrometer, which are usually released during clinker combustion process in the cement kilns at high temperatures (Ervik et al., 2022; Guo et al., 2022). Human exposure to these ultrafine particles poses acute health risks such as rapid penetration into alveoli and bloodstream, shortness of breath and irritation, as well as oxidative stress and inflammation. While in long-term (chronic effects) health risks associated with exposure to PM₁ include cardiovascular diseases (e.g., hypertension, atherosclerosis), lung cancer and neurological disorders as these effects translate even into the human brain Chauhan et al., 2024; Lachowicz and Gać, 2025).

PM_{2.5} (Fine Particles $\leq 2.5 \mu\text{m}$)

These are fine inhalable particles suspended in the air with aerodynamic diameters of 2.5 or less (≤ 2.5) micrometers. These fine particles are 30 times smaller compared to the width of a human hair, making them invisible to the naked eyes (Kodzius et al., 2028; Damiati et al., 2025). Their emission sources during cement production stem from fine grinding of cement raw materials, fuel combustion (coal, petcoke), including kiln and calcination processes. Health risks of human exposure to these fine particulates are irritation of the nose and throat, asthma exacerbation, and decreased lung function in short-term. While exposure in long-term leads to ischemic heart disease, chronic obstructive pulmonary disease (COPD), stroke, and premature death (Chukwu et al., 2021).

PM₄ (Respirable Fraction $\leq 4 \mu\text{m}$)

Airborne particles with an aerodynamic diameter of 4 micrometers or smaller. These particulates represent the respirable fraction of particulate matter. In other words, they are small enough to penetrate beyond the upper respiratory system into the gas-exchange regions of the lungs (Maeteletja, 2018; Bralewska et al., 2019). They are discharged during cement manufacturing, quarrying, crushing operations and material transfer points. Short-term exposure risks include bronchial

irritation, coughing and wheezing, while prolonged exposure risks are chronic bronchitis, lungs and pulmonary disfunction over time (Shieh et al., 2004; Maeteletja, 2018).

PM₇ (Thoracic Fraction $\leq 7 \mu\text{m}$)

Particulates with aerodynamic diameter of 7 micrometers (μm) or less, representing the thoracic fraction of airborne particles and could penetrate beyond the nose and throat (upper respiratory tract) and deposit within the trachea and bronchi (thoracic region) of the lungs. They are generally larger than finer particles (e.g., PM₁, PM_{2.5}, and PM₄) to reach the alveolar region (Chauhan et al., 2024; Damiati et al., 2025). Although, these particulates not deeply penetrate as finer particles, they contribute immensely to respiratory health effects, especially in dust-generating industries such as cement manufacturing, and exposure effects include upper and mid-respiratory tract irritation in short-term and further develop into asthma in long-term (Yadav et al., 2024).

PM₁₀ (Coarse Particles $\leq 10 \mu\text{m}$)

Inhalable particulate matter with an aerodynamic diameter of ≤ 10 micrometers, including both fine and coarse particles. In industrial setting like cement, these particles are discharged from quarrying such as limestone, shale, clay, sand, including packaging and loading materials and dust from unpaved roads and surfaces. The harmful impacts of exposure to these particulates in short-term include eye, nose, and throat irritation, and coughing. While exposure in prolonged terms causes chronic respiratory diseases, lung disfunction with increased hospital admissions (Zaharia, 2014; Salem, 2024).

The atmospheric concentration of these pollutants is however influenced by meteorological conditions (local weather) parameters such as wind speed and direction, temperature, rainfall and relative humidity of an area (Matthew et al., 2019; Yang et al., 2020). Similarly, Guo et al. (2022) and Wagh (2022) added that air pollutants generally get dispersed swiftly towards the downwind direction when strong turbulent wind blows, resulting in lower concentration. Also, Mushtaq et al. (2020), Yang et al. (2020) and Hassen et al. (2023) reported that when the air is calm, pollutants cannot disperse rapidly resulting in high concentration in the atmosphere.

The dynamic nature of these weather conditions especially, wind speed and direction consistently dispersed ambient particulates from cement production processes, distributing them to diverse locations near the cement plant and farther distances, depending on speed and direction of the wind, thereby affecting the human population.

2. Materials and Methods

This study was carried out around a cement plant in North-Central Nigeria. A control site located at a distance of 21 km away from the cement plant was used to compare measured results. The coordinates at each sampling point were taken and recorded with a Global Positioning System (GPS). A 50m (YUE BAO) tape was used to measure the varying distances surrounding the cement plant and control site. In-situ measurements of the PM pollutants (PM₁, PM_{2.5}, PM₄, PM₇ and PM₁₀) were carried out surrounding both the study area and the control site. A total of 12 monitoring points were set up surrounding the cement plant. Four sampling points were considered at the four cardinal points (i.e. North, East, South and West) each at three varying distances, buffer of 0, 250 and 500 m in the study area. Similarly, the same technique was undertaken at the control points. Data from all the sampling points were collected three times in a day between June and August, 2023. A Met-One Instrument (AEROCET-model 531S), a hand-held device, was used to measure PM₁, PM_{2.5}, PM₄, PM₇ and PM₁₀ concurrently. This is an automatic digital device that runs for an uninterrupted period of 60 seconds (1 minute) and stops until it is operated to restart. Therefore, at each 60 seconds, readings for particulate matter concentrations were recorded and the procedure continued for at least three times at each sampling point to get average result.

The coordinates at each sampling point were taken and recorded with a Global Positioning System (GPS). A 50m (YUE BAO) tape was used to measure the varying distances surrounding the cement plant and control site. Data from all the sampling points both surrounding the cement plant and the control were collected three times in a day (morning, 08.00–10.00 hours; afternoon, 12.00–14.00 hours; and evening, 16.00–18.00 hours) from June-August months 2023. Furthermore, meteorological parameters such as wind speed and direction were measured at all the sampling points along with the PM pollutants using hand-held environmental meter (KESTREL-model 5500).

All the devices were held at an average height of 1.5 meters during measurements, which corresponds to the average position of the human airways, and were pre-calibrated before usage for effectiveness and quality assurance purposes.

Data Analysis

Descriptive statistical tools such as averages, percentages and standard error including tables were employed to present the data for easy understanding of the concentration levels and variations of air quality at different periods of the day, distances and directions.

3. Results

Observed Concentration of the Particulate Matter Pollutants

Table 1 presents results for overall mean concentrations of particulate matter pollutants surrounding a cement plant and the control site for three different periods of the day (morning, afternoon and evening). Results revealed the overall mean concentration of PM_1 were $59.02 \pm 4.15 \mu\text{g}/\text{m}^3$ around the cement plant, and $26.18 \pm 1.50 \mu\text{g}/\text{m}^3$ in the control. $PM_{2.5}$ were $60.20 \pm 4.15 \mu\text{g}/\text{m}^3$ around the cement, $28.08 \pm 2.01 \mu\text{g}/\text{m}^3$ in the control. PM_4 were $64.56 \pm 4.18 \mu\text{g}/\text{m}^3$ surrounding the cement plant and $29.41 \pm 1.54 \mu\text{g}/\text{m}^3$ in the control. Other results were PM_7 $64.83 \pm 4.18 \mu\text{g}/\text{m}^3$ around the cement and $30.12 \pm 1.54 \mu\text{g}/\text{m}^3$ in the control, while PM_{10} , $64.97 \pm 4.18 \mu\text{g}/\text{m}^3$ around the cement and $30.14 \pm 1.54 \mu\text{g}/\text{m}^3$ in the control respectively. Results further demonstrated the mean concentrations during morning measurements were $48.89 \pm 1.43 \mu\text{g}/\text{m}^3$ for PM_1 around the cement plant and $23.77 \pm 1.45 \mu\text{g}/\text{m}^3$ at the control site. Results also revealed that the mean concentrations of $PM_{2.5}$ were $54.23 \pm 3.50 \mu\text{g}/\text{m}^3$ around the cement plant, $25.29 \pm 1.50 \mu\text{g}/\text{m}^3$ at the control site during morning measurement respectively.

Other results as illustrated in (Table 1) are PM_4 , $58.40 \pm 4.06 \mu\text{g}/\text{m}^3$ around the cement plant, $26.91 \pm 1.52 \mu\text{g}/\text{m}^3$ in the control site; PM_7 , $58.84 \pm 4.13 \mu\text{g}/\text{m}^3$ around the cement plant, $26.95 \pm 1.51 \mu\text{g}/\text{m}^3$ in the control site and PM_{10} , $59.10 \pm 4.15 \mu\text{g}/\text{m}^3$ around the cement plant and $27.01 \pm 2.01 \mu\text{g}/\text{m}^3$ in the control site during morning measurements respectively. It was also found that the mean concentrations of PM during the afternoon measurements were PM_1 , $48.95 \pm 2.05 \mu\text{g}/\text{m}^3$ around the cement plant and $26.63 \pm 1.54 \mu\text{g}/\text{m}^3$ in the control site (Table 1).

Particulate Matter Pollutants ($\mu\text{g}/\text{m}^3$) Measured in the Morning at Varying Distances and Directions Surrounding a Cement Plant and the Control

Figure 1 describes the concentrations of PM as measured according to varying distances (0-metres, 250-metres and 500-metres) surrounding the cement plant and at different directions such as (a) North, (b) East, (c) South and (d) West respectively around the cement plant and the control site during morning measurement period. Results revealed that the mean concentrations of PM at (a) North direction were, PM_1 $42.7 \pm 3.78 \mu\text{g}/\text{m}^3$ at 0-metre, $30.79 \pm 1.63 \mu\text{g}/\text{m}^3$ at 250-metres, $24.52 \pm 0.87 \mu\text{g}/\text{m}^3$ at 500-metres distances and $32.65 \pm 0.54 \mu\text{g}/\text{m}^3$ in the control site (Fig. 1a).

It was also found that the mean concentrations of PM_{2.5} during the morning measurement at (a) North direction were 46.12 ± 3.82 µg/m³ at 0-metre, 33.87 ± 1.73 µg/m³ at 250-metres, 27.48 ± 1.04 µg/m³ at 500-metres distances respectively, and 35.25 ± 0.59 µg/m³ in the control site.

Similarly, results revealed the mean concentrations of PM₄ were 50.20 ± 4.18 µg/m³ at 0-metre, 36.18 ± 1.89 µg/m³ at 250-metres, 29.28 ± 1.02 µg/m³ at 500-metres distances and 36.91 ± 0.57 µg/m³ in the control site. Other results showed that the mean concentrations of PM₇ during the morning measurement were 50.49 ± 4.17 µg/m³ at 0-metre, 36.25 ± 1.89 µg/m³ at 250-metres, 29.56 ± 1.04 µg/m³ at 500-metres distances and 36.91 ± 0.57 µg/m³ in the control site. Results finally indicated that the mean concentration of PM₁₀ were 50.56 ± 4.17 µg/m³ at 0-metres, 36.51 ± 1.88 µg/m³ at 250-metres, 29.56 ± 1.04 µg/m³ at 500-metres distances accordingly and 36.93 ± 0.57 µg/m³ in the control site (Fig. 1a).

Results further indicated that in (b) East direction, the mean concentrations of PM during morning measurement were PM₁ 192.46 ± 8.10 µg/m³ at 0-metre, 66.55 ± 5.57 µg/m³ at 250-metres, 47.12 ± 3.27 µg/m³ at 500-metres distances correspondingly, and 32.36 ± 0.67 µg/m³ in the control site.

Table 1

Overall mean concentrations ± standard deviation of PM pollutants (µg/m³) in the study area and the control site located in North-Central Nigeria.

Pollutants (µg/m ³)	Periods of Measurement							
	Morning		Afternoon		Evening		Overall Mean	Overall Mean
	Cement plant	Control site	Cement plant	Control site	Cement plant	Control site	Cement plant	Control site
PM ₁	48.89 ± 1.43	23.77 ± 1.45	48.95 ± 2.05	26.63 ± 1.54	79.23 ± 5.02	28.13 ± 0.96	59.02 ± 4.15	26.18 ± 1.50
PM _{2.5}	54.23 ± 3.50	25.29 ± 1.50	39.94 ± 1.80	28.50 ± 2.11	86.42 ± 6.04	30.44 ± 1.13	60.20 ± 4.15	28.08 ± 2.01
PM ₄	58.40 ± 4.06	26.91 ± 1.52	42.67 ± 2.02	29.06 ± 2.16	92.62 ± 6.15	32.27 ± 1.15	64.56 ± 4.18	29.41 ± 1.54
PM ₇	58.84 ± 4.13	26.95 ± 1.51	42.77 ± 2.02	31.12 ± 2.14	92.88 ± 6.17	32.28 ± 1.17	64.83 ± 4.18	30.12 ± 1.54
PM ₁₀	59.10 ± 4.15	27.01 ± 2.01	42.71 ± 2.03	31.13 ± 2.14	93.11 ± 6.18	32.29 ± 1.17	64.97 ± 4.18	30.14 ± 1.54

Whereas the mean concentrations for PM_{2.5} were 208.68 ± 8.52 µg/m³ at 0-metres, 73.09 ± 5.91 µg/m³ at 250-metres, 55.82 ± 3.36 µg/m³ at 500-metres distances respectively, and 35.00 ± 0.72 µg/m³ in the control site (Fig. 1b). Other results revealed PM₄ concentrations were 223.51 ± 8.89 µg/m³ at 0-metre, 78.78 ± 6.38 µg/m³ at 250-metres, 62.91 ± 3.79 µg/m³ at 500-metres distances accordingly, and 36.67 ± 0.72 µg/m³ in the control site. Similarly, the mean concentrations of PM₇ were 225.64 ± 8.99 µg/m³ at 0-metre, 78.94 ± 6.37 µg/m³ at 250-metres, 63.14 ± 3.78 µg/m³ at 500-metres distances and 36.68 ± 0.72 µg/m³ in the control site. Lastly, results indicated that the mean concentration of PM₁₀ were 226.11 ± 8.98 µg/m³ in 0-metre, 79.32 ± 6.43 µg/m³ at 250-metres, 64.15 ± 4.07 µg/m³ at 500-metres distances respectively, and 36.79 ± 0.72 µg/m³ in the control site. The results of mean concentration of PM at (c), south direction around the cement plant and the control site in the morning illustrated PM₁ were 33.76 ± 2.18 µg/m³ at 0-metre, 31.89 ± 1.82 µg/m³ at 250-metres, 27.42 ± 0.99 µg/m³ at 500-metres distances respectively and 29.33 ± 0.45 µg/m³ in the control site. Results also show the

mean concentrations of PM_{2.5} were $38.69 \pm 2.15 \mu\text{g}/\text{m}^3$ at 0-metre, $36.44 \pm 1.83 \mu\text{g}/\text{m}^3$ at 250-metres, $32.32 \pm 1.00 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $31.64 \pm 0.49 \mu\text{g}/\text{m}^3$ in the control site. Results further showed that PM₄ were $42.52 \pm 2.16 \mu\text{g}/\text{m}^3$ at 0-metre, $38.71 \pm 1.88 \mu\text{g}/\text{m}^3$ at 250-metres, $34.97 \pm 0.94 \mu\text{g}/\text{m}^3$ at 500-metres distances and $33.34 \pm 0.49 \mu\text{g}/\text{m}^3$ in the control site. Similarly, results revealed PM₇ were $43.38 \pm 2.19 \mu\text{g}/\text{m}^3$ at 0-metre, $39.21 \pm 1.84 \mu\text{g}/\text{m}^3$ at 250-metres, $35.18 \pm 0.94 \mu\text{g}/\text{m}^3$ at 500-metres distances and $33.46 \pm 0.50 \mu\text{g}/\text{m}^3$ in the control site. Whereas PM₁₀ results were $43.71 \pm 2.18 \mu\text{g}/\text{m}^3$ at 0-metre, $39.21 \pm 1.84 \mu\text{g}/\text{m}^3$ at 250-metres, $35.19 \pm 0.94 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $33.46 \pm 0.50 \mu\text{g}/\text{m}^3$ in the control site (Fig. 1c).

Furthermore, results demonstrated that the mean concentrations of PM in the morning at (d) Western direction were PM₁ $34.43 \pm 1.68 \mu\text{g}/\text{m}^3$ at 0-metre, $28.29 \pm \mu\text{g}/\text{m}^3$ at 250-metres, $26.71 \pm 0.94 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, while the control site was $28.72 \pm 0.52 \mu\text{g}/\text{m}^3$. Result also indicted that PM_{2.5} were $37.37 \pm 1.70 \mu\text{g}/\text{m}^3$ at 0-metre, $31.22 \pm 0.84 \mu\text{g}/\text{m}^3$ at 250-metres, $29.66 \pm 0.99 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, whereas the control site was $31.25 \pm 0.54 \mu\text{g}/\text{m}^3$. Similarly, results showed PM₄ were $39.41 \pm 1.91 \mu\text{g}/\text{m}^3$ at 0-metre, $33.24 \pm 0.88 \mu\text{g}/\text{m}^3$ at 250-metres, $31.05 \pm 0.96 \mu\text{g}/\text{m}^3$ at 500-metres distances and $32.70 \pm 0.53 \mu\text{g}/\text{m}^3$ in the control site. Also, it was observed that PM₇ were $39.62 \pm 1.91 \mu\text{g}/\text{m}^3$ at 0-metre, $33.50 \pm 0.90 \mu\text{g}/\text{m}^3$ at 250-metres, $31.18 \pm 0.97 \mu\text{g}/\text{m}^3$ at 500-metres distances accordingly, and $32.74 \pm 0.53 \mu\text{g}/\text{m}^3$ in the control site. Finally, results demonstrated that PM₁₀ were $39.90 \pm 1.90 \mu\text{g}/\text{m}^3$ at 0-metre, $33.79 \pm 0.89 \mu\text{g}/\text{m}^3$ at 250-metres, $31.18 \pm 0.97 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively and $32.86 \pm 0.54 \mu\text{g}/\text{m}^3$ in the control site.

Concentration of PM Pollutants ($\mu\text{g}/\text{m}^3$) Measured in the Afternoon at Varying Distances and Directions Surrounding a Cement Plant and the Control Site

Figure 2 illustrates variations in the mean concentrations of PM pollutants where results revealed PM₁ were $37.13 \pm 1.63 \mu\text{g}/\text{m}^3$ at 0-metre, $34.14 \pm 0.86 \mu\text{g}/\text{m}^3$ at 250-metres, $28.09 \pm 0.45 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively and $39.34 \pm 0.69 \mu\text{g}/\text{m}^3$ in the control site (Fig. 2a).

Results also showed the mean concentrations of PM_{2.5} were $40.31 \pm 1.61 \mu\text{g}/\text{m}^3$ at 0-metres, $36.39 \pm 0.85 \mu\text{g}/\text{m}^3$ at 250-metres, $29.86 \pm 0.46 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively and $42.70 \pm 0.81 \mu\text{g}/\text{m}^3$ in the control site. The mean concentrations of other PM during the afternoon measurement were PM₄ $43.14 \pm 1.62 \mu\text{g}/\text{m}^3$ at 0-metre, $37.93 \pm 0.89 \mu\text{g}/\text{m}^3$ at 250-metres, $31.98 \pm 0.52 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively and $44.38 \pm 0.78 \mu\text{g}/\text{m}^3$ in the control site. While PM₇ results were $43.27 \pm 1.62 \mu\text{g}/\text{m}^3$ at 0-metre, $37.94 \pm 0.89 \mu\text{g}/\text{m}^3$ at 250-metres, $31.98 \pm 0.52 \mu\text{g}/\text{m}^3$ at 500-metres distances, and $44.58 \pm 0.78 \mu\text{g}/\text{m}^3$ in the control site. Similarly, the mean concentrations of PM₁₀ were $43.32 \pm 1.62 \mu\text{g}/\text{m}^3$ at 0-metre, $38.03 \pm 0.89 \mu\text{g}/\text{m}^3$ at 250-metres, $32.12 \pm 0.51 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively and $44.58 \pm 0.78 \mu\text{g}/\text{m}^3$ in the control site (Fig. 2a).

Again, results obtained shows the mean concentrations of PM during afternoon measurement at (b) East direction were PM₁ $71.09 \pm 5.78 \mu\text{g}/\text{m}^3$ at 0-metre, $45.19 \pm 4.51 \mu\text{g}/\text{m}^3$ at 250-metres, $192.46 \pm 8.10 \mu\text{g}/\text{m}^3$ at 500-metres distances, and $43.69 \pm 0.64 \mu\text{g}/\text{m}^3$ in the control site (Fig. 2b). Similarly, the mean concentrations PM_{2.5} were $79.01 \pm 6.49 \mu\text{g}/\text{m}^3$ at 0-metre, $49.40 \pm 4.68 \mu\text{g}/\text{m}^3$ at 250-metres, $41.70 \pm 2.60 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $46.92 \pm 0.84 \mu\text{g}/\text{m}^3$ in the control site as in (Fig. 2b). Whereas the mean concentrations of PM₄ were $84.02 \pm 6.96 \mu\text{g}/\text{m}^3$ at 0-metre, $52.52 \pm 4.72 \mu\text{g}/\text{m}^3$ at 250-metres, $45.35 \pm 2.59 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $48.39 \pm 0.80 \mu\text{g}/\text{m}^3$ in the control site. More so, results show the concentration of PM₇ were $84.02 \pm 6.96 \mu\text{g}/\text{m}^3$ at 0-metre, $52.53 \pm 4.72 \mu\text{g}/\text{m}^3$ at 250-metres, $45.76 \pm 2.57 \mu\text{g}/\text{m}^3$ at 500-metres distances accordingly, and $48.39 \pm 0.80 \mu\text{g}/\text{m}^3$ in the control site. It was

also observed that the mean concentrations PM_{10} in are $84.02 \pm 6.96 \mu\text{g}/\text{m}^3$ at 0-metre, $50.91 \pm 4.55 \mu\text{g}/\text{m}^3$ at 250-metres, $46.03 \pm 2.56 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $48.39 \pm 0.80 \mu\text{g}/\text{m}^3$ in the control site.

Results further demonstrated the mean concentrations of PM during afternoon in (c), South direction were PM_1 $35.24 \pm 1.22 \mu\text{g}/\text{m}^3$ at 0-metre, $29.52 \pm 0.84 \mu\text{g}/\text{m}^3$ at 250-metres, $31.94 \pm 0.63 \mu\text{g}/\text{m}^3$ at 500-metres distances, ($37.12 \pm 0.80 \mu\text{g}/\text{m}^3$ in the control site. Results also showed $PM_{2.5}$ concentrations were $38.53 \pm 1.17 \mu\text{g}/\text{m}^3$ at 0-metre, $34.72 \pm 0.73 \mu\text{g}/\text{m}^3$ at 250-metres, $38.32 \pm 1.22 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $39.72 \pm 0.88 \mu\text{g}/\text{m}^3$ in the control site. It similarly observed that of PM_4 concentrations were $41.36 \pm 1.24 \mu\text{g}/\text{m}^3$ at 0-metre, $37.31 \pm 0.75 \mu\text{g}/\text{m}^3$ at 250-metres, $41.74 \pm 1.36 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, with $41.26 \pm 0.88 \mu\text{g}/\text{m}^3$ at the control site (Fig. 2c). More results obtained indicated the mean concentrations of PM_7 were $41.42 \pm 1.24 \mu\text{g}/\text{m}^3$ at 0-metre, $37.38 \pm 0.75 \mu\text{g}/\text{m}^3$ at 250-metres, $42.02 \pm 1.35 \mu\text{g}/\text{m}^3$ at 500-metres distances accordingly with $41.27 \pm 0.88 \mu\text{g}/\text{m}^3$ at the control site. Whereas the mean concentrations of PM_{10} were $41.44 \pm 1.24 \mu\text{g}/\text{m}^3$ at 0-metre, $37.51 \pm 0.73 \mu\text{g}/\text{m}^3$ at 250-metres, $42.19 \pm 1.34 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $41.27 \pm 0.88 \mu\text{g}/\text{m}^3$ at the control site (Fig. 2c).

Furthermore, concentrations of PM pollutants during afternoon period in (d) the West direction revealed PM_1 had $26.24 \pm 0.98 \mu\text{g}/\text{m}^3$ at 0-metre, $31.11 \pm 0.37 \mu\text{g}/\text{m}^3$ at 250-metres, $25.26 \pm 0.46 \mu\text{g}/\text{m}^3$ at 500-metres distances, with $34.38 \pm 0.53 \mu\text{g}/\text{m}^3$ at the control site (Fig. 2d). Results again indicate mean concentrations for $PM_{2.5}$ were $28.72 \pm 1.00 \mu\text{g}/\text{m}^3$ at 0-metre, $34.52 \pm 0.40 \mu\text{g}/\text{m}^3$ at 250-metres, $27.8 \pm 0.42 \mu\text{g}/\text{m}^3$ at 500-metres distances, and $36.67 \pm 0.59 \mu\text{g}/\text{m}^3$ at the control site.

Other results obtained indicated the mean concentrations of PM_4 were $30.46 \pm 1.05 \mu\text{g}/\text{m}^3$ at 0-metres, $36.79 \pm 0.38 \mu\text{g}/\text{m}^3$ at 250-metres, $29.42 \pm 0.43 \mu\text{g}/\text{m}^3$ at 500-metres distances, and $38.2 \pm 0.58 \mu\text{g}/\text{m}^3$ in the control site. The PM_7 had $30.46 \pm 1.05 \mu\text{g}/\text{m}^3$ at 0-metre, $36.85 \pm 0.38 \mu\text{g}/\text{m}^3$ at 250-metres, $29.56 \pm 0.43 \mu\text{g}/\text{m}^3$ at 500-metres distances accordingly, and $38.22 \pm 0.58 \mu\text{g}/\text{m}^3$ in the control site. Lastly, PM_{10} concentrations were $30.46 \pm 1.05 \mu\text{g}/\text{m}^3$ at 0-metre, $36.85 \pm 0.38 \mu\text{g}/\text{m}^3$ at 250-metre, $29.56 \pm 0.43 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $38.28 \pm 0.58 \mu\text{g}/\text{m}^3$ at the control site (Fig. 2d).

Concentration of PM Pollutants ($\mu\text{g}/\text{m}^3$) Measured in the Evening at Varying Distances and Directions Surrounding a Cement Plant and the Control Site

Figure 3 illustrates the spatial analysis of characterised PM pollutants in the evening according to varying distances and diverse directions, where results indicated the mean concentrations of PM_1 in (a) North direction were $105.79 \pm 12.44 \mu\text{g}/\text{m}^3$ at 0-metres, $151.1 \pm 13.93 \mu\text{g}/\text{m}^3$ at 250-metres, $44.59 \pm 1.41 \mu\text{g}/\text{m}^3$ at 500-metres and $29.20 \pm 0.63 \mu\text{g}/\text{m}^3$ in the control site (Fig. 3a). The $PM_{2.5}$ results indicated $114.77 \pm 12.47 \mu\text{g}/\text{m}^3$ at 0-metre, $158.3 \pm 14.1 \mu\text{g}/\text{m}^3$ at 250-metres, $48.08 \pm 1.41 \mu\text{g}/\text{m}^3$ at 500-metres distances and $31.54 \pm 0.66 \mu\text{g}/\text{m}^3$ in the control site. While PM_4 concentrations were $120.97 \pm 12.47 \mu\text{g}/\text{m}^3$ at 0-metre, $163.8 \pm 13.92 \mu\text{g}/\text{m}^3$ at 250-metres, $51.47 \pm 1.41 \mu\text{g}/\text{m}^3$ at 500-metres distances and $33.78 \pm 0.62 \mu\text{g}/\text{m}^3$ in the control site respectively. Still in the North direction, results showed the PM_7 concentrations were $121.17 \pm 12.46 \mu\text{g}/\text{m}^3$ at 0-metre, $163.80 \pm 13.92 \mu\text{g}/\text{m}^3$ at 250-metres, $51.49 \pm 1.41 \mu\text{g}/\text{m}^3$ at 500-metres distances accordingly, and $33.78 \pm 0.62 \mu\text{g}/\text{m}^3$ in the control site. Similarly, the mean concentrations of PM_{10} were $121.18 \pm 12.46 \mu\text{g}/\text{m}^3$ at 0-metre, $163.80 \pm 13.92 \mu\text{g}/\text{m}^3$ at 250-metres, $51.60 \pm 1.41 \mu\text{g}/\text{m}^3$ at 500-metres distances and $33.84 \pm 0.62 \mu\text{g}/\text{m}^3$ in the control site (Fig. 3a).

Results further revealed in (b) East direction the mean concentrations of PM_1 were $241.62 \pm 4.86 \mu\text{g}/\text{m}^3$ at 0-metre, $100.4 \pm 7.77 \mu\text{g}/\text{m}^3$ at 250-metres, $52.98 \pm 4.03 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $26.54 \pm 1.31 \mu\text{g}/\text{m}^3$ in the

control site (Fig. 3b). It was further observed that the mean concentrations of $PM_{2.5}$ in the same direction were $273.56 \pm 6.35 \mu\text{g}/\text{m}^3$ at 0-metre, $109.5 \pm 7.61 \mu\text{g}/\text{m}^3$ at 250-metres, $59.06 \pm 4.02 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $28.66 \pm 1.39 \mu\text{g}/\text{m}^3$ in the control site. In the same vein, the concentrations of PM_4 were $298.92 \pm 7.72 \mu\text{g}/\text{m}^3$ at 0-metres, $17.8 \pm 7.68 \mu\text{g}/\text{m}^3$ at 250-metres, $64.88 \pm 4.12 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $30.22 \pm 1.39 \mu\text{g}/\text{m}^3$ in the control site. Whereas, that of PM_7 were $300.49 \pm 7.86 \mu\text{g}/\text{m}^3$ at 0-metre, $117.8 \pm 7.68 \mu\text{g}/\text{m}^3$ at 250-metres, $65.08 \pm 4.12 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $30.22 \pm 1.39 \mu\text{g}/\text{m}^3$ in the control site. While the mean concentrations of PM_{10} were $300.66 \pm 7.85 \mu\text{g}/\text{m}^3$ at 0-metre, $117.8 \pm 7.67 \mu\text{g}/\text{m}^3$ at 250-metres, $65.31 \pm 4.11 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $30.22 \pm 1.39 \mu\text{g}/\text{m}^3$ in the control site. Results further demonstrated that the mean concentrations in (c) south direction during the evening measurement were PM_1 $53.96 \pm 1.97 \mu\text{g}/\text{m}^3$ at 0-metres $48.60 \pm 2.46 \mu\text{g}/\text{m}^3$ at 250-metres, $35.68 \pm 0.65 \mu\text{g}/\text{m}^3$ at 500-metres distances and $31.18 \pm 0.51 \mu\text{g}/\text{m}^3$ in the control site. While $PM_{2.5}$ indicated concentrations of $57.54 \pm 2.02 \mu\text{g}/\text{m}^3$ at 0-metre, $52.50 \pm 2.50 \mu\text{g}/\text{m}^3$ at 250-metres, $38.23 \pm 0.67 \mu\text{g}/\text{m}^3$ at 500-metres distances and $33.70 \pm 0.47 \mu\text{g}/\text{m}^3$ in the control site. Results further revealed the concentrations of PM_4 were $61.51 \pm 2.23 \mu\text{g}/\text{m}^3$ at 0-metre, $55.50 \pm 2.67 \mu\text{g}/\text{m}^3$ at 250-metre, $41.16 \pm 0.73 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively and $35.64 \pm 0.52 \mu\text{g}/\text{m}^3$ in the control site (Fig. 3c).

While the mean concentrations of PM_7 were $61.95 \pm 2.27 \mu\text{g}/\text{m}^3$ at 0-metre, $55.60 \pm 2.67 \mu\text{g}/\text{m}^3$ at 250-metres, $41.31 \pm 0.73 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, with $35.64 \pm 0.52 \mu\text{g}/\text{m}^3$ in the control site. Whereas, the mean concentrations of PM_{10} were $61.95 \pm 2.27 \mu\text{g}/\text{m}^3$ at 0-metre, $57.10 \pm 2.64 \mu\text{g}/\text{m}^3$ at 250-metres, $41.51 \pm 0.74 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively, and $35.64 \pm 0.52 \mu\text{g}/\text{m}^3$ at the control site (Fig. 3c).

Furthermore, results illustrated the mean concentrations in (d) West direction during the evening measurement were PM_1 $46.71 \pm 2.52 \mu\text{g}/\text{m}^3$ at 0-metre, $37.50 \pm 1.67 \mu\text{g}/\text{m}^3$ at 250-metres, $31.81 \pm 0.97 \mu\text{g}/\text{m}^3$ at 500-metres distances and $25.58 \pm 0.44 \mu\text{g}/\text{m}^3$ at the control site (Fig. 3d). It was then observed that the mean concentrations of $PM_{2.5}$ were $49.95 \pm 2.67 \mu\text{g}/\text{m}^3$ at 0-metres, $40.30 \pm 1.72 \mu\text{g}/\text{m}^3$ at 250-metres, $35.20 \pm 1.14 \mu\text{g}/\text{m}^3$ at 500-metres distances accordingly, and $27.87 \pm 0.49 \mu\text{g}/\text{m}^3$ at the control site. Other results revealed PM_4 concentrations were $53.02 \pm 2.76 \mu\text{g}/\text{m}^3$ at 0-metre, $43.60 \pm 1.80 \mu\text{g}/\text{m}^3$ at 250-metres, $38.82 \pm 1.22 \mu\text{g}/\text{m}^3$ at 500-metres distances accordingly, and $29.44 \pm 0.46 \mu\text{g}/\text{m}^3$ in the control site. For PM_7 , results showed the mean concentrations were $53.07 \pm 2.75 \mu\text{g}/\text{m}^3$ at 0-metre, $43.80 \pm 1.79 \mu\text{g}/\text{m}^3$ at 250-metres, $39.03 \pm 1.22 \mu\text{g}/\text{m}^3$ at 500-metres distances accordingly, and $29.46 \pm 0.45 \mu\text{g}/\text{m}^3$ in the control site. Similarly, the concentrations of PM_{10} were $53.25 \pm 2.74 \mu\text{g}/\text{m}^3$ at 0-metre, $44.00 \pm 1.77 \mu\text{g}/\text{m}^3$ at 250-metres, $39.10 \pm 1.22 \mu\text{g}/\text{m}^3$ at 500-metres distances respectively and $29.46 \pm 0.45 \mu\text{g}/\text{m}^3$ in the control site (Fig. 3d).

Variations in the PM Pollutants ($\mu\text{g}/\text{m}^3$) Surrounding a Cement Plant on Wet Days during the Study Period

Figure 4 illustrated observed PM pollutants concentrations on the wet/rainy days in four different directions at three distinct periods in the study area. Results showed the concentration in (a) the North direction in the morning were PM_1 $14.53 \pm 1.02 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $16.53 \pm 1.04 \mu\text{g}/\text{m}^3$, PM_4 $18.37 \pm 1.10 \mu\text{g}/\text{m}^3$, PM_7 $18.37 \pm 1.10 \mu\text{g}/\text{m}^3$, and PM_{10} $18.37 \pm 1.10 \mu\text{g}/\text{m}^3$. During the afternoon, PM_1 had $14.30 \pm 1.02 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $15.8 \pm 1.04 \mu\text{g}/\text{m}^3$, PM_4 $17.37 \pm 1.10 \mu\text{g}/\text{m}^3$, PM_7 $17.37 \pm 1.10 \mu\text{g}/\text{m}^3$, PM_{10} $17.37 \pm 1.10 \mu\text{g}/\text{m}^3$. And in the evening, concentrations showed PM_1 $20.20 \pm 1.13 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $21.47 \pm 1.13 \mu\text{g}/\text{m}^3$, PM_4 $23.90 \pm 1.15 \mu\text{g}/\text{m}^3$, PM_7 $23.90 \pm 1.15 \mu\text{g}/\text{m}^3$, PM_{10} $25.17 \pm 1.18 \mu\text{g}/\text{m}^3$ respectively. Results in (b) the East direction showed the concentrations were PM_1 $41.97 \pm 3.03 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $44.23 \pm 3.08 \mu\text{g}/\text{m}^3$, PM_4 $50.27 \pm 5.10 \mu\text{g}/\text{m}^3$, PM_7 $50.27 \pm 5.10 \mu\text{g}/\text{m}^3$, PM_{10} $50.27 \pm 5.10 \mu\text{g}/\text{m}^3$, in the morning.

The afternoon, concentrations were PM_1 $18.60 \pm 1.01 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $20.67 \pm 1.12 \mu\text{g}/\text{m}^3$, PM_4 $22.53 \pm 1.14 \mu\text{g}/\text{m}^3$, PM_7 $22.53 \pm 1.14 \mu\text{g}/\text{m}^3$, PM_{10} $22.53 \pm 1.14 \mu\text{g}/\text{m}^3$. Lastly, the evening measurements of the same east direction showed PM_1 $55.60 \pm 4.41 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $61.03 \pm 5.32 \mu\text{g}/\text{m}^3$, PM_4 $66.70 \pm 5.66 \mu\text{g}/\text{m}^3$, PM_7 $66.70 \pm 5.66 \mu\text{g}/\text{m}^3$, PM_{10} $66.70 \pm 5.66 \mu\text{g}/\text{m}^3$ respectively. More so, results revealed that in (c) the South direction, the observed PM concentrations were PM_1 $13.97 \pm 0.13 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $16.53 \pm 0.16 \mu\text{g}/\text{m}^3$, PM_4 $17.53 \pm 0.16 \mu\text{g}/\text{m}^3$, PM_7 $18.33 \pm 1.15 \mu\text{g}/\text{m}^3$, PM_{10} $18.33 \pm 1.15 \mu\text{g}/\text{m}^3$ in the morning.

During the afternoon, PM_1 $16.17 \pm 0.16 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $20.00 \pm 1.19 \mu\text{g}/\text{m}^3$, PM_4 $21.70 \pm 1.19 \mu\text{g}/\text{m}^3$, PM_7 $21.70 \pm 1.19 \mu\text{g}/\text{m}^3$, PM_{10} $21.70 \pm 1.19 \mu\text{g}/\text{m}^3$. Whereas in the evening, concentrations were thus; PM_1 $20.23 \pm 1.19 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $21.60 \pm 1.19 \mu\text{g}/\text{m}^3$, PM_4 $23.17 \pm 1.19 \mu\text{g}/\text{m}^3$, PM_7 $23.17 \pm 1.19 \mu\text{g}/\text{m}^3$, PM_{10} $23.17 \pm 1.19 \mu\text{g}/\text{m}^3$. Lastly in the (d) West direction, results revealed the observed concentrations were PM_1 $12.50 \pm 0.10 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $13.87 \pm 0.10 \mu\text{g}/\text{m}^3$, PM_4 $14.83 \pm 0.14 \mu\text{g}/\text{m}^3$, PM_7 $15.13 \pm 0.16 \mu\text{g}/\text{m}^3$, PM_{10} $15.20 \pm 0.16 \mu\text{g}/\text{m}^3$ in the morning. For the afternoon, results were PM_1 $14.93 \pm 0.16 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $16.07 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_4 $16.90 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_7 $16.90 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_{10} $16.90 \pm 0.18 \mu\text{g}/\text{m}^3$. And in the evening, PM_1 $14.37 \pm 0.16 \mu\text{g}/\text{m}^3$, $PM_{2.5}$ $15.67 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_4 $17.90 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_7 $17.90 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_{10} $17.90 \pm 0.18 \mu\text{g}/\text{m}^3$ (Fig. 4d).

Variations in the PM Pollutants ($\mu\text{g}/\text{m}^3$) Surrounding a Cement Plant on Dry Days during the Study Period

Figure 5 showed the observed PM concentrations on the dry days at various directions and different periods, where results demonstrated in (a) North direction, PM concentrations were as follows: PM_1 , $15.97 \pm 0.16 \mu\text{g}/\text{m}^3$, $PM_{2.5}$, $17.70 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_4 , $18.90 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_7 , $18.90 \pm 0.18 \mu\text{g}/\text{m}^3$, and PM_{10} , $19.13 \pm 0.18 \mu\text{g}/\text{m}^3$ during the morning measurement. While the afternoon results showed, PM_1 , $17.87 \pm 0.17 \mu\text{g}/\text{m}^3$, $PM_{2.5}$, $18.67 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_4 , $19.83 \pm 0.18 \mu\text{g}/\text{m}^3$, PM_7 , $19.83 \pm 0.18 \mu\text{g}/\text{m}^3$ and PM_{10} , $19.83 \pm 0.18 \mu\text{g}/\text{m}^3$. Whereas in the evening, results indicated PM_1 , $28.90 \pm 1.12 \mu\text{g}/\text{m}^3$; $PM_{2.5}$, $30.70 \pm 2.14 \mu\text{g}/\text{m}^3$; PM_4 , $34.20 \pm 2.32 \mu\text{g}/\text{m}^3$; PM_7 , $34.27 \pm 2.32 \mu\text{g}/\text{m}^3$ and PM_{10} , $34.27 \pm 2.32 \mu\text{g}/\text{m}^3$ (Fig. 5a). The results further indicated the concentrations of PM on the dry days in (b) the East direction during the morning measurements were PM_1 , $92.60 \pm 7.11 \mu\text{g}/\text{m}^3$, $PM_{2.5}$, $99.80 \pm 8.14 \mu\text{g}/\text{m}^3$; PM_4 , $103.87 \pm 10.13 \mu\text{g}/\text{m}^3$; PM_7 , $105.50 \pm 10.18 \mu\text{g}/\text{m}^3$ and PM_{10} , $34.27 \pm 10.18 \mu\text{g}/\text{m}^3$. For the afternoon measurement, the results were PM_1 , $16.20 \pm 0.15 \mu\text{g}/\text{m}^3$; $PM_{2.5}$, $18.77 \pm 1.14 \mu\text{g}/\text{m}^3$; PM_4 , $20.23 \pm 1.19 \mu\text{g}/\text{m}^3$; PM_7 , $20.23 \pm 1.19 \mu\text{g}/\text{m}^3$ and PM_{10} , $20.23 \pm 1.19 \mu\text{g}/\text{m}^3$ (Fig. 5b).

During the evening, the concentrations were PM_1 , $97.50 \pm 8.15 \mu\text{g}/\text{m}^3$; $PM_{2.5}$, $104.13 \pm 10.13 \mu\text{g}/\text{m}^3$; PM_4 , $107.93 \pm 10.19 \mu\text{g}/\text{m}^3$; PM_7 , $108.20 \pm 10.19 \mu\text{g}/\text{m}^3$ and PM_{10} , $108.20 \pm 10.19 \mu\text{g}/\text{m}^3$ as illustrated in Fig. 4.10b. Results further revealed that the concentrations of PM in (c), the South direction during the morning period were PM_1 , $16.03 \pm 0.15 \mu\text{g}/\text{m}^3$; $PM_{2.5}$, $16.93 \pm 0.15 \mu\text{g}/\text{m}^3$; PM_4 , $17.77 \pm 0.19 \mu\text{g}/\text{m}^3$; PM_7 , $17.77 \pm 0.19 \mu\text{g}/\text{m}^3$ and PM_{10} , $17.77 \pm 0.19 \mu\text{g}/\text{m}^3$. whereas the afternoon results indicated thus: PM_1 , $14.20 \pm 0.13 \mu\text{g}/\text{m}^3$; $PM_{2.5}$, $16.23 \pm 0.15 \mu\text{g}/\text{m}^3$; PM_4 , $17.63 \pm 0.15 \mu\text{g}/\text{m}^3$; PM_7 , $17.77 \pm 0.19 \mu\text{g}/\text{m}^3$; PM_{10} , $17.77 \pm 0.19 \mu\text{g}/\text{m}^3$. It was further observed that during the evening period, concentrations were PM_1 , $25.37 \pm 2.12 \mu\text{g}/\text{m}^3$; $PM_{2.5}$, $26.97 \pm 2.15 \mu\text{g}/\text{m}^3$; PM_4 , $29.10 \pm 2.15 \mu\text{g}/\text{m}^3$; PM_7 , $29.17 \pm 2.15 \mu\text{g}/\text{m}^3$ and PM_{10} , $29.17 \pm 2.15 \mu\text{g}/\text{m}^3$ (Fig. 5c).

Finally, the concentrations of PM in (d), the West direction on the dry days were PM_1 , $15.17 \pm 0.15 \mu\text{g}/\text{m}^3$; $PM_{2.5}$, $16.40 \pm 0.15 \mu\text{g}/\text{m}^3$; PM_4 , $16.60 \pm 0.15 \mu\text{g}/\text{m}^3$; PM_7 , $16.60 \pm 0.15 \mu\text{g}/\text{m}^3$ and PM_{10} , $16.60 \pm 0.15 \mu\text{g}/\text{m}^3$ in the morning. During afternoon, concentrations were PM_1 , $13.50 \pm 0.12 \mu\text{g}/\text{m}^3$; $PM_{2.5}$, $14.83 \pm 0.14 \mu\text{g}/\text{m}^3$; PM_4 , $15.60 \pm 0.15 \mu\text{g}/\text{m}^3$; PM_7 , 15.83

$\pm 0.15 \mu\text{g}/\text{m}^3$ and PM_{10} , $15.83 \pm 0.15 \mu\text{g}/\text{m}^3$. While the evening concentrations were PM_1 , $25.10 \pm 1.15 \mu\text{g}/\text{m}^3$; $\text{PM}_{2.5}$, $26.93 \pm 2.14 \mu\text{g}/\text{m}^3$; PM_4 , $28.13 \pm 2.17 \mu\text{g}/\text{m}^3$; PM_7 , $28.13 \pm 2.17 \mu\text{g}/\text{m}^3$ and PM_{10} , $28.13 \pm 2.17 \mu\text{g}/\text{m}^3$ (Fig. 5d).

Comparison of Means of the Measured PM Pollutants with the Regulatory Standards

Table 2 depicts comparison of observed mean concentrations for PM_4 showed $64.56 \mu\text{g}/\text{m}^3$ within the cement, while threshold limits for WHO was $50.00 \mu\text{g}/\text{m}^3$, but no standards for NESREA. Similarly, mean concentrations for PM_7 indicated $64.83 \mu\text{g}/\text{m}^3$ within the cement plant, $50.00 \mu\text{g}/\text{m}^3$ WHO permissible limits and no threshold limits for the NESREA. Finally, results showed mean concentrations for PM_{10} were $64.97 \mu\text{g}/\text{m}^3$ within the cement plant, with $50.00 \mu\text{g}/\text{m}^3$ and $150.00 \mu\text{g}/\text{m}^3$ for the WHO and NESREA threshold limits respective.

Table 2
Comparison of Means of the Measured PM Pollutants with the WHO and the NESREA Set Standards.

PM Pollutants ($\mu\text{g}/\text{m}^3$)	Measurement				Standards	
	Morning	Afternoon	Evening	Overall Mean	WHO	NESREA
PM_1	48.89	48.95	79.23	59.02	25.00	-
$\text{PM}_{2.5}$	54.23	39.94	86.42	60.20	25.00	80.00
PM_4	58.40	42.67	92.62	64.56	50.00	-
PM_7	58.84	42.77	92.88	64.83	50.00	-
PM_{10}	59.10	42.71	93.11	64.97	50.00	150.00

WHO- World Health Organisation; NESREA - National Environmental Standards and Regulations Enforcement Agency

Source

(Ezekwe et al., 2016; Ishaya et al., 2023)

4. Discussion

The results of overall mean concentration of the observed PM pollutants indicated the concentrations surrounding the cement plant were significantly higher compared to the concentrations in the control site (Table 1). This is basically due to numerous identified emission sources originating from the general intensive industrial activities involving machinery, kilns, and other equipment that operate continuously Isaiah et al., 2021; Zainudeen and Jeyamathan, 2021; Abdelgader et al., 2022). In addition, such operational activities release PM pollutants through various production stages including limestone calcination, fuel combustion in kilns, clinker cooling, and grinding processes.

However, these operational activities and emission sources are seldom scarce in the control site, leading to lower atmospheric concentration of pollutants. Also, emission sources such as dust from raw materials, combustion of fossil fuels, like coal or petroleum coke in the kiln for clinker production, crushing and grinding raw materials, movement of raw materials and intermediate products within the cement plant, such as conveyor belts, loaders and trucks may emit PM within a cement plant and, dispersed around its vicinity through wind speed (Isaiah et al., 2021; Gboe, 2023; Oguntola and Simske, 2023). The PM results as illustrated are in agreement with the findings of Nkhama et al. (2017) whose results indicated the mean concentrations of PM within and around cement factories were significantly higher than obtainable in the control community during day time considered to be the major working hours (Table 1). It was also observed that the

concentration of coarse particles (PM_{10}) generally surpassed the concentrations of lower particles sizes. This scenario as revealed in the findings of Das et al. (2022) and Hottle et al. (2022) might emanate as a result of diverse operational activities in a cement plant involving handling and processing of large quantities of raw materials, such as limestone, clay, and gypsum, crushing, grinding, including the transportation of these materials which releases large quantities of coarse PM sizes.

Results also indicated the mean concentrations of PM were generally higher in the evening than the morning and afternoon hours (Table 1). This scenario as justified in previous studies like Cheruiyot (2021), Anjum et al. (2021) and Rincon et al. (2023) where it was obtained that cement plants usually operate all day, and in an effort to increase production to meet their growing demand, there may be a spike in production activities in the evenings. This may lead to greater emissions and PM concentrations surrounding a cement plant than it is at a control location that might not have similar industrial activities. Additionally, the findings of Saxena et al. (2019), Kwarteng et al. (2020), Wang et al. (2021) and Nguyen et al. (2023) revealed that weather conditions have a significant impact on PM dispersion. Thus, the dispersion of PM and vertical mixing may be limited in the evening, particularly in specific weather scenarios when the atmosphere becomes more stable. Hence, PM may build up within and around the cement factory as a result of this.

Podstawczyńska and Chambers (2019), Wang et al. (2019), Huang et al. (2021) and Kikaj et al. (2023) reported that evenings and nights are more prone to temperature inversions, which occur when a layer of warm air traps colder air and pollutants close to the ground. Conversely, this contributes to the deposition of PM and other pollutants in the lower atmosphere, increasing concentrations around industrial operations like cement plants. While studies such as Luo et al. (2020), Liu et al. (2020) and Hossain, (2023) postulated that decreased wind speed in the evening as was observed during field measurement could limit the diffusion and transport of particulate matter away from the source. As a result, any emissions from the cement plant may build up in the vicinity, causing higher PM levels.

The analysis of spatial dispersion of the PM pollutants in the study area during the morning period considered at various distances (0-metre, 250-metres and 500-metres) and diverse directions (North, East, South and east) revealed all pollutants were generally more concentrated at 0-metre (i.e near the emission sources) in the Eastern direction of the cement plant (Fig. 1). Higher concentrations of pollutants near the emission sources as obtained in previous scholars such as Haugen et al. (2022) and Boikos et al. (2024) are said to be due to concentration gradient where pollutants are directly released at their highest concentrations near the emission sources. But as the distances increase away from the source, they disperse with decrease in concentrations creating a gradient with the highest concentration at the emission source and lower concentrations farther apart. Also, dilution effect could cause higher concentrations of pollutants near the emission sources, but as they move away from the source, they dispersed and mix with the surrounding air. This dispersion is influenced by certain factors such as the wind speed, wind direction, atmospheric stability, and turbulence, leading to a decrease in concentration with increasing distance (Huertas et al., 2021).

Whereas the higher concentrations of pollutants in the Eastern direction of the cement plant were due to influence of the wind pattern as the direction of movement was towards the NE. This was evident during in-situ measurements as deposits of dust particles were observed on the surrounding vegetation and roof-tops in the Eastern part of the cement plant. The health risks associated with exposure to these pollutants are aggravated respiratory conditions like asthma, irritation of the throat, eyes, and nose, coughing, and shortness of breath. It can also cause a general feeling of discomfort, fatigue, coughing, and etc. in acute term. On the other hand, prolonged exposure to these pollutants has been connected to the aggravated long-term respiratory conditions like chronic obstructive pulmonary disease (COPD), reduced lung function, lung cancer, and an increased risk of cardiovascular diseases like hypertension, atherosclerosis, and heart disease (Nkhama et al., 2017; Mallongi et al., 2023; Chamdimba et al., 2023). However, residents along the Eastern part of the cement plant are more vulnerable of exposure to potential health risks hence higher pollutants concentration as indicated by the results in the East direction.

The spatial analysis of the PM pollutants during the afternoon period indicated a similar pattern of results with that of the morning period where pollutants were generally more concentrated near the emission sources (0-metre) in the Eastern direction of the cement plant (Fig. 2). However, there were exceptional cases as illustrated in Fig. 2b, where the ultra-fine (PM_{10}) and fine particles ($PM_{2.5}$ and PM_4) were observed to be more concentrated at farther distance of 500-metres than at 0-metre near the emission sources around the cement plant. In this regard, Watkins (2019) and Bartz et al. (2021) postulated that nearby the emission sources where the dust particles are directly released into the atmosphere, both fine and coarse PM may be present in relatively high concentrations. However, as the distances increase from the emission sources, coarse heavier particulate matter like PM_{10} tend to settle quickly due to gravity leading to their lower concentrations but the ultra-fine particles like PM_1 on the other hand remain suspended in the air for longer periods, and could travel longer distances before depositing resulting in higher concentrations than the coarse particles.

Whereas spatial analysis of the PM pollutants during the evening period again demonstrated a similar pattern where pollutants were generally higher near the emission sources in the Eastern side of the cement (Fig. 3). It was however observed that all PM pollutants were more concentrated at far distance of 250-metres compared to 0-metre (emission sources) in the Northern part of the cement plant (Fig. 3). This could be attributed to specific wind patterns such as the wind speed as it disperses PM to locations further from the source as similarly reported by Eibedingil et al. (2022) and Hassan et al. (2023). They continued that steady winds for instance blowing in a particular direction can transport PM to farther distances, leading to higher concentrations in the direction of the wind compared to the immediate vicinity of the source.

The results of the observed PM pollutants when compared to the air quality standards indicated the concentrations of ($PM_{2.5}$ and PM_{10}) were below the NESREA standards (Table 2). However, all the pollutants exceeded the WHO threshold limits. This signifies exposure to associated health risks of these PM pollutants such as eye, throat and skin irritations, headaches, coughing, dizziness in short-term and asthma, unconsciousness, lung cancer in chronic term (WHO, 2021; Kondracka et al., 2022; Kumar et al., 2023).

Finally, the results of measurements on both rainy and dried days demonstrated rainfall is directly responsible for wet deposition of atmospheric pollutants in that, the raindrops transiting through the atmosphere directly enhances the washing away of atmospheric PM pollutants down the surface of the earth, thereby reducing their build-up in a specified location (Linden et al., 2023). This rainfall factor was observed to be one of the significant factors influencing the atmospheric concentration of pollutants through comparison of measurements on the wet and dry days.

The results of the measured PM pollutants on wet days (Fig. 4) and dry days (Fig. 5) revealed comparatively, concentrations of the pollutants on dry days were higher than on wet days. Although there were production activities within the cement plant with continues emission of criteria pollutants on the wet days, decrease in concentrations were obtainable as scholars such as Kwak et al. (2023), and Yuan et al. (2023) revealed that rainfall acts as a natural cleaning mechanism for the atmosphere where raindrops wash the suspended particles from the atmosphere, depositing them on the surface of the earth. This cleansing effect is particularly effective for PM which was equally observed during the study period.

Declarations

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- Consent to participate: Not applicable.
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Author Contribution

Mzaga K. Saater¹: Conceptualisation of research idea, writing of original draft of the manuscript, review & editing, visualisation. Matthew Jonathan Olaniran: Supervision of the research, and Ekpa Dave E. editing and review of the manuscript

Data Availability

2. The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

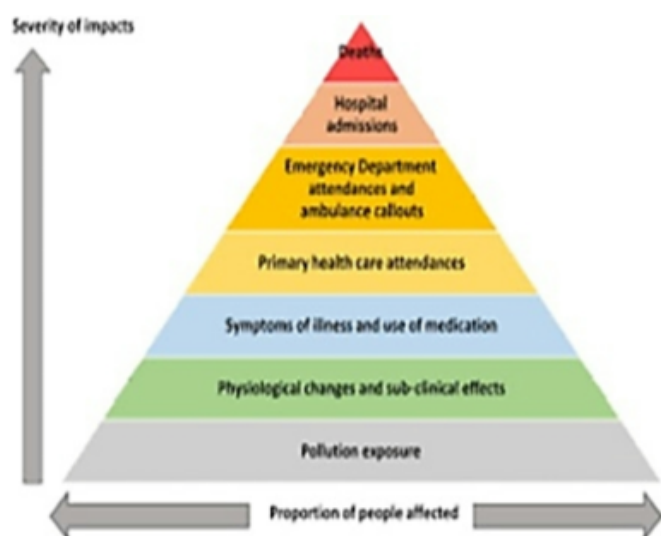


Figure 1: Pyramid of Impact of Air Pollution
Source: Melody and Johnston, 2015

Figure 1

See image above for figure legend.

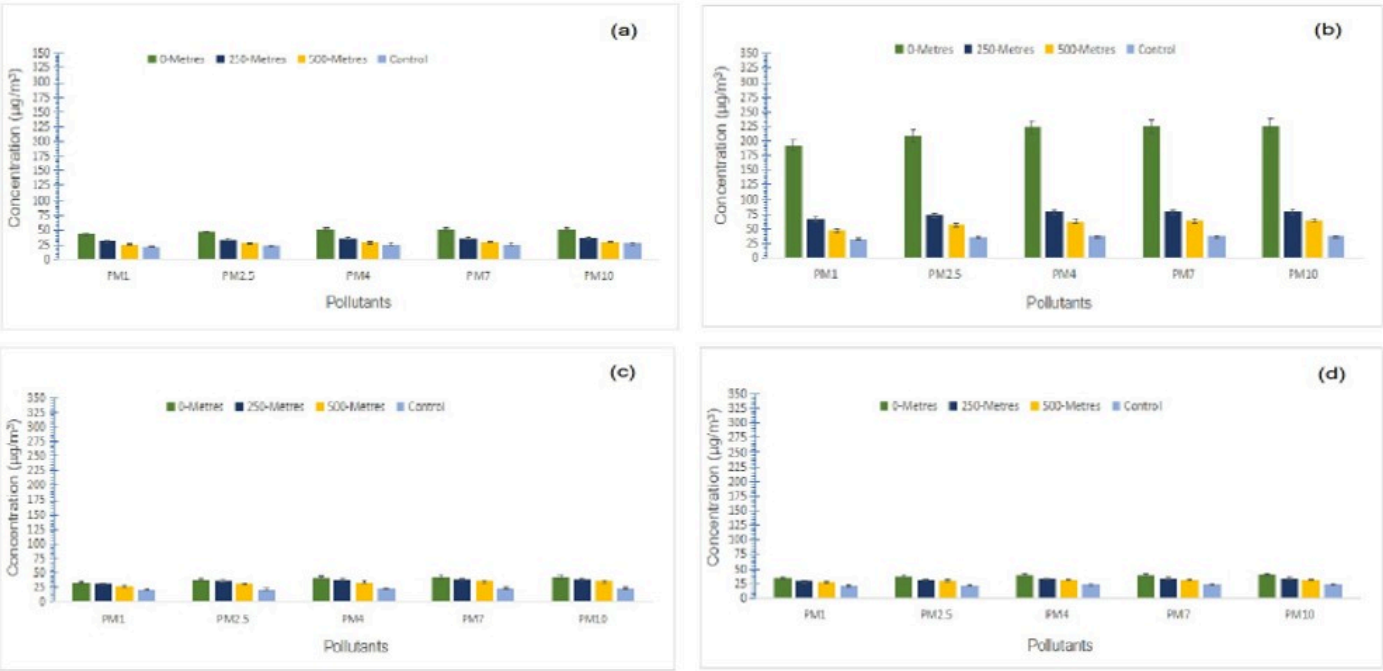


Figure 2

Figure 1: Concentration of PM Pollutants ($\mu\text{g}/\text{m}^3$) Measured in the Morning at Varying Distances and Directions in the study area and Control during Study Period; (a) North, (b) East, (c) South and (d) West Directions.

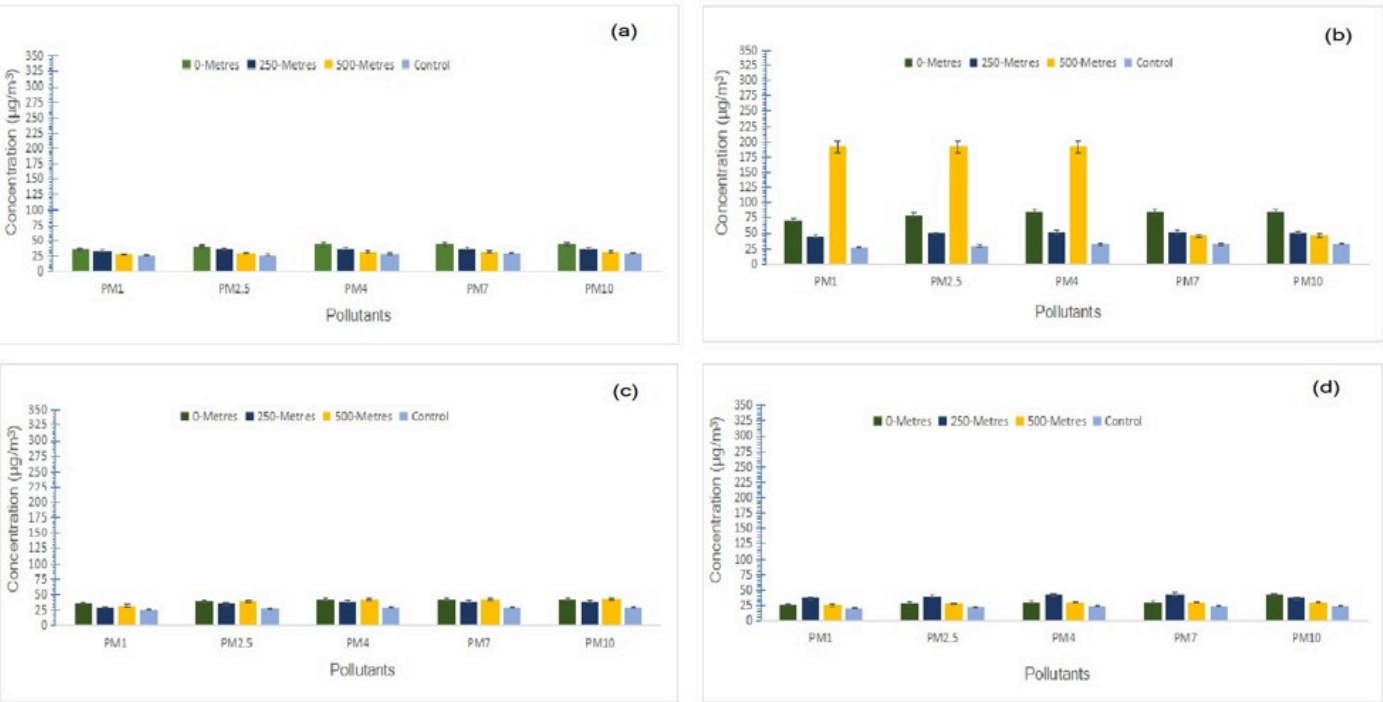


Figure 3

Figure 2: Concentration of PM Pollutants ($\mu\text{g}/\text{m}^3$) Measured in the Afternoon at Varying Distances and Directions in the study area and the Control during Study Period; (a) North, (b) East, (c) South and (d) West Directions

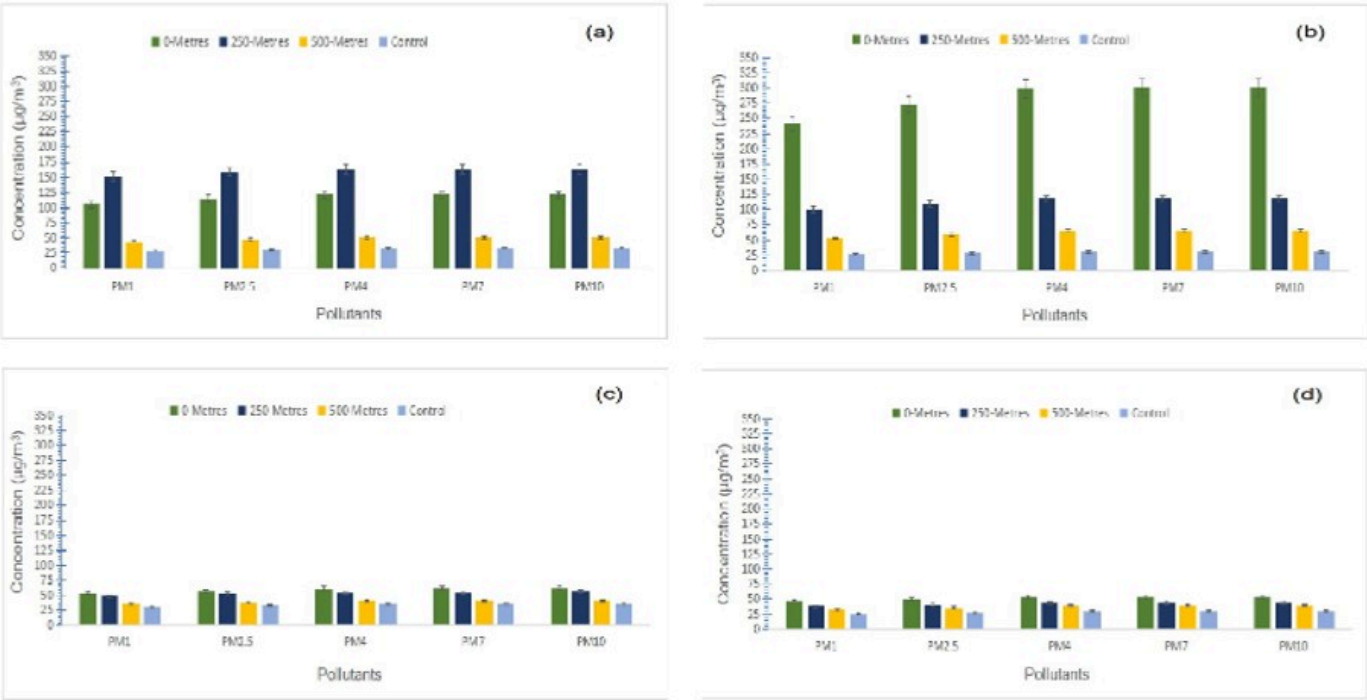


Figure 4

Figure 3: Concentration of PM Pollutants ($\mu\text{g}/\text{m}^3$) Measured in the Evening at Varying Distances and Directions in the study area and the Control during Study Period; (a) North, (b) East, (c) South and (d) West Directions.

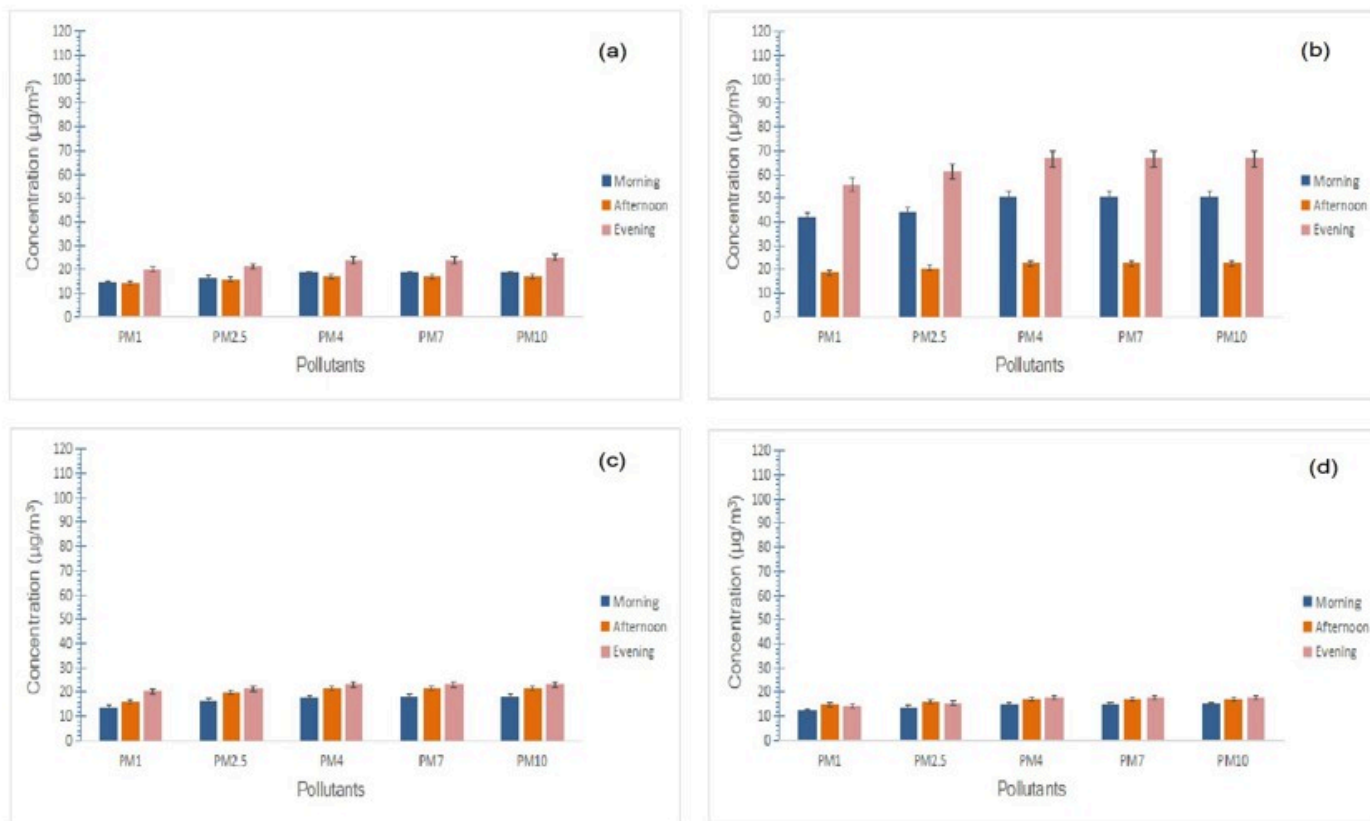


Figure 5

Figure 4: Variations in the PM Pollutants ($\mu\text{g}/\text{m}^3$) in the study area on Wet Days during the Study Period; (a) North, (b) East

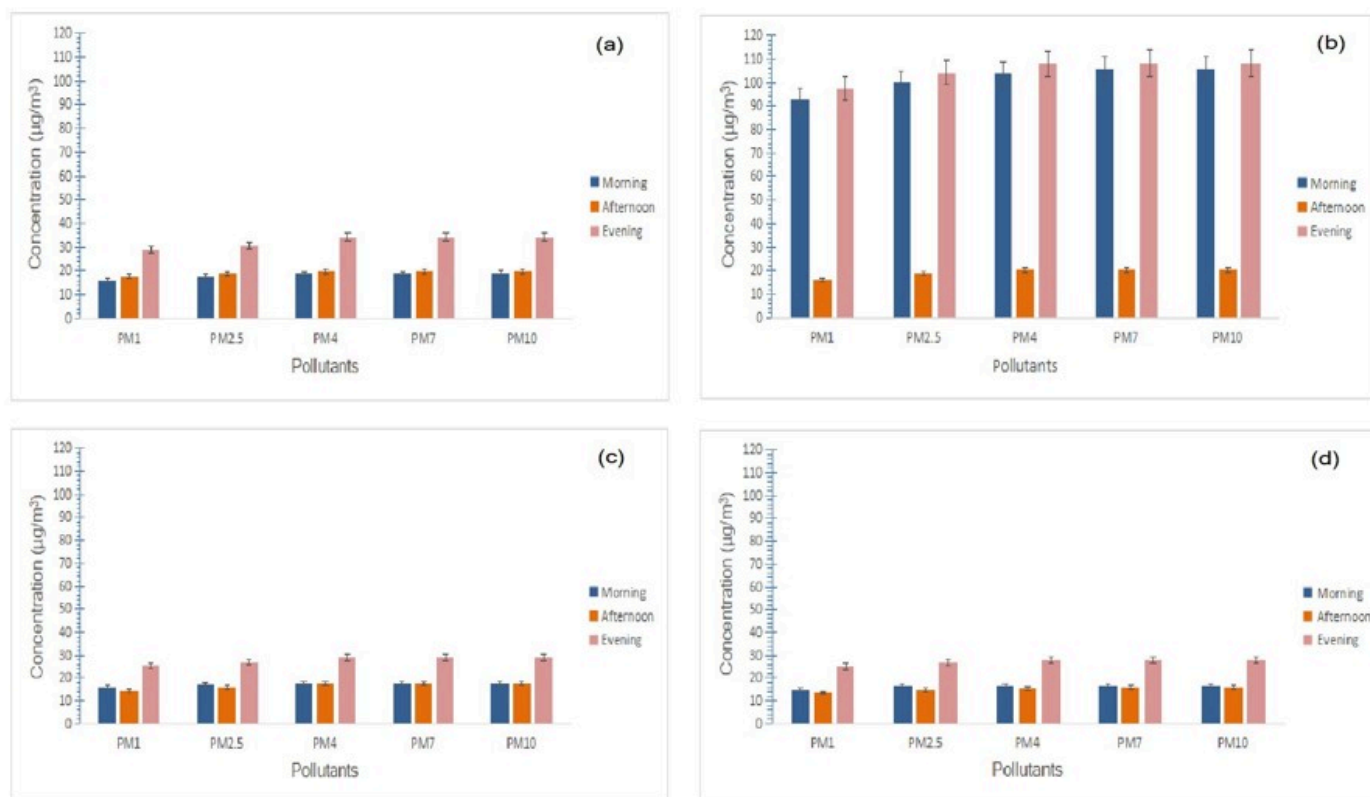


Figure 6

Figure 5: Variations in the PM Pollutants ($\mu\text{g}/\text{m}^3$) in the study area on Dry Days during the Study Period; (a) North, (b) East, (c) South and (d) West Directions.