Research article

Ambient $PM_{2.5}$, soot, black carbon and organic carbon concentrations in a residential area in the Bojanala Platinum District Municipality, North West province, South Africa

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Abstract

Air pollution is a major threat to human health globally. In 2021, the World Health Organization (WHO) reported that 7 million premature deaths, mainly from non-communicable diseases, are due to air pollution. Air quality studies on $PM_{2.5}$ and its composition are lacking in South Africa and Africa. To find ways to reduce $PM_{2.5}$ sources and its associated health impact in the Bojanala Platinum District Municipality (BPDM), North West province, South Africa, it is necessary to determine $PM_{2.5}$ concentrations, its chemical composition and distant air pollution source areas in this area. $PM_{2.5}$ filter samples were collected manually during 24 hours every sixth day from 10 May 2021 and 4 June 2022 in a residential area in Bapong. Bapong is located in the BPDM. The average $PM_{2.5}$ level during the sampling period was 21 $\mu g.m^{-3}$ (range: 2.0 to 78 $\mu g.m^{-3}$), which is higher than the yearly WHO guideline (5 $\mu g.m^{-3}$), and South African National Ambient Air Quality Standards (SANAAQS) (20 $\mu g.m^{-3}$). The 24-hour $PM_{2.5}$ levels exceeded the daily WHO guideline (15 $\mu g.m^{-3}$) and daily SANAAQS (40 $\mu g.m^{-3}$) on 27 and nine occasions, respectively. The highest $PM_{2.5}$ levels were observed during the cold autumn season (78 $\mu g.m^{-3}$: May 2022). Soot levels ranged from 0.1 to 8.0 $m^{-1} \times 10^{-5}$ with an annual average of 1.8 $m^{-1} \times 10^{-5}$. The black carbon (BC) levels ranged from 0.1 to 6.0 $\mu g.m^{-3}$ with an average of 1.3 $\mu g.m^{-3}$. The average level of organic carbon (OC) was 1.4 $\mu g.m^{-3}$ (range: 0.1 to 5.0 $\mu g.m^{-3}$). Most of the geographical air masses were found to be originating inland (65%). This pioneering study in Bapong provides key insights into the seasonal and weekly variation of $PM_{2.5}$, soot, BC and OC concentrations, distant air pollution source areas that contribute to their concentrations and their potential public health risk in the area.

Keywords

$PM_{2.5}$, soot, black carbon, organic carbon, South Africa, Bapong

Introduction

Air pollution is a complex mixture of gases such as sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and ground-level ozone (O_3) along with particulate matter (PM), many of which are classified and monitored as criteria pollutants (WHO, 2021). PM refers to particulate matter, a mixture of solid and liquid particles suspended in the air (WHO, 2021). PM is typically categorised by size: PM_{10}, $PM_{2.5}$, and ultrafine particles (PM_1 or nanoparticles). Among these, $PM_{2.5}$ poses the greatest health concern due to its ability to penetrate deep into the lungs, reaching the alveoli and entering the bloodstream. In contrast, PM_{10} is generally filtered out by the upper respiratory tract (WHO, 2021).

Carbonaceous aerosols, comprising OC and BC, are major constituents of $PM_{2.5}$ and play a significant role in both climate and health. These particles originate from incomplete

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combustion processes associated with traffic, domestic solid-fuel burning, industry, and biomass burning, as well as from secondary organic aerosol formation (Segakweng et al., 2022). BC is strongly light-absorbing and contributes to atmospheric warming, while OC influences hygroscopicity, cloud interactions, and may enhance the radiative effects of BC (Segakweng et al., 2022). In African settings, carbonaceous aerosols often constitute a substantial proportion of $PM_{2.5}$ mass. A recent continental analysis reported that OC is among the dominant $PM_{2.5}$ components in southern Africa, including South Africa, driven by seasonal biomass burning and domestic combustion (Cheng et al., 2023).

The health relevance of carbonaceous aerosols is well established. Globally, $PM_{2.5}$ including BC and organic aerosol fractions, is estimated to contribute to approximately 4.23 million excess deaths annually due to its strong associations with cardiovascular and respiratory diseases (Burnett et al., 2022). BC exposure has been linked to impaired lung function, cardiovascular morbidity, and systemic inflammatory responses, while OC contains reactive species capable of inducing oxidative stress and inflammation (Josipovic et al., 2019). Evidence from South Africa reflects these concerns: in Pretoria, 24-hour $PM_{2.5}$ averaged 21 $\mu g.m^{-3}$, exceeding WHO guidelines, with BC, OC, and soot showing distinct seasonal contributions from combustion sources (Adeyemi et al., 2022). In Kimberley, mean ambient BC and OC concentrations were 0.6 $\mu g.m^{-3}$ and 0.4 $\mu g.m^{-3}$, respectively, consistent with mixed traffic and domestic fuel burning sources (Becker et al., 2024). Low-income areas relying heavily on solid fuels show particularly elevated wintertime OC and BC levels, including within the PM_1 fraction (Segakweng et al., 2022). Meanwhile, aerosol samples from the Vaal Triangle displayed high oxidative potential, further underscoring the toxicological burden of carbonaceous particles in industrialised regions (Josipovic et al., 2019).

Studies across Africa, including South Africa (Mwase et al., 2022), Kenya (Gaita et al., 2014), and Nigeria (Agbo et al., 2021), similarly identify carbonaceous aerosols as key drivers of adverse health outcomes in regions affected by biomass burning, traffic emissions, and industrial activities.

According to the World Health Organization (WHO, 2021), exposure to ambient and household $PM_{2.5}$ contributes to approximately 7 million premature deaths annually. Ambient exposure is a major contributor, with well-documented links to cardiovascular diseases (CVD) and respiratory diseases (RD), especially in vulnerable groups such as children and individuals with pre-existing conditions (WHO, 2021; Brauer et al., 2024; Health Effects Institute, 2024).

Populations in low- and middle-income countries (LMICs) are particularly vulnerable to the health impacts of air pollution due to limited access to healthcare, underdeveloped infrastructure, lower technological capacity, and diverse livelihood strategies (Green et al., 2019; Safo-Adu et al., 2023). A substantial share of global air pollution-related deaths occurs in LMICs (WHO, 2021; Brauer et al., 2024; Health Effects Institute, 2024). As a result, WHO (2021) has called for more epidemiological studies in LMICs such as South Africa to better understand context-specific health risks.

In addition, WHO (2021) emphasised the need for health studies that examine not only $PM_{2.5}$ mass concentrations, but also its chemical components such as BC, OC, soot, trace elements, sulphates, and nitrates to understand source-specific toxicity and guide policy more effectively. Despite some progress in quantifying $PM_{2.5}$ concentrations in select African cities, substantial gaps remain in long-term monitoring and PM composition data across the continent (Katoto et al., 2019; Agbo et al., 2021; Jia et al., 2022; Health Effects Institute, 2022; Safo-Adu et al., 2023; WHO, 2023).

South Africa is one of the few African countries with a long-standing air quality legislative framework, dating back to 1965 and significantly updated in 2004 (United Nations Environment Programme, 2021). However, the national air quality monitoring infrastructure is aging and poorly maintained, leading to equipment failures and frequent data gaps (Department of Fisheries, Forestry and the Environment, 2022). While $PM_{2.5}$ monitoring became a legal requirement in 2012, many municipalities have yet to implement it. Moreover, PM speciation data is rarely collected, except at a few stations south of Johannesburg (e.g. Sebokeng and Sharpeville), which monitor BC, but suffer from poor data quality (Mwase et al., 2022).

To address critical air pollution hotspots, the Waterberg–Bojanala Priority Area (WBPA) was declared as South Africa's third National Air Pollution Priority Area on 15 June 2012 (Environmental Affairs, 2015). The WBPA spans parts of Limpopo and North West provinces and includes the Waterberg District Municipality (WDM) and Bojanala Platinum District Municipality (BPDM), covering nine local municipalities. Although air quality management plans (AQMPs) were developed for the WBPA (last published in 2015: Environmental Affairs, 2015) and BPDM, last published in 2011: (BPDM AQMP,2011), these are outdated and overdue for revision, as required every five years by the National Environmental Management: Air Quality Act (2004). Within BPDM, the Rustenburg Local Municipality had an AQMP published in 2005, but the Madibeng Local Municipality also part of the WBPA has never developed a formal AQMP and lacks a permanent air quality monitoring station. Major sources of air pollution in Bapong include platinum mining and smelting operations, vehicular emissions from the N4 highway, domestic biomass fuel use, informal waste burning, and agricultural residue burning (BPDM AQMP,2011).

Given this context, the current study provides critical baseline data that could support the development of an AQMP for Madibeng Local Municipality as well as contribute to updating the AQMPs of the WBPA and BPDM. While previous studies have assessed $PM_{2.5}$ and some of its composition in South African residential areas (e.g., Novela et al., 2020; Williams et al., 2021; Becker et al., 2024), none have focused on the WBPA, BPDM, or Madibeng Local Municipality.

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Health data from the 2023/2024 District Health Barometer (Ndlovu et al., 2025) indicate that many of the leading causes of death in WBPA municipalities, such as respiratory diseases, preterm birth complications, cerebrovascular disease, hypertensive heart disease, and diabetes, are conditions known to be exacerbated by air pollution (WHO, 2021; Brauer et al., 2024; Health Effects Institute, 2024). This highlights the urgent need for more region-specific research on the health impacts of air pollution in the WBPA, BPDM, and the Madibeng Local Municipality.

This study seeks to address these research gaps by providing the first detailed assessment of $PM_{2.5}$ mass and some of its chemical composition in the Madibeng Local Municipality, North West Province, South Africa, while also evaluating temporal patterns and likely pollution source regions.

Materials and methods

Study area

Data were collected from the rooftop of a home in Bapong (25.722408°S, 27.659532°E), a small village located approximately 24 km west of Brits in the North West province of South Africa (Figure 1). Bapong and Brits are part of the Madibeng Local Municipality which is located in the BPDM, as mentioned above. The capital of the Madibeng municipality is Brits.

The $PM_{2.5}$ sampling site is situated in a complex environment with multiple potential sources of air pollution. Opencast platinum mines are located approximately 3 km to the west and 5 km to the east of the site, with additional mining activity extending along the northern edge of the Magaliesberg mountain range up to 85 km westward. The busy N4 highway lies about 1 km south of the site, and the Magaliesberg mountain range itself is situated approximately 5 km to the south, potentially influencing local airflow and pollutant dispersion. An industrial area is present about 20 km to the east, while numerous farms are scattered throughout the surrounding area. The site is also embedded within residential zones where biomass fuels are still commonly used for cooking and space heating. Additionally, natural sources such as windblown dust may contribute to elevated $PM_{2.5}$ concentrations in the area.

$PM_{2.5}$ sampling and gravimetric analysis

Samples (including 10 duplicate samples) were collected every sixth day over 24 hours (7am to 7am) between 10 May 2021 and 4 June 2022. Filter samples were collected on 37 mm Teflon (PTFE) membrane filters (Zefon International, Florida, USA) using a single-channel GilAir5 personal air sampler (Sensidyne, Schauenburg Electronic Technologies Group, Mulheim-Ruhr, Germany) and a GK 2.05 KTL $PM_{2.5}$ cyclone (Sensidyne, Schauenburg Electronic Technologies Group, Mulheim-Ruhr, Germany); as done in other local studies (Figure S1) (van der Westhuizen et al., 2022; Alfeus et al., 2024; Becker et al., 2024). The flow rate of the GilAir5 pump, set at 4.0 $L.min^{-1}$, was

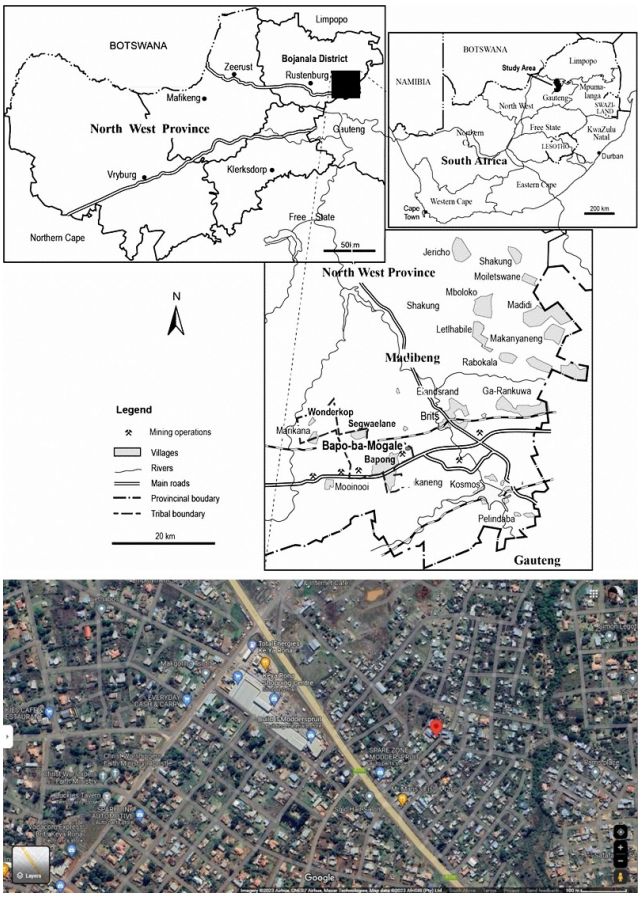

Figure 1: *$PM_{2.5}$ filter sampling site in a residential area in Bapong, Madibeng local municipality, North West Province, South Africa.*

checked using a field rotameter before and after each sampling session. The field rotameter was calibrated with a GilAir calibrator. The selection of sampling equipment was based on its accessibility and cost-effectiveness relative to continuous real-time monitoring instruments. Sampling was performed every sixth day (weekly) to balance equipment constraints, and resource availability, while ensuring representative coverage of meteorological and pollution conditions throughout the year.

Filter weights were measured using a Mettler-Toledo microbalance in a climate-controlled weighing room at the School of Health Systems and Public Health (SHSPH), University of Pretoria, maintained at 21 ± 0.5 °C and 50 ± 5% relative humidity. Prior to weighing, filters were conditioned in the weighing room for a minimum of 24 hours. After weighing, filters were stored in individual holders and kept refrigerated at 4 °C. Both exposed and unexposed filters were transported monthly between Pretoria and Bapong in their individual filter holders.

Soot, BC and OC analyses

Following gravimetric analysis of the exposed $PM_{2.5}$ filter samples, reflectance measurements were carried out to assess soot content. This was done using an EEL43 reflectometer (Diffusion Systems Ltd., EEL model 43 D) at the SHSPH, University of Pretoria (Howlett-Downing et al., 2022; van der Westhuizen et

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al., 2022). Soot concentrations were expressed as the absorption coefficient calculated using Equation (1), as outlined by Davy et al. (2017) and Cesaroni et al. (2014).

$$a = (A/2V) * \ln(R_0/R_f) \quad (1)$$

where A is the absorption coefficient ($m^{-1} \times 10^{-5}$), V the sampled volume (m^3), R_0 the reflection of a primary control filter (%), R_f the reflection sampled filter (%) and A the loaded filter area (m^2).

Carbonaceous aerosols were analysed using a Model OT21 Optical Transmissometer (Magee Scientific Corp., Berkeley, CA, USA) at the University of Gothenburg, Sweden. The instrument measures **light attenuation** through loaded filters at specific wavelengths, following procedures applied in similar South African studies (Novela et al., 2020; Howlett-Downing et al., 2022; van der Westhuizen et al., 2022; Becker et al., 2024).

BC was estimated from absorption at 880 nm, a wavelength specific to soot-like carbon, while absorption at 370 nm was used as a proxy for ultraviolet-absorbing organic carbon (OC), often associated with biomass burning.

The following equations were applied to convert the light attenuation to mass concentration ($\mu g.m^{-3}$) for BC and OC.

Attenuation is defined as:

$$ATN = 100 \times \ln(I_0/I) \quad (2)$$

Where I_0 is the transmitted light through a clean blank filter and I is the transmitted light through the exposed filter.

Attenuation is converted to the aerosol absorption coefficient (b_{abs} in m^{-1}) using:

$$b_{abs} = (ATN/100) \times (A/V) \quad (3)$$

where A is the exposed area on the filter where $PM_{2.5}$ was collected (m^2) and V is the sampled air volume (m^3)

To obtain a **mass concentration**, an **assumed mass absorption cross-section (MAC)** is required:

$$C=b_{abs}/MAC \quad (4)$$

Where C is the BC-equivalent (880 nm) or OC-equivalent (370 nm) and MAC is the mass absorption cross-section ($m^2.g^{-1}$).

A commonly used value for Magee instruments is 16.6 $m^2.g^{-1}$ at 880 nm (for BC–equivalent mass) and 39.5 $m^2.g^{-1}$ at 370 nm (for OC–equivalent mass)

Geographical origin of air mass clusters

The geographical origin of air masses passing over the sampling site in Bapong was used as a proxy for long-range transported air pollution from distant sources (Howlett-Downing et al., 2022; van der Westhuizen et al., 2022; Becker et al., 2024).

During the 13-month study period, 72-hour backward air mass trajectories were calculated daily using the HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model (Stein et al. 2015). The model was run on the NOAA Air Resources Laboratory (ARL) online platform, utilising meteorological data from the NCEP/NCAR Global Reanalysis. This dataset provides atmospheric fields with a spatial resolution of 2.5° × 2.5° and 17 vertical levels, updated every six hours (00:00, 06:00, 12:00, and 18:00). Wind fields were linearly interpolated between these time steps for the trajectory calculations.

Given the inherent uncertainty of single trajectory paths, an ensemble approach was adopted. Trajectories were initiated from a starting height of 500 m, with additional offsets of ±250 m (i.e., 250 m and 750 m) to increase reliability. In total, 4 692 backward trajectories were computed and used for cluster analysis in HYSPLIT. Six distinct clusters were identified as the optimal solution.

Meteorological data

Hourly temperature, relative humidity, wind speed and rainfall data were obtained from the South African Weather Services (SAWS). Data were extracted from the Hartebeespoort Dam climate station (-25.7480S, 27.8320E), located approximately 24 km from the sampling site. Although not co-located, this station is considered broadly representative of regional meteorological conditions; however, minor site-specific variations cannot be ruled out. The hourly data were used to calculate 24-hour averages from 7am to 7am, i.e. to correspond to the $PM_{2.5}$ sampling time.

Statistical analysis

Statistical analyses were conducted using Stata version 14. Descriptive statistics were generated for $PM_{2.5}$, soot, BC, OC, and meteorological parameters.

As the Shapiro-Wilk test indicated that these variables did not follow a normal distribution, non-parametric methods were employed. Spearman's rank correlation was used to examine associations among $PM_{2.5}$, soot, BC, OC, and meteorological variables. Seasons were categorised as autumn (March–May), winter (June–August), spring (September–November), and summer (December–February). The Kruskal–Wallis test was applied to assess whether median values of air pollutants and meteorological variables varied significantly across season and air mass origins. Additionally, the Wilcoxon rank-sum test was used to evaluate differences in median pollutant and meteorological values between weekdays and weekends/public holidays.

Ethics approval

This study received approval from the Faculty of Health Sciences Research Ethics, University of Pretoria (References 536/2023 and 143/2021).

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Results and discussion

In total 76 $PM_{2.5}$ filter samples were collected during the study period. Twelve filter samples were discarded due to technical errors, e.g. GilAir pump stopped due to power failures in the area. Of the remaining 64 filter samples, eight were duplicate samples. The values of duplicate samples were averaged. The final number of samples included in the statistical analyses was 56 that were collected on 56 days.

Meteorological conditions

During the 56 days of $PM_{2.5}$ filter sampling, the median temperature was 18.2 °C (range: 5.8–25.3 °C), relative humidity was 61.2% (range: 25.3–87.3%), and wind speed was 0.5 m·s^{-1} (range: 0–2.6 m·s^{-1}), as shown in Table 1 and Figures S2 to S3. Daily rainfall ranged from 0 to 40.2 mm.

Temperature, relative humidity, and rainfall showed significant seasonal variation, whereas wind speed did not (Figure S4). Wind plays a critical role in shaping air pollution concentrations, as it can disperse pollutants by transporting them away from the source or intensify concentrations through atmospheric chemical or physical processes (Department of Fisheries, Forestry and the Environment, 2017).

$PM_{2.5}$ concentrations

The $PM_{2.5}$ levels ranged from 2.0 to 78 µg.m^{-3} with an annual average of 21 µg.m^{-3}. The daily $PM_{2.5}$ concentrations exceeded the daily WHO air quality guidelines (15 µg.m^{-3}) (WHO, 2021) and daily South African NAAQS (40 µg.m^{-3}) (Department of Fisheries, Forestry and the Environment, 2012) on 27 and nine occasions, respectively (Figure 2). The annual average $PM_{2.5}$ concentration was four times higher than the WHO's yearly air quality guideline (5 µg.m^{-3}) and slightly higher than the yearly South African NAAQS (20 µg.m^{-3}).

The median $PM_{2.5}$ levels did not differ significantly by seasons ($p > 0.05$), with the highest median $PM_{2.5}$ level observed in autumn (23 µg.m^{-3}) followed by spring (20 µg.m^{-3}) (Table 1, Figure S5). Daily $PM_{2.5}$ levels exceeded the daily WHO air quality guidelines on 6, 10, 4 and 7 occasions during summer, autumn, winter and spring, respectively. As previously mentioned, the sampling was conducted in residential zones where biomass fuels are still commonly used for cooking and space heating. This could be a contributing factor to the higher $PM_{2.5}$ concentrations observed during colder months. The interior of South Africa also experiences temperature inversions during autumn and winter which traps air pollutants near the surface. Bapong village is situated in a summer rainfall zone. The higher $PM_{2.5}$ concentrations observed in spring can be attributed to the yearly burning of fields prior to the summer rains (BPDM AQMP,2011). The fewer exceedances observed in winter may result from stable atmospheric conditions that limit dust resuspension and open burning compared to other seasons (Novela et al., 2020).

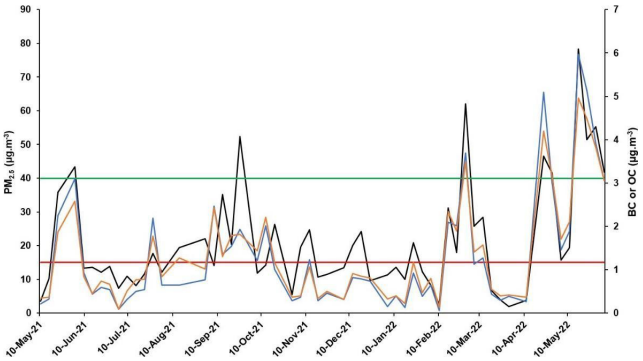

Figure 2: *Time-series graph of $PM_{2.5}$, BC and OC concentrations during 10 May 2021 to 4 June 2022 in Bapong, Madibeng local municipality, North West Province, South Africa. Red line: Daily World Health Organization $PM_{2.5}$ air quality guideline (15 µg.m^{-3}). Green line: Daily South African National Ambient Air Quality Standard $PM_{2.5}$ (40 µg.m^{-3})*

Table 1: *Descriptive statistics of 24-hour levels of $PM_{2.5}$, soot, black carbon, organic carbon and meteorological conditions at a residential area in Bapong, Madibeng local municipality, North West Province, South Africa during 10 May 2021 to 4 June 2022.*

Variables*	Mean	Std dev	Median	Min	Max
All year					
$PM_{2.5}$	21	16	14	2.0	78
Soot	1.8	1.9	1.2	0.1	8.0
BC	1.3	1.4	0.8	0.1	6.0
OC	1.4	1.2	0.9	0.1	5.0
Temperature	17.1	5.6	18.2	5.8	25.4
Relative humidity	58.1	13.8	61.2	25.3	87.3
Wind speed	0.7	0.5	0.5	0.0	2.6
Precipitation	1.6	6.0	0.0	0.0	40.2
Autumn					
$PM_{2.5}$	27	23	23	2.0	78
Soot	2.5	2.6	1.4	0.1	8.0
BC	2.1	2.0	1.4	0.2	6.0
OC	2.0	1.6	1.6	0.3	5.0
Winter					
$PM_{2.5}$	17	12	13	7.4	43
Soot	1.9	1.7	1.3	0.3	6.2
BC	1.0	1.0	0.6	0.1	3.1
OC	1.1	0.9	0.8	0.1	3.1
Spring					
$PM_{2.5}$	21	12	20	5.5	52
Soot	1.1	1.0	0.9	0.2	3.5
BC	1.1	0.7	1.2	0.3	2.5
OC	1.2	0.7	1.2	0.3	2.4
Summer					
$PM_{2.5}$	18	14	14	2.5	62
Soot	1.4	1.3	0.9	0.1	5.0
BC	0.9	1.0	0.7	0.1	3.7
OC	1.0	1.0	0.8	0.1	3.5

**Units: $PM_{2.5}$, BC and OC (µg.m^{-3}), soot (m^{-1} x 10^{-5}), temperature (°C), relative humidity (%), wind speed (m.s^{-1}), rainfall (mm).*
$p>0.05$ for median levels of $PM_{2.5}$, soot, BC, OC and windspeed by seasons
$p<0.05$ for temperature, relative humidity and rain by seasons

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In South Africa, reported annual mean $PM_{2.5}$ concentrations include 10 $\mu g.m^{-3}$ (range: 1.1–37.5 $\mu g.m^{-3}$) in Thohoyandou (Novela et al., 2020; Edlund et al., 2021), 11 $\mu g.m^{-3}$ (range: 0.5–33 $\mu g.m^{-3}$) in Bloemfontein (Van Der Westhuizen et al., 2022), 13.4 $\mu g.m^{-3}$ (range: 1.17–39.1 $\mu g.m^{-3}$) in Cape Town (Williams et al., 2022; Alfeus et al., 2024), 21.1 $\mu g.m^{-3}$ (range: 0–66 $\mu g.m^{-3}$) in Pretoria (Adeyemi et al., 2021; Howlett-Downing et al., 2022) and (6.3 $\mu g.m^{-3}$) in Kimberley (Becker et al., 2024). These values are generally lower than those observed at the Bapong study site. Although these values provide useful national context, the data set from Bapong study site reflects limited range and relatively low captured data due to short sampling period. Several factors could also account for this discrepancy, including differences in site location, proximity to pollution sources and local meteorological conditions.

Due to limited availability of ground-based $PM_{2.5}$ monitoring across Africa, researchers often depend on models to estimate concentrations. Bachwenkizi et al. (2021) used a combination of satellite data, chemical transport model simulations, and limited ground measurements to estimate $PM_{2.5}$ levels between 1998 and 2018. Their findings indicated an estimated annual mean of 13 $\mu g.m^{-3}$ in South Africa, 14 $\mu g.m^{-3}$ in Angola, and 69 $\mu g.m^{-3}$ in Nigeria. In Nairobi, Kenya, Gaita et al. (2014) reported mean $PM_{2.5}$ concentrations of 21 $\mu g.m^{-3}$ at an urban background site and 13 $\mu g.m^{-3}$ at a suburban location. In Uganda, Kirenga et al. (2015) documented outdoor daily $PM_{2.5}$ concentrations ranging from 0 to 535 $\mu g.m^{-3}$ in Jinja and Kampala, and from 8 to 384 $\mu g.m^{-3}$ in industrial areas of Kampala. Similarly, Agbo et al. (2021) reported that daily $PM_{2.5}$ concentrations exceeded the WHO guideline of 15 $\mu g.m^{-3}$ in the majority of the 22 African cities studied.

Exceedances of both the daily and annual WHO air quality guidelines, as well as South Africa's NAAQS, observed in this study suggest that residents of Bapong may face elevated health risks due to poor air quality (WHO, 2021; WHO, 2022). Numerous studies have demonstrated the adverse health impacts of $PM_{2.5}$ exposures. Achilleos et al. (2017), in a meta-analysis of 41 studies conducted across 142 cities (excluding African locations), reported increases in all-cause mortality (0.9%), RD mortality (1.1%), and CVD mortality (0.8%) per 10 $\mu g.m^{-3}$ increase in short-term $PM_{2.5}$ exposures. Similarly, in the industrial Vaal Triangle Air Pollution Priority Area of South Africa, Mwase et al. (2022) found a 1.0% (95% CI: -0.3% to 2.4%) increase in RD hospitalisations per 10 $\mu g.m^{-3}$ rise in daily $PM_{2.5}$ concentrations. The long-term exposure effects have also been well documented. Cesaroni et al. (2014) reported a 13% increase in the risk of coronary events per 5 $\mu g.m^{-3}$ increase in long-term $PM_{2.5}$ exposures, while a pooled European cohort study found a 30% (95% CI: 14% to 47%) rise in natural-cause mortality for the same exposure increment (Brunekreef et al., 2021). In the African context, Bachwenkizi et al. (2021) reported that a 48.8 $\mu g.m^{-3}$ increase in ambient $PM_{2.5}$ was associated with a 3% increase in infant mortality across 15 countries, including South Africa, even after adjusting for household fuel use.

Soot levels, BC and OC concentrations

There are limited studies in Africa that have examined ambient soot levels and concentrations of BC, and OC, as well as their associated health impacts. Currently, neither the South African NAAQS nor the WHO provide air quality guidelines specifically for soot, BC, or OC. BC and OC together contributed approximately 13% of total $PM_{2.5}$ mass in Bapong, consistent with findings in other South African cities (Novela et al., 2020; Alfeus et al., 2024).

Soot levels, expressed as absorption coefficient, ranged from 0.1 to 8.0 $m^{-1} \times 10^{-5}$ with an annual average of 1.8 $m^{-1} \times 10^{-5}$. Seasonal variation of soot levels are illustrated in Figure 3. No significant difference in median soot levels could be seen between the seasons (Table 1). This suggests that residences use biomass fuel for cooking and heating throughout the year. In addition, informal burning of waste in residential areas due to lack of proper waste disposal services may also contribute to localized soot levels. Autumn is also associated with temperature inversions, especially during early mornings and evenings which can trap pollutants like soot near the surface.

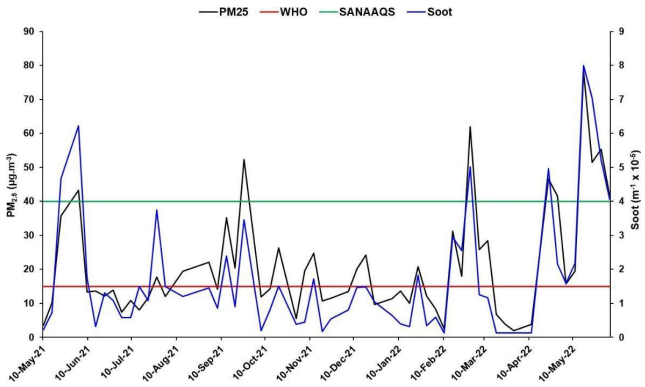

Figure 3: *Time-series graph of $PM_{2.5}$ and soot concentrations during 10 May 2021 to 4 June 2022 in Bapong, Madibeng local municipality, North West Province, South Africa. Red line: Daily World Health Organization $PM_{2.5}$ air quality guideline (15 $\mu g.m^{-3}$). Green line: Daily South African National Ambient Air Quality Standard $PM_{2.5}$ (40 $\mu g.m^{-3}$)*

The mean soot levels observed in this study were higher than those reported in previous local studies conducted in Cape Town (1.4×10^{-5} m^{-1}), Thohoyandou (0.7×10^{-5} m^{-1}), Pretoria (1.4×10^{-5} m^{-1}), Bloemfontein (1.2×10^{-5} m^{-1}) and Kimberley (0.5×10^{-5} m^{-1}), but lower than those recorded in a study conducted in Pretoria (2.3×10^{-5} m^{-1}) (Adeyemi et al., 2022; Howlett-Downing et al., 2022; Novela et al., 2020; Williams et al., 2020; van der Westhuizen et al., 2022; Becker et al., 2024). For comparison, soot levels across 11 European countries ranged from 0.6 to 3.2×10^{-5} m^{-1} (Cesaroni et al., 2014). These variations can be attributed to several factors, including differences in site locations, proximity to local pollution sources, and prevailing meteorological conditions.

In terms of the health effects associated with soot exposure, a study conducted across 11 European countries reported a 10% increase in coronary disease hospitalizations per unit $m^{-1} \times 10^{-5}$ increase in soot levels (Cesaroni et al., 2014). Another study conducted in 17 European countries concluded that an increase

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in the risk of lung cancer development is associated with a unit $m^{-1} \times 10^{-5}$ increase in soot levels (Raaschou-Nielsen et al., 2013).

BC concentrations ranged from 0.1 to 6.0 $\mu g.m^{-3}$ with an annual average of 1.3 $\mu g.m^{-3}$. Figure 2 illustrates the seasonal variation of BC concentrations. Median BC concentrations did not differ significantly between seasons (Table 1). As observed with soot, this pattern may be attributed to the continued use of wood, coal, and other solid fuels for heating and cooking by residents of Bapong throughout the year. Smelters, furnaces, and mining operations contribute to year-round combustion-related emissions, which include BC especially when air dispersion conditions are poor in autumn. The other contributing factor may be seasonal clean-up activities, such as burning agricultural residue.

Several South African studies have reported higher median BC concentrations than those observed in this study (0.8 $\mu g \cdot m^{-3}$). Reported median values include 8 $\mu g \cdot m^{-3}$ in Thohoyandou, 3 $\mu g \cdot m^{-3}$ in the industrial area of the Vaal Triangle Air Pollution Priority Area, and 2 $\mu g \cdot m^{-3}$ in both Pretoria and Cape Town (Novela et al., 2020; Howlett-Downing et al., 2022; Mwase et al., 2022; Alfeus et al., 2024). In contrast, Bloemfontein and Kimberley recorded lower means of 0.3 $\mu g \cdot m^{-3}$ and 0.6 $\mu g \cdot m^{-3}$, respectively (van der Westhuizen et al., 2022; Becker et al., 2024). Outside South Africa, mean BC levels were higher in Nairobi, Kenya (3 $\mu g \cdot m^{-3}$) (Gaita- et al., 2014), and extremely elevated concentrations in Benin (16 $\mu g \cdot m^{-3}$), while South Africa had the lowest mean among countries in that comparison (2 $\mu g \cdot m^{-3}$) (Bachwenkizi et al., 2021). Similarly, elevated mean concentrations were reported in London, UK (2 $\mu g \cdot m^{-3}$), and the Uzice region of Serbia (33.9 $\mu g \cdot m^{-3}$) (Samoli et al., 2016; Tomic-Spiric et al., 2019). A broader review, primarily comprising studies from China, found BC concentrations ranging from 2 to 55 $\mu g \cdot m^{-3}$ (Bachwenkizi et al., 2025). These differences are likely influenced by factors such as geographical location, proximity to pollution sources, and local meteorological conditions.

With regard to the health impacts of ambient BC exposure, evidence from Africa is emerging. Bachwenkizi et al. (2021) found that in 15 African countries, including South Africa, the risk of infant mortality increased by 4% for every 6.6 $\mu g.m^{-3}$ rise in BC concentrations. A recent review by Yan et al. (2025) reported that each 1 $\mu g.m^{-3}$ increase in short-term BC exposure was associated with increases of 0.5% in all-cause mortality, 0.6% in CVD mortality, 1.0% in RD mortality, and 1.5% in CVD hospital admissions. Furthermore, long-term BC exposure was linked to a 13.4% increase in CVD mortality per 1 $\mu g.m^{-3}$ rise. Similarly, Song et al. (2021) identified a 1.2% increase in RD hospitalisations per 1 $\mu g.m^{-3}$ increase in BC across 10 studies. These findings align with results from one of the few African epidemiological studies on BC, conducted in South Africa's heavily polluted Vaal Triangle Priority Area, which also observed associations between BC exposure and hospital admissions (Mwase et al., 2022).

OC concentrations ranged from 0.1 to 5.0 $\mu g.m^{-3}$ with an annual average of 1.4 $\mu g.m^{-3}$. Figure 2 illustrates the seasonal variation of OC concentrations. As with BC, median OC concentrations in autumn (1.6 $\mu g.m^{-3}$) was not significantly higher than in winter (0.8 $\mu g.m^{-3}$), spring (1.2 $\mu g.m^{-3}$) and summer (0.8 $\mu g.m^{-3}$) (Table 1). This trend may be due to similar factors influencing soot and BC.

The mean OC concentration observed in this study was lower than those reported in Thohoyandou (1.5 $\mu g.m^{-3}$) and Pretoria (2.0 $\mu g.m^{-3}$) (Howlett-Downing et al., 2022; Novela et al., 2020). In contrast, lower mean OC concentrations were observed in Kimberley (0.4 $\mu g.m^{-3}$) and Bloemfontein (0.5 $\mu g.m^{-3}$), (van der Westhuizen et al., 2022; Becker et al., 2024). According to Bachwenkizi et al. (2021), mean concentrations of organic matter PM (equivalent to our OC measure) ranged from 2 $\mu g.m^{-3}$ in South Africa to 13 $\mu g.m^{-3}$ in Nigeria. A broader review by Bachwenkizi et al. (2025), which focused mainly on studies from China, reported a range of 4 to 60 $\mu g.m^{-3}$. As with BC, an increase in OC has been associated with an increase in likelihood of infant mortality in Benin (4% increase per 5.7 $\mu g.m^{-3}$ increase in OC) (Bachwenkizi et al., 2021). These variations in OC can be attributed to several factors, including the geographical settings of the monitoring sites, proximity to local pollution sources, and differing meteorological conditions.

In a study across 15 African countries, a 4% increase in infant mortality was associated with every 5.7 $\mu g.m^{-3}$ rise in annual exposure to organic matter PM (Bachwenkizi et al., 2021). A recent review by Yan et al., (2005) reported several short-term health effects associated with a 5 $\mu g.m^{-3}$ increase in OC concentrations, including a 0.6% rise in all-cause mortality, 2.1% in cardiovascular disease (CVD) mortality, 2.4% in respiratory disease (RD) mortality, 1.2% in CVD hospitalisations, and 1.6% in RD hospitalisations. However, compared to black carbon (BC), fewer cohort studies have assessed the long-term health impacts of OC (Yan et al., 2025).

Correlations

$PM_{2.5}$, soot, BC and OC were all significantly correlated ($p < 0.001$) (Figure 4, Table 2). The strongest correlation was observed between BC and OC, suggesting shared sources such as coal and fuel combustion. In contrast, the weakest correlation was observed between $PM_{2.5}$ and OC. Similar patterns were reported in a large study covering 15 African countries, which found correlation coefficients of 0.67 between estimated $PM_{2.5}$ and BC, and 0.65 between estimated $PM_{2.5}$ and organic matter particulate matter (Bachwenkizi et al., 2021).

Table 2: *Correlation between 24-hour $PM_{2.5}$, soot, BC and OC on 56 sampling days at a residential area in Bapong, Madibeng local municipality, North West Province, South Africa during 10 May 2021 to 4 June 2022.*

	Soot	BC	OC
$PM_{2.5}$	0.840	0.846	0.828
Soot		0.852	0.822
BC			0.984

$p<0.001$ for all correlations

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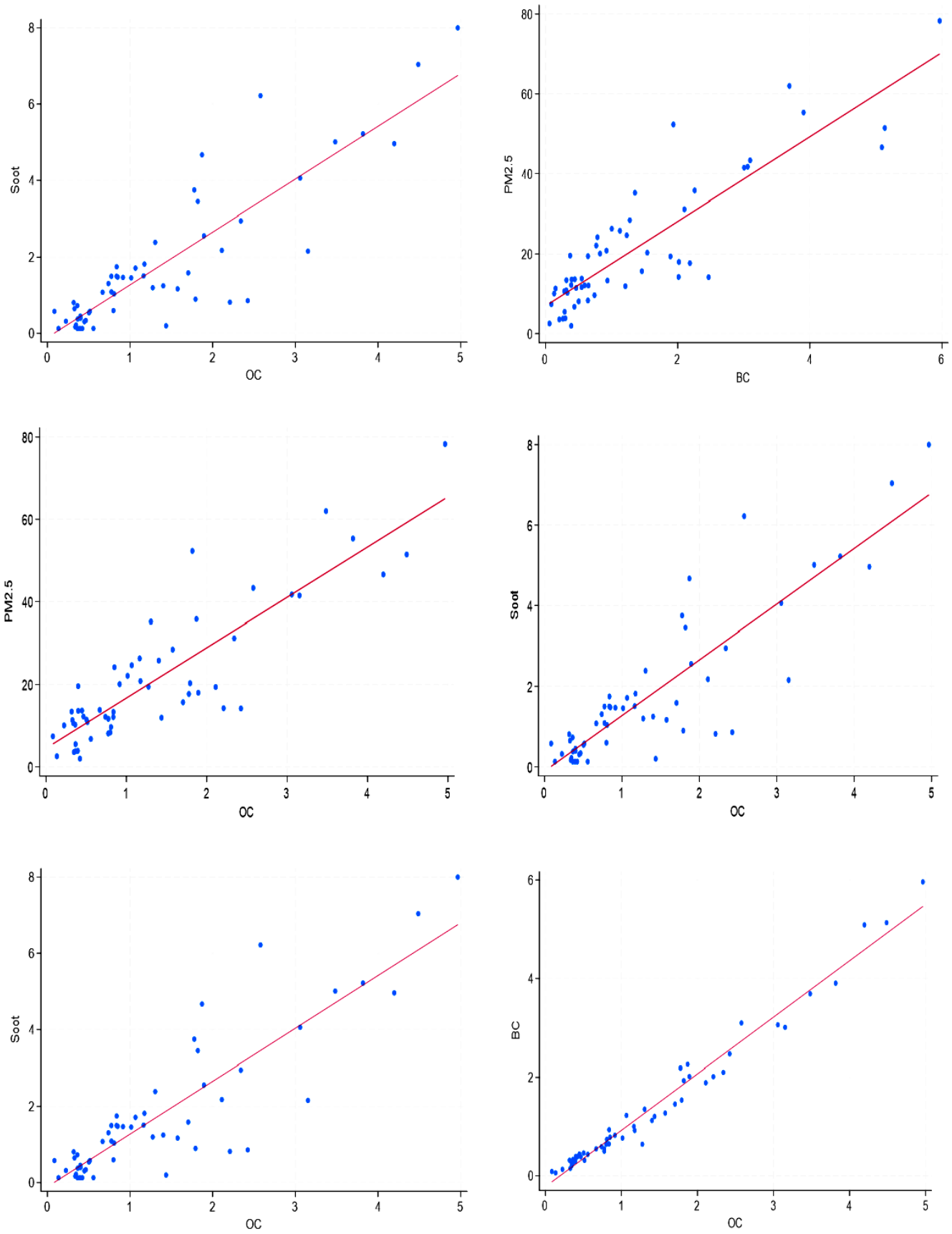

Figure 4: *Correlation plots between 24-hour $PM_{2.5}$, soot, BC and OC on 56 sampling days at a residential area in Bapong, Madibeng local municipality, North West Province, South Africa during 10 May 2021 to 4 June 2022.*
**Units: PM2.5, BC and OC ($\mu g.m^{-3}$), soot ($m^{-1} \times 10^{-5}$).*

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Meteorological conditions play an important role in the dispersion, dilution, and accumulation of air pollutants. As shown in Table 3, most of the correlations between meteorological variables and pollutant concentrations were not statistically significant ($p > 0.05$). The only significant relationship observed in this study was a negative correlation between temperature and soot.

Table 3: *Correlation between 24-hour meteorological variables and $PM_{2.5}$, soot, BC and OC on 56 sampling days at a residential area in Bapong, Madibeng local municipality, North West Province, South Africa during 10 May 2021 to 4 June 2022.*

	$PM_{2.5}$	Soot	BC	OC
Temperature	-0.052	-0.301*	-0.170	-0.174
Relative humidity	0.061	0.095	0.093	0.112
Wind speed	-0.032	-0.024	0.049	0.074
Rainfall	0.082	-0.128	-0.064	-0.067

**p<0.05*

Pollutant concentrations by geographical origins of air masses

Six geographical origin of air masses were identified in the 72-hour backward trajectory model runs (Figure 5, Table 4). During the 56 sampling days most of the air masses emanated from the north (cluster 3, 20 days), followed by the northeast (cluster 5, 13 days), west (cluster 2, 6 days), northwest (cluster 4, 5 days), southeast (cluster 6, 6 days) and southwest (cluster 1, 6 days). The percentages indicated in Figure 5 are based on all days during the study period, whereas Table 4 only reports on the 56 sampling days. These clusters indicate possible distant source areas that may have an influence in an increase in $PM_{2.5}$ concentrations at the sampling site in Bapong. These distant source areas are located in the Northern Cape and Limpopo provinces of South Africa (Cluster 2 and 3) which are well known

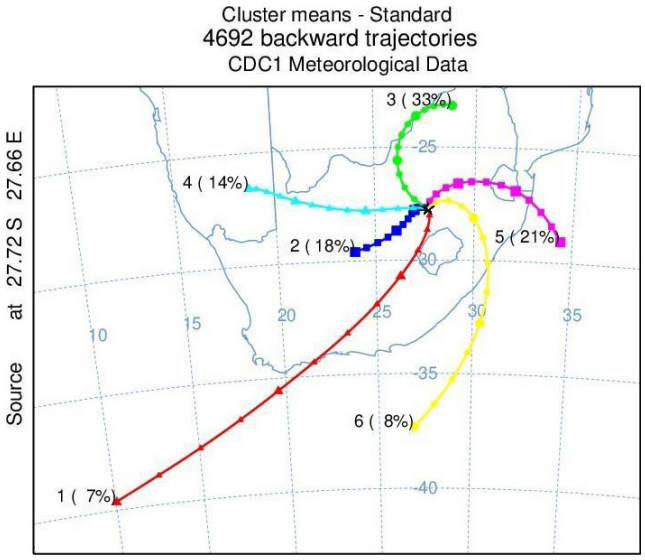

Figure 5: *Six clusters of geographical origin of air masses identified in the 72-hour backward trajectory model runs on all days during the study period May 2021 to June 2022 in Bapong, Madibeng local municipality, North West Province, South Africa.*

Table 4: *Descriptive statistics of 24-hour $PM_{2.5}$, soot, BC and OC levels on 56 sampling days at a residential area in Bapong, Madibeng local municipality, North West Province, South Africa during 10 May 2021 and 4 June 2022.*

Variable*	Mean	Median	Std Dev	Min	Max
Cluster 1: 6 days					
$PM_{2.5}$	18	9.4	17	3.6	43
Soot	2.2	0.9	2.6	0.2	6.2
BC	1.1	0.4	1.2	0.2	3.1
OC	1.0	0.6	1.0	0.3	2.6
Cluster 2: 6 days					
$PM_{2.5}$	16	17	7.9	2.5	26
Soot	1.4	1.6	1.0	0.1	2.6
BC	1.1	1.2	0.8	0.1	2.0
OC	1.2	1.4	0.8	0.1	2.1
Cluster 3: 20 days					
$PM_{2.5}$	22	13	18	3.9	62
Soot	1.6	0.9	1.7	0.1	5.2
BC	1.4	0.7	1.5	0.1	5.1
OC	1.4	0.8	1.3	0.2	4.2
Cluster 4: 5 days					
$PM_{2.5}$	18	20	6.9	7.4	25
Soot	1.1	1.1	0.5	0.5	1.7
BC	0.6	0.5	0.4	0.1	1.2
OC	0.6	0.7	0.4	0.1	1.1
Cluster 5: 13 days					
$PM_{2.5}$	24	20	20	2.0	78
Soot	2.0	1.3	2.2	0.1	8.0
BC	1.7	1.3	1.6	0.3	6.0
OC	1.7	1.4	1.3	0.4	5.0
Cluster 6: 6 days					
$PM_{2.5}$	24	22	16	6.8	51
Soot	2.2	1.3	2.6	0.1	7.0
BC	1.6	0.7	1.8	0.4	5.1
OC	1.7	1.1	1.5	0.5	4.5

**Units: $PM_{2.5}$ ($\mu g.m^{-3}$), soot ($m^{-1} \times 10^{-5}$), BC ($\mu g.m^{-3}$), OC ($\mu g.m^{-3}$)*
$p>0.05$ for all air pollutants

for their mining activities, and are likely to be the sources of air pollution coming from those areas. Cluster 4 originating from Namibia, points to additional pollution sources such as the mining industry, vehicle emissions and open waste burning.

Table 4 shows the descriptive statistics of $PM_{2.5}$, soot, BC and OC across the six geographical air masses clusters. None of the median values differed significantly between clusters (Table 4, Figure S7). The highest median concentration of $PM_{2.5}$ was observed when air mass originated from a south-easterly direction (cluster 6, 24 $\mu g.m^{-3}$). The southeast of Bapong extends toward Rustenburg, which is home to several platinum group metal (PGM) smelters and refineries. Air pollution from the

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southeast of Bapong is likely influenced by industrial activities in Rustenburg, traffic on the N4, and residential fuel use. BC and OC displayed higher median concentrations when air masses passed the Mpumalanga province (to the east) which hosts many coal mines and power stations (Figure S7), although not significantly higher compared to the other five air mass origins. Soot had higher median concentrations for air mass clusters 1 and 6 (2.2 $m^{-1} \times 10^{-5}$) (Figure S7), although not significantly higher compared to the other four air mass origins. Soot from the southeast of Bapong likely originates from platinum smelters, residential solid fuel use, and heavy traffic on the N4. In contrast, soot from the southwest is mainly from mining machinery, domestic burning, and open waste fires. Both directions reflect consistent and combustion-driven sources, contributing to elevated black carbon levels in the region.

The median temperature was lowest (12.0°C) when air masses originated from a south-westerly (cluster 1), although not significantly different compared to the other five clusters ($p>0.05$) (Figure S8). This pattern is expected as cold fronts originate in the Atlantic Ocean south of Cape Town and move northwards towards the interior of the country. Similarly, none of the other meteorological variables differed significantly across air mass origin clusters (Figure S8).

The wind direction was mostly from north-west and south-west (Figures S3) and none of the exposure variables differed significantly by wind direction ($p \geq 0.05$) (Figures S9 to S10). Wind speed was generally low (0-3 $m.s^{-1}$), which may also be another reason why wind direction did not influence the exposure variables.

Conclusion

The elevated concentrations of $PM_{2.5}$ and its carbonaceous fractions, soot, BC, and OC, observed in Bapong present significant public health concerns. $PM_{2.5}$ exposure is strongly associated with increased cardiovascular and respiratory morbidity and mortality, including outcomes such as ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), asthma exacerbations, and premature mortality (WHO, 2021; Achilleos et al., 2017; Brauer et al., 2024). Carbonaceous aerosols represent some of the most toxic components of $PM_{2.5}$. BC contributes to systemic oxidative stress and inflammation and has been consistently linked to increased cardiopulmonary mortality and hospital admissions, even at relatively low exposure levels. OC, which contains a range of reactive organic compounds, can further aggravate both respiratory and cardiovascular conditions (Burnett et al., 2022; Yan et al., 2025; Song et al., 2022). The frequency and magnitude of WHO and South African $PM_{2.5}$ guideline exceedances in this study underscore the substantial exposure burden experienced by residents. With the annual mean $PM_{2.5}$ concentration exceeding WHO guidelines more than four-fold, the local population is likely subject to increased risks of both short-term and long-term adverse health outcomes.

The results of this study indicate that Bapong faces a substantially higher health risk burden than residential or peri-urban locations such as Thohoyandou (Novela et al., 2020; Edlund et al., 2021), Bloemfontein (Van Der Westhuizen et al., 2022), Cape Town (Williams et al., 2022; Alfeus et al., 2024), Pretoria (Howlett-Downing et al., 2022) and Kimberley (Becker et al., 2024) examined in prior research. This elevated risk profile arises from several interconnected environmental and socio-economic factors. Bapong is surrounded by multiple high-intensity emission sources, including platinum mining and smelting operations, major transport corridors such as the N4 highway, agricultural burning activities, and residential areas that rely heavily on domestic solid fuels. Together, these sources contribute to continuous emissions of combustion-derived pollutants, particularly BC and soot, which are potent drivers of cardiopulmonary toxicity.

Measured levels of soot and BC in Bapong were also higher than levels reported in many earlier South African studies (Adeyemi et al., 2022; Howlett-Downing et al., 2022; Novela et al., 2020; Williams et al., 2020; Becker et al., 2024) suggesting that residents are exposed to a more toxic aerosol mixture. Given the strong and well-documented associations between BC exposure and both short- and long-term cardiopulmonary outcomes, these elevated concentrations imply a greater potential for adverse health effects in the community (Cesaroni et al., 2014; Raaschou-Nielsen et al., 2014; Yan et al., 2025). In addition to local emissions and unfavourable dispersion conditions, long-range transport contributes further to the pollutant burden in Bapong. Back-trajectory analyses show that air masses arriving at the site often pass over heavily industrialised and mining-intensive regions in Limpopo, Mpumalanga, and the Northern Cape, thereby introducing additional pollution that compounds the existing local emissions. This cumulative loading from both local and distant sources distinguishes Bapong from many other South African study locations.

Finally, the underlying vulnerability of the local population intensifies the health risks associated with these exposures. The District Health Barometer (Ndlovu et al., 2025) reports high burdens of respiratory diseases, cerebrovascular disease, hypertensive disorders, diabetes, and other conditions in the Bojanala Platinum District, many of which are known to be exacerbated by $PM_{2.5}$ (WHO, 2021; Achilleos et al., 2017). In communities where baseline disease prevalence is already elevated, additional exposure to high levels of $PM_{2.5}$, BC, and OC substantially amplifies the overall health burden. Taken together, these factors highlight the significant and multifaceted nature of the health risks faced by residents of Bapong.

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Authors' contributions

All authors contributed to the study conception and design. Boitshoko Lekwe collected the $PM_{2.5}$ filter samples, performed the soot analyses of the filter samples, conducted the statistical analyses and wrote the manuscript during her MPH studies. Adewale Adeyemi assisted with the gravimetric analysis during his postdoctoral fellowship at UP (2021-2022). Janine Wichmann, main supervisor of the first author, ran the HYSPLIT model and conducted the BC and OC measurements. Peter Molnár and Johan Boman provided access to the Model OT21 Optical Transmissometer to perform the BC and OC measurements. Anna Alfeus was the co-supervisor of the first author. All authors critically reviewed the manuscript and approved the submission.

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