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Assessment of Particulate Matter Pollution in Gold Mining Communities in Southwestern Ghana

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Abstract

This study analyzed the concentrations of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ across three distinct sites (Mile 7, Agric Hill, and Akoon) over a 6- to 9-month period to investigate the influence of local sources and meteorology using an IQAir Quality Monitor. Results revealed a consistent spatial hierarchy: Akoon, a community gold mining site, exhibited the highest concentrations (e.g., PM_{10} up to 121 $\mu g/m^3$), followed by Mile 7 and background Agric Hill. This confirms that local source strength is the primary determinant of pollution. Temporally, high humidity (>87%) and stable high-pressure conditions promoted PM hygroscopic growth and atmospheric stagnation, exacerbating pollution episodes. A notable November anomaly, with peak concentrations across all sites despite favourable dispersion meteorology, demonstrating how intense emission events can overwhelm regional dispersive capacity. $PM_{2.5}/PM_{10}$ and $PM_{1.0}/PM_{2.5}$ ratios indicated a significant contribution from derived fine and ultrafine particles. The high $PM_{1.0}$ fraction poses a serious health risk due to its potential for systemic inflammation and extra-pulmonary effects. Three-way ANOVA showed significant effects of Month, Site, and PM Size on PM concentrations, and regression analysis indicated that temperature increased while humidity and pressure decreased PM levels, together explaining 51–62% of the variability. The study concludes that effective mitigation requires a dual strategy: stringent, source-specific controls at identified hotspots and a regional early warning system that triggers actions during forecasted meteorological stagnation and seasonal burning periods.

Keywords: Air quality, emission hotspots, health risk, meteorology, particulate matter

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Introduction

The Tarkwa Nsuaem Municipality in Ghana's Western Region is a critical hub for gold extraction, characterised by both large-scale mining (LSM) operations and extensive artisanal small-scale gold mining (ASGM) activities. The environmental footprint of these activities, particularly air pollution from particulate matter (PM), poses a significant threat to the ecosystem and human health (Kim et al., 2015; Abidin et al., 2025). PM, especially the fine fractions ($PM_{2.5}$ and PM_{10}), is a well-established pollutant of concern due to its ability to penetrate deep into the respiratory system and carry adsorbed toxic elements causing respiratory and cardiovascular diseases to the receptors (Joshi et al., 2025). Based on the WHO's 2016 report, exposure to polluted air causes approximately 7 million deaths annually with ambient air pollution causing 4.2 million deaths in low- and middle-income countries.

Globally, mining is a dominant source of ambient particulate matter (PM) (Boente et al., 2022). Operations such as drilling, blasting, hauling, crushing, and waste disposal generate significant fugitive dust emissions, contributing substantially to the load of PM_{10} and the more hazardous $PM_{2.5}$ (Trivedi & Chakraborty, 2008**;** Pandey et al., 2014). The health implications of chronic exposure to this mine-derived PM are severe and well-documented. Numerous epidemiological and toxicological studies have established a strong link between exposure and increased incidence of debilitating respiratory diseases, including pneumoconiosis, silicosis, and chronic obstructive pulmonary disease

(COPD) (Petsonk, Rose, & Cohen, 2013; Pope et al., 2020). The risk extends beyond the lungs, with robust evidence connecting long-term exposure to elevated rates of cardiovascular morbidity, including ischemic heart disease and stroke, and premature mortality (Burnett et al., 2018; WHO, 2021). The risk is compounded by mining-derived PM, which is rarely inert. This air pollutant often serves as a vector for toxic elements and compounds (e.g., silica, heavy metals, polycyclic aromatic hydrocarbons), which can exacerbate its health impacts (Gottesfeld, Andrew, & Dalhoff, 2015; Mantey et al., 2020).

In Ghana, the discourse on mining pollution has historically centered on water contamination from heavy metals like mercury and cyanide, as well as the subsequent contamination of soil and food crops (Hilson, 2002; Obiri et al., 2016). However, the issue of air quality degradation is gaining prominence due to the visible and pervasive nature of dust pollution in mining communities. The Tarkwa Nsuaem Municipality area, as one of the most active mining districts, exemplifies this environmental challenge. Research in Ghana has begun to quantify the PM problem, often highlighting the distinct yet compounding impacts of LSM and ASGM. LSM companies are mandated to implement dust control measures, but studies indicate that ambient air quality standards are frequently exceeded. Evidence from Tarkwa confirms that blasting and haulage activities cause significant short-term spikes in PM levels, based on direct measurements taken in the area (Bansah & Amegbeh, 2012; Amegbeh et al., 2016). This supports the earlier work of Mantey et al. (2020), whose crucial study in Tarkwa measured $PM_{2.5}$ and PM_{10} concentrations across various land uses. Their findings revealed that areas near active mining operations, particularly those near waste rock dumps and haul roads, consistently recorded levels that exceeded the World Health Organization (WHO) 24-hour guidelines by wide margins, establishing a clear link between specific mining infrastructure and elevated PM concentrations.

Meanwhile, the ASGM sector, often informal and unregulated, presents a more diffuse and complex pollution source, emitting both atmospheric mercury and silica-rich dust (Hilson, & McQuilken, 2014; Hilson, 2016). Activities such as uncontrolled excavation, the milling of ore with grinding machinery, and the open burning of mercury-amalgam release large quantities of PM that is often enriched with toxic metals (Gottesfeld, Andrew, & Dalhoff, 2015). Artisana Small-scale Gold Mining activities create hotspots contributing significantly to regional PM load with a more hazardous toxicological profile (Snow et al., 2021). These studies, along with those of Aram et al., (2024) and Agbeshie et al., (2025) underscores that communities settled within ASGM hotspot zones experience continuous exposure to hazardous mixture with limited regulatory oversight, leading to documented adverse health outcomes. Tarkwa has served as a specific case study for several environmental and health investigations. Research works in the Municipality provide a foundational spatial assessment of PM and furthermore studies on health have started to emerge (Mantey et al., 2020). Research shows the prevalence of respiratory symptoms among residents in a mining community near Tarkwa, finding a statistically significant correlation between self-reported respiratory illnesses (chronic cough, wheezing) and proximity to mining activities, inferring PM exposure as a primary causative agent (Ayaab et al., 2017; Krampah, Amegbey, & Ndur, 2021).

However, a critical analysis of the extant literature reveals a significant gap. Most studies, including those cited, treat "mining communities" as monolithic entities or focus on a single type of source. There is a lack of comparative analysis that systematically investigates the spatial and source-specific variation of PM exposure *within* the same municipality with key unanswered questions on 1) How do $PM_{1.0}$, $PM_{2.5}$ and PM_{10} concentrations differ between a community adjacent to an LSM haul road, one engulfed by ASGM activities, and a peri-urban area where urban traffic pollution dominates? 2) What attributable risk and source apportionment of PM from LSM, ASGM, and non-mining urban activities in different communities? and 3) Which demographic groups in which specific locations are at the highest risk, necessitating targeted public health interventions? A study designed to concurrently monitor and compare PM levels in three (3) strategically chosen communities within the Tarkwa Nsuaem Municipality is, therefore, not just rational but necessary. Monitoring settlement directly downwind of a major LSM operation's active pit or waste dump, a village where the primary economic activity is community ASGM and a community where pollution is likely a mixture of mining-related dust (transported) and non-mining sources (construction, vehicle emissions, road dust). Such a comparative design would move beyond general conclusions. This would provide actionable data to stakeholders including the Environmental Protection Agency (EPA), municipal planners, mining companies, and community leaders on the precise sources and magnitudes of exposure in different settings. This is essential for developing effective, targeted mitigation strategies, enforcing regulations where they are most needed, and advancing environmental justice by identifying the most vulnerable populations.

The principal aim of this research is to quantitatively assess and compare the concentration levels, potential sources, and associated health risks of particulate matter ($PM_{1.0}$, $PM_{2.5}$ and PM_{10}) across three distinct communities in the Tarkwa Nsuaem Municipality that are influenced by different primary pollution sources (large-scale mining, community artisanal small-scale gold mining, and urban activity). The findings are intended to provide a robust evidence base for targeted air quality management and public health intervention strategies. This research aims to conduct a detailed comparative analysis of air pollution in three distinct communities within the Tarkwa Nsuaem

Municipality by focusing on three core objectives: to measure and compare the levels and patterns of three sizes of particulate matter ($PM_{1.0}$, $PM_{2.5}$, and PM_{10}) over time and space in Mile 7 (impacted by large-scale mining near a waste dump), Akoon (impacted by community artisanal small-scale gold mining), and Agric Hill (impacted mainly by urban sources like traffic and construction); to determine how local weather conditions specifically temperature, pressure and relative humidity influence the distribution and concentration of the measured particulate matter; and to evaluate the potential public health dangers by benchmarking the measured PM levels against WHO air quality standards. This study will help determine where pollution is worst, its sources, and its effects on human health.

Materials and Methods

Study Area

The survey was done in the Tarkwa-Nsuaem Municipality, which is one of the fourteen Metropolitan, Municipal and District Assemblies (MMDAs) located in the southwestern region of Ghana. The municipality is bounded by Latitudes 4°00′N and 5°04′N and Longitudes 1°45′W and 2°01′W, with a total land area of about 978.26 km² (GSS, 2021). Elevations range from 60 m to 225 m above sea level. This Municipality borders the Prestea Huni-Valley District to the North, Nzema East District to the West, Ahanta West District to the South, and the Mpohor District to the East (GSS, 2021). The Tarkwa-Nsuaem Municipality is located in the south-western equatorial climatic zone of Ghana, with a tropical climate, where rainfall, high humidity, and warmth prevail almost all year round. The municipality experiences rainfall during two seasons each year, exceeding 1,750 mm per annum (Mensah et al., 2015; Ghana Chamber of Mines, 2022). The temperature ranges between 28°C and 33°C, while relative humidity prevails in the area for much of the year. The physical features of this region are mainly hills and valleys trending in a northeast-southwest direction as a result of folding and erosion related to the Tarkwaian rock formation. As per the 2021 Population and Housing Census report by the Ghana Statistical Service, the total population of the municipality stands at 218,664 individuals, comprising 438 communities, namely Tarkwa Urban Council, and zonal councils of Nsuaem, Nsuta, Simpa, Dompim, and Benso (Akabzaa & Darimani, 2001).

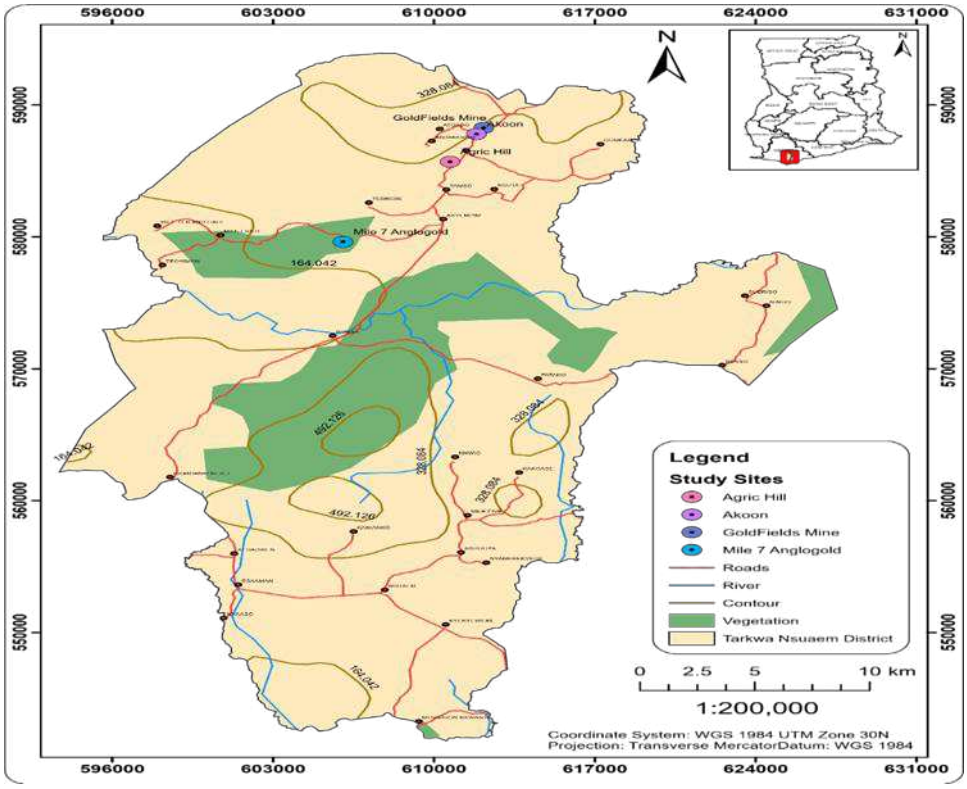


Fig. 1: A map indicating Akoon, Mile 7, and Agri Hill in the Tarkwa Nsuaem Municipality, Southwestern Ghana.

Mining operations are the primary source of economic development in the municipality and have influenced the environmental and socio-economic situation in the region (UNEP, 2012; Hilson, G., 2016; WHO, 2016; World Bank, 2019; USGS, 2020). Tarkwa-Nsuaem has large-scale mining companies and Ghana's single manganese mine,

positioning itself as one of the most significant mining areas in Ghana. Mining activities carried out in the municipality are large-scale surface and underground mining, small-scale mining, and ASGM (Hilson & Potter, 2003). Large-scale mining firms use predominantly open-pit mining and cyanide heap leaching methods, whereas ASGM uses simple and ineffective means and mercury amalgamation (Esdaile & Chalker, 2018). These processes lead to the creation of dust and other particulate matter, gas emissions, and noise pollution. Additionally, the mercury amalgamation process produces dangerous mercury vapour that negatively affects not only the miners but also the people living close by (Kortatsi & Akabzaa, 2009). Despite the positive impact of mining activities in terms of employment and economic development, the negative impact on the environment cannot be underestimated. Among these impacts are deforestation, land degradation, soil erosion, damage to agricultural land, and contamination of water resources.

The Municipality is located within the high forest zone in Ghana, which is an Upper Guinean Forest eco-region, categorised among the global biodiversity hotspots (Telmer & Veiga, 2009; Streets et al., 2019; UNEPA, 2019). The initial state of the environment in the area was comprised of dense evergreen and semi-deciduous rainforest, which provided various ecological services, including the provision of carbon sink, climatic regulation, maintenance of biodiversity, and watersheds (Veiga & Baker, 2004). The current state of the landscape has been adversely affected by such activities as mining, farming, and urbanisation. Large-scale open-cast mining, combined with mining operations within the communities, has caused massive destruction of forest cover and fragmentation of the ecosystem (Bryan et al., 2013; Mensah, 2015). Degradation of the soil has been intensified as a result of forest degradation, owing to the fact that there is no vegetation cover anymore (Esdaile & Chalker, 2018). Destruction of vegetation cover causes soil dryness and dust pollution due to mining activities. It is worth noting that forest degradation affects human beings as it leads to the destruction of natural resources and habitat for diverse wildlife species (Acheampong et al., 2019; Hilson & Potter, 2003).

There were three study sites chosen in the municipality, and these include Mile 7, Agric Hill, and Akoon. Mile 7 is one of the mining-influenced environments which features mine waste dumps, unpaved roads, surface disturbances, and a higher degree of dust production due to mining operations. Agric Hill is a place that mainly comprises the residence and learning environment of the University of Mines and Technology. The environment is placed on a higher topographic position and is therefore less polluted compared to the other two sites, and has better plant cover. Akoon site is located in a valley which has mining, residential and commercial activities, with parts of the plants influenced by the mining activities done by the community members. There is similarity in climatic conditions of the three selected environments in terms of high rainfall, humidity and tropical temperature. These factors affect the distribution of pollutants.

Sampling Collection and Analysis

Sample plan

Data collection was done by mounting the IQ AirVisual air quality monitor. Three houses from Mile 7, Agric Hill, and Akoon were chosen based on permission granted by residents to allow the monitors to be pasted on their houses. The GPS coordinates and the land elevations of each location were recorded. Purposive sampling was used to focus on three specific locations within Tarkwa Municipality; Mile 7, Agric Hill, and Akoon. This selection was based on the need to assess the diverse pollution sources that are critical for understanding variations in PM levels.

IQAir Monitor

The IQ AirVisual air quality (09Type) sensor modules with a default rate of measurement of every 5 minutes. It has a PM sensor with a light scattering photo sensor, American & China AQI output for PM_{10} (0.3–10.0µm), $PM_{2.5}$ (0.3–2.5µm), and $PM_{1.0}$ (0.0–1.0 µm). The detection limit for the PMs ranges from 0 to 4000µg/m^3. The IQ AirVisual air quality was designed to provide accurate, configurable, and continuous air monitoring in covered outdoor areas. The device was mounted vertically at each sampling site, Mile 7, Akoon, and Agric Hill. The device gave real-time data using a 4G dongle with constant mobile data.

Sample Collection

Three (3) IQAir quality monitors were conveniently fixed at heights between 4 to 5 meters at Mile 7, Agric Hill, and Akoon in the Tarkwa Nswaem Municipality in Southwestern Ghana from March to November 2024. Sampling was automatically sampled every 5 minutes for nine (9) months for Mile 7 and Akoon sites, and six (6) months at Agric Hill. PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ in mg/m^3 were simultaneously sampled in all three sites.

Quality assurance and quality control

Particulate matter ($PM_{1.0}$, $PM_{2.0}$ and PM_{10}) levels were monitored using low-cost IQAir AirVisual Outdoor Monitors. These devices detect particles range from 0 to 1000 µg/m³ (accuracy of ±10–15%) for $PM_{2.5}$ and PM_{10} as stated by the manufacturer. The IQAir air quality sensors were mounted 1.5 meters above ground to sample ambient air and were cleaned weekly as recommended. Data was checked monthly for errors, such as sudden zero readings or unrealistically high values.

Before use, sensors were checked with factory calibration certificates. The sensors were collocated with a high-standard Teledyne T640 analyzer at the Afri-SET facility at the University of Ghana 168 hours under typical local urban conditions on the field. Strong correlations ($PM_{2.5}$: r = 0.78; p≤0.00) between the IQAir and the Teledyne T640 analyzer, meeting accepted validation standards and aligning with findings from similar studies in developing regions were shown.

When assessing the agreement between the two datasets for $PM_{2.5}$, the paired t-test yielded a significant t-statistic of -5.99 (df = 131, p≤0.00), indicating a strong and consistent offset where values in high-standard Teledyne T640 analyzer average 1.264 units below those of IQAir air quality (SD = 2.424). Furthermore, the root mean square error (RMSE) of 2.726 quantifies the overall deviation between the paired observations.

The high-standard Teledyne T640 analyzer at the Afri-SET facility at the University of Ghana measured only $PM_{2.5}$.

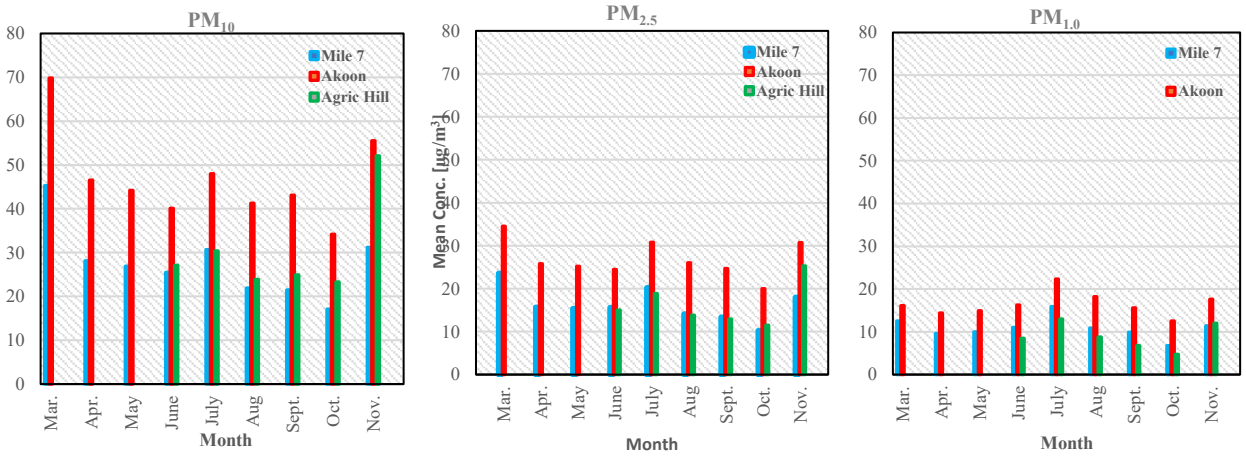
RESULTS

This study focused on the assessment of the distribution of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ from the three communities. The range of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ concentration (µg/m³) reported within nine (9) months (March to November) in Mile 7 and Akoon communities, and six (6) months at Agric Hill are presented in Table 1. The highest range of PM recorded at Mile 7 (PM_{10}: 24.7– 69.8, *n* = 19) in March, Akoon (PM_{10}: 39.9–121, *n* = 19) in November, and Agric Hill (PM_{10}: 37.0–105, *n* = 19) in November; $PM_{2.5}$ from Mile 7 ($PM_{2.5}$: 5.00–36.9, *n* = 30) in June, Akoon ($PM_{2.5}$: 18.0–70.5, *n* =31) in July, and Agric Hill ($PM_{2.5}$: 16.8–38.1, *n* = 19) in November; and $PM_{1.0}$ from Mile 7 ($PM_{1.0}$: 10.2–28.0, *n* = 30), Akoon ($PM_{1.0}$: 12.8–45.1, *n* = 31) and Agric Hill ($PM_{1.0}$: 8.04–20.8, *n* = 31) all in July.

The highest mean concentration of PM_{10} at each site was recorded in March (Mile 7: 45.3±14.9µg/m³, *n*=30); March (Akoon: 69.8±25.6µg/m³, *n*=30); and November (Agric Hill: 53.6±17.8µg/m³, *n*=30). Also, $PM_{2.5}$ in March (Mile 7: 23.6±7.30, *n*=15), March (Akoon: 34.5±10.3, *n*=30); and November (Agric Hill: 25.3±6.14, *n*=30); and $PM_{1.0}$ in July (Mile 7: 15.9±3.95, *n*=31), July (Akoon: 22.3±6.15, *n*=31) and July (Agric Hill: 12.7±3.05, *n*=31) were recorded. Among the three sites in the Tarkwa Nsueam Municipality, Akoon site, a community closer to Gold Fields Ghana Limited and engages in community ASGM, recorded the highest PM_{10}, $PM_{2.5}$, and $PM_{1.0}$. Comparing the PMs among the three sites in Figure 2 indicates that PM_{10} was the highest, followed by $PM_{2.5}$ and then $PM_{1.0}$. Mile 7 registered the least PM_{10} and $PM_{2.5}$, whilst Agric Hill registered the least $PM_{1.0}$ in the Tarkwa Nsuaem Municipality. Mile 7 is closer to Anglo Gold Ghana dumping sites with no community mining activities, whilst Agric Hill is closer to Gold Fields Ghana Limited with no community mining activities. All three sites, Mile 7, Akoon, and Agric Hill, recorded their highest $PM_{1.0}$ in July.

The Spearman correlation (Figures 6, 7, and 8) between PM_{10} and $PM_{2.5}$ shows a strong linear correlation (0.88–1.0; *p-value* = 0.00) across all the communities, signifying a PM_{10} and $PM_{2.5}$ originate from the same sources within the communities. Also, there were significant correlations (0.86, *p-value* = 0.00) between $PM_{2.5}$ and $PM_{1.0}$ in all the communities; however, PM_{10} and $PM_{1.0}$ show a moderate correlation (0.69, *p-value* = 0.00) yet significant in Agric Hill.

242 **Fig. 2: Mean Concentrations (µg/m^3) of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ measured in Mile 7, Akoon, and Agric Hill in**
243 **the Tarkwa-Nsuaem Municipality in the Western Ghana.**



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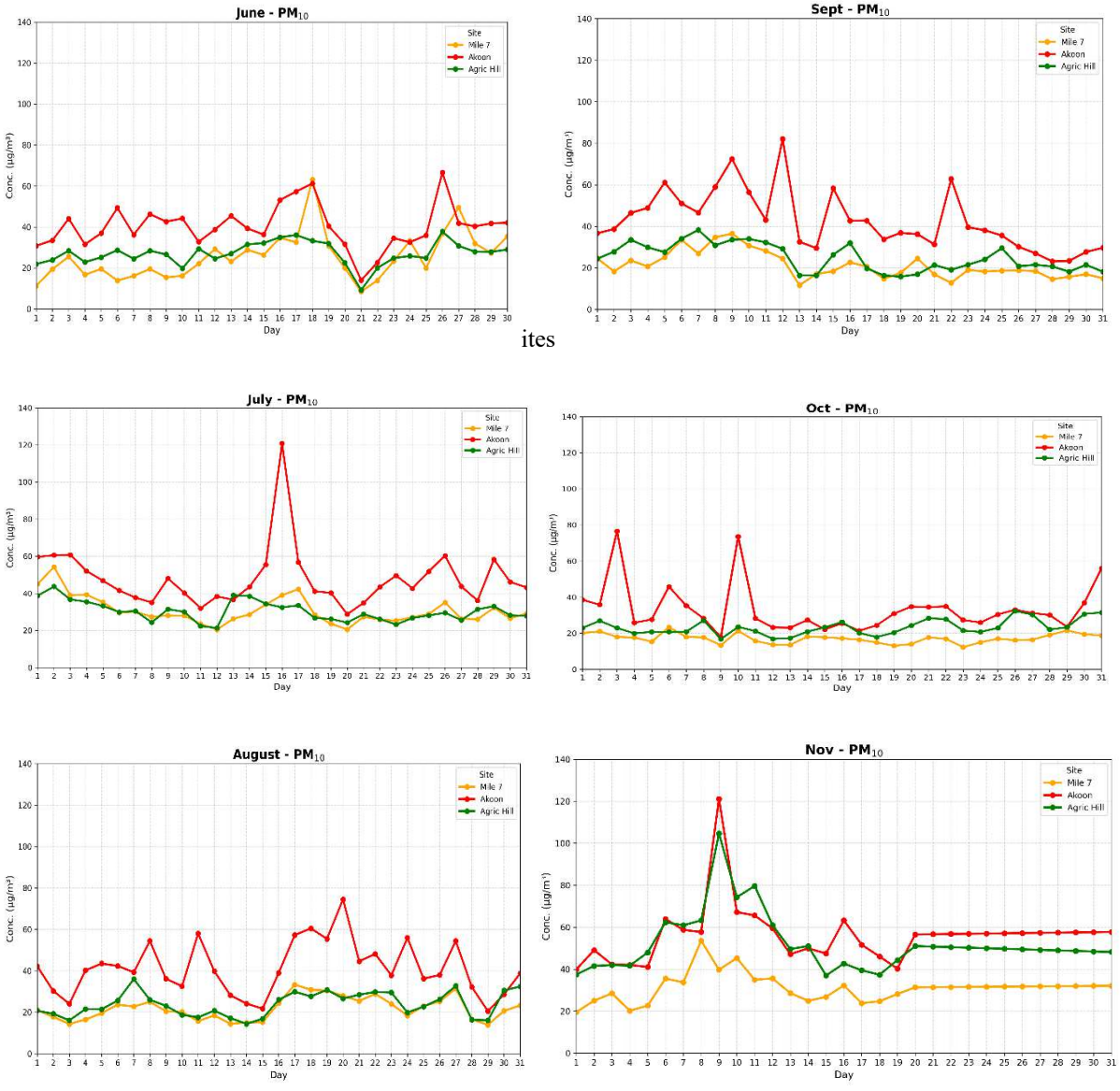
Table 1: The range (µg/m^3) of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ determined in Mile 7, Akoon, and Agric Hill in the Tarkwa Nswaem Municipality, Western Ghana.

Month	Mile 7			Akoon			Agric Hill		
	PM_{10} [µg/m^3]	$PM_{2.5}$ [µg/m^3]	$PM_{1.0}$ [µg/m^3]	PM_{10} [µg/m^3]	$PM_{2.5}$ [µg/m^3]	$PM_{1.0}$ [µg/m^3]	PM_{10} [µg/m^3]	$PM_{2.5}$ [µg/m^3]	$PM_{1.0}$ [µg/m^3]
March	24.7 - 69.8	13.1 - 36.5	5.90 - 17.5	35.71-107	19.0 - 47.6	9.33 - 22.4	0.00	0.00	0.00
April	15.1- 44.4	9.11 - 21.8	5.27 - 13.8	30.0 - 90.0	16.1 - 50.3	8.83 - 29.8	0.00	0.00	0.00
May	14.1 - 56.7	21.8 - 8.42	5.67 - 14.7	24.5 - 96.4	13.9 - 53.5	8.17 - 32.2	0.00	0.00	0.00
June	8.43 - 63.2	5.00 - 36.9	3.17 - 23.6	14.0 - 66.6	8.46 - 38.4	5.79 - 29.8	9.21 - 36.1	4.67 - 21.6	2.29 - 14.9
July	20.5 - 54.2	13.2 - 35.7	10.2 - 28.0	28.8 - 121	18.0 - 70.5	12.8 - 45.1	21.4 - 43.7	12.5 - 28.1	8.04 - 20.8
August	13.9 - 33.3	8.79 - 21.9	6.30 - 16.4	20.6 - 74.5	12.6 - 46.8	8.57 - 32.7	14.4 - 32.7	7.79 - 20.8	3.83 - 15.3
September	11.6 - 36.5	6.92 - 22.7	4.54 - 17.2	23.1 - 82.1	13.7 - 47.2	8.59 - 28.0	15.8 - 38.3	7.71 - 19.1	2.29 – 12.0
October	12.3 - 23.3	7.46 - 13.5	4.30 - 10.1	17.8 - 76.5	10.5 - 45.9	6.55 - 29.8	16.4 - 32.4	8.17 - 16.3	3.04 - 8.88
November	19.5 - 53.6	11.0 - 26.6	6.58 - 12.8	39.9 - 121	22.1 - 52.3	12.5 - 27.0	37.0 - 105	16.8 – 38.1	5.60 – 16.5

Table 2: Mean and Standard Deviation results on Temperature (°C), Humidity (%), and Pressure (Pa) recorded at the Tarkwa Nsuaem Municipality, Western Ghana.

Months	Temperature [°C]	Humidity [%]	Pressure (Pa)
June	27.1±0.86	87.1±2.82	100481±118
July	25.9±0.74	88.8±2.73	100586±92.9
August	25.2±0.69	87.7±2.97	100528±76.2
September	26.4±0.64	83.5±3.26	100422±85.7
October	26.9±0.64	87.0±2.34	100353±86.7
November	27.9±0.55	83.2±2.36	100173±92.5

Fig. 3: Graphical representation of PM_{10} concentrations (µg/m^3) from June to November determined at Akoon, Agric Hill and Mile in the Tarkwa Nsuaem Municipality, Southwestern Ghana.



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Fig. 4: Graphical representation of $PM_{2.5}$ concentrations (µg/m^3) from June to November determined at Akoon, Agric Hill and Mile in the Tarkwa Nsuaem Municipality, Southwestern Ghana.

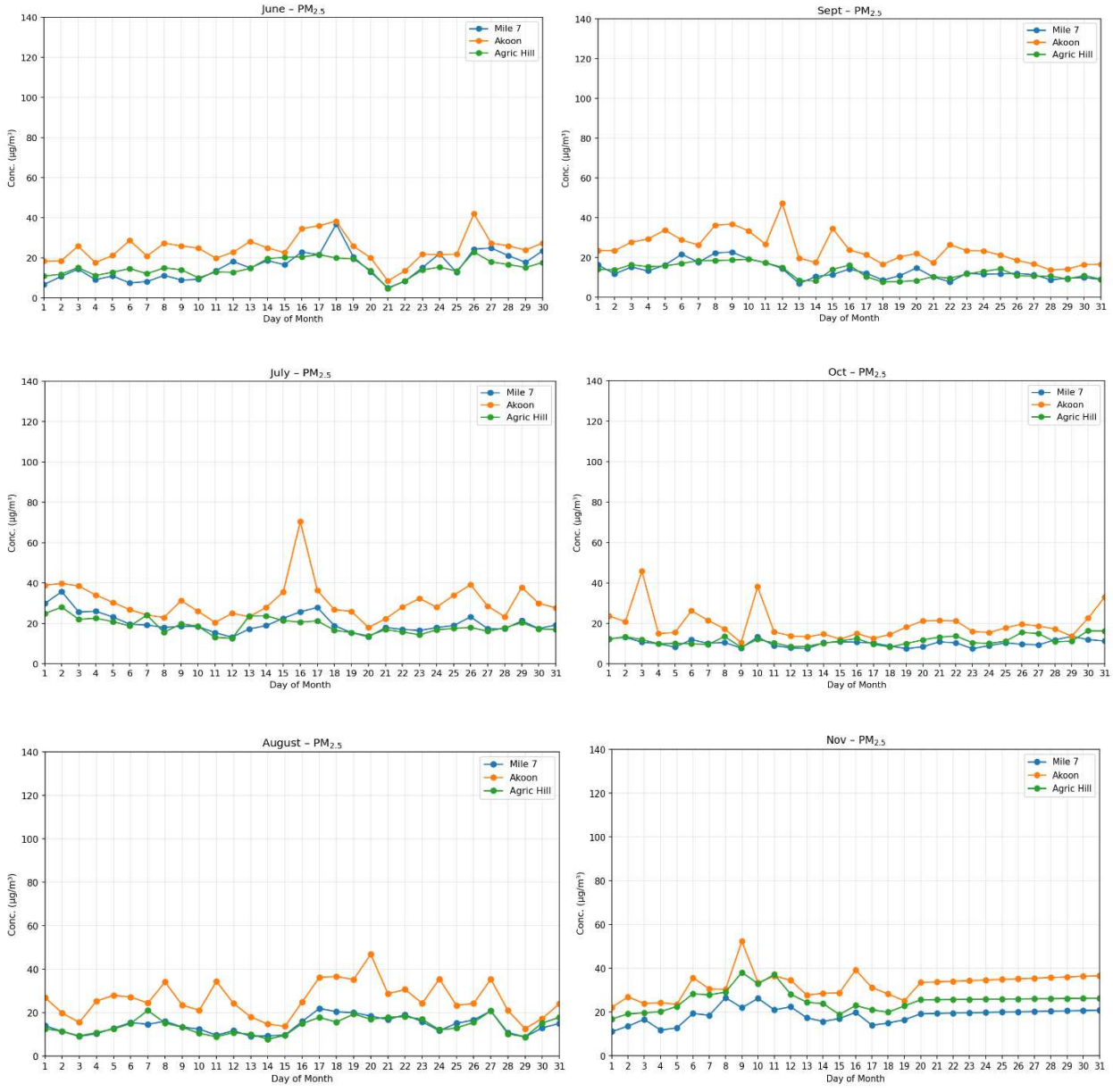


Fig. 5: Graphical representation of $PM_{1.0}$ concentrations ($\mu g/m^3$) from June to November determined at Akoon, Agric Hill and Mile in the Tarkwa Nsuaem Municipality, Southwestern Ghana.

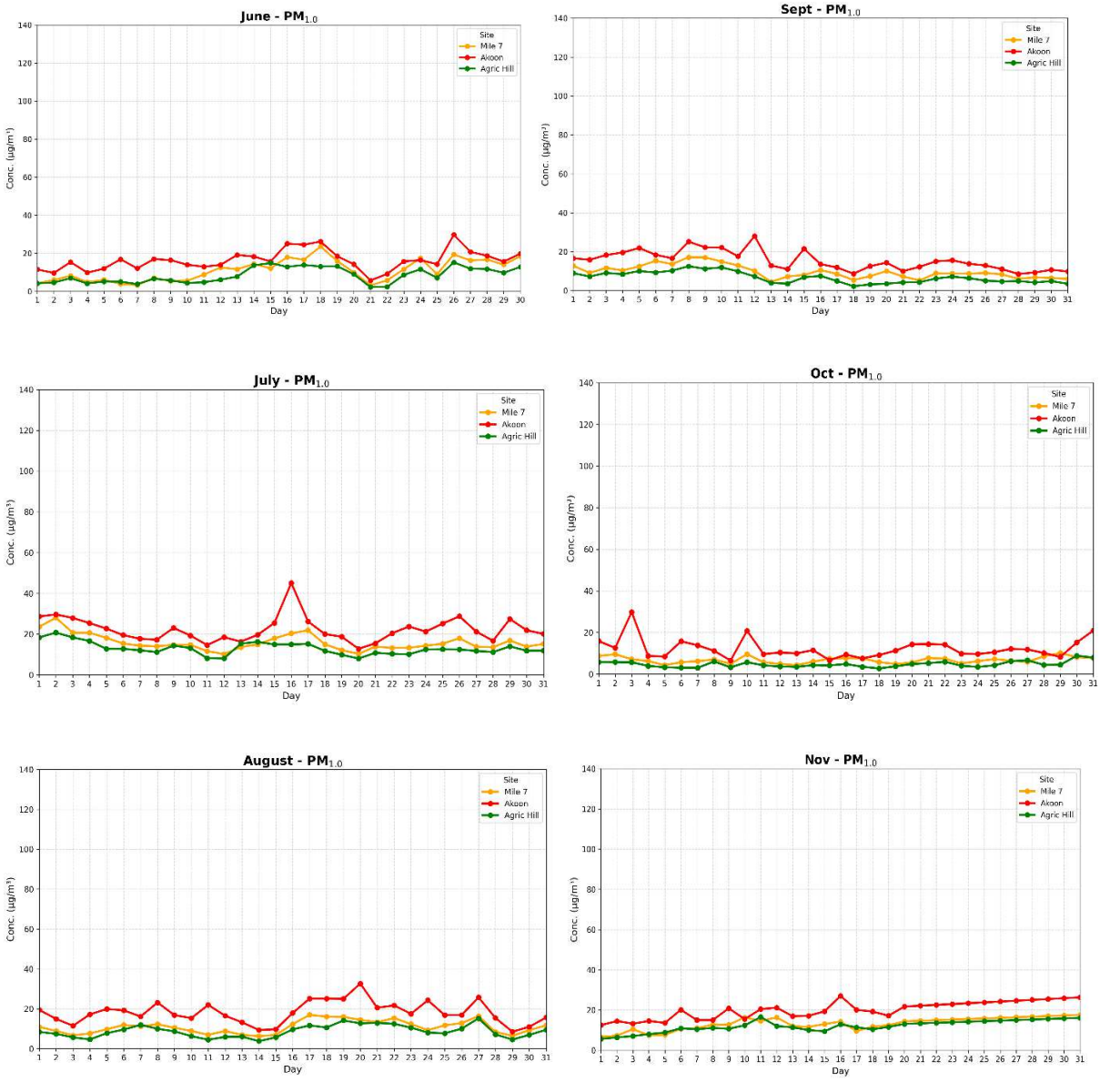


Fig. 6: Scatter plots of all areas to visualize the linear patterns in each dataset at Agric Hill, Tarkwa Nsuaem Municipality, Southwestern Ghana.

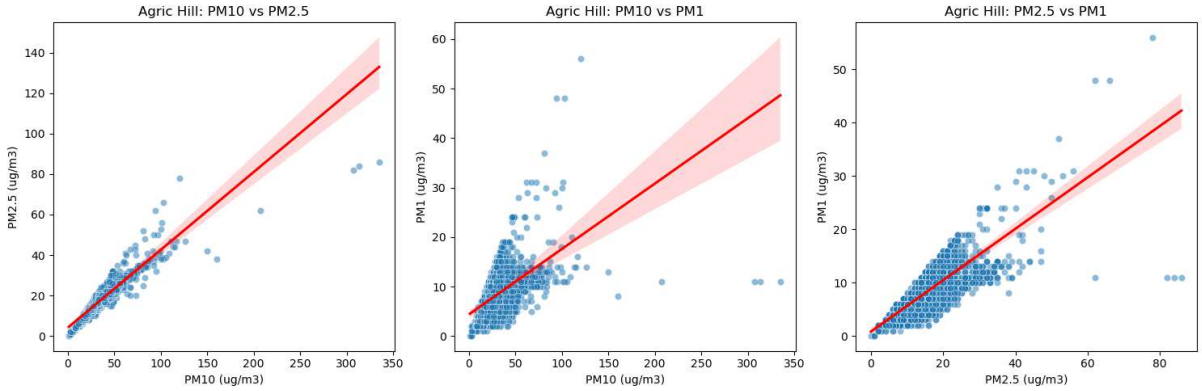


Fig. 7: Scatter plots of all areas to visualize the linear patterns in each dataset at Akoon, Tarkwa Nsuaem Municipality, Southwestern Ghana.

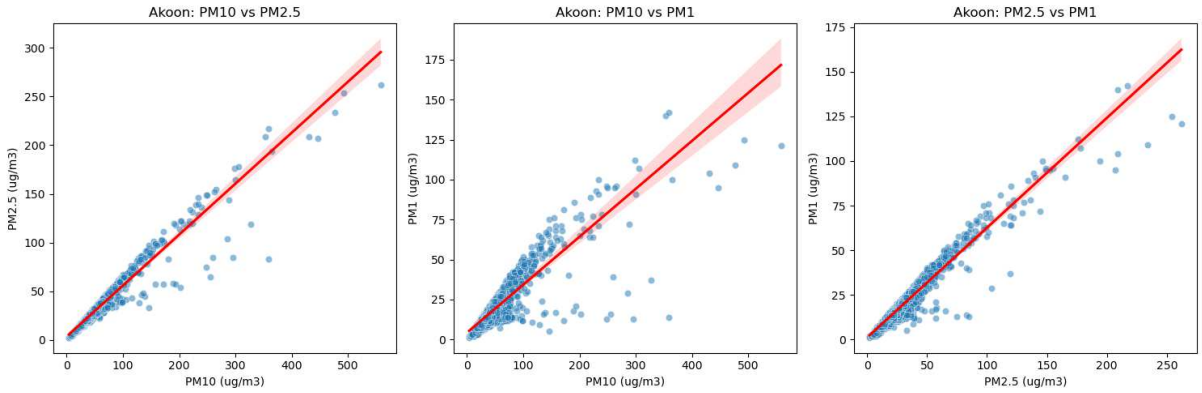


Fig. 8: Scatter plots of all areas to visualize the linear patterns in each dataset at Mile 7, Tarkwa Nsuaem Municipality, Southwestern Ghana.

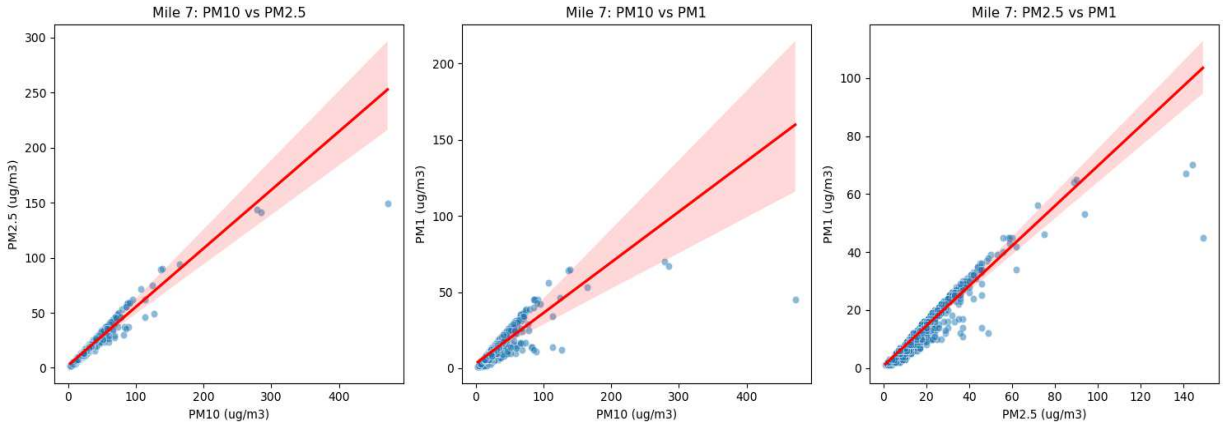


Table 3: Three-Way Analysis of Variance of Particulate Matter Concentrations: Effects of Month, Site, and Particle Size with Interaction Effects.

Effect	F	p-value	Partial η^2
Month	5.82	0.001	0.31

Site	18.4	0.001	0.65
PM Size	12.5	0.001	0.44
Month × Site Interaction	3.21	0.009	0.22
Month × PM Size Interaction	2.87	0.02	0.19
Site × PM Size Interaction	5.45	0.001	0.35
Month × Site × PM Size	2.31	0.04	0.17

Table 3 describes the ANOVA test carried out to evaluate the interaction between Month, Site, and PM Size in influencing particulate matter concentrations (PM_{10}, $PM_{2.5}$, and $PM_{1.0}$). The ANOVA test was conducted to evaluate the interaction between Month, Site, and PM Size in influencing particulate matter concentrations. The ANOVA model used was:

$$PM_{ijk} = \mu + \alpha_i(\text{Month}) + \beta_j(\text{Site}) + \gamma_k(\text{PM Size}) + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \epsilon_{ijk}$$

The results showed that there were significant main effects of Month ($F = 5.82$, $p = 0.001$, partial $\eta^2 = 0.31$), Site ($F = 18.35$, $p < 0.001$, partial $\eta^2 = 0.65$), and PM Size ($F = 12.47$, $p < 0.001$, partial $\eta^2 = 0.44$), which indicated that there were variations in PM levels at different months, across different sites, and for various particle sizes. Significant two-way interactions were found to exist between Month × Site ($F = 3.21$, $p = 0.009$, partial $\eta^2 = 0.22$), Month × PM Size ($F = 2.87$, $p = 0.02$, partial $\eta^2 = 0.19$), and Site × PM Size ($F = 5.45$, $p = 0.001$, partial $\eta^2 = 0.35$), which showed that all three factors, namely time, site, and particle size, had a significant combined influence on PM levels. Finally, a significant three-way interaction was found to exist between Month × Site × PM Size ($F = 2.31$, $p = 0.04$, partial $\eta^2 = 0.17$), which revealed that all three factors, namely time, location, and particle size, had a significant combined influence on PM levels.

Table 4: Temperature, Humidity, and Pressure Effects on Particulate Matter Concentrations

PM Size	Predictor	β (Coeff.)	SE	t	p-value
PM_{10}	Intercept	12.5	0.42	4.17	<0.001
	Temperature	1.75	0.42	4.17	<0.001
	Humidity	-0.98	0.31	-3.16	0.003
	Pressure	-0.55	0.21	-2.62	0.009
Model Summary	R^2 / Adj R^2	0.62 / 0.60			
	F (model)	35.4			<0.001
$PM_{2.5}$	Intercept	7.8	0.38	3.16	0.003
	Temperature	1.2	0.38	3.16	0.003
	Humidity	-0.72	0.28	-2.57	0.012
	Pressure	-0.36	0.19	-1.89	0.067
Model Summary	R^2 / Adj R^2	0.57 / 0.54			
	F (model)	28.1			<0.001
$PM_{1.0}$	Intercept	4.5	0.33	2.88	0.007
	Temperature	0.95	0.33	2.88	0.007
	Humidity	-0.55	0.25	-2.2	0.029
	Pressure	-0.25	0.16	-1.56	0.13
Model Summary	R^2 / Adj R^2	0.54 / 0.51			
	F (model)	24.6			<0.001

Table 4 presents impact of temperature, humidity, and pressure on concentration levels of PM_{10}, $PM_{2.5}$, and $PM_{1.0}$. The multiple linear regression analysis was employed to investigate the impact of temperature, humidity, and pressure on the concentration levels of PM. The model used was:

$$\text{PM} = \beta_0 + \beta_1(\text{Temperature}) + \beta_2(\text{Humidity}) + \beta_3(\text{Pressure}) + \epsilon$$

Temperature was a significant positive predictor of PM_{10} ($\beta = 1.75$, $p < 0.001$), while both humidity ($\beta = -0.98$, $p = 0.003$) and pressure ($\beta = -0.55$, $p = 0.009$) were significant negative predictors. The $PM_{2.5}$ regression analysis resulted in an R-squared value of 0.57, with the F-statistic and p-value being $F = 28.1$, $p < 0.001$. The result showed that temperature was a significant positive predictor ($\beta = 1.20$, $p = 0.003$), while humidity was a significant negative predictor ($\beta = -0.72$, $p = 0.012$). Pressure was a marginal negative predictor ($\beta = -0.36$, $p = 0.067$). $PM_{1.0}$ regression analysis was able to explain the variability in the data by 54% ($R^2 = 0.54$, Adj $R^2 = 0.51$; $F = 24.6$, $p < 0.001$). It was able to positively predict $PM_{1.0}$ ($\beta = 0.95$, $p = 0.007$), while it was negatively predicted by humidity ($\beta = -0.55$, $p = 0.029$). Pressure had a non-significant negative effect ($\beta = -0.25$, $p = 0.13$).

Discussion

The data reveals consistent daily patterns of PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ across Akoon, Mile 7 and Agric Hill sites, and particle sizes, highlighting the complex interplay between local emission sources and meteorological conditions. This study focused on three unique communities, Mile 7, Akoon, and Agric Hill, over nine months from March to November 2024, for Akoon and Mile 7, and June to November for Agric Hill. Mile 7, located near AngloGold Ashanti Limited waste dumping sites, has untirred roads and vegetation but no ongoing road construction, though Artisanal Small-scale Gold Mining (ASGM) activities are not present. Akoon, situated in a valley, is close to Gold Fields Ghana Limited (situated on a hill), with untarred paths, less vegetation, biomass burning, and extensive on-going community ASGM activities. Agric Hill, near Gold Fields Ghana Limited, is characterized by private housing construction activities, lots of vegetation and situated on a hill as the name implies.

Overall Pattern and Source Characterization

A clear and persistent hierarchy is evident across all months: Akoon, Mile 7, and Agric Hill for all PM fractions (PM_{10}, $PM_{2.5}$, $PM_{1.0}$). This indicates that local emission sources are the primary determinant of air pollution levels, overriding the regional meteorological influence. Akoon shows as a major air pollution source hotspot. The site consistently records the highest concentrations and the widest ranges (e.g., PM_{10} up to 121 $\mu g/m^3$ in July and November). This extreme variability, with very high peaks (Figures 3, 4, and 5), is characteristic of a location immediately downwind of a primary particulate matter source from extensive community mining (ASGM activities), less vegetation, untarred pavements and road, road construction, and biomass burning. alley with one open ended. At the Akoon site, a deep, human-made valley with only one entrance, cold-air pooling can occur even in summer under suitable synoptic conditions. Such events underline that cold-air pooling is not strictly seasonal and can drive pollutant buildup whenever terrain and meteorology combine appropriately (Chemel & Burns, 2015). On the top of the valley, is a LSM company situated. Mile 7 shows results moderate to high levels of PMs, suggesting it is influenced by urban pollution but not directly adjacent to a major point source like Akoon. It is a sited adjacent to LSM waste dumping site, untarred road but with more vegetation cover.

In contrast, air quality at elevated sites such as Agric Hill shows the lowest recorded particulate matter (PM) levels, reflecting minimal influence from local emissions. Its hilltop position enhances ventilation and pollutant dispersion, while extensive vegetation promotes PM deposition. The absence of local ASGM activities, with larger-scale mining located farther away, further reduces its pollution burden. Agric Hill therefore represents an ideal background site, capturing regional PM that has been dispersed and atmospherically aged (Major et al., 2022).

PM Ratios for Source Apportionment

The ratios between particulate matter (PM) sizes are highly informative for source apportionment. This interpretation is strongly supported by Spearman correlation analysis, which shows a strong linear relationship between PM_{10} and $PM_{2.5}$ (0.88–1.00; *p-value* = 0.00) across all communities, indicating they originate from common sources (Ye, Ma

& Liu, 2025). For example, the maximum values in June showed $PM_{2.5}/PM_{10}$ ratios of 0.58 (Akoon) and 0.60 (Agric Hill). These relatively consistent values (often between 0.50–0.70) suggest a mixed origin of particles from both coarse (e.g., dust, sea salt) and fine (e.g., combustion) modes (Belis et al., 2013). Further analysis of the finer fractions reveals more specific sources: the significant correlation between $PM_{2.5}$ and $PM_{1.0}$ (0.86, *p-value* = 0.00) and the higher $PM_{1.0}/PM_{2.5}$ ratio at Akoon (0.78 vs. 0.69 at Agric Hill) suggest a significant contribution from primary emission sources which emit predominantly in the ultrafine and fine fractions, such as industrial combustion processes including milling and roasting (Rodríguez et al., 2022). The moderate correlation between PM_{10} and $PM_{1.0}$ (0.69, *p-value* = 0.00) at Agric Hill further underscores the differing influence of coarse particles at that site.

Analysis of Monthly Variability and Meteorological Influence

Meteorology modulates the emission strength and governs the dispersion, transformation, and removal of PM. June, July, and August are early rainy season. The meteorology conditions showed High humidity (~87-89%), stable high pressure (~1005-1006 hPa) and relatively constant (~25-27°C) temperatures. The high humidity promotes hygroscopic growth, where particles absorb water and increase in mass, leading to higher recorded concentrations (Zhou et al., 2018). The stable high-pressure conditions suppress vertical mixing, trapping the air pollutants near the ground (Seinfeld & Pandis, 2016). This explains the significant peaks observed, especially at Akoon. The slightly lower pressures in August and September may contribute to slightly better dispersion and lower peak values compared to July.

October is known to be the transitional season where humidity remains high (87%), but pressure begins to drop (100353 Pa). in analyzing PM in the Municipality, a noticeable drop in PM levels at all sites occurred, especially in the minimum concentrations. The lower pressure indicates less atmospheric stability, potentially allowing for better dispersion of pollutants. This is particularly clear at Agric Hill, which shows its lowest values for the dataset.

In November, dry, and low-pressure was observed. A significant shift with the lowest humidity (83.2%), lowest pressure (100173 Pa), and highest temperature (27.9°C were observed. This month presents the most interesting paradox. The low pressure and high temperature should promote atmospheric mixing and dispersion. However, November had the highest PM peaks across all sites (e.g., PM_{10} at Akoon and Agric Hill exceed 120 and 100 µg/m³, respectively). This unequivocally points to a dramatic increase in emission strength. The most likely cause is burning. This seasonal practice which is associated with emission enormous quantities of primary $PM_{2.5}$ and $PM_{1.0}$ (Titos et al., 2017) occurring during the dry season (low humidity), allowing smoke plumes to persist. The resulting haze and smoke can dominate the regional airshed, overwhelming any dispersive benefits from the lower pressure.

Analysis by Particle Size

The data consistently shows $PM_{10} > PM_{2.5} > PM_{1.0}$ for both average and peak concentrations at every site. However, the relative proportions change. Coarse particles (PM_{10}) Showed the greatest absolute variability, especially at Akoon. This reflects the variable nature of coarse PM sources like dust resuspension (from traffic or wind), construction, and industrial processes. Their larger size means they settle out of the atmosphere more quickly.

Fine and Ultrafine Particles ($PM_{2.5}/PM_{1.0}$): Exhibit less absolute variability but are a more constant fraction of the total mass. They are primarily from combustion processes (vehicles, industry, burning) and secondary formation. Their small size allows them to remain suspended for long periods and be transported over regional distances. The high $PM_{1.0}/PM_{2.5}$ ratios indicate that combustion sources are a very significant contributor to the fine particle pollution.

The PM pollution across Akoon, Mile 7 and Agric Hill sites are dominantly driven by local emission sources, with Akoon site being a major hotspot likely due to community mining (ASGM) and/or industry. Meteorological parameters, particularly high humidity and atmospheric pressure, act as amplifying factors, exacerbating pollution episodes by trapping particles and promoting hygroscopic growth. The extreme pollution in November is a clear example of seasonal emission activity (burning which may be caused by gold-mercury amalgamation and

bimass) overpowering moderately favorable dispersion conditions, highlighting that inventorying and managing sources is the most critical step for air quality management.

Health Risks by Particle Size

Akoon in the Tarkwa Nsuaem Municipal is the most critical public health concern, with pollutant levels far exceeding WHO guidelines (PM_{10}: Annual = 15 µg/m³, 24-Hours = 45 µg/m³, and $PM_{2.5}$: Annual = 5 µg/m³, 24-Hours = 15 µg/m³**)**. Peak values reach PM_{10}: 121 µg/m³ and $PM_{2.5}$: 70.5 µg/m³**,** both well above the 24-hour guideline limits (WHO, 2021). Such exceedances pose immediate threats, including asthma attacks, acute bronchitis, severe respiratory distress, and triggering of cardiovascular events such as myocardial infarction in vulnerable individuals (Guan et al., 2016). Long-term exposure, consistently above WHO's annual means, increases risks of reduced lung growth in children, chronic obstructive pulmonary disease (COPD), lung cancer, and ischemic heart disease (Cohen et al., 2017). Moreover, the high share of ultrafine particles ($PM_{1.0}$) suggests systemic inflammatory effects, potentially worsening diabetes and impairing cognitive function (Terzano et al., 2010). Akoon therefore represents a public health emergency, requiring urgent mitigation.

Mile 7 illustrates the broader health challenges of dense urban populations. Though peaks (Figures 3, 4, and 5) are lower than Akoon, pollutant levels still regularly exceed WHO guidelines (WHO, 2021). During stagnation events, such as periods of high pressure and high humidity, concentrations approach or exceed the 24-hour limits, aggravating asthma, chronic obstructive pulmonary disease (COPD), and cardiovascular disease, while also causing discomfort even in healthy individuals. Persistent exposure above WHO's annual thresholds further contributes to an elevated prevalence of asthma, cardiovascular disease, and reduced life expectancy (Cohen et al., 2017). While the individual risk at Mile 7 is lower than at Akoon, the much larger number of people exposed makes the cumulative public health impact highly significant. Effective emission controls from traffic and industry could therefore yield substantial health benefits for this population.

Agric Hill records the lowest PM levels but still exceeds WHO's annual $PM_{2.5}$ guideline of 5 µg/m³, confirming that no exposure is entirely safe (WHO, 2021) and represent a benchmark for the municipal. Even low-level exposure above WHO standards contributes to long-term cardiovascular and respiratory disease (Pope et al., 2020). Episodes of acute risk also occur, such as the November biomass burning event when $PM_{2.5}$ spiked to 38.1 µg/m³, surpassing the 24-hour guideline of 15 µg/m³ and creating a period of acute vulnerability. Although Agric Hill residents enjoy a relative health advantage compared to Akoon and Mile 7, the site underscores that compliance with WHO limits across all areas is essential to fully protect public health.

Environmental Implications

The comparative analysis of particulate matter (PM) across the three communities reveals critical environmental concerns. At Mile 7, coarse particles (PM_{10}) dominate due to haul road dust and excavation activities, consistent with findings that such operations contribute up to 78% of PM_{10} emissions in similar mining areas (Baddoo et al., 2022). Uncontrolled dispersion of these particles may exacerbate soil degradation, reduce air quality, and impact nearby vegetation (Janhäll, 2015; Odubo & Kosoe, 2024; Wang et al., 2024).

In Akoon, fine particulate matter ($PM_{2.5}$ /PM_1) from artisanal gold processing poses significant ecological risks (Buyela, 2024; Richard & Odubo, 2024). These particles, may contain heavy metals like mercury, can contaminate water bodies and soil, disrupting aquatic ecosystems and bioaccumulating in food chains (Hartono et al., 2017). The persistence of fine PM also increases atmospheric haze, potentially altering local microclimates (Luan et al., 2018; Kutty & Jain, 2025).

Agric Hill demonstrates the environmental benefits of regulated industrial controls, with PM emissions 40–60% lower than unregulated sites (El-Fadel et al., 2009). However, residual exposure from blasting and ore processing still contributes to localised air pollution, with potential long-term effects on surrounding forest health and biodiversity.

The extreme PM_{10} levels at Mile 7 and elevated $PM_{2.5}$ at Akoon high spot the need for environmental monitoring, particularly given the propensity of mining-related particles to travel long distances and affect non-mining areas (Duarte et al., 2022). Additionally, the non-normal distribution of PM data underscores the importance of robust statistical approaches, such as extreme value analysis, to assess high-magnitude pollution events.

Given that most recorded particulate matter (PM) levels in this study exceeded WHO air quality guidelines, the findings underscore substantial environmental and public health risks, particularly in mining-intensive regions such as Tarkwa, Ghana. These implications directly intersect with multiple United Nations Sustainable Development Goals (SDGs), as outlined in Table 2, highlighting the urgency for targeted policy interventions.

Temporal, Spatial, and Meteorological Determinants of Particulate Matter Concentrations

The analysis of variance results shown in Table 3 for three-way ANOVA revealed that Month, Site, and PM Size have significant effects on particulate matter concentration. The main effect of Month ($F = 5.82$, $p = 0.001$) implies that there are temporal factors like seasonality, rainfall, and wind movement that influence particulate matter concentration. Particularly, in areas like Agric Hill, areas around when it is dry season, dust can be resuspended in the air, while rainfall decreases, thus increasing particulate matter concentration. Additionally, in areas like Akoon, where small-scale gold mines exist, PM concentration increased. The significant effect of Site ($F = 18.35$, $p < 0.001$) implies that particulate matter was higher in areas with larger-scale mines, shown in Mile 7. In areas like Agric Hill, which is a residential area, particulate matter was lower. Pant et al. (2016) found increased particulate matter in areas with mines rather than in areas like Agric Hill. Additionally, the analysis pointed out significant variance among PM size categories ($F = 12.47$, $p < 0.001$), and it implies that PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ move differently in the air.

The two-way interactions show that the differences in time, location, and particle size are not independent. The Month × Site interaction ($F = 3.21$, $p = 0.009$) suggests that the level of PM at a particular location is not uniform over the months. Mining at Mile 7 might occur at peak levels during dry seasons to elevated levels of PM_{10}. Also, the traffic flow at Agric Hill might consistently cause elevated levels of $PM_{2.5}$ over the months. The interaction for the Month and PM Size ($F = 2.87$, $p = 0.02$) suggests that the effects of the months differ for the various sizes of the particles. This might be caused by differences in the levels of humidity that suspend particulates for longer periods in the dry months. The Site × Particle size interaction ($F = 5.45$, $p = 0.001$) shows that the level of the particulates differs at various sites. Hence, the particulates at the mining and the urban areas differ, as found by Chen et al. (2014). The significant three-way interaction for Month × Site × PM Size ($F = 2.31$, $p = 0.04$) shows that PM concentrations are a function of a combination of temporal, geographical, and size-related factors. The combined effect of natural events and anthropogenic activities shows that escalated temperatures influence dust suspension. Additionally, precipitation can contribute to a decrease in PM concentrations, even for the largest particles. Similarly, as presented in Table 4, temperature is a factor that positively influences PM concentrations. On the other hand, humidity and pressure work to decrease these concentrations.

Table 5: Environmental and Health Implications of PMs aligning with United Nations Sustainable Development Goals (SDG).

SDG	Relevance to PM Pollution	Key Linkages
SDG 3: Good Health & Well-being	$PM_{2.5}$ causes respiratory & cardiovascular diseases.	Mining-related PM affects local communities (WHO, 2021).
SDG 6: Clean Water & Sanitation	PM deposition contaminates water sources.	Acid mine drainage & PM runoff pollute rivers (GSS, 2021).
SDG 11: Sustainable Cities & Communities	Urban air pollution from mining & transport.	Tarkwa's high PM levels require mitigation (Zhang et al., 2021).

SDG	Relevance to PM Pollution	Key Linkages
SDG 13: Climate Action	Black carbon ($PM_{2.5}$) accelerates warming.	Reducing PM emissions supports climate goals (IPCC, 2021).
SDG 15: Life on Land	PM harms soil & vegetation.	Deforestation & dust from mining degrade ecosystems (EPA Ghana, 2020).

CONCLUSION

This study compared particulate matter (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) across Mile 7, Agric Hill and Akoon in Tarkwa Nuseam Municipality. The research on the particulate matter concentrations emissions in Mile 7, Agric Hill and Akoon in Tarkwa Nuseam Municipality exhibits that there is variability in PMs (PM_{10}, $PM_{2.5}$ and $PM_{1.0}$) across the different months in the communities. In Mile 7, PM_{10} reported the highest in March while Agric Hill reported the highest PM_{10} and $PM_{2.5}$ in July and May respectively and Akoon reported the highest PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ in March and July respectively. In all the three communities, Akoon reported the highest PM concentration levels of $PM_{2.5}$ and $PM_{1.0}$ which were higher than WHO's limit in more than 19% and 62% respectively indicating hotspots. This study shows that the individuals in the community maybe exposed to high potential health risk such as respiratory and cardiovascular health issues due to anthropogenic factors such as mining activities (community ASGM and mining), construction of roads, vehicular emissions emerging as primary contributors to elevated PM levels. Also, fine particulate matter ($PM_{2.5}$ /PM_1) from artisanal gold processing in Akoon site poses significant ecological risks and potentially alter local microclimates. Three-way ANOVA and multiple regression analyses showed that particulate matter levels differed significantly across months, sites, and particle sizes. Temperature increases PM concentrations, whereas humidity and pressure have reducing effects. The interconnections between PM levels, health outcomes, and environmental implications emphasis the need for comprehensive strategies that address both immediate and underlying causes of air pollution.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

Consent

The contributing authors have given their consent for the manuscript to be published

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