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Article

Source Apportionment of Air Quality Parameters and Noise Levels in the Industrial Zones of Blantyre City

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Abstract: The increase in industrial activities has raised concerns regarding air quality in urban areas within Malawi. To assess the source apportionment of air quality parameters (AQPs) and noise levels, concentrations of AQPs (CO, TSP, $PM_{2.5}$, PM_{10}) and noise levels were monitored at 15 sites in Makata, Limbe, Maselema, Chirimba, and Maone during dry and wet seasons, respectively. Active mobile multi-gas monitors and a Dylos DC1100 PRO Laser Particle Counter (2018 model) were used to monitor AQPs, while Integrated Sound Level Meters were used to measure noise levels. Monitoring and analysis were guided by the World Health Organization (WHO) and Malawi Standards (MS). A Positive Matrix Factorization (PMF) model was used to determine source apportionment of AQPs, and matrix trajectories analysed air mass movement. In the wet season, the average concentration values of CO, TSP, PM_{10}, and $PM_{2.5}$ were 0.49 ± 0.65 mg/m^3, 85.03 ± 62.18 µg/m^3, 14.65 ± 8.13 µg/m^3, and 11.52 ± 7.19 µg/m^3, respectively. Dry season average concentration values increased to 1.31 ± 0.81 mg/m^3, 99.86 ± 30.06 µg/m^3, 24.35 ± 9.53 µg/m^3, and 18.28 ± 7.14 µg/m^3. Noise levels remained below public MS and WHO standards (85 dB). Positive correlations between AQPs and noise levels were observed, strengthening from weak in the dry season to moderately strong in the wet season. PMF analysis identified key factors influencing AQPs accumulation, emphasizing the need for periodic sampling to monitor seasonal pollution trends, considering potential impacts on public health and environmental sustainability. Further studies should look at factors affecting the dynamics of PMF in Blantyre City.

Keywords: air quality; noise levels; pollution; positive matrix factorization; industrial zones

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1. Introduction

Pollution refers to the introduction and presence of contaminants, pollutants, or harmful substances into the environment, including air, water, or soil [1]. The issue of global pollution poses a significant challenge for both developed and developing nations, leading to adverse consequences for living and non-living entities. This challenge acts as an impediment to the growth and prosperity of the affected nations [2]. Various sources contribute to pollution, but industries play a significant role in accelerating environmental degradation [3–5].

Air pollution is characterised as a harmful phenomenon affecting the ecological system and the normal conditions of human existence and development. It occurs when specific substances in the atmosphere exceed a particular concentration [6]. In Malawi, air pollution is identified as the second-highest risk factor contributing to death and disability, following poor water and sanitation. Overall, it is ranked as the fourth-highest risk factor, trailing malnutrition, unsafe sex, and poor water and sanitation [7]. Matrix trajectories are a precise and efficient tool for analysing the movement pattern of air mass in a region. A study by Lv et al. [8] analysed $PM_{2.5}$ as well as backward air mass trajectories using a HYSPLIT-4 model which characterized the way movements of air caused shifts in pollution concentrations in four big cities in China.

Noise pollution is typically characterized by nuisance-causing sounds that impact not only humans, but also animals [9]. Diverse noise sources contribute to environmental noise, with industrial activities like machinery, heavy equipment, and transportation being the predominant contributors. These noise sources not only affect the environment, but also cause discomfort to the surrounding communities [10]. This is underscored by a study carried out in Blantyre, Malawi, revealing that noise levels in most industries exceeded the acceptable limit of 85 dBA [11].

Analysing sources serves as a fundamental analytical tool in preventing and managing pollution [12]. Positive matrix factorization (PMF) exhibits superior capabilities in general source allocation and can identify sources through a multivariate factor analysis [13]. A three-factor solution of the PMF model is used to showcase the sources of air quality parameters (AQPs) in a precise way [14].

There are a few studies associated with evaluating the air quality and noise levels of Blantyre city. One of these studies examined outdoor air pollution of Blantyre City's major highway and industrial areas (Makata) and revealed that the presence of non-methane volatile organic compounds (NMVOCs) and carbon monoxide (CO) levels contributed to the deterioration of air quality in these locations [15]. Another was conducted at Queen Elizabeth Central Hospital in Blantyre and showed that air quality thresholds considered safe were consistently surpassed across various locations and time periods within the vicinity of the shelter for caregivers and individuals undergoing HIV/AIDS treatment, thus significantly affecting both staff and visitors within the premises [16]. A study conducted in the Mpemba-Blantyre rural area showed that village residents experience elevated levels of personal exposure to airborne particulate matter and carbon monoxide, primarily attributed to cooking activities as the predominant source of exposure [17]. A single study was conducted on noise level assessment in the Blantyre industrial area, and it indicated that noise levels from industries ranged between 75 dBA and 102 dBA. The findings also revealed non-compliance with MS on workplace noise by numerous industries [11]. This further indicates a knowledge gap in industrial regions. Due to air quality and noise pollution hazards presented by industrial sites, it is very important to monitor such areas.

More than 80% of Malawi's industrial sector, dominated by manufacturing, agriculture, and construction materials production, increase the risk of environmental pollution [18]. There have been no extended studies involving an analysis of $PM_{2.5}$, PM_{10}, TSP, CO, and noise levels, around the main industrial areas in Blantyre, namely Makata, Limbe, Maselema, Chirimba, and Maone. This indicates a knowledge gap in industrial areas in Blantyre. Other countries have conducted similar studies to assess the extent of pollution in these areas, which is crucial for protecting public health and ensuring environmental sustainability [3].

To investigate source apportionment of AQPs and examine their correlation with noise levels, the concentrations of four AQPs (CO, TSP, $PM_{2.5}$, PM_{10}) and levels of noise were studied in 15 sites, which were located in Makata, Limbe, Maselema, Chirimba, and Maone industrial areas of Blantyre City during the months of January–February (wet season) and August–September (dry season) of 2023. CO concertation was recorded using an active mobile multi-gas monitor, whereas TSP, $PM_{2.5}$, and PM_{10} concentrations were measured using a Dylos DC1100 PRO Laser Particle Counter (2018 model), and lastly, noise levels were measured using an Integrated Sound Level Meter. The environmental monitoring at each site was in a set of three, with each set consisting 10 days, making the total number of sampled days being 30 per monitored site. These three distinct sampling sets were conducted in the period of the rainy season in January–February 2023 and the dry season in August–September 2023. This has been revised. Sampling and analysis of air and noise employed the use of standardized methods detailed in the World Health Organization (WHO) and Malawi Standards (MS). A Positive Matrix Factorization (PMF) model was used to conduct source apportionment of AQPs. Matrix trajectories were used for analysing the movement pattern of air mass in the sites. This study is crucial for protecting public health, ensuring environmental sustainability and compliance with regulations, policy enforcement, as well as raising community awareness. Therefore, in this work, AQPs concentrations and noise levels were monitored, a correlation between AQPs and noise levels was performed, and a quantitative analysis of AQPs sources using PMF model was conducted.

2. Materials and Methods

2.1. Description of Study Area

Blantyre City is the urban centre of Blantyre District in Malawi, which is found in the southern region of this nation at $-15°29'59.99''$ S, $35°00'0''$ E and has an area of 240 km^2. Blantyre District has an overall population of about 1 million people [19].

The study was conducted at 15 sites selected from industrial zones, specifically Makata, Limbe, Maselema, Chirimba, and Maone, as shown in Figure 1, with corresponding Geographical Positioning System (GPS) coordinates provided in Appendix A.1. Monitoring of air quality concentrations and noise levels was performed in the rainy season (January–February 2023) and dry season (August–September 2023). All industrial zones are positioned alongside the main rivers or streams in Blantyre city, as they rely on water in their line production process, leading to the generation of effluents that are subsequently discharged into the water bodies [20]. Industries in Blantyre fall under the following categories: textile and leather products, paints, pharmaceuticals and other chemicals, metal and wood processing, petroleum and plastics, power distribution, dairy products and abattoir, beer breweries, tobacco processing, and food processing. The types of industries where monitoring happened in this work included plastic, food, metal processing, soap, cement, beverage, and furniture manufacturing industries.

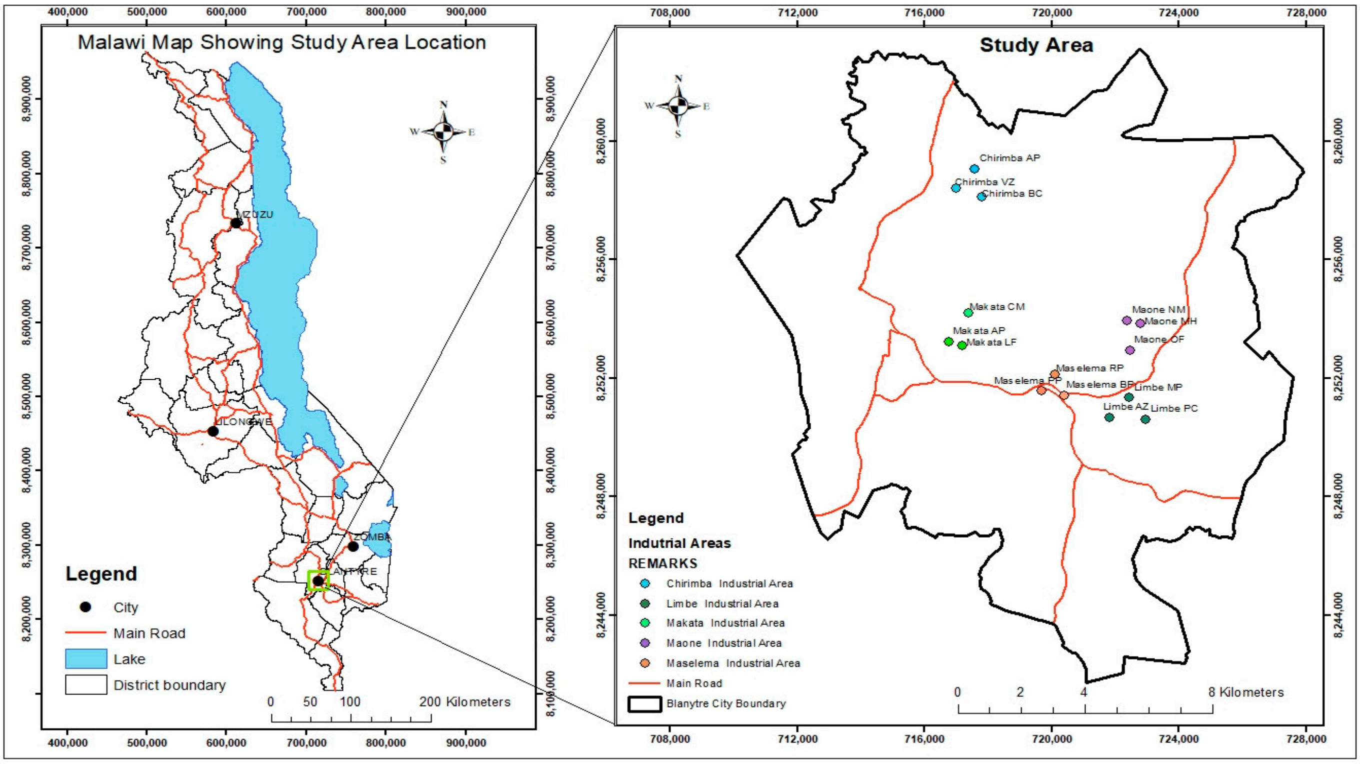


Figure 1. Map of Blantyre showing sampling points.

2.2. Air Monitoring

Air quality monitoring was performed using an active mobile multi-gas monitor (Drager X-am 7000, manufactured by Dräger, Cheshire, UK) [21]. The monitor is equipped with electrochemical sensors that measured continuous concentrations of CO. A Dylos DC1100 PRO Laser Particle Counter (2018 model, manufactured by Dylos Coporation, Riverside, CA, USA) was used to monitor Particulate Matter (TSP, $PM_{2.5}$, and PM_{10}). Before sampling, the multi gas monitor was calibrated in air which was free of the gases measured according to the instrument operational manual provided by the manufacturer [21]. In all the locations, the equipment was placed at a minimum of 1.5 m from the ground to simulate the average breathing height. Air quality assessments at each site were in a set of 3, with each set consisting of 10 days, making a total number of sampled days being 30 per monitored site. The distance from the anticipated emission source was at least 30 m from the nearest building [22]. During data collection, 10 min consecutive average measurements were recorded in an Excel sheet during morning (09:00–10:30), midday (11:30–13:00), and afternoon (15:30–17:00), providing 10 sets of values per session per day which assisted in minimizing the volume of captured data. This was aimed at ensuring a wider range of data, which could lead to a better reliability of results [22]. These 3 distinct sampling sets were performed in the period of the rainy season in January–February 2023 and the dry season in August–September 2023.

2.3. Noise Monitoring

An Integrated Sound Level Meter (ISLM) was used for the assessment of noise levels. The selection of ISLM was made due to its appropriate statistic averaging technique, enabling the derivation of a succinct measure of the equivalent continuous sound pressure level (Leq). Prior to conducting measurements at each chosen site, the meter underwent calibration using the Castle Acoustic Calibrator, with the model specified as GA 601. The calibration was carried out according to the instrument operational manual provided by the manufacturer [23]. Noise measurement was conducted manually, with the instrument held at a height of 1.5 m above the ground and positioned 30 m away from the potential noise sources. The microphone was directed towards the primary noise source's front, following the guidelines outlined by Castle Group Ltd. [23], to minimize the sound field. LAi (A-weighted instantaneous sound pressure level), which is an "A fast" scale, was used to record 30 measurements through 10 min consecutive average measurements during morning (09:00–10:30), midday (11:30–13:00), and afternoon (15:30–17:00), providing 10 sets of values per session per day [24]. These time intervals were selected to ensure that samples were collected during onset of production up to when the production was winding down. Noise level monitoring at each site was in a set of 3, with each set consisting of 10 days, making the total number of sampled days being 30 per monitored site. These 3 distinct sampling sets were performed in the period of the rainy season in January–February 2023 and the dry season in August–September 2023.

2.4. Data Analysis

The open-source software R Studio version 4.3.1 was used to analyse the data [25]. A *t*-test was used to observe the variations among the sample means and between the sample types, respectively, at 95% confidence interval. The Microsoft Excel 2007 Windows program was used to analyse data such as the geo-accumulation index. A significance level (α) of 0.05 was used for all statistical tests in this study. A Pearson (r) correlation examined the relationship between the levels of parameters in air with those of noise [26].

To quantitively identify the source of the AQPs in the study area, the Positive Matrix Factorization (PMF) model was used to analyse the data by using EPA PMF 5.0 (USA) software [27].

The HYSPLIT model by Air Resources Lab (National Oceanic and Atmospheric Administration, Silver Spring, MD, USA) was used to collect and determine the movement pattern of air pollutants through backward and forward trajectories as also used by Lv et al. [8].

PMF was calculated using Equation (1) below, where X_{ij} is composed of the j-th compound concentration measured in the i-th sample, source contribution matrix g_{ik} represents the contribution of the k-th source to the i-th sample, source profile matrix f_{kj} is made up of the j-th compound from the k-th source, and e_{ij} is the residual matrix.

$$X_{ij} = \sum_{k=1}^{p} g_{ij} f_{kj} + e_{ij} \quad (1)$$

The objective of PMF analysis is to minimize Q as per Equation (2) below.

$$Q = \sum_{i=1}^{n} \sum_{j=1}^{m} \left[\frac{x_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj}}{u_{ij}} \right]^2 subject\ to\ g_{ik} \geq 0\ and\ f_{kj} \geq 0 \quad (2)$$

PMF 5.0 requires the input of concentration of samples species as well as uncertainty. Equation (3) below is used to calculate uncertainty of the concentrations.

$$\sqrt{(error\ fraction \times c)^2 + MDL^2}$$

For

$$c \leq MDL,\ u_{ij} = 5/6 \times MDL \text{ For } c > MDL,\ u_{ij} \quad (3)$$

The factor numbers were configured to 2, 3, 4, 5, and 6, with 40 runs as a total to ensure stability of the model [28].

3. Results

3.1. Air Quality Parameters and Noise Levels

The values for air quality concentrations and noise levels in Table 1 are presented in comparison to the limits set by the World Health Organization and Malawi Standards for specific parameters [22,24,29,30].

Table 1. The mean values of air quality parameters ($\mu g/m^3$) and noise levels (dB) during the dry and wet seasons.

Sampling Point	CO (mg/m^3)		TSP ($\mu g/m^3$)		PM_{10} ($\mu g/m^3$)		$PM_{2.5}$ ($\mu g/m^3$)		Noise (dB)	
	Wet Season	Dry Season	Wet Season	Dry Season	Wet Season	Dry Season	Wet Season	Dry Season	Wet Season	Dry Season
Maone MH	0 ± 0.00	0 ± 0.00	30.5 ± 13.37	112 ± 39.02	13.8 ± 2.70	21.3 ± 8.41	10.3 ± 2.61	16 ± 6.21	38.5 ± 5.90	49.1 ± 10.23
Maone NM	0.667 ± 0.58	1.7 ± 1.13	45.4 ± 19.97	95.9 ± 29.47	25.4 ± 11.25	27 ± 12.98	19 ± 8.35	20.3 ± 9.80	42.4 ± 8.26	47.5 ± 3.88
Maone OF	0 ± 0.00	0 ± 0.00	15 ± 6.10	75.7 ± 9.00	5.33 ± 1.89	13.6 ± 3.65	3.67 ± 1.36	10.3 ± 2.65	34.8 ± 1.30	45.6 ± 1.22
Limbe AZ	0 ± 0.00	0 ± 0.00	66.3 ± 52.10	105 ± 44.09	17 ± 15.97	24.7 ± 7.15	12.8 ± 11.87	18.7 ± 5.16	48.9 ± 2.24	47.8 ± 2.58
Limbe MP	0.333 ± 0.58	1.67 ± 0.58	214 ± 76.46	147 ± 37.82	36.2 ± 17.72	47.8 ± 16.68	27.1 ± 13.32	35.8 ± 12.58	51.9 ± 2.82	50.8 ± 5.99
Limbe PC	0 ± 0.00	0 ± 0.00	23.9 ± 14.11	115 ± 11.57	6.93 ± 3.52	26.6 ± 6.65	5.17 ± 2.63	20 ± 4.95	43.4 ± 6.02	48.9 ± 6.26
Maselema BP	2 ± 3.46	4.33 ± 2.31	174 ± 90.06	184 ± 114.00	18.3 ± 8.24	25.7 ± 7.91	13.8 ± 6.17	19.3 ± 5.91	58.4 ± 1.69	58.1 ± 2.69
Maselema PP	2.67 ± 3.06	3.67 ± 2.08	46.7 ± 25.67	184 ± 5.86	13.5 ± 7.82	25.7 ± 4.49	10.1 ± 5.84	19.3 ± 3.30	41.1 ± 1.10	47.4 ± 1.14
Maselema RP	1.33 ± 1.53	3 ± 2.00	44.9 ± 20.32	105 ± 27.59	4.3 ± 0.17	45.7 ± 13.36	12.5 ± 15.93	34.3 ± 10.00	39.4 ± 1.83	47.4 ± 3.32
Chirimba AP	0 ± 0.00	0.667 ± 1.15	319 ± 319.35	52.3 ± 5.61	23.1 ± 17.63	13.6 ± 5.98	17.1 ± 13.34	10.1 ± 4.61	53.5 ± 2.47	52.4 ± 5.09
Chirimba BC	0.33 ± 0.58	1.33 ± 0.58	18.3 ± 5.44	76.3 ± 37.86	5.07 ± 1.01	13.3 ± 6.91	3.6 ± 0.85	9.83 ± 5.27	39 ± 3.60	46.2 ± 0.67
Chirimba VZ	0 ± 0.00	0 ± 0.00	26.4 ± 6.92	68.7 ± 15.72	7.03 ± 2.03	15.7 ± 1.81	5.13 ± 1.46	11.8 ± 1.32	38.7 ± 3.95	46.7 ± 1.93
Makata AP	0 ± 0.00	1.33 ± 0.58	22 ± 6.75	51 ± 20.44	9.23 ± 2.35	21.6 ± 19.92	6.87 ± 1.76	16.4 ± 14.85	40.3 ± 2.27	51.6 ± 3.23
Makata CM	0 ± 0.00	0.667 ± 1.15	41 ± 3.79	50.4 ± 29.98	9.5 ± 2.51	17.1 ± 15.70	7.1 ± 1.91	12.7 ± 11.84	52.5 ± 4.82	47 ± 1.96
Makata LF	0 ± 0.00	1.33 ± 0.58	188 ± 272.32	75.6 ± 22.86	25.1 ± 27.10	25.9 ± 11.34	18.6 ± 20.50	19.4 ± 8.66	38.9 ± 5.53	42.5 ± 0.66
Malawi Standard	10 mg/m^3		230 $\mu g/m^3$		150 $\mu g/m^3$		25 $\mu g/m^3$		85 dB	
WHO Standard	10 mg/m^3		N/A		45 $\mu g/m^3$		15 $\mu g/m^3$		110 dB	

Values are in the form of mean ± standard deviation.

3.1.1. Carbon Monoxide (CO) Concertation Levels

In the wet season, the range of CO concentration in the air was from 0 to 2.67 mg/m^3, while in the dry season it was from 0 to 4.33 mg/m^3 (Table 2). A comparison of the results showed that the dry season CO concertation levels were significantly higher ($p < 0.05$) than the wet season values. This might be attributed to washout of the pollutants by rainfall in the wet season. The air sampled from Maselema BP showed the highest concentrations of CO, measuring 2 mg/m^3 during the wet season and 4.33 mg/m^3 during the dry season. The concentration of CO was generally below the limit of Malawi [22] and WHO standards of 10 mg/m^3 [29], as shown Figure 2. These elevated levels, potentially originating from vehicle emissions due to the nearby highway, align with the air mass trajectory at 500 m (shown in Figure 3). The figure indicates a predominant flow of air mass from the western side, contributing to the peak CO concertation levels at the site.

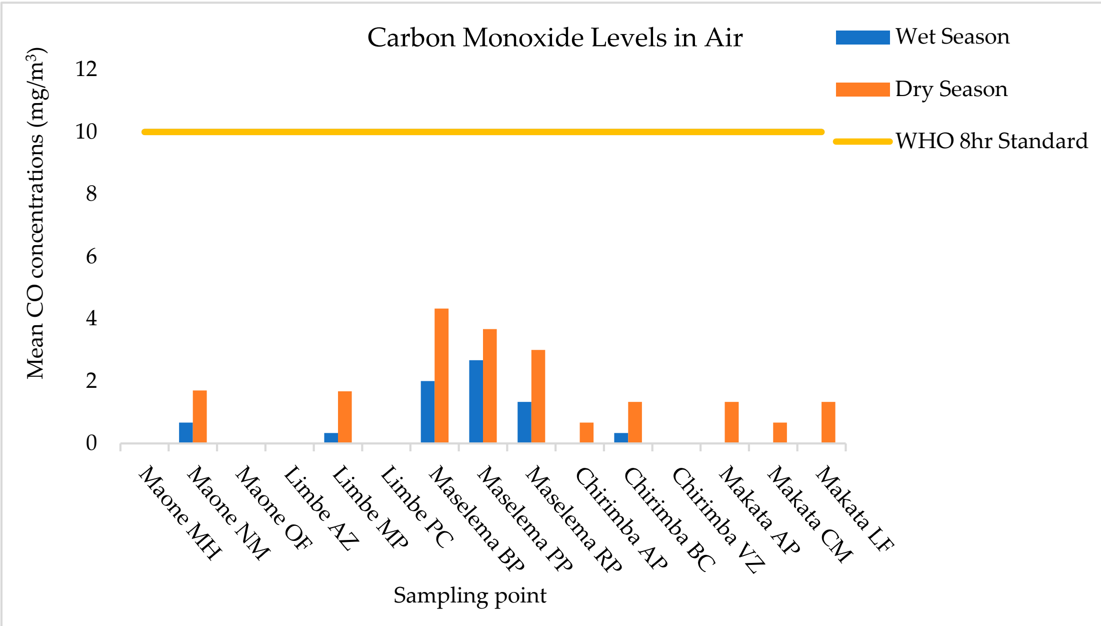
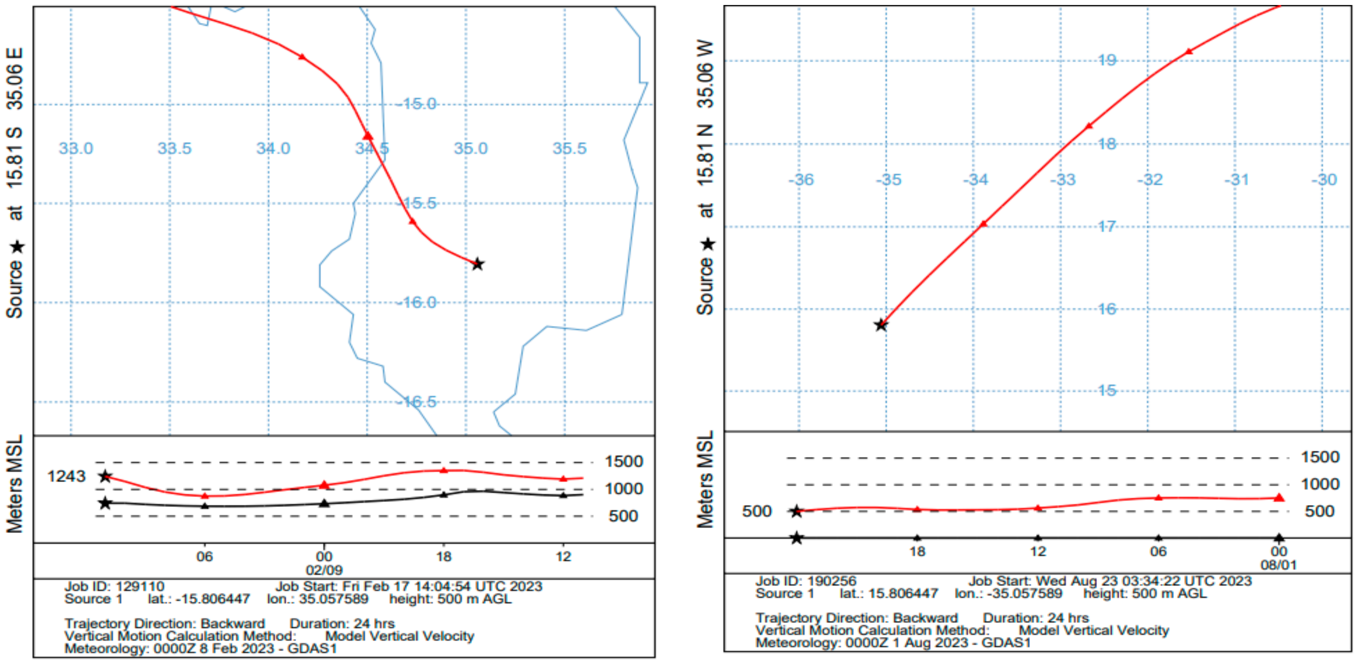


Figure 2. Carbon monoxide levels in the air for wet and dry season.



(**a**) (**b**)

Figure 3. NOAA HYSPLIT MODEL backward trajectory generated during the wet (**a**) and dry (**b**) season for Maselema BP located in the Maselema industrial area.

The trajectory in Figure 3 shows that the air was moving from the study area going towards the southeast. The concentrations recorded corresponded well with a study conducted by Mapoma et al. [15] on spatial variation of volatile organic compounds and carbon monoxide in Blantyre City, Malawi, which showed that the CO levels were found to be significantly higher ($p < 0.05$) than those found in a similar study of 2004. In research conducted by Ukpebor et al. [31] in Benin City, Nigeria, examining the effects of enhanced traffic control measures on air quality and noise levels in both commercial and unrestricted traffic areas, comparable findings were observed. The study revealed that CO levels ranged from 1.30 to 3.20 ppm after the implementation of traffic control measures. In the dry and wet season, 100% of CO values were within the Malawian and WHO Standards, respectively.

3.1.2. Total Suspended Particle Concertation Levels

In the wet season, maximum TSP concentration in the air was 319 $\mu g/m^3$, while in the dry season it was 184 $\mu g/m^3$ (Table 2). A comparison of rainy season and dry season air TSP values indicated no significant difference ($p > 0.05$). During the wet season, the highest TSP concentration was observed from air sampled at Chirimba AP, and was 319 $\mu g/m^3$. During the dry season, the highest TSP concentration was observed from air sampled at Maselema BP and Maselema PP, both with values of 184 $\mu g/m^3$. It was also observed that in some cases, the concentrations of TSP were higher in the wet season than during dry seasons. For example, during dry season monitoring, some sites such as Chirimba AP and Makata LF had lower concentrations of TSP in the higher season as compared to the dry season due to the fact that production was not at full capacity in these industries. This confirms that industries are contributing to pollution because once there is no production, the air quality seem to be better than when production is in full swing. The concentration of TSP was generally below the limit of Malawi Standard [22] of 230 $\mu g/m^3$, as per Figure 4. These concentrations may have come from operations-related emissions, as more air mass at 500 m trajectory was moving from the sampling point to other surroundings within Malawi during the wet season, while in the dry season the levels could be emanating from surrounding areas, as per the trajectories shown in Figure 5. The concentrations recorded were much higher than 75 $\mu g/m^3$, as recorded by Sarpong et al. [32], who studied $PM_{2.5}$, PM_{10}, and TSP exposure in the Tema Metropolitan area of Ghana, as well as by Sabuti and Mohamed [33], who found the level of TSP to be within the range of 13 to 74 $\mu g/m^3$. In the wet season, 93% of TSP values were within the Malawi Standard, while 7% were above it, and in the dry season, 100% of the TSP values were within the allowable Malawi Standard.

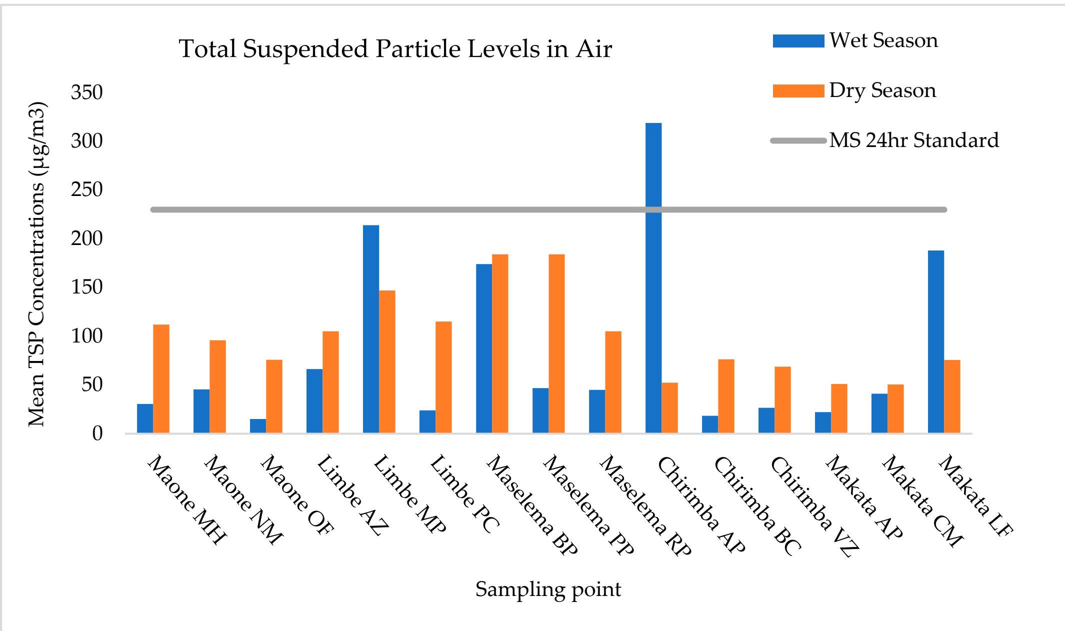


Figure 4. Total suspended particle levels in air for wet and dry seasons.

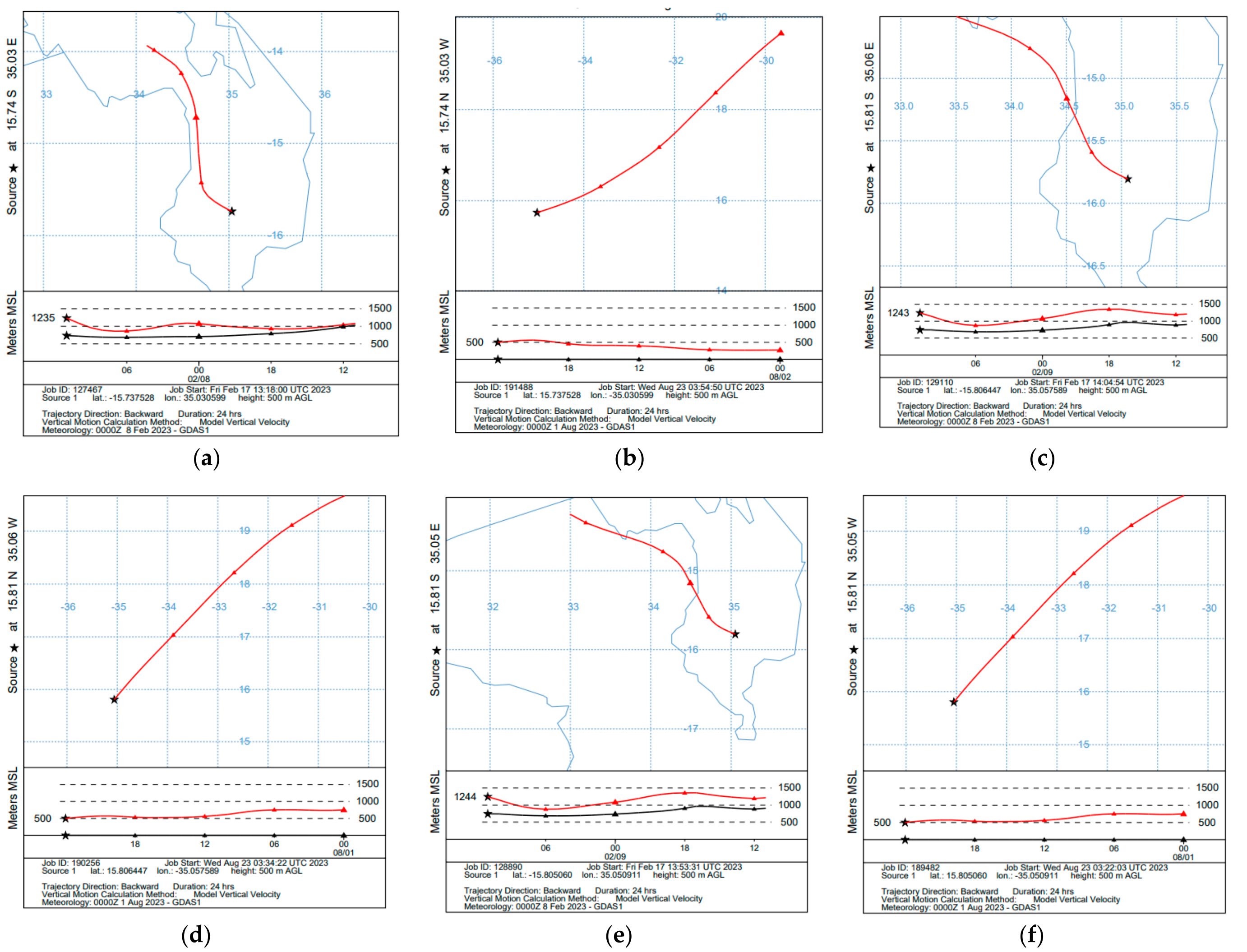


Figure 5. NOAA HYSPLIT MODEL Backward trajectory generated during the wet (**a**) and dry (**b**) season for Chirimba AP located in Chirimba industrial area; NOAA HYSPLIT MODEL Backward trajectory generated during the wet (**c**) and dry (**d**) season for Maselema BP located in Maselema industrial area; NOAA HYSPLIT MODEL Backward trajectory generated during the wet (**e**) and dry (**f**) season for Maselema PP located in Maselema industrial area.

3.1.3. PM_{10} Concertation Levels

In the wet season, the range of PM_{10} concentration in the air was from 4.3 to 36.2 μg/m^3, while in the dry season it was from 13.3 to 47.8 μg/m^3 (Table 2). The dry season PM_{10} values were significantly higher ($p < 0.05$) than the wet season values. The concentration of PM_{10} was generally below the limit of the Malawian [22] and WHO [29] standards of 150 and 45 μg/m^3, as per Figure 6. The highest PM_{10} concentrations were observed from air sampled from Limbe MP, and were 36.2 μg/m^3 as well as 47.8 μg/m^3 during the wet season and dry seasons, respectively (which may have come from operations-related emissions, as more air mass at 500 m trajectory was moving from the sampling point to other surroundings within Malawi in the wet season, while in the dry season, the levels could be emanating from surrounding industries in Malawi, as per trajectories in Figure 7). The concentrations recorded were lower than 56.24 μg/m^3, recorded by Sarpong et al. [32], who studied $PM_{2.5}$, PM_{10}, and total suspended particle exposure in the Tema Metropolitan Area of Ghana, but were higher than the 20.7 μg/m^3 concentration recorded in 2017 found by Rovira et al. [34] in a study conducted in Catalonia, Spain, on air quality, health impacts, and burden of disease due to air pollution (PM_{10}, $PM_{2.5}$, NO_2, and O_3). In the wet season, 100% of TSP values were within the Malawian and WHO Standards, respectively. In the dry season, 100% of the values were within Malawi Standard and 87% were within the WHO standard, while the remainder (13%) were above this international standard.

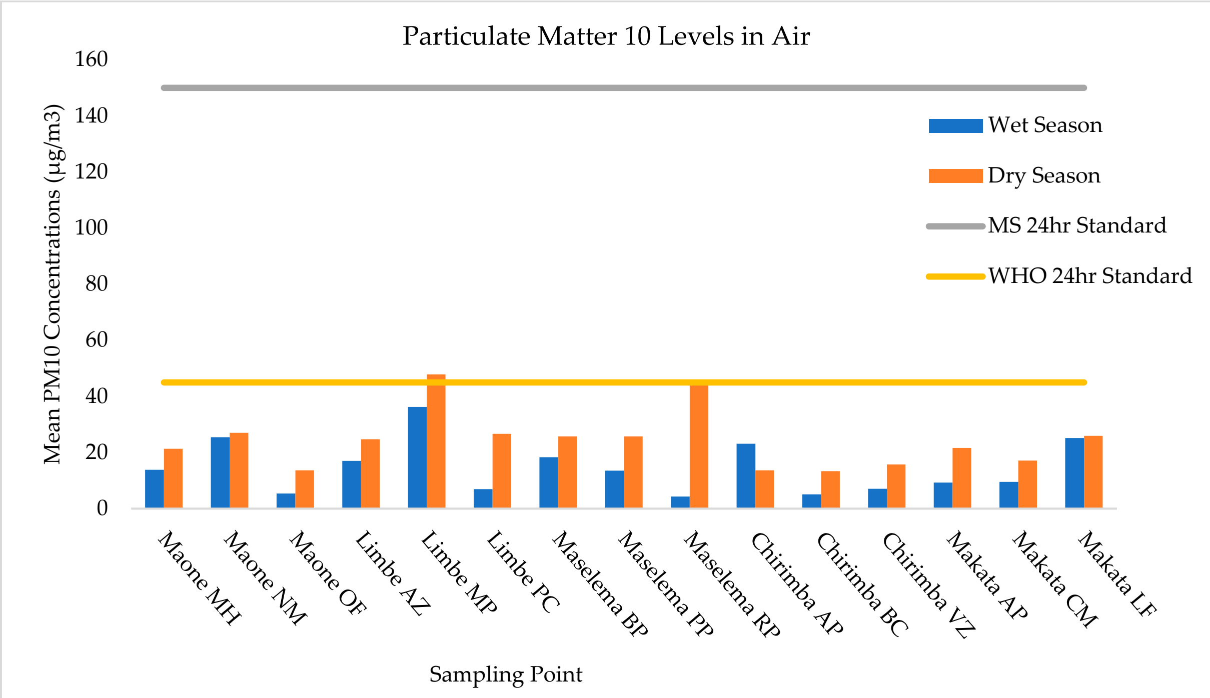
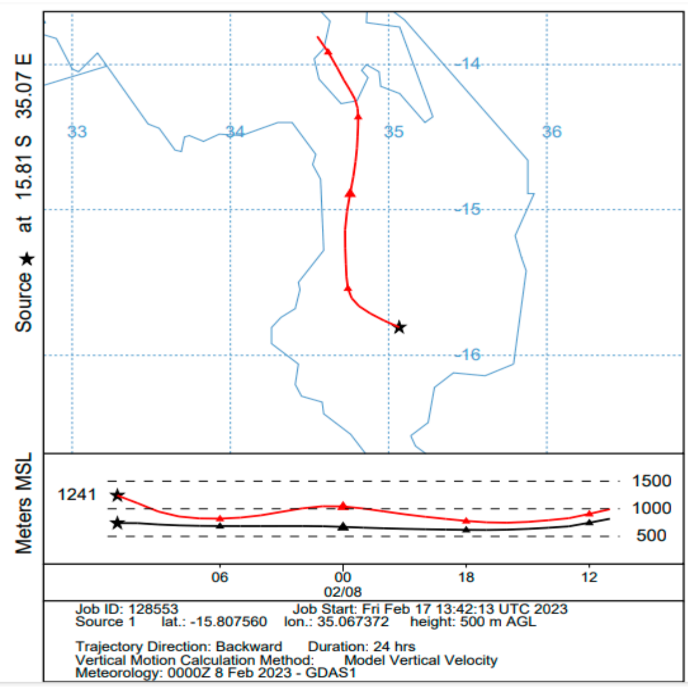
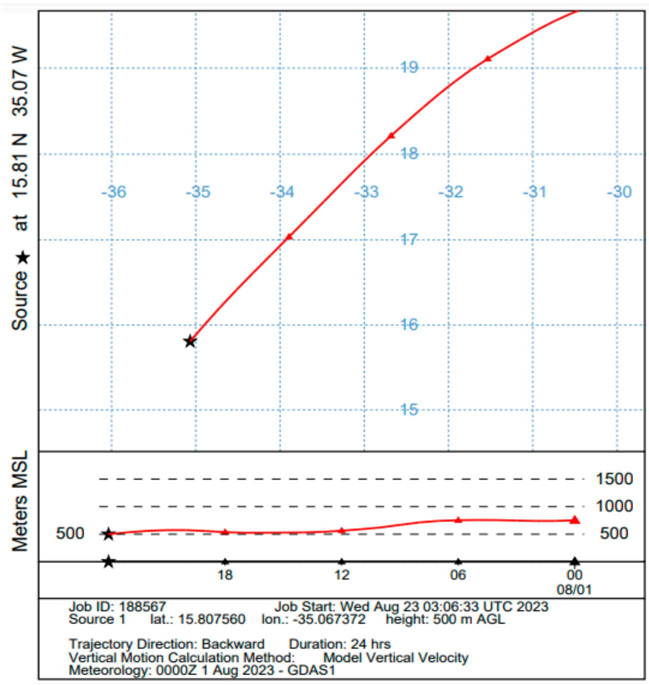


Figure 6. Particulate matter 10 levels in air for wet and dry seasons.



(**a**)



(**b**)

Figure 7. NOAA HYSPLIT MODEL Backward trajectory generated during the wet (**a**) and dry (**b**) season for Limbe MP located in the Limbe industrial area.

3.1.4. Particulate Matter 2.5 Concentration Levels

In the wet season, the range of $PM_{2.5}$ concentration in the air was from 3.6 to 27.1 µg/m^3, while in the dry season it was from 9.83 to 35.8 µg/m^3 (Table 2). The dry season $PM_{2.5}$ values were significantly higher ($p < 0.05$) than the dry season values. The concentration of $PM_{2.5}$ was generally below the limit of the Malawian [22] and WHO [29] standards of 25 and 15 µg/m^3, as per Figure 8. The highest $PM_{2.5}$ concentrations were observed from air sampled from Limbe MP, and were 27.1 µg/m^3 as well as 35.8 µg/m^3 during the wet season and dry seasons, respectively (which may have come from operations-related emissions, as more air mass at 500 m trajectory was moving from the sampling point to other surroundings in the wet season, while in the dry season the levels could be emanating from surrounding industries, as per the trajectories in Figure 9). The concentrations recorded were lower than 38.09 µg/m^3, recorded by Sarpong et al. [32], who studied $PM_{2.5}$, PM_{10}, and total suspended particle exposure in the Tema Metropolitan Area of Ghana, but were higher than the 11.8 µg/m^3 concentration recorded in 2017 found by Rovira et al. [34], in a study conducted in Catalonia, Spain, on air quality, health impacts, and burden of disease due to air pollution (PM_{10}, $PM_{2.5}$, NO_2, and O_3). In the wet season, 93% of $PM_{2.5}$ values were within the Malawian standard while 7% were above this standard, and 73% of the values were within the WHO Standard while 27% of these were above it. In the dry season, 93% of the values were within Malawi Standard while 7% were above this standard, and 40% were within the WHO standard while the remainder of 60% of were above it.

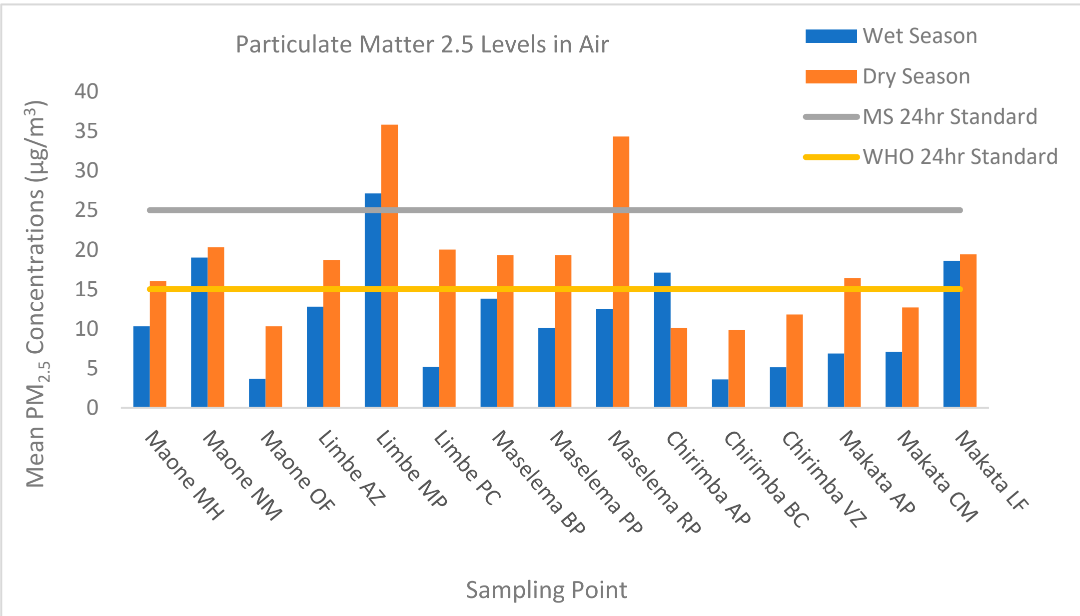
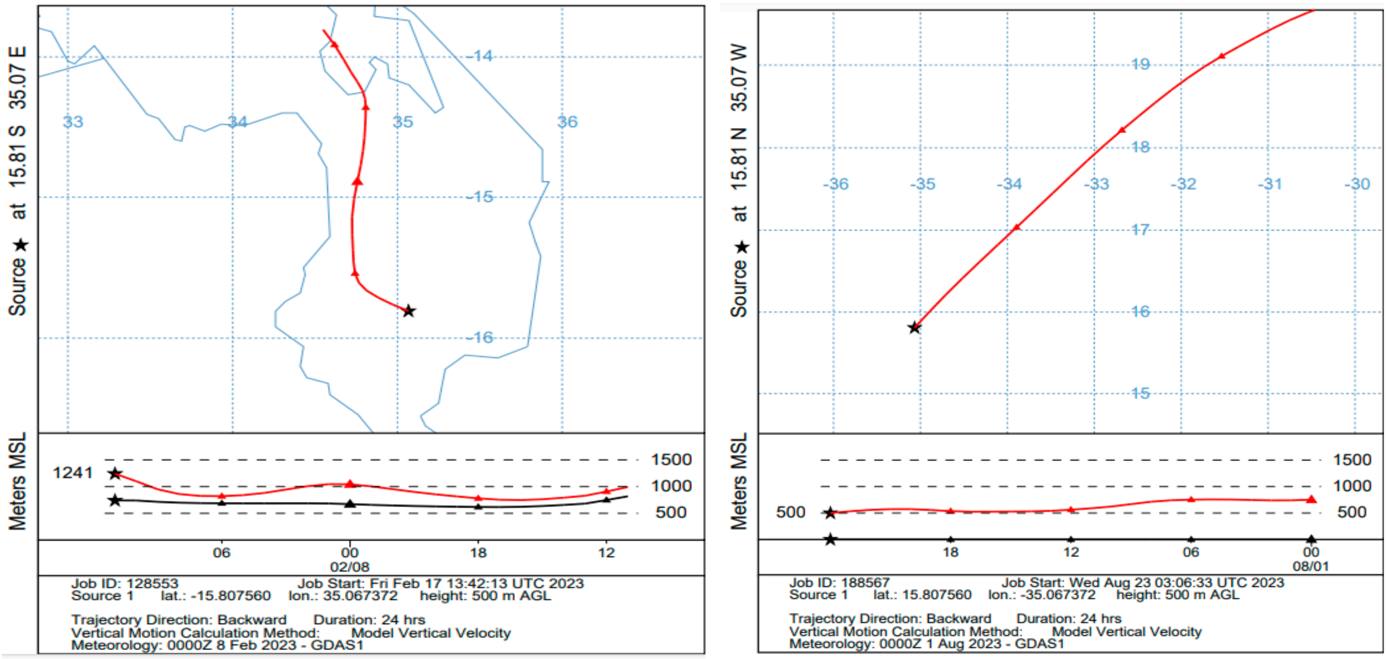


Figure 8. Particulate matter 2.5 levels in the air for the wet and dry seasons.

3.1.5. Noise Levels

In the wet season, the range of Noise level was from 34.8 to 58.4 dB, while in the dry season it was from 42.5 to 58.1 dB (Table 2). Comparison of wet season and dry season Noise level values indicated a significant difference ($p = 0.0011$). The highest Noise level readings were observed from Maselema BP, and were 58.4 dB as well as 58.1 dB during the wet season and dry seasons, respectively (which may have come from vehicle movement and honking, as the highway is in proximity). Higher Noise level readings were recorded from Chirimba AP and Limbe MP. Chirimba AP noise level readings were 53.5 dB as well as 52.4 dB during the wet season and dry seasons, respectively. Limbe MP noise level readings were 51.9 dB as well as 50.8 dB during the wet season and dry seasons, respectively. The concentrations recorded by Manojkumar et al. [5], who conducted the assessment, prediction, and mapping of noise levels in Vellore City, India, were much higher and were within the range of 67–87 dB. A study on the impacts of improved traffic control measures on air quality and noise level in Benin City, Nigeria, by Ukpebor et al. [31] found different results of noise levels which were much higher, in the range of 70 to 79 dB, after traffic control measures were put in place. The Noise level was generally below the limit of the Malawian [24] and WHO [30] standards of 85 and 110 dB, respectively, as per Figure 10. In the wet and dry seasons, 100% of the Noise level values were within the Malawian and WHO Standards.



(**a**) (**b**)

Figure 9. NOAA MODEL Backward trajectory generated during the wet (**a**) and dry (**b**) season for Limbe MP located in the Limbe industrial area.

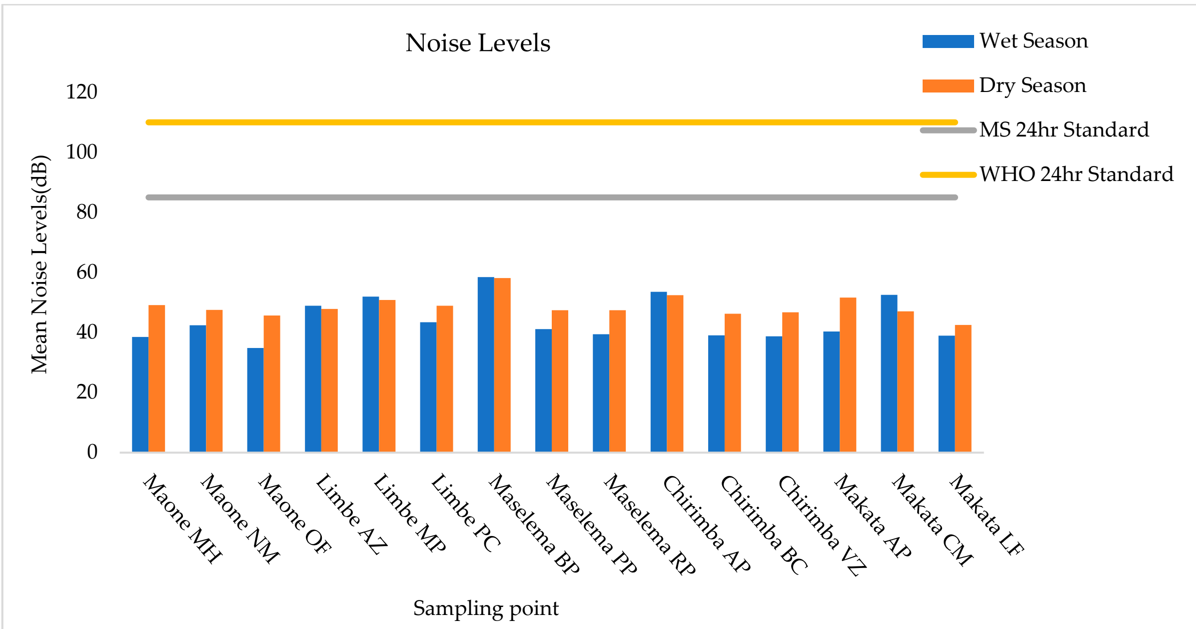


Figure 10. Noise levels for the wet and dry seasons.

3.2. Source Apportionment (Examination of Sources) for Air Quality Parameters from the Industrial Areas

After using the PMF model with a factor count of six, the difference between Qtrue and Qrobust were minimum and stable. The scaled residuals for air quality parameters exhibited values ranging from 0.00746 to 0.00773 during the dry season, while registering at 0.00002 during the wet season. This suggests that the parameters follow a normal distribution, as the values fall within the range of +3 to −3 [27]. Furthermore, this means that the model is reliable and the Factor Analysis in the Section above is accurate. In the dry season, the signal-to-noise (S/N) ratios for all air quality parameters varied between 0.609 and 3.693, while during the wet season, the range was 0.091 to 2.314 (Table 2). This variability indicates that CO, TSP, PM_{10}, and $PM_{2.5}$ exhibited signals ranging from "poor" to "strong," with TSP registering the highest concentration. This underscores the importance for industries engaged in metal processing and beverage manufacturing to enhance their emission management practices throughout both the dry and wet seasons.

Table 2. The signal-to-noise ratio of air quality parameters during the dry and wet seasons.

	S/N Values	
Species	Dry Season	Wet Season
CO	0.609	0.091
TSP	3.693	1.843
PM_{10}	2.426	2.314
$PM_{2.5}$	2.466	1.528

As per Figures 11–14 below, during dry season in Factor 1, TSP, and CO provided 25.1% and 0.6% respective contributions. The contribution of the various parameters to each factor was shown in the factor fingerprints (Figures 12 and 14). During the wet season in Factor 1, $PM_{2.5}$, PM_{10}, and TSP provided 14.8%, 14.1%, and 12.7% of the respective contributions. As demand for cement is high for development purposes, TSP levels are usually high around cement production plants [35]. Furthermore, the outcome of a study conducted by Olatunde et al. [36] present important data on pollution of soils by heavy metals around Dangote cement factory, Ibese, which showed the need for an overhaul of the waste management initiatives of the factory and an emphasis on complying with the regulatory from relevant agencies. Another study by Egbe et al. [37] highlighted that that cement production processes are a source of pollutants through deposition. This makes Factor 1 linked to cement manufacturing industries.

During dry season in Factor 2, CO, $PM_{2.5}$, and PM_{10} provided 55.1%, 13.6%, and 13.5% respective contributions. During the wet season in Factor 2, CO, $PM_{2.5}$, and TSP provided 100%, 3.5%, and 2.1% respective contributions. As shown in a previous study by Mapoma et al. [15], the increased levels of CO may be due to emissions coming from the moving vehicles along the roads. Another study conducted by Zhu et al. [38] stated that industrial, facilities such as factories, emit a variety of pollutants such as CO. Studies conducted by many authors showed that one of the well-known types of air pollutants found in urban areas is CO, which is mostly sourced from fossil fuel use such as coal and gasoline [39–42], which the sampling sites utilize during production processes. As such, whilst considering the parameter concentration distribution as well as aspects in Section 3.1.1 to 3.1.4, Factor 2 represents the food production industries.

During the dry season in Factor 3, $PM_{2.5}$ and PM_{10} provided 11.1% and 10.9% of the respective contributions. During the wet season in Factor 3, $PM_{2.5}$ and TSP provided 15.2% and 4.5% of the respective contributions. A study conducted by Yuan et al. [43] showed that the putty and sanding processes in furniture making increases levels of particulate matter less than 2 μm. Another study by Zheng and Xu [44] showcased the role which furniture manufacturing companies take in PM 2.5 emission and how the impact needs to be mitigated. A study by Ro'in et al. [45] also illustrated that wood sanding production in the furniture production process exhibits the highest level of dust which means that Factor 3 includes furniture manufacturing industries.

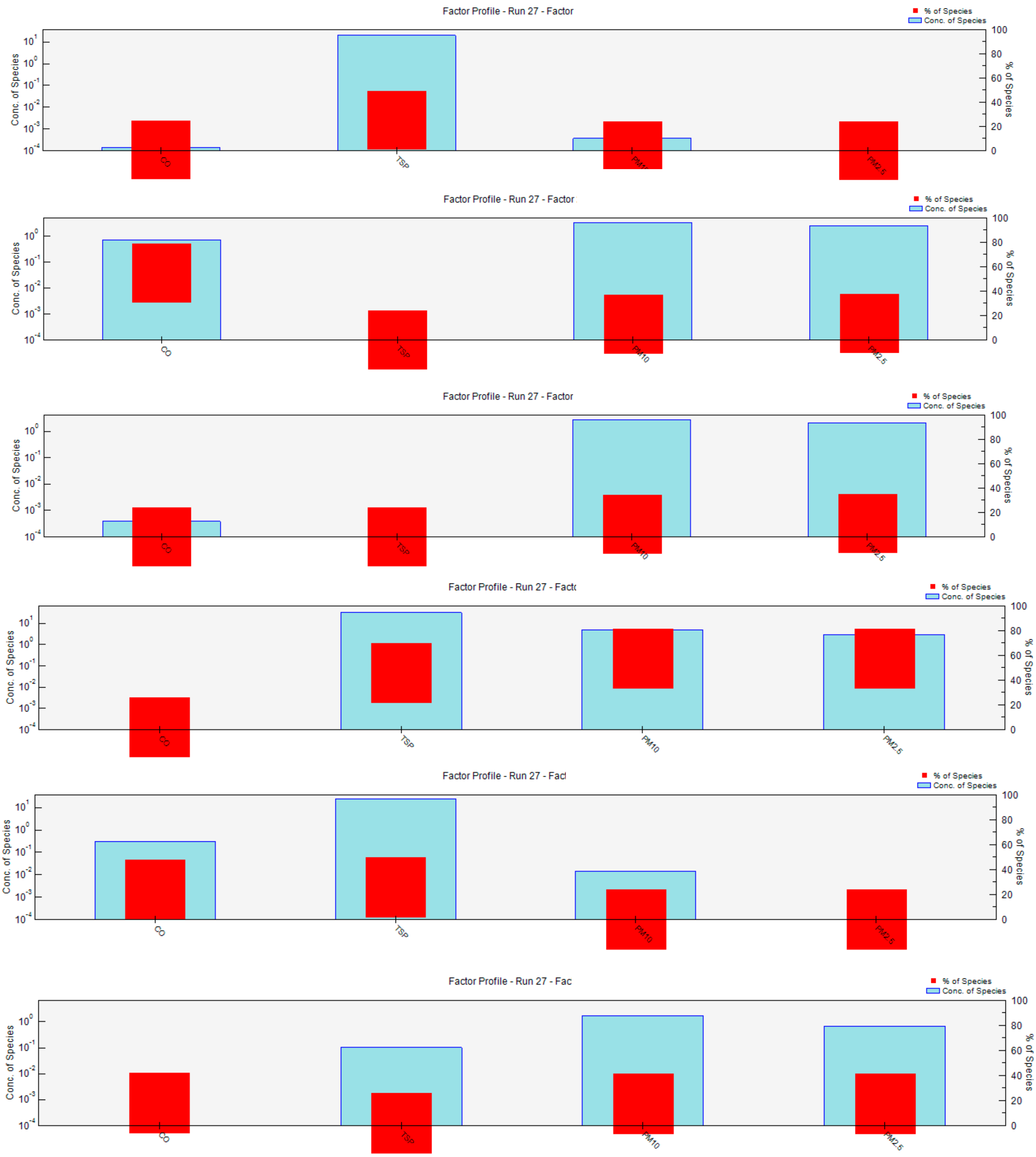


Figure 11. Factor profile and concentration percentage of air quality parameters during the dry season from the PMF model.

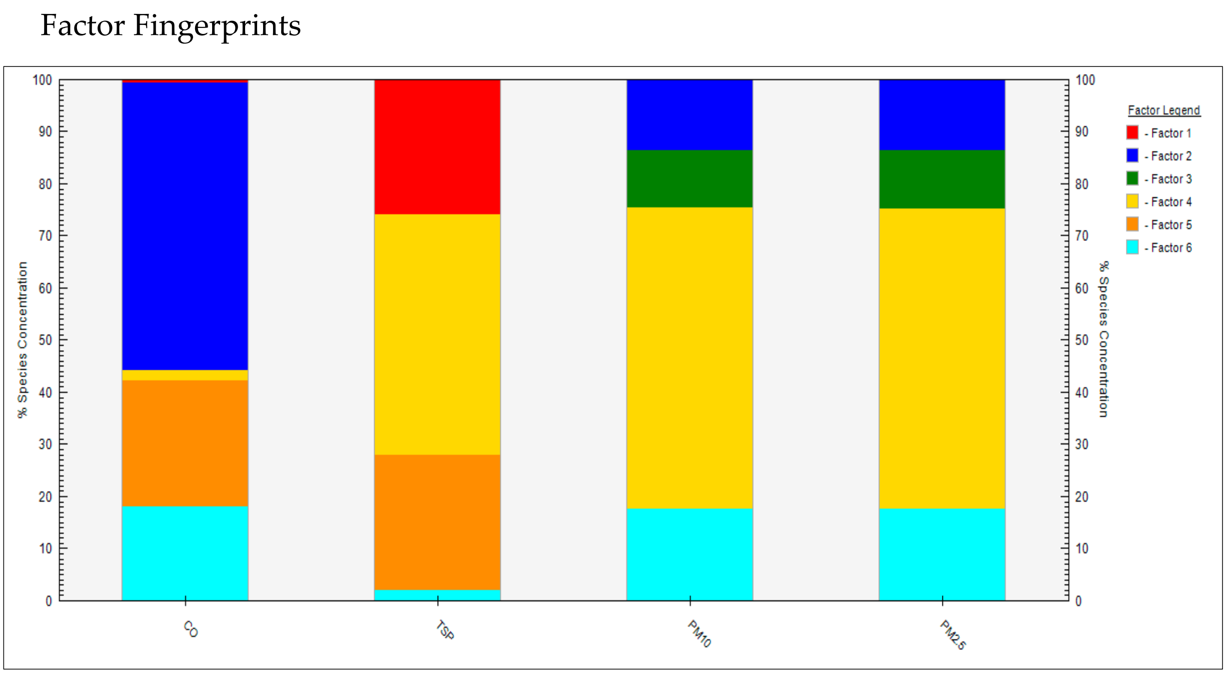


Figure 12. Factor fingerprint of four air quality parameters based on species concentration (%) during the dry season.

During dry season in Factor 4, PM_{10}, $PM_{2.5}$, TSP and CO provided 57.8%, 57.6%, 46.2%, and 2.0% respective contributions. During the wet season in Factor 4, PM_{10}, and TSP provided 16.7% and 4.6% of the respective contributions. A study by Yusuf et al. [46] highlighted that the levels of PM_{10} increased significantly in a plastic-processing industry which corresponds with the percentage of carbon monoxide seen here. Aspects in Section 3.1.1 to Section 3.1.4 should also be put into consideration. Another study by Alves et al. [47] showed that the plastics industry was a source of PM 10 in road dust. A study by Chirino et al. [48] also states that plastic manufacturing industries are one of the main sources of PM_{10} emission into the environment. Therefore, Factor 4 represents the plastic manufacturing industries.

During dry season in Factor 5, TSP and CO provided 26.7% and 24.7% respective contributions. During wet season in Factor 5, PM_{10}, $PM_{2.5}$, and TSP provided 41.9%, 41.9%, and 1.5% contributions. Ashrafi et al. [49] stated that metal production is one of the industrial processes causing the higher value of TSP. Another study conducted by Sonibare and Akeredolu [50] stated that a common source of TSP is the metal processing industry as the grinding and heating processes among others are employed. A study by Guol et al. [51] iterated that the steel and iron producing industries were common sources of TSP. This means that Factor 5 represents metal processing and manufacturing industries.

During dry season in Factor 6, CO, $PM_{2.5}$, PM_{10}, and TSP provided 18.2%, 17.7%, 17.6%, and 2% of the respective contributions. During the wet season in Factor 6, TSP, PM_{10}, and $PM_{2.5}$ provided 74.4%, 27%, and 24.6% of the respective contributions. One of the main sources of TSP and CO is the food and beverage industry through the heating, fuel utilization, as well as machinery processing aspects [52]. Furthermore, a study conducted by Jadoon and Nawazish [53], stated that some of the common sources of CO are industrial boilers and incomplete combustion processes from food and beverage manufacturing industries. As such, it reflects the percentages seen here, and may mean that Factor 6 represents the beverage manufacturing industries.

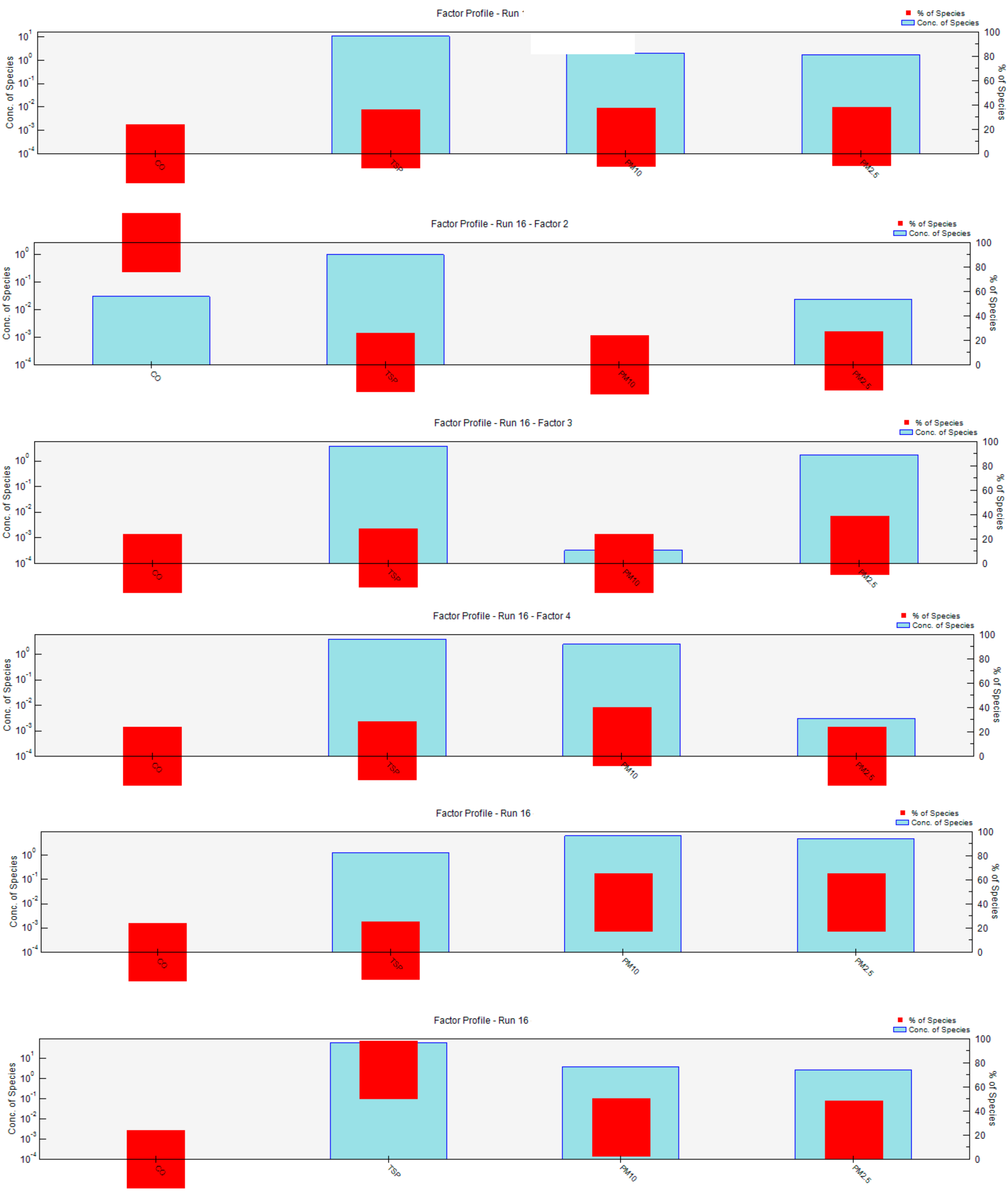


Figure 13. Factor profile and concentration percentage of air quality parameters during the wet season from the PMF model.

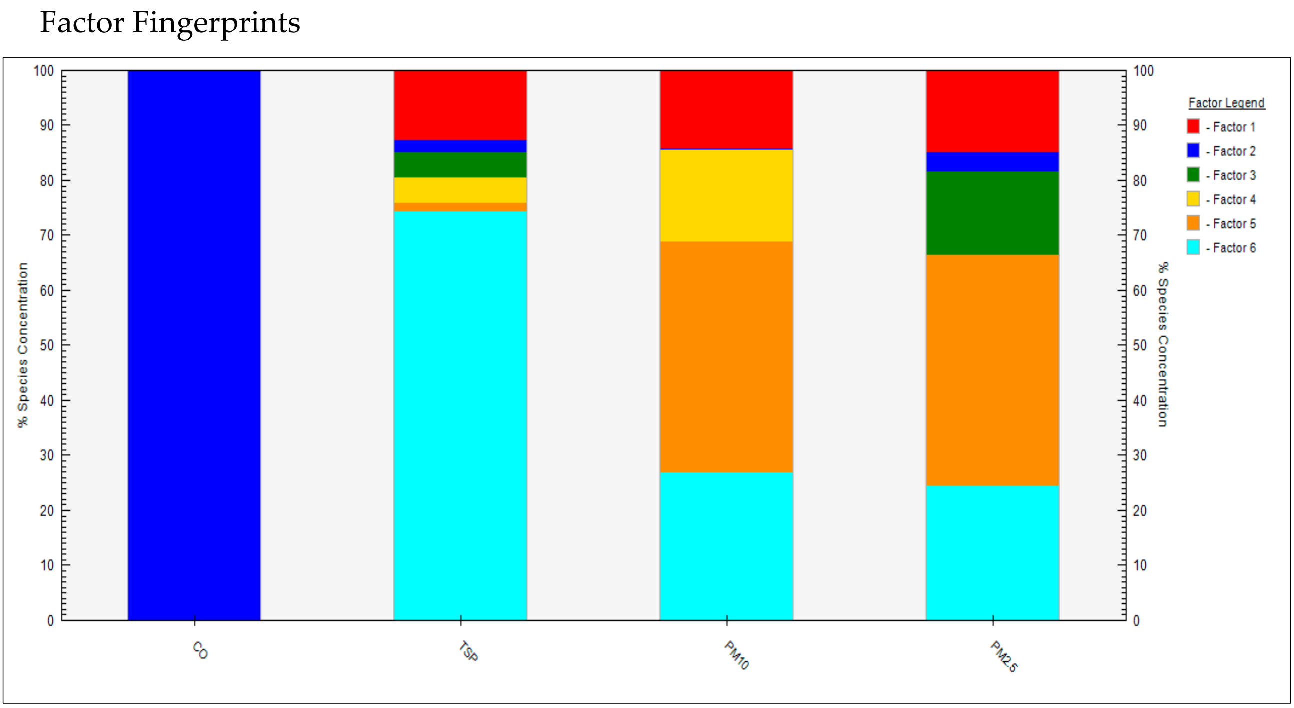


Figure 14. Factor fingerprint of four air quality parameters based on species concentration (%) during the wet season.

As such, this means that during both wet seasons the plastic manufacturing industries contribute highly towards TSP in the air around the industrial sites which means that mitigation measures need to be implemented accordingly. This should be extended to food manufacturing industries which are the highest contributing sources of CO in the air during the dry and wet season. The other industries, namely metal processing and beverage manufacturing are also sources of $PM_{2.5}$, PM_{10}, and CO and need to be targeted for needed remedial actions.

3.3. Correlation between Air Quality Parameters and Noise Levels

Correlations were conducted between air quality parameters and noise levels for both seasons. This was performed to determine whether air quality parameters can be used as an indicator for noise level pollution. The following were the correlations as per Table 3 below, which shows that air quality has an influence on noise levels. CO correlation with noise is shown to be lower during the wet season as compared to the dry season. It is also observed that air quality has an influence on noise levels with a seasonality effect, as we can see the correlations between (TSP, PM_{10}, and $PM_{2.5}$) and noise level changes from weak during dry season to moderately strong in the wet season. The positive correlation between air quality parameters and noise levels suggests potential shared sources or synergistic effects, and as such, further investigations are needed to understand the mechanisms driving these associations. This kind of correlation is also seen in various studies, such as the one conducted by Lacerda et al. [54], who compared the hearing thresholds of two groups of workers—one exposed to both noise (90 dB) and CO and another exposed solely to noise (90 dB). The findings indicated a significant increase in hearing thresholds (at high frequencies of 3, 4, and 6 kHz) in the "noise + CO group" when compared to the "noise group".

Table 3. Correlations between air quality parameters and noise level.

Variable	Noise Level	
	Dry Season	Wet Season
CO	0.205 (0.177)	0.062 (0.687)
TSP	0.241 (0.110)	0.401 (0.006)
PM_{10}	0.011 (0.941)	0.358 (0.016)
$PM_{2.5}$	0.011 (0.942)	0.306 (0.041)

Brackets have the significance levels.

4. Conclusions

This study determined the concentration levels of air quality (CO, TSP, $PM_{2.5}$, and PM_{10}) and noise from industrial sites (Makata, Limbe, Maselema, Chirimba, and Maone). During the wet season, CO, TSP, PM_{10}, and $PM_{2.5}$ averaged 0.49 ± 0.65 mg/m^3, 85.03 ± 62.18 μg/m^3, 14.65 ± 8.13 μg/m^3, and 11.52 ± 7.19 μg/m^3, respectively, whereas in the dry season, the average concentrations rose to 1.31 ± 0.81 mg/m^3, 99.86 ± 30.06 μg/m^3, 24.35 ± 9.53 μg/m^3, and 18.28 ± 7.14 μg/m^3. In the wet season, the highest concentrations of CO, TSP, PM_{10}, and $PM_{2.5}$ were 2.67 ± 3.06 mg/m^3, 319 ± 319.35 μg/m^3, 36.2 ± 17.72 μg/m^3, and 27.1 ± 13.32 μg/m^3, respectively. Dry season highest concentrations were 4.33 ± 2.31 mg/m^3, 184 ± 114.00 μg/m^3, 47.8 ± 16.68 μg/m^3, and 35.8 ± 12.58 μg/m^3. Noise levels remained below MS and WHO standards. The study also determination of movement pattern of the air pollutants using trajectory models from the National Oceanic and Atmospheric Administration (NOAA). The study found that the concentrations of air quality parameters generally remained within the permissible limits set by Malawi and the World Health Organization (WHO), except for a limited number of samples. This deviation was attributed to the movement of air masses, as indicated by the generated trajectories. Noise levels were found to be within the maximum allowable standard of Malawi and the WHO. Correlations between air quality parameters and noise levels were made which showed a seasonality effect, as such air quality has an influence on noise pollution.

The analysis results of the Positive Matrix Factorization (PMF) model indicated that there were six main factors affecting the accumulation of air quality parameters, namely: (1) plastic manufacturing industries, (2) food manufacturing industries, (3) metal processing and manufacturing industries, (4) cement manufacturing industries, (5) beverage manufacturing industries, and (6) furniture manufacturing industries.

Recommendations

Future PMF assessments need to be performed to include other parameters such as Nitrogen dioxide (NO_2), Sulfur dioxide (SO_2), and Volatile Organic Carbons (VOCs), which are also important since they may be of concern to the health of people, but were not included due to time and financial limitations. Further studies should be conducted to better understand the factors affecting the PMF flow dynamics in the industrial zones and their influence. These should include climatological factors (wind, precipitation, and temperature). There is a need to collect samples during the nighttime, which was not performed due to security concerns, since the sampling was not conducted within the industrial compounds.

Author Contributions: C.C.U.: Conceptualisation, Sampling, Laboratory work, and writing; C.C.K., F.G.D.T. and I.B.M.K.: Conceptualisation, Supervising, reviewing, and writing; F.T., U.C.-M. and H.S.: reviewing and writing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the ethical and regulatory requirements and approved by the National Commission for Science and Technology (NCST) for the risk assessment aspect of the study.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available from the corresponding author upon request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Appendix A.1. Table of Coordinates for Sampling Points

Sampling Points	Geographical Coordinate System	
Maone Industrial Area	(Latitude, Longitude)	(UTM)
Maone OF	−15.79248, 35.07676	722,465.48, 8,252,921.50
Maone MH	−15.78429, 35.07958	722,776.63, 8,253,824.17
Maone NM	−15.78332, 35.07571	722,362.96, 8,253,936.39
Makata Industrial Area		
Makata LF	−15.79132, 35.02744	717,182.33, 8,253,101.41
Makata AP	−15.79029, 35.02339	716,748.68, 8,253,219.58
Makata CM	−15.78641, 35.03355	717,841.57, 8,253,638.50
Chirimba Industrial Area		
Chirimba AP	−15.73752, 35.03059	717,577.34, 8,259,052.29
Chirimba BC	−15.74260, 35.03074	717,587.15, 8,258,489.82
Chirimba VZ	−15.74120, 35.02713	717,201.70; 8,258,647.93
Limbe Industrial Area		
Limbe AZ	−15.80686, 35.06551	721,243.21, 8,251,341.22
Limbe MP	−15.80755, 35.06737	721,442.83, 8,251,262.55
Limbe PC	−15.80511, 35.06359	721,442.83, 8,251,536.57
Maselema Industrial Area		
Maselema PP	−15.80506, 35.05091	719,681.90, 8,251,556.40
Maselema RP	−15.80405, 35.05219	719,820.04, 8,251,666.62
Maselema BP	−15.80644, 35.05758	720,395.01, 8,251,396.02

Appendix A.2. Statistical Analysis (Seasonal Variations Using Paired t-Test)

	Mean Difference	Confidence Interval		t	df	Stderr	*p*-Value (α = 0.05)
Variable		lower	upper				
CO	−0.824	−1.491	−0.158	−2.494	44	0.3306125	0.01647
TSP	−9.507	−49.941	30.928	−0.474	44	20.06316	0.638
PM_{10}	−10.418	−15.950	−4.885	−3.795	44	2.745143	0.0004478
$PM_{2.5}$	−7.262	−11.612	−2.912	−3.3644	44	2.158538	0.001599
Noise	−4.493	−7.075	−1.912	−3.508	44	1.280761	0.001053

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