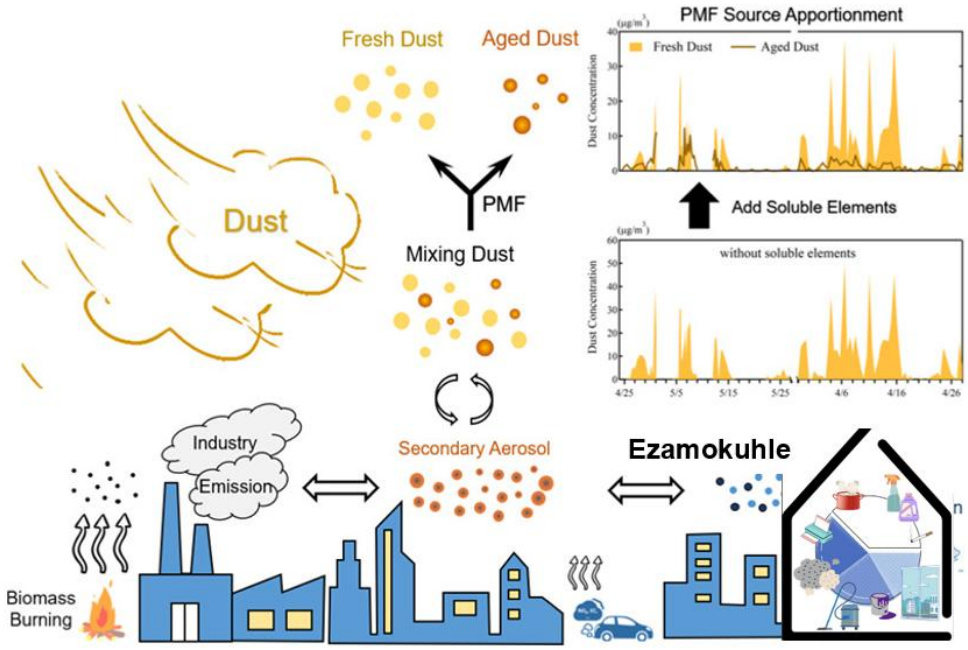
Activity 10: Source apportionment (baseline) eZamokuhle

Activity 10.8: Source apportionment (baseline) Ezamokuhle



Document by:

ARM
AIR RESOURCE MANAGEMENT

Final Report

26th March 2024

Document Title

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EXECUTIVE SUMMARY

1. Background

South African towns are characterised by elevated concentrations of particulate matter (PM) (DFFE,2023). Coarse, fine and ultrafine particulates pose both health and ecological risks and as such, legislation has been implemented worldwide to reduce these risks. For reducing the adverse health impacts from PM air pollution, it is important to know what sources (e.g., veld fires, residential, power generation etc) contribute to human exposure, and by how much. Source apportionment is a technique used to relate emissions from various pollution sources to air pollution concentrations at a given location and for a given time period.

2. Study Objective

In accordance with the scope of work, for Activity 10.8 Source apportionment (baseline) for Ezamokuhle, Air Resource Management (ARM) must undertake a scientifically credible source apportionment to identify the potential sources of the particulate matter during the winter baseline for Ezamokuhle. This report presents the results of the source apportionment winter campaign that was conducted in Ezamokuhle.

3. Study Methodology

3.1 Source Apportionment Samplers

In this study, the University of North Carolina (UNC) passive sampler were be utilised to capture the ambient particulates. These samplers have been applied for both indoor and outdoor studies and performed exceptionally well as highlighted by numerous validation studies (Leith, Sommerlatt and Boundy 2007, Ott and Peters 2007, Ott, Kumar and Peters 2007, Byeon, Willis and Peters 2007, Aseal et al 2010, Ashiro and Leith 2012, Sawvel et al 2015).

3.2 Sampling Site Selection, Consent & Analysis

For the PM source apportionment sampling campaign, 3 household outdoor sampling sites were selected in Ezamokuhle. The samplers were distributed across the area to capture the spatial

distribution of PM. It is noted that household (owner) permission was first obtained from each household prior to placing the PM samplers herein. Additionally, a fourth site was located at the Majuba Power Station Air Quality Monitoring Site (AQMS) to evaluate the PM source category footprint herein. The PM samplers were installed at all 4 sampling sites for a 3-week winter period in July 2023. The samplers were exposed to determine both the concentration & elemental composition of PM. For each sampling site, the duration of the exposure period was seven consecutive days. Thereafter the samplers were retrieved at each site and a new set of samplers were then installed. After removal from the sample holders, the samplers were analysed utilising: microscopy analysis to determine particle projected area diameters and chemical composition of particulates. Thereafter hierarchical cluster analysis was performed on multiple particle data using the Minitab software. Finally, the US EPA Positive Matrix Factorization (PMF) Model was utilised to classify the source profile for each emission source type.

4. STUDY RESULTS

4.1 PM CONCENTRATIONS

At Ezamokuhle house 1 and house 2, the concentration values were lower than at Majuba AQMS ranging between 5.1 -12.8 µg/m³ and 9.5 – 12.9 µg/m³, respectively for July 2023. Higher concentrations were measured at Ezamokuhle house 3 with values ranging from 18.7 – 44.4 µg/m³ as depicted in Figure 10. For Ezamokuhle house 3, the PM samplers were placed in the backyard. However, on the adjacent boundary wall for Ezamokuhle house 3, the neighbour (backyard shack) was utilising a coal stove and plausibly these emissions results in the elevated PM concentrations recorded herein. The average PM_{10} concentrations at Majuba AQMS ranged between 8.6 µg/m³ and 24.3 µg/m³ for the three-weekly exposure periods. It is noted herein that the duration of the exposure period was seven consecutive days, hence values are typically lower as opposed to a measured hourly exposure averaging period wherein short-term peaks are captured. It is noted that as part of Activity 10.1, the impact of short-term peaks are captured by utilising the Environmental Beta Attenuation Monitors (E-BAM) to measure baseline particulate matter) ambient concentrations in Ezamokuhle (ARM, 2024).

4.2 SOURCE CONTRIBUTIONS

4.2.1 OUTDOOR

4.2.1.1 EZAMOKUHLE HOUSEHOLDS

Figure i) illustrates the potential sources of outdoor PM that were analysed for three households at Ezamokuhle.

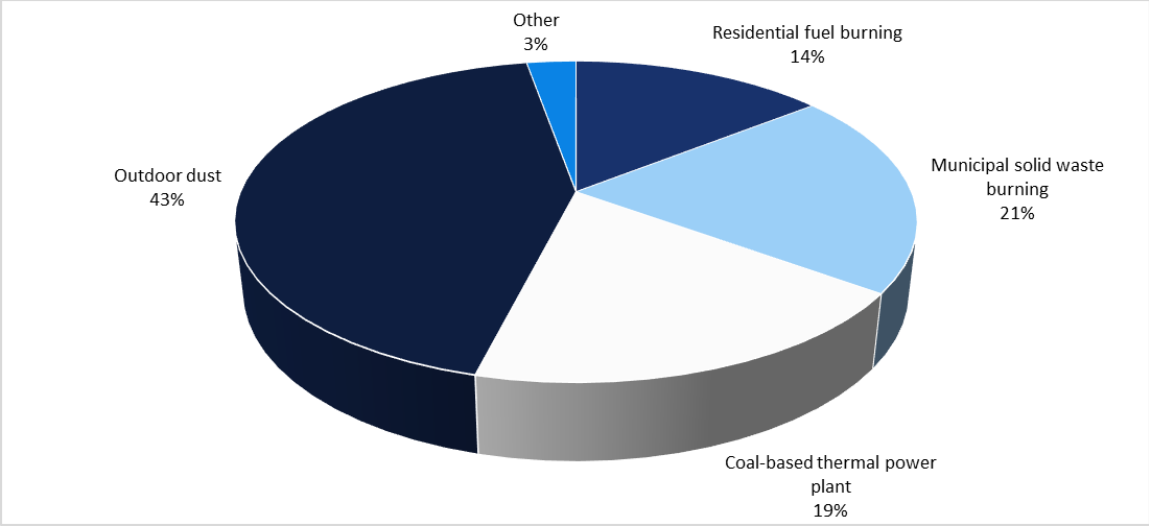

Figure i: Particulate source contribution average in ambient air for all sampled households in Ezamokuhle

Outdoor dust was found to be the largest contributing source. This is primarily from exposed surfaces like unpaved roads, unvegetated areas??, where dust usually enters the house through openings like doors, windows, vents, and wall crevices. It is noted that all of the roads outside Ezamokuhle household 1, 2 and 3 are unpaved. Mechanical disturbance of these unpaved road surfaces by vehicular and pedestrian traffic results in agitation and entrainment of the dust particles.

Burning of municipal solid waste was the second largest contributor to outdoor PM respectively for the winter sampling campaign. ARM conducted a household source survey in 2023 in Ezamokuhle (ARM, 2023) wherein the survey respondents (39%) indicated that in cases when waste was not collected the homeowner often (~39% of the time) resorted to burning the waste.

Furthermore, numerous waste piles were observed through the Rapid in-situ survey (2022) and Community source survey (ARM, 2023).

Coal-based thermal power plant emissions were the third highest source category contributing to ambient particulate matter. Particles from industrial activities are typically larger in size and have distinctive elemental compositions, making them distinguishable from other sources. In this instance, industrial emissions were taken to emanate from power generation activities in the region using coal as a thermal source.

Residential fuel burning is a significant contributor to ambient PM concentration measured at Ezamokuhle. Both the 2022 and 2023 survey campaigns have consistently demonstrated that elevated short-term PM in the winter months is clearly attributable to residential fuel burning in Ezamokuhle (ARM, 2024). The Openair analysis further supported that the elevated particulate matter concentrations occurring during winter were associated with localized non-bouyant sources (residential fuel burning) as opposed to tall stack emissions (PM) (ARM, 2024).

The source apportionment results also indicated the contribution of other sources. These sources included industrial activities and natural sources that can contribute secondary aerosols and mineral deposits.

4.2.1.2 MAJUBA AQMS

Outdoor dust was the largest PM contributor to the Majuba AQMS (Figure ii). Its noted that the area surrounding the Majuba AQMS is both sparsely vegetated and has an unpaved road surface. The mechanical disturbance of this unpaved road surface results in the entrainment of dust at the Majuba AQMS. At Majuba AQMS, emissions from a coal based thermal power plant was the second largest contributor, which is not unexpected given that the sampler was with a close proximity, downwind of the Majuba power station. Open burning of municipal solid waste and residential burning were the third and fourth largest contributors to the PM at Majuba AQMS respectively.

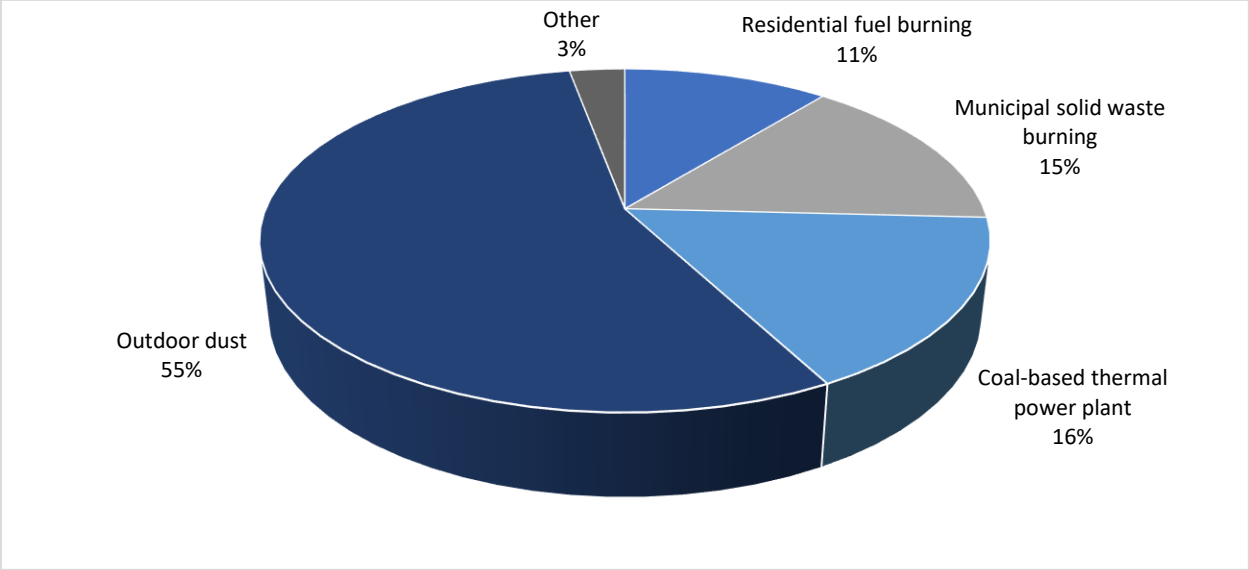

Figure ii: Source contributions of particulates found in ambient air at the Majuba AQMS

4.2.2 INDOOR

In accordance with the scope of work, for Activity 11: Indoor Air Quality Monitoring, ARM has undertaken indoor PM air quality, source apportionment and temperature measurements at Ezamokuhle. This sampling was conducted for same winter sampling period as this study. It's noted the costing and analysis for Activity 11 are separate and independent of this study (Activity 10.8).

4.2.2.1 COMPARISON OF OUTDOOR/INDOOR PARTICULATE CONTRIBUTION IN EZAMOKUHLE

A comparison of the of potential sources of outdoor and indoor PM that were analysed for three households at Ezamokuhle shows is shown in Figure iii. In general, the source contribution of PM attributable to outdoor dust; coal-based thermal plants; and municipal solid waste burning decreases substantially indoors. Furthermore, the indoor source apportionment results for PM show that a tobacco smoking signature was detected indoors. It's critical to note that indoor source

PM contribution profiles show that the dominant signature and PM contribution indoors is residential fuel burning.

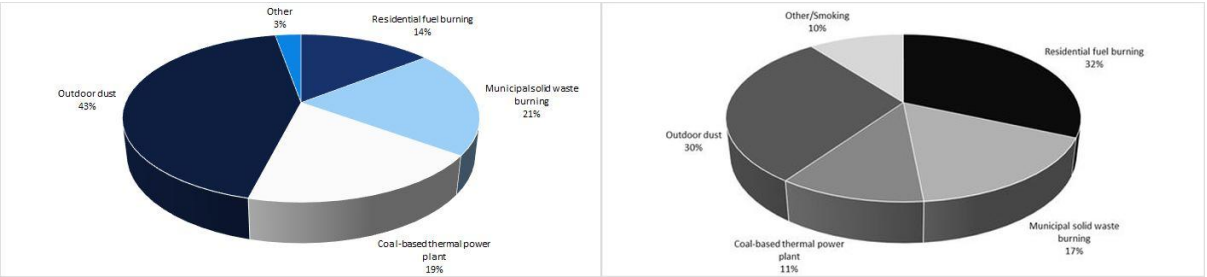

Figure iii: Comparison of the particulate source contribution at both outdoor (left) and indoor (right) for all sampled households in Ezamokuhle

5. INTERPRETATION OF RESULTS

The sources with the largest PM contributions in source apportionment studies may or may not have the most significant air quality impacts, and this depends on several factors which include *inter alia*: toxicity and health impacts; meteorology and dispersion & exposure period to PM.

The Harvard Six Cities cohort study found that fine particulate ($PM_{2.5}$) pose a greater risk to human health because this can penetrate deep into the lungs and is more toxic than larger particles (PM_{10}) (Dockery, 1993). Thus whilst, the study results have demonstrated that outdoor dust is the largest source contributor in in Ezamokuhle, its noted that these are coarser particles. Whereas residential fuel burning although a smaller source contribution poses a greater risk to human health of to the community as they are finer particulates than outdoor dust and coal-based thermal particulates.

Furthermore, air quality is strongly influenced by meteorology which covers this array of atmospheric processes. The study results have demonstrated that the ambient PM contribution of both coal-based thermal and residential emissions is of a similar magnitude however their air quality impact is not necessarily the same. Residential fuel burning has a higher air quality impact in Ezamokuhle than coal-based thermal sources due to its low release height, in adverse and

unfavourable meteorological conditions in winter that inhibit dispersion which results in elevated PM concentrations (ARM, 2024).

The WHO recommends a procedure to be followed to calculate health impacts that can be attributed to the exposure of air pollution in the Environmental Burden of Disease Series (WHO 2004). The higher the exposure period to a PM pollutant, the higher the risk of adverse human health impacts (WHO, 2005). The indoor source PM contribution results show that the dominant source is residential fuel burning. This prolonged indoor exposure to PM, particularly from the domestic use of solid fuels, has significant health implications, plausibly leading to respiratory diseases and other health conditions for the Ezamokuhle households.

6. CONCLUSION

Overall, while sources with the largest contributions are certainly important to consider in source apportionment studies, the significance of their impacts depends on a variety of factors beyond just their contribution to measured ambient PM pollutant concentrations. This includes inter alia: toxicity and health impacts; meteorology and dispersion & exposure period to PM. Taking these factors into consideration an analysis of the Ezamokuhle source apportionment results demonstrate that the residential fuel burning sources poses the greatest risk to human health of to the community. Furthermore, the indoor source contribution results shows that residential fuel burning is the most significant source of PM. Thus, its clear residential fuel burning has a significant air quality impact both outdoor and indoors in the Ezamokhule community. Therefore, it's evident that Eskom's AQO household interventions which are been rolled out have the potential to reduce indoor PM concentrations and ultimately reduce ambient concentrations due to the reduction in use of solid fuels for space heating and for cooking. Hence supporting the roll-out of Eskom's PMV air quality offset household intervention project in Ezamokuhle.

1. BACKGROUND

1.1 Air Quality Offsets Guideline

An environmental offset is an action(s), designed to compensate for a negative environmental impact of resource use, a discharge, emission, or other activity. The Department of Environment, Forestry & Fisheries (DEFF) defines air emissions offsets as an intervention, or interventions, specifically implemented to counterbalance the adverse and residual environmental impact of atmospheric emissions in order to deliver a net ambient air quality benefit within, but not limited to, the affected airshed where ambient air quality standards are being or have the potential to be exceeded and whereby opportunities and need for offsetting exist (Notice 333 of 2016).

1.2 ESKOM'S Approach to Air Quality Offsets

DEFF's Air Quality Offset Guideline has shaped and informed Eskom's Air Quality Offsets Implementation Plan. This Plan has been based on a scientific process of feasibility studies, testing and demonstration, and on consultation with key stakeholders. Figure 1 illustrates the concept schedule for the phased implementation of Eskom's air quality offsets.

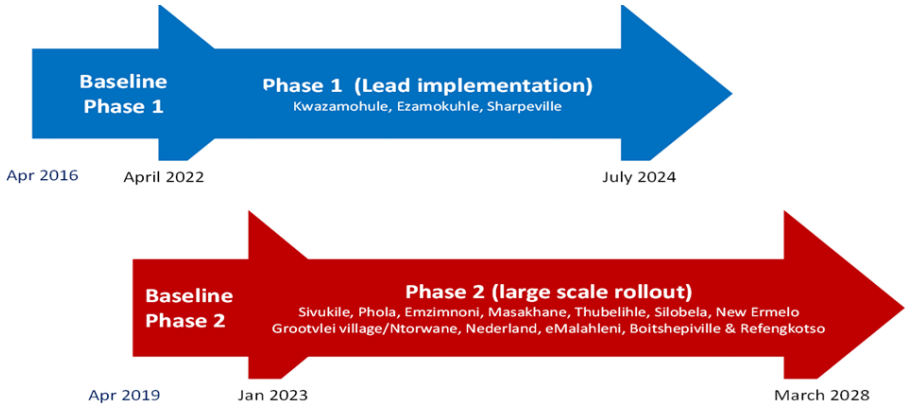

Figure 1: Concept Schedule for the implementation of Eskom's air quality offsets (Matimolane, 2023).

Eskom has adopted the phased approach (Figure 2) herein to increase the probability of success and to ensure that learnings from early phases are incorporated into the large-scale roll-out. (Matimolane, 2020).

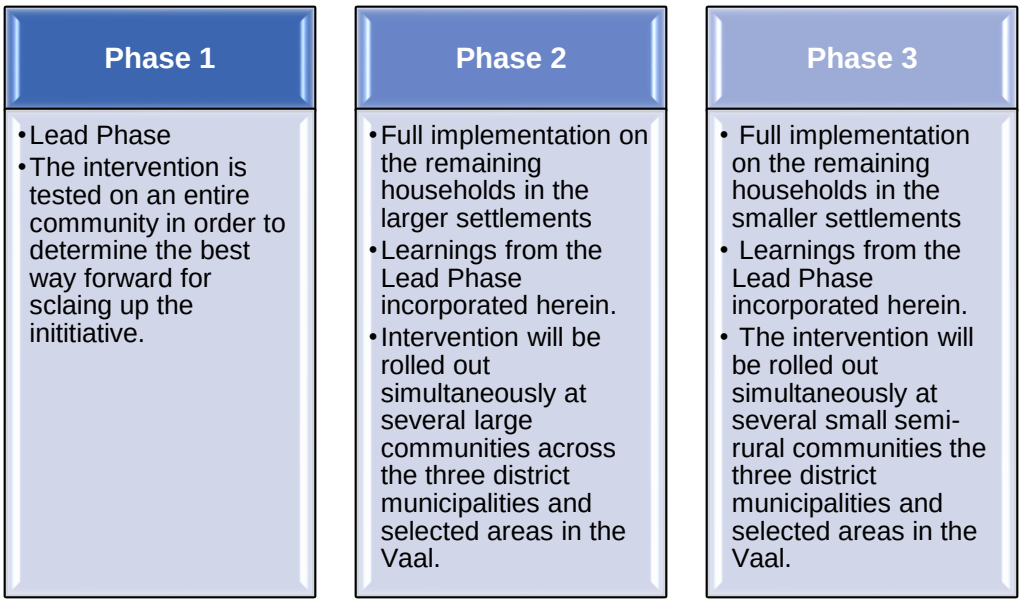

Figure 2: Eskom's Phased approach to the rollout of air quality offset interventions (Matimolane, 2020).

Eskom's air quality offsets programme is designed to reduce human exposure to harmful levels of air pollution by reducing emissions from local sources, like domestic coal burning and waste burning. Thus, air quality offsets can improve ambient air quality in low-income communities in the vicinity of Eskom's power stations. Eskom has developed air quality offset (AQO) implementation plans for Majuba Power Station (Ezamokuhle township); Hendrina Power Station (KwaZamokuhle township) and Lethabo Power station (Sharpeville).

1.3 ESKOM'S PLANNING, MONITORING AND VERIFICATION (PMV) PROJECT

For Eskom's PMV Project, interventions to reduce household emissions from domestic coal/wood burning will be rolled out in KwaZamokuhle and Ezamokuhle in the Mpumalanga Highveld. For formal dwellings the intervention will be a thermal insulation retrofit and an electricity starter pack and installation. The intervention for informal dwellings still needs to be selected and tested. Interventions also need to be identified and implemented to improve air quality in Sharpeville, Gauteng. Since domestic coal burning is less prevalent in Sharpeville, it is expected that a community-scale intervention, like reducing waste burning, will be more suitable there.

Air Resource Management (ARM) (Pty) Ltd has been appointed by Eskom to support the PMV services in support of the *Phase 1: Lead implementation* at: KwaZamokuhle; Ezamokuhle and Sharpeville. Its ARM (Pty) Ltd understanding that the overall objective *Lead Implementation Phase* is to benefit the specific local communities, minimize implementation risk, increase practical and scientific knowledge, and develop and refine monitoring, reporting and verifications processes. To achieve this, Eskom has included sixteen targeted work package Activities (Table 1) for these respective communities. This report focuses on *Activity 10.8 Source apportionment (baseline) for Ezamokuhle.*

Table 1: Eskom PMV Activity Schedule (Eskom PMV NEC Contract,27082020)

Activities	Kwazamokuhle	Ezamokuhle	Sharpeville
Activity 1: Preliminary air quality assessment		✓	
Activity 2: Gather Area intelligence		✓	
Activity 3: Rapid in situ assessment		✓	
Activity 4: Obtain ethical clearance		✓	
Activity 5: Census	✓	✓	✓
Activity 6: Community source survey		✓	
Activity 7: Fuel source survey		✓	
Activity 8: Household surveys		✓	
Activity 9: Annual (household/community) surveys and monitoring of project effectiveness	✓	✓	✓
Activity 10: Ambient air quality monitoring	✓	✓	✓
Activity 11: Conduct indoor air quality monitoring	✓	✓	
Activity 12: Atmospheric Dispersion Model	✓	✓	✓
Activity 13: Design of Intervention		✓	✓
Activity 14: Development of Database Reporting	✓	✓	✓
Activity 15: Strategic Assistance and offsets methodology	✓	✓	✓
Activity 16: Research and Development	✓	✓	✓

1.4 Scope of Work

In accordance with the scope of work, for *Activity 10.8 Source apportionment (baseline) for Ezamokuhle*, ARM must undertake a scientifically credible source apportionment to identify the potential sources of the particulate matter during the winter baseline for Ezamokuhle. The analysis and interpretation of the source apportionment results is to be completed within 6 months of the samples being collected for the campaign. This report presents the results of the baseline source apportionment winter campaign that was conducted in Ezamokuhle in 2023. Its noted that post the full-scale roll-out of Eskom's AQO intervention in Ezamokuhle, the study will be again repeated in the winter of 2024.

2. INTRODUCTION

2.1 PARTICULATE MATTER

South African towns are characterised by elevated concentrations of particulate matter (PM) as illustrated by Figure 3 and Figure 4.

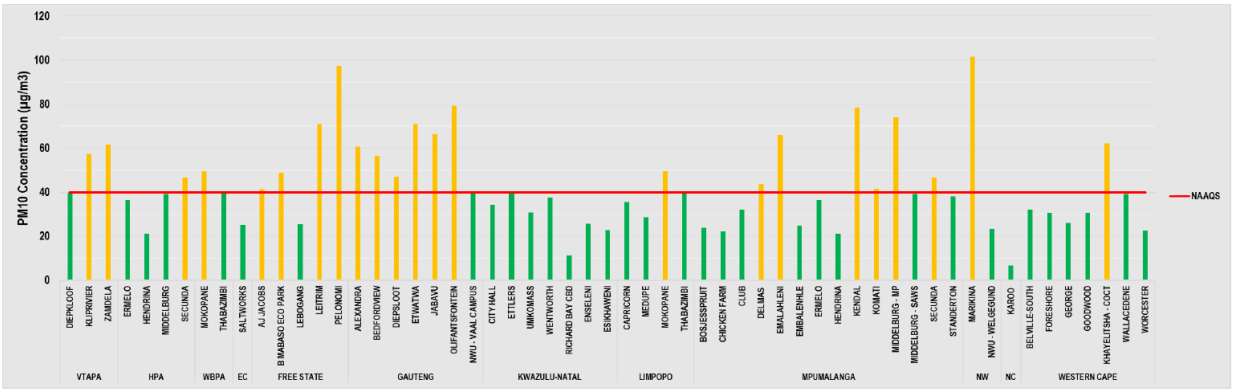

Figure 3: 2021 annual average for PM_{10} (Source: DFFE 2022 State of Air Report, DFFE 2023)

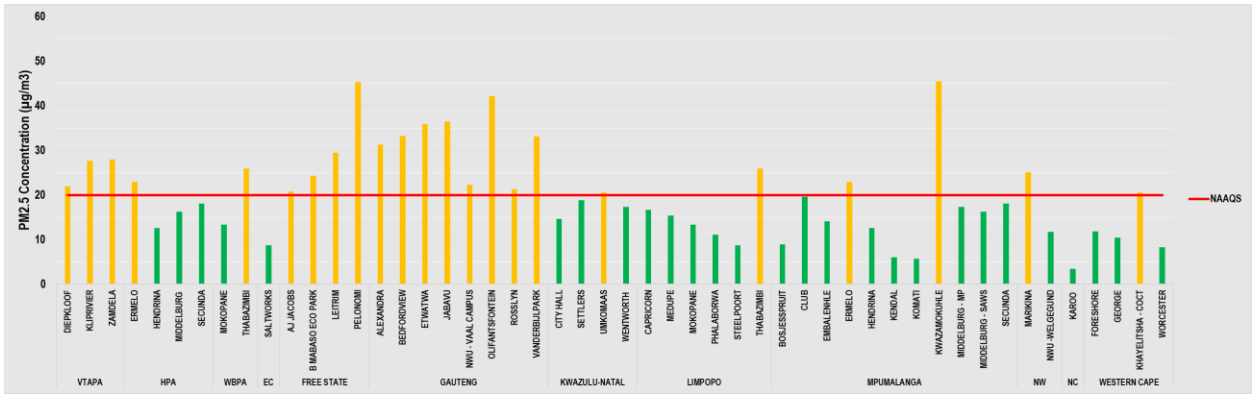

Figure 4: 2021 annual average for $PM_{2.5}$ (Source: DFFE 2022 State of Air Report, DFFE 2023)

PM represents a complex mixture of organic and inorganic substances as well as a mixture of primary and secondary compounds. Primary compounds are emitted directly to the atmosphere from sources such as industrial activity, transportation, power generation and natural processes (e.g., windblown dust, oceanic bubble bursting and volcanic eruptions) while secondary particles emanate from gas-to-particle conversions and heterogeneous reactions within the atmosphere (Keywood, 2016) (Table 2).

Table 2: Particle sources and their causal action

Source Type	Source	Causal Action
Natural	**Volcanic Eruption**	Release of solid particles, gases and heat waves
	Sandstorm	Dust particles spread through wind circulation around the Earth
	Vegetation fire	Smoke from wildfire and forestry management
	Plant pollen	Spread of plant pollen spread through wind motion
	Sea spray	Liquid droplets spread through wind near coastlines
Man-made	**Transport**	Combustion of petrol/diesel and generation of particles and gases
	Power generation	Release of particles and gases of combustion
	Industry	Manufacturing and processing of steel, non-iron metals, textiles, refining of petroleum, handling of materials
	Construction	Particle pollution due to material handling and other associated activities
	Agriculture	Emissions from ploughing and the use of fertilisers, pesticides and insecticides
	Leisure activities	Emissions from motor racing, barbeque, boats, private planes, lawnmowers, and other leisure-related appliances

Particles are distinguished as coarse, fine and ultrafine. Coarse particles are those of size between 10 and 2.5 μm (PM10-2.5); fine particles are those with an equivalent aerodynamic diameter of 2.5 μm and less (denoted as PM2.5) and ultrafine particles are those of size less than 0.1 μm (Schwela, 2010).

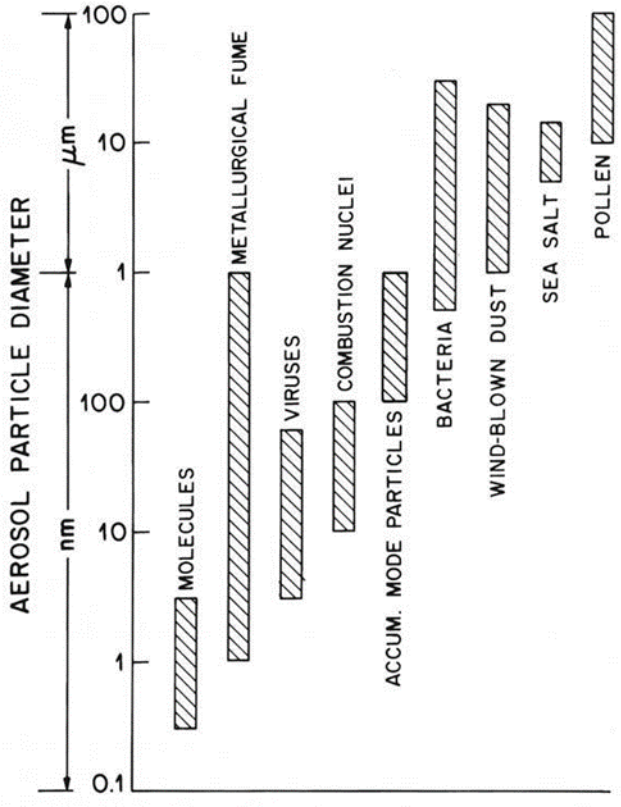

Figure 5: Characteristic size ranges of particles from different sources with molecular sizes shown for comparison (Source: Tiwary and Colls, 2013)

2.2 Impact Of Particulate Matter

Coarse, fine and ultrafine particulates pose both health and ecological risks and as such, legislation has been implemented worldwide to reduce these risks.

2.2.1 Health Impact

The health effects of airborne particles have been extensively investigated (Dockery et al., 1993; Pope III et al., 2002; U.S. Environmental Protection Agency, 2004; Pope, 2007). PM has been strongly correlated to several adverse human health effects including an upsurge in hospital admissions and emergency room visits, respiratory symptoms, exacerbation of chronic respiratory and cardiovascular diseases, decreased lung function, and premature mortality.

2.2.2 Impact on Vegetation

PM is also known to affect vegetation resulting in reduced biodiversity and the loss of ecosystem (Westman, 1977). Exposure of vegetation to ambient PM can occur either on the vegetative surfaces, through the soil or both. The particulate deposition and its subsequent effects on vegetation include but are not limited to; (1) nitrate and sulphate and their associations in the form of acidic and acidifying deposition and (2) trace elements and heavy metals, including lead (Whitby, 1978).

2.3 Source Apportionment

For reducing the adverse health impacts from PM air pollution, it is important to know what sources (e.g., veld fires, residential, power generation) contribute to human exposure, and by how much (Figure 6). Source apportionment is a technique used to relate emissions from various pollution sources to air pollution concentrations at a given location and for a given time period (Thunis, 2020). In this study a source apportionment analysis of particulate matter is conducted during winter in Ezamokuhle.

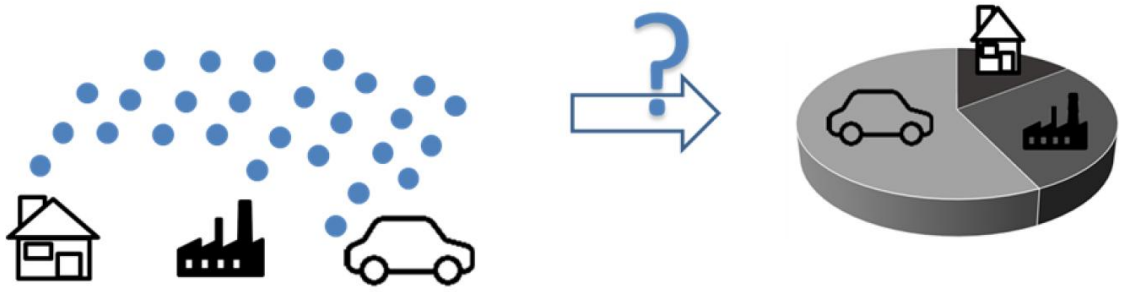

Figure 6: Objective of source apportionment

3. METHODOLOGY

3.1 SOURCE APPORTIONMENT SAMPLERS

In this study, the University of North Carolina (UNC) passive sampler developed by Wagner and Leith (2001) were utilised to capture the ambient particulates. These samplers have been applied for both indoor and outdoor studies, (Leith, Sommerlatt and Boundy 2007, Ott and Peters 2007, Ott, Kumar and Peters 2007, Byeon, Willis and Peters 2007, Aseal et al 2010, Ashiro and Leith 2012, Sawvel et al 2015). These samplers have performed exceptionally well as highlighted by the validation studies in Table 3.

Table 3: Summary of validation studies conducted with UNC passive samplers

Reference	Result or conclusion
(Wagner & Leith, 2001)	R^2=0.80 and R^2=0.93 for $PM_{2.5}$ and PM_{10} respectively. A coefficient of variation (CV) of 20 % was recorded.
(Ott, Cyrs, et al., 2007)	R^2=0.97 for PM_{10} and a CV of 11.6 %
(Leith et al., 2007)	Measured concentrations were found to be within one standard deviation of the concentrations measured with the FRM samplers and ranged from 10 µg/m³ to 40 µg/m³.
(Ott, Kumar, et al., 2007)	The weekly CV (23 % ≤ CV ≤ 29 %) was greater than the criteron of 20 % to indicate heterogeineity and the maximum coefficient of divergence (COD) ranged between 0.21 to 0.36 which is above the criterion suggested by the EPA to indicate heterogeinity.
(Assael et al., 2010)	No statistical procedures were employed in this study to determine the exact agreement with the reference methods although the authors concluded the results recorded using passive samplers are in good agreement with those from the official monitoring stations.
(Arashiro & Leith, 2013)	Samplers provided mass concentrations of $PM_{2.5}$ and PM_{10} in the field with relative standard deviations that approach 15 % with greater precision associated with higher concentrations ($PM_{2.5}$ > 5 µg/m³ and PM_{10} > 20 µg/m³)
(Sawvel et al., 2015)	The work demonstrated that some components of coarse particles are considerably more spatially heterogeneous than other components and PM_{10} mass in general.

The sampler consists of a standard scanning electron microscope (SEM) stub, a collection substrate, and a protective mesh cap (Figure 7). During sampling, particles are transported by gravity, convective diffusion, and inertia through the 157 μm-diameter

holes of the mesh cap and deposit on a substrate mounted on the stub. The stub is oriented such that the substrate axis lies parallel to and is in the same plane as that of the stub, (i.e. horizontal). After sampling, the mesh cap is removed, the stub can be placed in an SEM, (if the substrate is a poly-carbonate tape), or on an optical microscope, and the particles are counted and sized to determine the particle flux. For this study, the substrate is a glass cover that was analysed using an optical microscope.

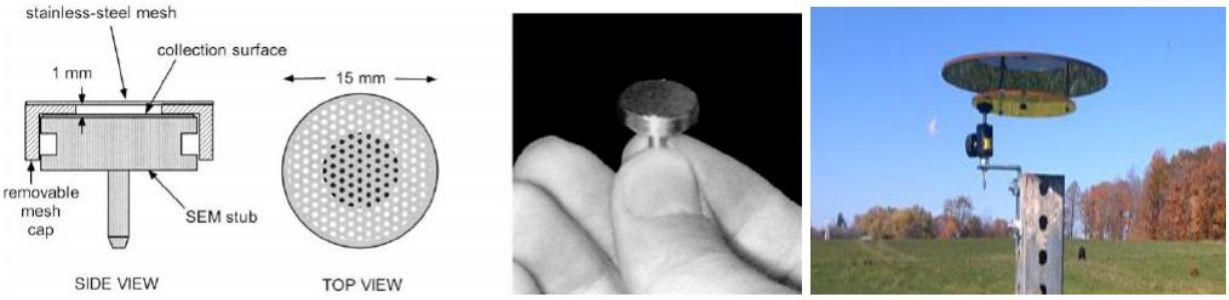

Figure 7:The UNC Passive Aerosol Sampler (Wagner and Leith, 2001)

3.2 SAMPLING

3.2.1 SAMPLING SITE SELECTION & CONSENT

The location and the positioning of the PM samplers were chosen based on the results of the *Baseline Modelling Assessment Report for Ezamokuhle* (ARM, 2021a). Based on this study, the prioritisation of air quality hotspots for Ezamokuhe was ranked on the basis of highest predicted impacts. This ensured that the areas that potentially pose the greatest particulate matter risk to human health and the environment were identified for optimum placement of the active ambient air quality analysers.

The *Baseline Modelling Assessment Report for Ezamokuhle* demonstrated that the highest predicted model concentrations occurred in China 2 (ARM, 2021a). Thus China

2 was identified as the highest priority air quality hotspot in Ezamokuhle. Thus, for the PM source apportionment sampling campaign, 3 household sampling sites were selected in Ezamokuhle (Figure 8). The samplers were distributed across the area to capture the spatial distribution of PM. Its noted household owner permission and consent was first obtained from each household prior to placing the PM samplers herein. Additionally, a fourth site was located at the Majuba Power Station AQMS to evaluate the PM source category footprint herein (Figure 8).

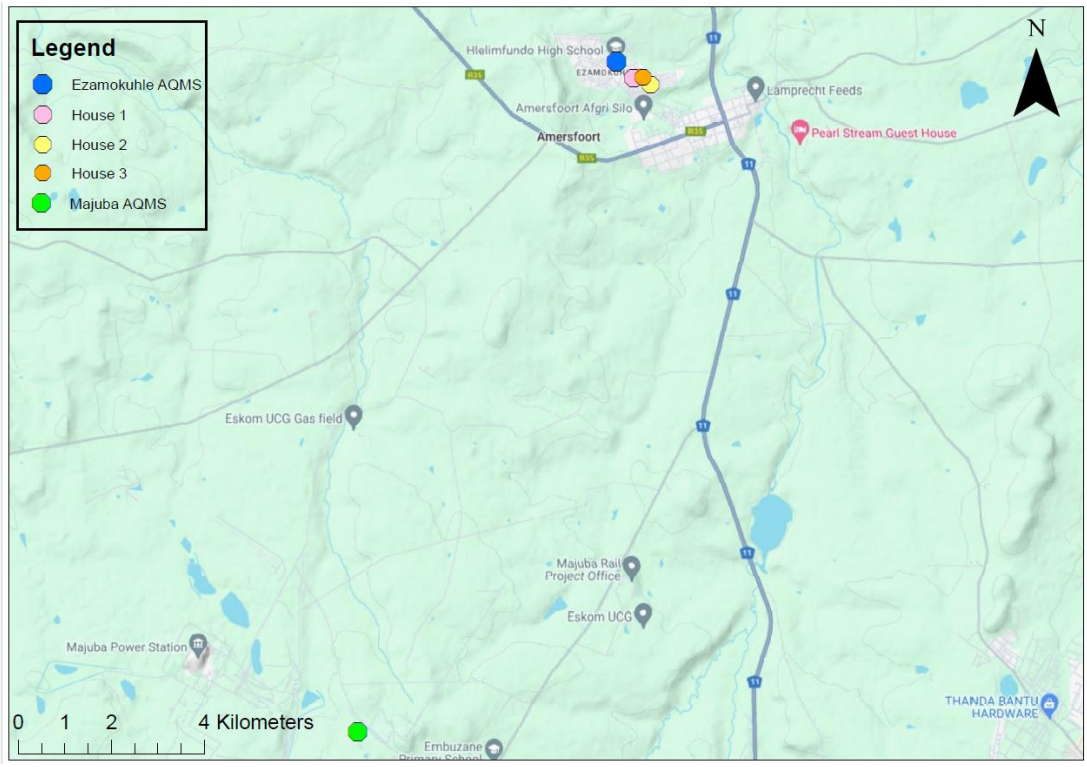

Figure 8: Location of the PM source apportionment sampling sites at the Ezamokuhle households and the Eskom Majuba AQMS

3.2.2 Sampling Period

The PM samplers were installed at all 4 sampling sites (Figure 8) for a 3-week winter period in July 2023. The samplers were exposed to determine both the concentration & elemental composition of PM. For each sampling site, the duration of the exposure period was seven consecutive days. Thereafter the samplers were retrieved at each site and a new set of samplers were then installed.

Its noted that a blank sampler was prepared, taken along with the other samplers to capture any artifacts that may arise during the transportation and handling process but not exposed. This blank sampler was also analysed to calculate and eliminate the error in the sampling process and to determine the limit of detection (LoD) and the limit of quantification (LoQ).

3.3 Source Apportionment Analysis

3.3.1 Microscopy Analysis

After removal from the sample holders, the samplers are transported back to the lab in airtight polytope bottles. The elemental composition of individual particles deposited on the passive sampler were determined by Computer Controlled Scanning Electron Microscopy with Electron Dispersion Spectroscopy (CCSEM -EDS) using the Zeiss Gemini 2 Crossbeam 540 FEG SEM. Energy-dispersive X-ray spectroscopy (EDS, also abbreviated EDX or XEDS) is an analytical technique that enables the chemical characterization/elemental analysis of materials.

A sample excited by an energy source (such as the electron beam of an electron microscope) dissipates some of the absorbed energy by ejecting a core-shell electron. A higher energy outer-shell electron then proceeds to fill its place, releasing the difference in energy as an X-ray that has a characteristic spectrum based on its atom of origin. This allows for the compositional analysis of a given sample volume that has been excited by

the energy source. The position of the peaks in the spectrum identifies the element, whereas the intensity of the signal corresponds to the concentration of the element.

Before sample analysis with CCSEM - EDS, the samples on the carbon substrate were coated with a thin layer of graphitic carbon under vacuum to clean off the charges induced by the electron beam in the SEM. The samples on the glass substrate were coated with a thin gold film to pick up any traces of carbonaceous material in the analyte. One control substrate was also coated with carbon to determine whether the other non-carbonaceous elements sampled are comparable to the gold coated substrates.

Analysis to acquire images to be used in determining the particle size distribution involved using a voltage of 1 kV at a working distance of 4.7 mm and at a magnification of 350 X. For the EDS to determine particle composition, the voltage was accelerated to 20 kV at a working distance of 7.3 mm and at a magnification ranging from 650 X to 950 X. During analysis, individual particles were selected for analysis. While substrate overloading was not generally an issue, care was taken to only select non-aggregated particles (i.e., distinct from neighbouring particles). This approach served to minimize interference between particles for elemental analysis but does assume that the distribution of non-aggregated particles on the sample filters is representative of the overall particle distribution.

For each particle, two main types of data were collected: (1) dimensions, and (2) the elemental spectra. The dimensions were used to determine particle projected area diameters and chemical composition of particulates.

The procedure to calculate PM concentrations from the imaged and analysed particles is outlined in Annexure 1.

3.3.2 Cluster Analysis

Data obtained from CCSEM is semi-quantitative, and therefore, to use the data for source contributions the particles need to be classified into homogenous groups by applying cluster analysis (Kim and Hopke, 2008; Lagudu et al., 2011; Song and Hopke, 1996.

Cluster analysis has been described in detail by Buhot and Krauth, (1999). In this study, hierarchical cluster analysis was performed on multiple particle data from SEM-EDS using Minitab software. Once the analyses were completed, cluster groups were assigned based on the weight percentage of 10 particles from each site (excluding the elements classified as miscellaneous).

Strong, weak and bad variables were designated for positive matrix factorisation (PMF) analysis, following the recommendations in the PMF user manual (Reff et al., 2007; Sierra-Vargas et al., 2009). This designation is based on the signal/noise ratio in such a way that variables with high uncertainty (noise) are weighed less than variables with low uncertainty. The spectral peak heights are used to classify particles by their mineralogy.

For a particle to be classified into a given category, the observed dominant elements spectral peak heights must exceed the minimums shown in Table 4. It should be noted that the atomic percentage equivalents shown in Table 4 are operationally defined (i.e., based experience of the author and preliminary analysis of many known particle compositions), and are not representative of stoichiometry expected in the mineral(s) in each category. This is because significant interference from the substrate background cannot be avoided for most particles in the respirable size range.

Table 4: Description of dust categories for particle classification by composition

Dust Category	Example Mineralogy	Parameters for Classification (Atomic % Equivalents)	Real Time Classification (Raw Peak Heights (Cps/eV))
Carbonaceous	Coal	Carbon ≥ 70% Oxygen ≤ 30%	*Carbon ≥ 80* *Oxygen ≤ 20*
Mixed Carbonaceous	Very thin clay minerals, or clay minerals with some carbon content.	4% > Silicon ≥ 2% 4% > Aluminium ≥ 2% Carbon > 70% Oxygen < 20%	*20 > Silicon ≥ 10* *20 > Aluminium ≥ 10* *Carbon ≥ 80* *Oxygen ≤ 20*
Alumino-silicate	Clay minerals, feldspars	Silicon ≥ 4% Aluminium ≥ 3% Oxygen > 20%	*Silicon ≥ 20* *Aluminium ≥ 20* *Oxygen > 20*
Quartz	Crystalline silica	Silicon ≥ 5% Oxygen > 20%	*Silicon ≥ 20* *Oxygen > 20*
Carbonate	Calcite, dolomite	Calcium/Magnesium ≥ 5% Oxygen > 20% Carbon < 70%	*Calcium/Magnesium ≥ 20* *Oxygen > 20* *Carbon < 80*
Heavy Mineral	Pyrite, titanium oxides	Iron/Titanium/Aluminium ≥ 5% Oxygen > 20%	*Iron/Titanium/Aluminium ≥ 20* *Oxygen > 20*

To identify composite particles, (i.e., those particles that contain more than one mineral), a mineral list that contains both minerals and mineral groups as well as elemental carbon and the manmade compound, stainless steel may be referred to. The elemental composition of the minerals included in the mineral reference library is shown in Figure 9. The mineral references are generally assigned form the particle elemental compositions to assign a stoichiometric composition and standard mineral formula.

Mineral	IMA Abbrev	Density	Formula	Al (%)	Ca (%)	Cl (%)	Cr (%)	Cu (%)	F (%)	Fe (%)	H (%)	K (%)	Mg (%)	Na (%)	Ni (%)	O (%)	P (%)	S (%)	Si (%)	Ti (%)	Unknown (%)	Zr (%)
Chalcopyrite	Ccp	4.2	$CuFe_2S_2$	0	0	0	0	34.62	0	30.43	0	0	0	0	0	0	0	34.94	0	0	0	0
Pyrite	Py	5.01	FeS_2	0	0	0	0	0	0	46.54	0	0	0	0	0	0	0	53.46	0	0	0	0
Chlorite *	Chl	3	CLO_2^-	8.72	0	0	0	0	0	18.05	1.3	0	11.78	0	0	46.53	0	0	13.62	0	0	0
Muscovite	Ms	2.83	$KAl_2(Si_3Al)O_{10}(OH)_2$	20.3	0	0	0	0	0.95	0	0.45	9.8	0	0	0	47.36	0	0	21.13	0	0	0
Amphibole *	Amp	3.4	$Mg_7Si_8O_{22}(OH)_2$	3	18.02	0	0	0	0	0	0	0	7.88	0	0	45.06	0	0	26.03	0	0	0
Quartz	Qz	2.63	SiO_2	0	0	0	0	0	0	0	0	0	0	0	0	53.26	0	0	46.74	0	0	0
Plagioclase *	Pl	2.62	$Na(AlSiO_3O_8)$	10.29	0	0	0	0	0	0	0	0	0	8.77	0	48.81	0	0	32.13	0	0	0
Orthoclase	Or	2.56	$K(AlSi_3O_8)$	9.69	0	0	0	0	0	0	0	14.04	0	0	0	45.99	0	0	30.28	0	0	0
Kaolinite	Kln	2.6	$Al_2Si_2O_5(OH)_4$	20.9	0	0	0	0	0	0	1.56	0	0	0	0	55.79	0	0	21.75	0	0	0
Zircon	Zrn	4.65	$Zr(SiO_4)$	0	0	0	0	0	0	0	0	0	0	0	0	34.91	0	0	15.32	0	0	49.76
Magnesium Silicate	---	3.3	$MgSiO_3$	0	0	0	0	0	0	0	0	0	24.22	0	0	47.81	0	0	27.98	0	0	0
Calcium Silicate	---	3.9	$Ca_3Fe^{3+}_2(SiO_4)_3$	0	23.65	0	0	0	0	21.97	0	0	0	0	0	37.79	0	0	16.58	0	0	0
Clinochlore	Clc	2.65	$Mg_5Al(AlSi_3O_{10})(OH)_8$	13.18	0	0	0	0	0	9.09	1.31	0	15.83	0	0	46.88	0	0	13.72	0	0	0
Iron Oxide	---	5.2	Fe_2O_3	0	0	0	0	0	0	72	0	0	0	0	0	28	0	0	0	0	0	0
Magnesium Oxide	---	3.8	MgO	0	0	0	0	0	0	0	3.6	0	41.6	0	0	54.8	0	0	0	0	0	0
Aluminium Oxide	---	3.04	AlO(OH)	44.97	0	0	0	0	0	0	1.68	0	0	0	0	53.35	0	0	0	0	0	0
Ilmenite	Ilm	4.72	$Fe^{2+}Ti^{4+}O_3$	0	0	0	0	0	0	36.8	0	0	0	0	0	31.64	0	0	0	31.56	0	0
Stainless Steel **	---	7.8	FeCr...	0	0	0	16	0	0	67	0	0	0	0	10	0	0	0	0	0	0	0
Aluminium	Al	2.7	Al	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Calcite	Cal	2.71	$Ca(CO_3)$	0	35	0	0	0	0	0	0	0	0	0	0	65	0	0	0	0	0	0
Gypsum	Gp	2.3	$Ca(SO_4)\cdot 2H_2O$	0	23.27	0	0	0	0	0	2.34	0	0	0	0	55.77	0	0	18.62	0	0	0
Sylvite	Syl	1.99	KCl	0	0	47.55	0	0	0	0	0	52.45	0	0	0	0	0	0	0	0	0	0
Halite	Hl	2.17	NaCl	0	0	60.67	0	0	0	0	0	0	0	39.33	0	0	0	0	0	0	0	0
Apatite *	Ap	3.19	$Ca_5(PO_4)(F,Cl,OH)$	0	39.37	2.32	0	0	1.24	0	0.06	0	0	0	0	38.76	18.25	0	0	0	0	0
Carbon ***	---	2.26	C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unknown		3		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0
Low_Counts		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0
No_XRay		0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	0

Figure 9: Mineral reference library extracted from the Minerals Liberation Analyser software

3.3.3 Source Profiling

Source profiling was assigned based on the associated chemical species found in literature for the possible sources that exist within the study area. Four likely sources that could lead to the deterioration of the air quality in the households are outlined (Table 5) and are:

- Domestic coal burning,
- Biomass burning,
- Outdoor and resuspended dust,
- Coal based thermal power plant
- Cooking, and
- Smoking.

Table 5: Source profiling as contained in literature

Source	Source Signatures	Reference
Residential solid fuel burning	As, Cr, K, NO_3^-, K^+, and EC F^-, As, Mg^{2+}, Ca^{2+}, Cr, and K^+ K, EC, OC, and Br OC, EC, K^+, and Cl^-	(Bano, et al., 2018), (Matawle, et al., 2015) (Gittikunda, 2009)
Biomass burning	C-rich, S-minor, K-rich	(Ballesteros-González , et al., 2020; Coelho Junior, et al., 2018; Colombi, et al., 2010; Cheng, et al., 2014).
Residential Kerosene stoves	K, Pb, V, NH_4^+, K^+, and EC Pb, Cd, Sb, F^-, Se, and V	(Bano, et al., 2018) (Matawle, et al., 2015)
Residential LPG stoves	Mo, Pb, Se, K^+, OC, and EC Sb, Cd, Pb, S, Mo, and Se	(Bano, et al., 2018) (Matawle, et al., 2015)
Smoking	EC, N-O	(Hoh, et al., 2012; Whitehead, et al., 2015; Sleiman, et al., 2014)
Municipal solid waste burning	Cd, K, Mo, NO_3^-, K^+, and OC F^-, Co, Cd, Ca^{2+}, Na^+, and K^+ K, Zn, Pb, and Sb OC, EC, K^+, As, Pb, and Zn Zn, Sb, Cu, Cd, and Hg	(Bano, et al., 2018) (Matawle, et al., 2015) (Gittikunda, 2009) (Watson, et al., 2017) (Mitra, et al., 2002)
Coal based thermal power plant	As, S, F-, $NO3^-$ K^+, and Mg^{2+} As, Cr, S, F–, NO_3−, and Al Zn, NO_3^-, Mg^{2+}, Cl^-, S, and Ni Al, Sc, Se, Co, As, Ti, Th, and S Se, As, Cr, Co, Cu, and Al	(Bano, et al., 2018) (Matawle, et al., 2015) (Kong, et al., 2014) (Gittikunda, 2009) (Mitra, et al., 2002)
Outdoor Dust	Mg-rich, Fe-rich, Si-rich, O-rich, Cr-rich,	(Akkaş et al., 2015; Campos-Ramos et al., 2009; de Boer & Crosby, 1995; Fuller et al., 2015; Illi et al., 2017)

4. STUDY RESULTS

As outlined in section 3.2.1, three outdoor household sites in Ezamokuhle and a fourth located at the Majuba Power Station AQMS were selected for the source apportionment sampling campaign. During the three weeks of sampling, the samples with the highest concentrations were used to identify outdoor sources at the four sites.

4.1 PM CONCENTRATIONS

Table 6 provides the calculated PM_{10} and $PM_{2.5}$ concentrations at the different outdoor locations over a three-week period. The average PM_{10} concentrations at Majuba AQMS ranged between 8.6 µg/m³ and 24.3 µg/m³ for the three-weekly exposure periods. Its noted herein that the duration of the exposure period was seven consecutive days, hence values are typically lower as opposed to a measured hourly exposure averaging period wherein short-term peaks are captured. Its noted that as part of Activity 10.1, the impact of short-term peaks are captured by utilising the Environmental Beta Attenuation Monitors (E-BAM) to measure baseline particulate matter (PM_{10} and $Pm_{2.5}$) ambient concentrations in Ezamokuhle (ARM, 2024).

At Ezamokuhle house 1 and house 2, the concentration values were lower than at the Majuba AQMS ranging between 5.1 -12.8 µg/m³ and 9.5 – 12.9 µg/m³, respectively. Higher concentrations were measured at Ezamokuhle house 3 with values ranging from 18.7 – 44.4 µg/m³ as depicted in Figure 10. For Ezamokuhle house 3, the PM samplers were placed in the backyard. However, on the adjacent boundary wall for Ezamokuhle house 3, the neighbour (backyard shack) was utilising a coal stove (Figure 12) and plausibly these emissions results in the elevated PM concentrations recorded herein.

The highest $PM_{2.5}$ concentrations were measured at Majuba AQMS with values ranging between 6.1 – 17.6 µg/m³ while the lowest were measured at Ezamokuhle house 2 and ranged between 3.7 – 7.2 µg/m³. PM2.5 concentrations at Ezamokuhle house 1 and house 3 ranged from 5.8 – 9.5 µg/m³ and 6.5 – 13.7 µg/m³, respectively, as illustrated in Figure 11.

Table 6: Measured PM_{10} and $PM_{2.5}$ concentrations (µg/m³) at the four outdoor locations

Site	Week 1		Week 2		Week 3	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Eza House 1	6.2	7.3	5.1	5.8	12.8	9.5
Eza House 2	10.4	6.2	9.5	3.7	12.9	7.2
Eza House 3	44.1	13.7	18.8	6.5	21.5	7.3
Majuba AQMS	23.4	17.6	8.6	9.4	13.6	6.1

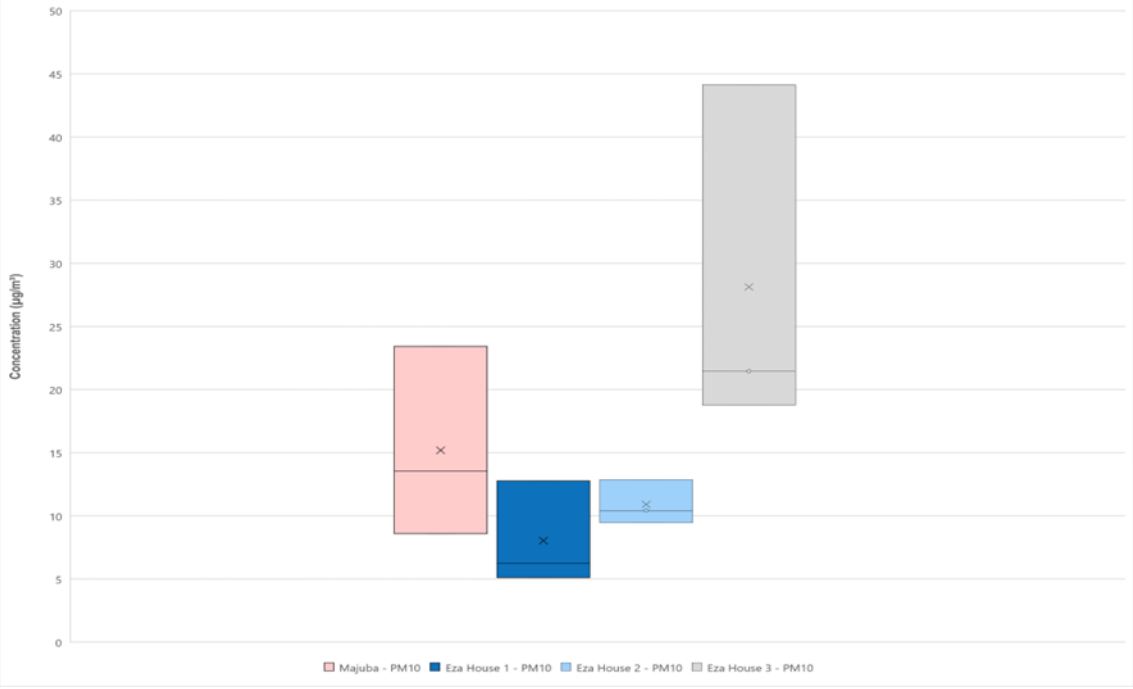

Figure 10: Box and whisker plot of PM_{10} concentrations measured at the four sampling sites

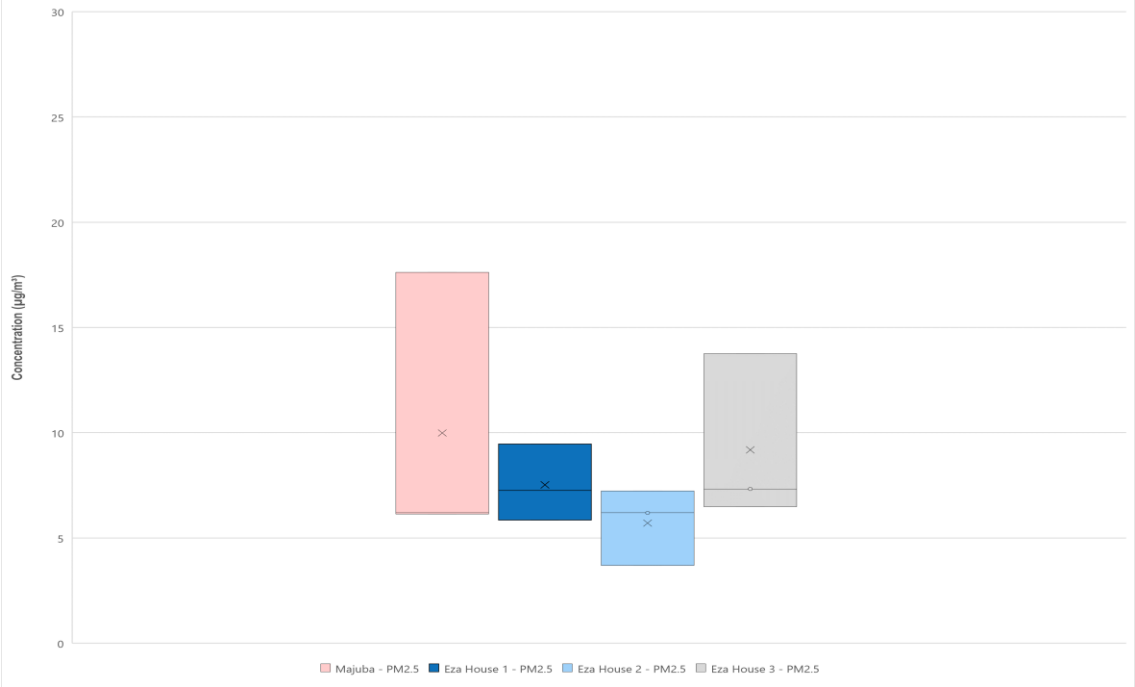

Figure 11: Box and whisker plot of $PM_{2.5}$ concentrations measured at the four sampling sites

Figure 12: Adjacent backyard shack RFB emissions contributing to elevated PM concentration at Ezamokuhle household 3

4.2 Source Apportionment

Source apportionment studies using SEM-EDS provide valuable insights into the composition and sources of particulate matter. PM from three Ezamokuhle households and the Majuba AQMS were analysed to determine its likely sources.

4.2.1 Source Profiling

Prior to analysing and apportioning the sources, the particulate matter was first classified according to the clusters illustrated in Table 7. The disqualifying criteria for a specific cluster are indicated in the table below by the grey-highlighted cells. It is noted that most of the particulates analysed can be classified as mostly consisting of mixed carbonaceous, alumino-silicates and quartz. Carbonaceous particles, including elemental carbon (EC) and organic carbon (OC), are often associated with combustion processes. Sources include vehicle exhaust, industrial emissions, biomass burning (e.g., wood, crop residues), and residential heating (e.g., coal, wood, oil). Alumino-silicates, which include minerals like kaolinite, montmorillonite, and illite, can be generated from industrial activities such as mining, quarrying, and construction. These minerals are often found in soil and rock and can become airborne during these activities. Quartz, a common form of crystalline silica, is often associated with windblown dust from exposed unvegetated areas, construction and demolition activities. It can be released into the air during cutting, drilling, grinding, and crushing of materials containing quartz, such as concrete, brick, and stone. Dust from agricultural activities, such as tilling, ploughing, and harvesting, can contain carbonaceous particles and alumino-silicates from soil and plant materials.

Table 7: Source profiling for particulate matter found at Ezamokuhle

Material Cluster	Element							
	C	O	Al	Si	Mg	Ca	Ti	Fe
Carbonaceous	≤70%	≥30%						
Mixed Carbonaceous	<70%	>20%	>5%	>4%				
Alumino-silicate		>20%	≥3%	≥4%				
Quartz		>20%		≥5%				
Carbonate	<70%	>20%			<5%	<5%		
Heavy Mineral		>20%	≥5%				<5%	<5%

4.2.2 Positive Matrix Factorization (PMF) Modelling

The Positive Matrix Factorization (PMF) Model was utilised herein. PMF is a mathematical receptor model developed by the US EPA. The PMF Model reduces the large number of variables in complex analytical data sets to combinations of source types and source contributions. The source types were identified by comparing them to measured profiles. Source contributions were used to determine how much each source contributed to a sample.

The PMF analysis was utilised to assign the sources at the four sampling sites (Ezamokuhle & Majuba AQMS). PMF uses concentration and uncertainty data to establish the source contributions to the concentrations. The data is bootstrapped, and the programme determines the number of factors that are representative of the data input. These factors are in essence, the potential sources that this input concentrations emanate from. ARM then assessed the elements associated with each of these factors before assigning a source, for instance: factor 1 has very high concentrations of Na, Mg, Si, K, Fe and O, suggesting that it is likely outdoor dust. The contribution of each of these sources (factors) is then calculated for each location.

Overall, interpreting PMF results requires a comprehensive understanding of the relationships between chemical species, emission sources, atmospheric processes, and environmental conditions. It involves integrating information from factor fingerprints, factor profiles, and variability in species graphs to identify and characterize sources of ambient particulate matter and understand their contributions to air quality. Additionally, validation of PMF results through comparison with independent data and knowledge of local emission sources is essential for robust interpretation. The factor species and variability is shown in Figure 13 and Annexure 2.

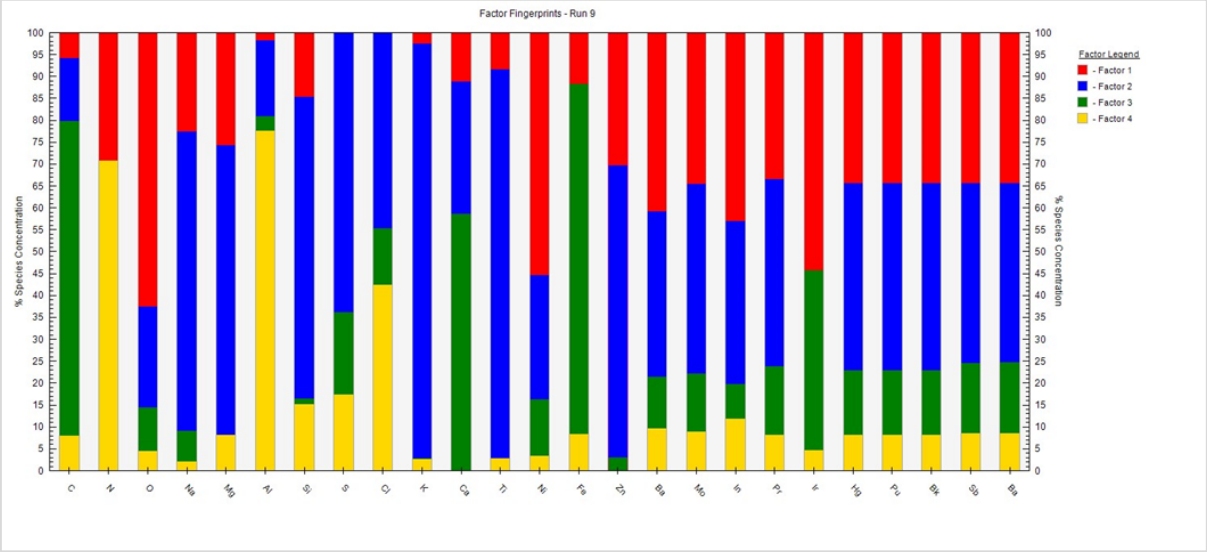

Figure 13: Factor Species and variability in PMF Modelling

4.2.3 Source Contributions

4.2.3.1 Ezamokuhle Households Outdoor

Figure 14 to Figure 16 shows the potential sources of outdoor PM that were analysed for three households at Ezamokuhle. Whereas Figure 17 shows the average PM source contribution for all three households in Ezamokuhle.

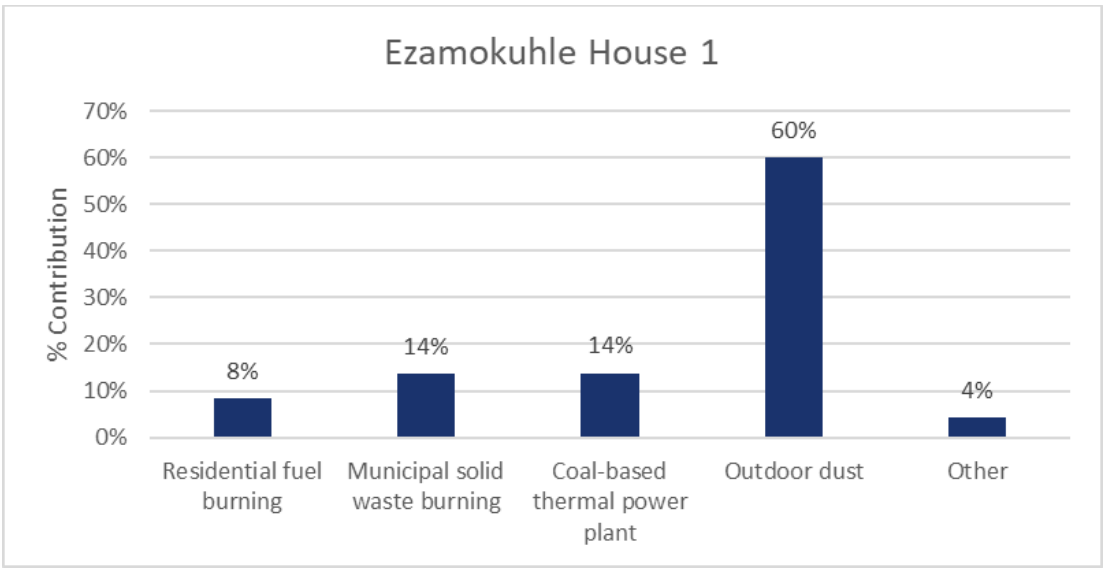

Figure 14: Source contributions of particulates found in ambient air at Ezamokuhle house 1

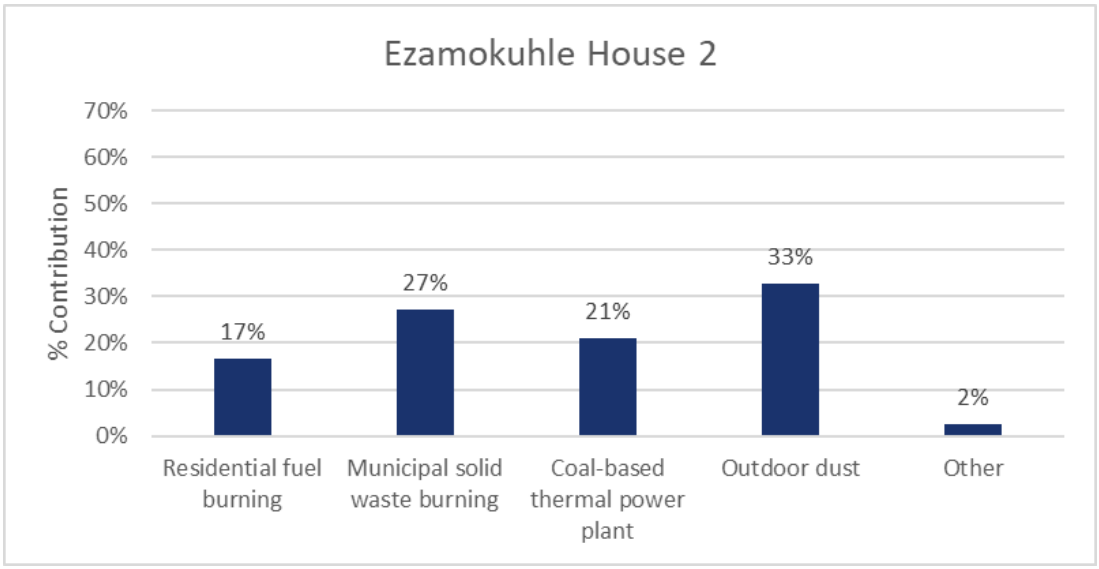

Figure 15: Source contributions of particulates found in ambient air at Ezamokuhle house 2

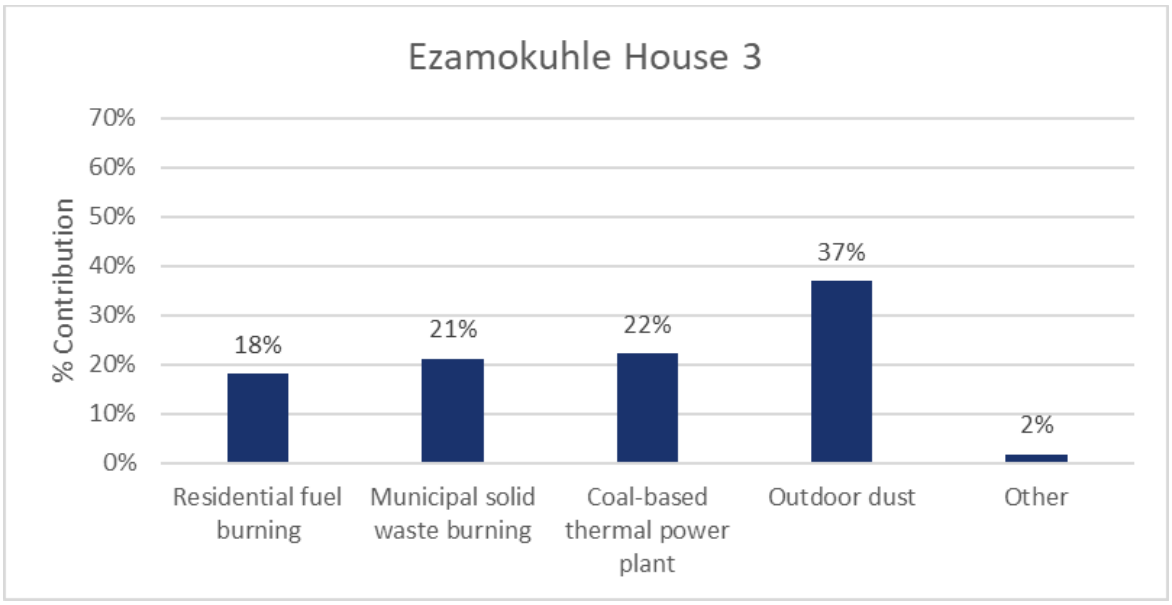

Figure 16: Source contributions of particulates found in ambient air at Ezamokuhle house 3

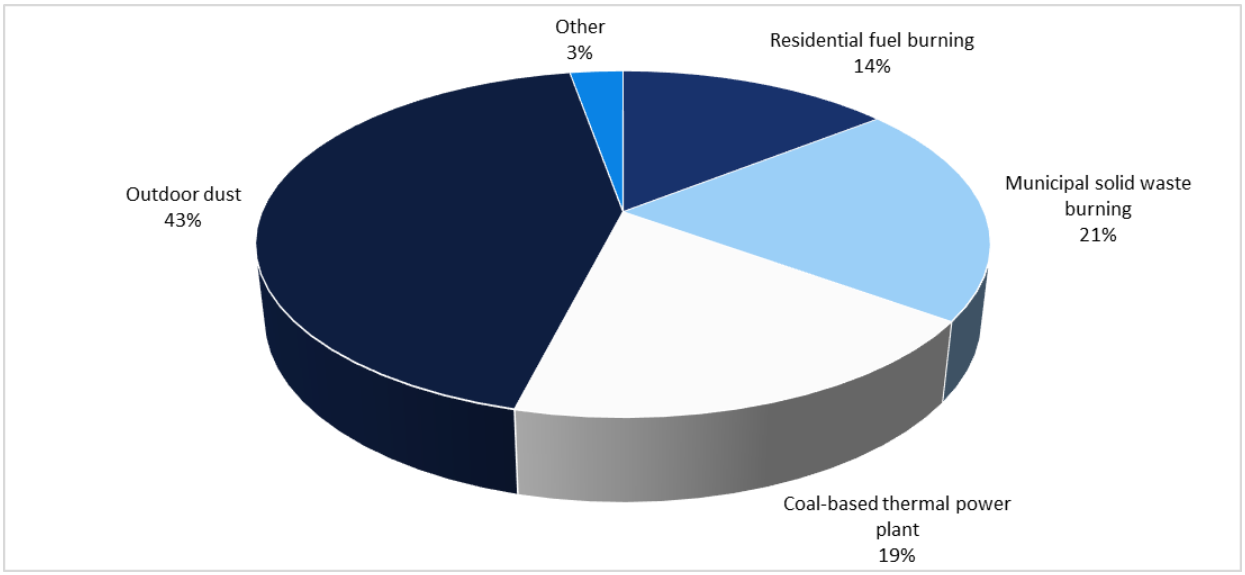

Figure 17: Particulate source contribution average in ambient air for all sampled households in Ezamokuhle

- *Outdoor dust*

Outdoor dust (Figure 17) was found to be the largest contributing source, and it was assumed that it was laden with particulates with elemental profiles consistent with silica and quartz. These particles typically contain minerals like silicon, aluminium, and calcium, with variable elemental compositions depending on the specific source. These indicate that outdoor dust, which is primarily from exposed surfaces like unpaved roads and unvegetated areas usually enters the house through openings like doors, windows, vents, and wall crevices.

Its noted that all of the roads outside Ezamokuhle household 1, 2 and 3 are unpaved. The PM sampler for Ezamokuhle household 1 was located in the front yard directly opposite a busy inner road in Ezamokuhle. This road is frequented by both pedestrians, private vehicles and taxis traffic. This results in significant visible atmospheric dust emissions due to the from the mechanical disturbance of the unpaved road surface. The PM sampler for Ezamokuhle household 2 was also located in the front yard and conversely the PM sampler for Ezamokuhle household 3 was located in the backyard. It's noted the inner road opposite Ezamokuhle household 2 is quite road with seldom pedestrian and private vehicle traffic whereas Ezamokuhle household 3 is located in an enclosed backyard with high walls. Thus due to these factors, the contribution of outdoor dust is significantly higher at Ezamokuhle household 1 (Figure 14) than Ezamokuhle household 2 (Figure 15) or 3 (Figure 16).

- *Municipal solid waste*

Burning of municipal solid waste were the second largest contributor (Figure 17) to outdoor PM respectively for the winter sampling campaign. ARM conducted a household source survey in 2023 in Ezamokuhle (ARM, 2023). A total of 409 households completed the questionnaire. The survey respondents indicated that whilst waste collection was reliable, in cases when waste was not collected the homeowner often (~39% of the time)

resorted to burning the waste (Figure 18). This suggested that Ezamokuhle has a waste collection issue as noted with the numerous waste piles observed through the *Rapid insitu survey (2022)* and *Community source survey* (ARM, 2023).

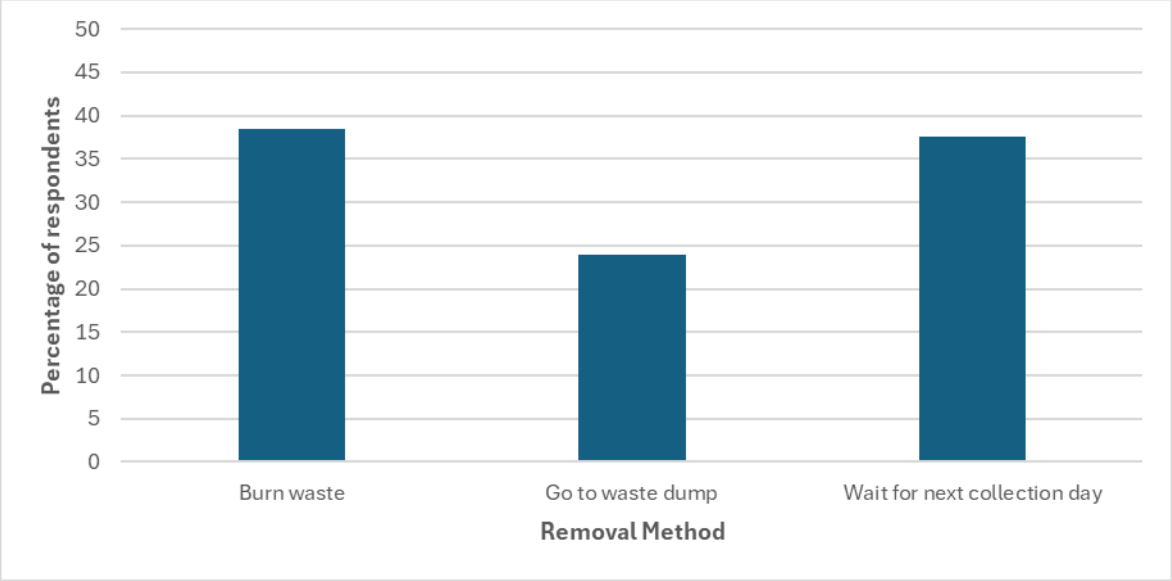

Figure 18: Alternate waste removal method if waste is not collected at respondent households in Ezamokuhle (ARM, 2023)

- *Coal-based thermal power plant*

Coal-based thermal power plant emissions were the third highest source category (Figure 17) contributing to ambient particulate matter. The presence of particles characteristic of industrial emissions, such as heavy metals (e.g., lead, mercury, cadmium), metallic oxides, is also common although at a lesser extent. Particles from industrial activities are typically larger in size and have distinctive elemental compositions, making them distinguishable from other sources. In this instance, industrial emissions were taken to emanate from power generation activities in the region using coal as a thermal source.

- *Residential fuel burning*

Residential fuel burning is a significant contributor to ambient PM concentration measured at Ezamokuhle (Figure 17). Particles derived from residential activities such as residential fuel burning (e.g., wood, coal) for heating and cooking often contain organic carbon, potassium, and other elements indicative of biomass combustion. Both the 2022 and 2023 survey campaigns have consistently demonstrated that elevated short term PM in the winter months are clearly attributable to residential fuel burning in Ezamokuhle (ARM, 2024). The daily NAAQS for PM was again exceeded at the three Ezamokuhle residential sampling sites in the 2023 survey. The Openair analysis further supported that the elevated particulate matter concentrations occurring during winter were associated with localized non-bouyant sources (residential fuel burning) as opposed to tall stack emissions (PM) (ARM, 2024).

- *Other sources*

Other sources (Figure 17) include industrial activities and natural sources that can contribute secondary aerosols (SOAs) and mineral deposits. The SOAs can form from the oxidation of volatile organic compounds (VOCs) in the atmosphere.

4.2.3.2 Majuba AQMS

Outdoor dust was the largest PM contributor to the Majuba AQMS (Figure 19). This dust was visibly evident in the unpaved road leading to the Majuba AQMS (Figure 20) as well as the coal stockpiles as the surrounding sparsely vegetated vicinity of the Majuba AQMS site (Figure 21). At Majuba AQMS, emissions from a coal based thermal power plant was the second largest contributor with some particles containing sulfur, zinc, and magnesium in their elemental spectra, which is not unexpected given that the sampler was with a close proximity, downwind of the Majuba power station (Figure 22). Open burning of municipal solid waste and residential burning were the third and fourth largest contributors

to the PM at Majuba AQMS respectively. Other sources include industrial activities and natural sources that can contribute secondary aerosols (SOAs) and mineral deposits.

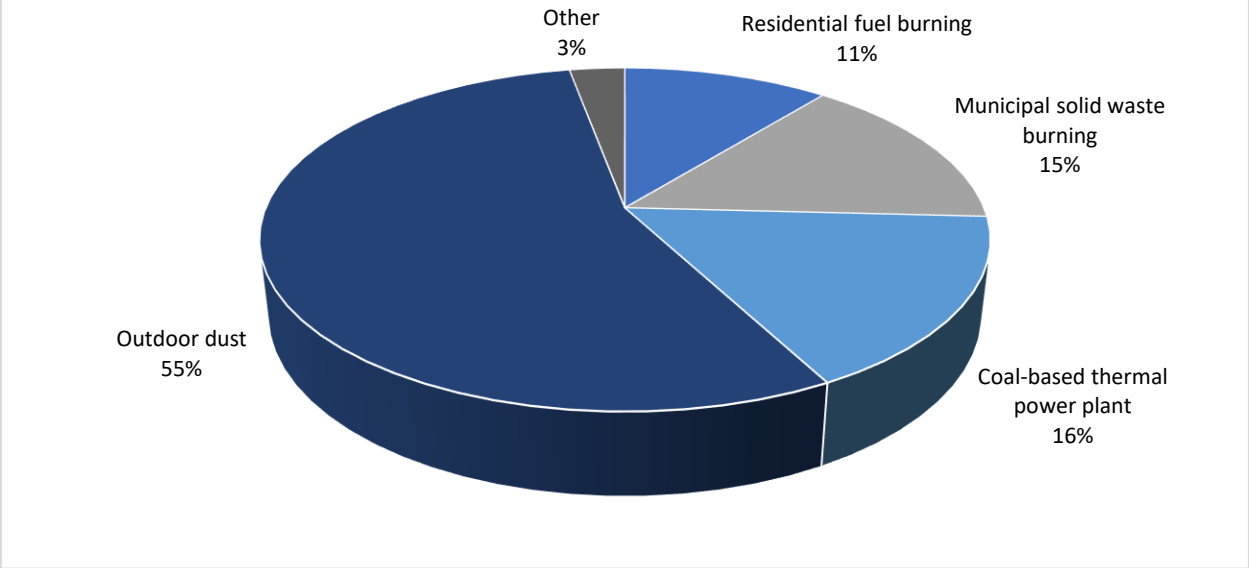

Figure 19: Source contributions of particulates found in ambient air at the Majuba AQMS

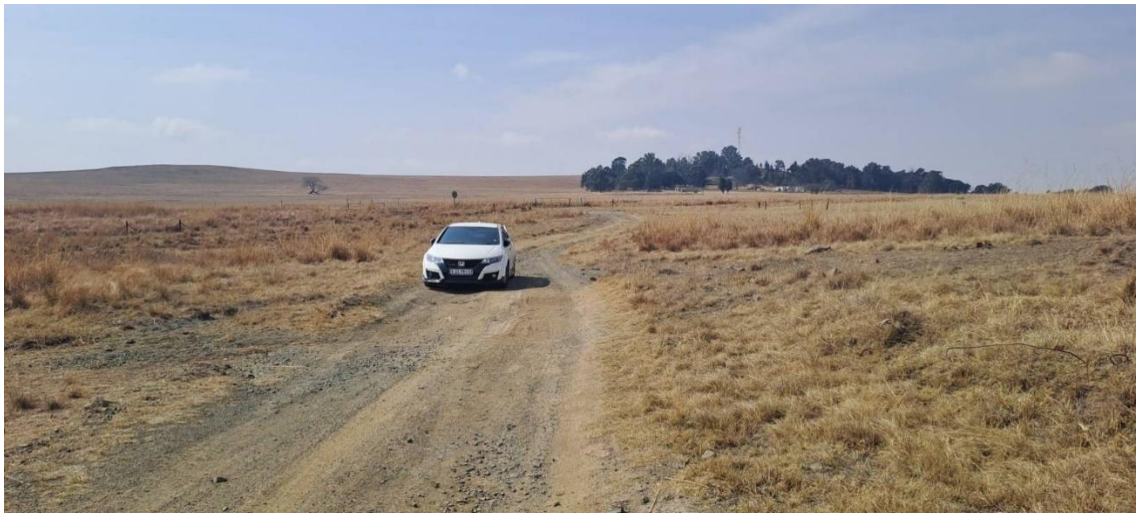

Figure 20: Unpaved dust road leading up to the Majuba AQMS

Figure 21: Sparsely vegetated and dusty area surrounding the Majuba AQMS

Figure 22: Majuba AQMS close proximity to Majuba Power Station

4.2.4 Comparison of Outdoor/Indoor Particulate Contribution In Ezamokuhle

In accordance with the scope of work, for Activity 11: Indoor Air Quality Monitoring, ARM has undertaken indoor PM air quality, source apportionment and temperature measurements at Ezamokuhle. This sampling was conducted for same winter sampling period as this Study (section). It's noted the costing and analysis for Activity 11 are separate and independent of this study (Activity 10.8). However, a comparison of the Activity 11 PM indoor source apportionment results for Ezamokuhle are presented herein as this provides a deep insight into the contribution and relationship of outdoor (ambient) and indoor PM contributions.

Figure 23 to Figure 25 shows the comparison of potential sources of outdoor and indoor PM that were analysed for three households at Ezamokuhle. It's important to note that indoor source PM contribution profiles show that the dominant signature and PM contribution indoors is residential fuel burning (Figure 23 to Figure 25). In general, the source contribution of PM attributable to: outdoor dust; coal-based thermal plants; and municipal solid waste burning decreases substantially indoors. Furthermore, the indoor source apportionment results for PM show that a tobacco smoking signature was detected indoors at all three households in Ezamokuhle.

Figure 26 shows the average indoor PM source contribution for all three households in Ezamokuhle. Its clear herein that residential fuel burning is the highest contributing source indoors. Thus supporting the roll-out of Eskom's PMV air quality offset household intervention project in Ezamokuhle.

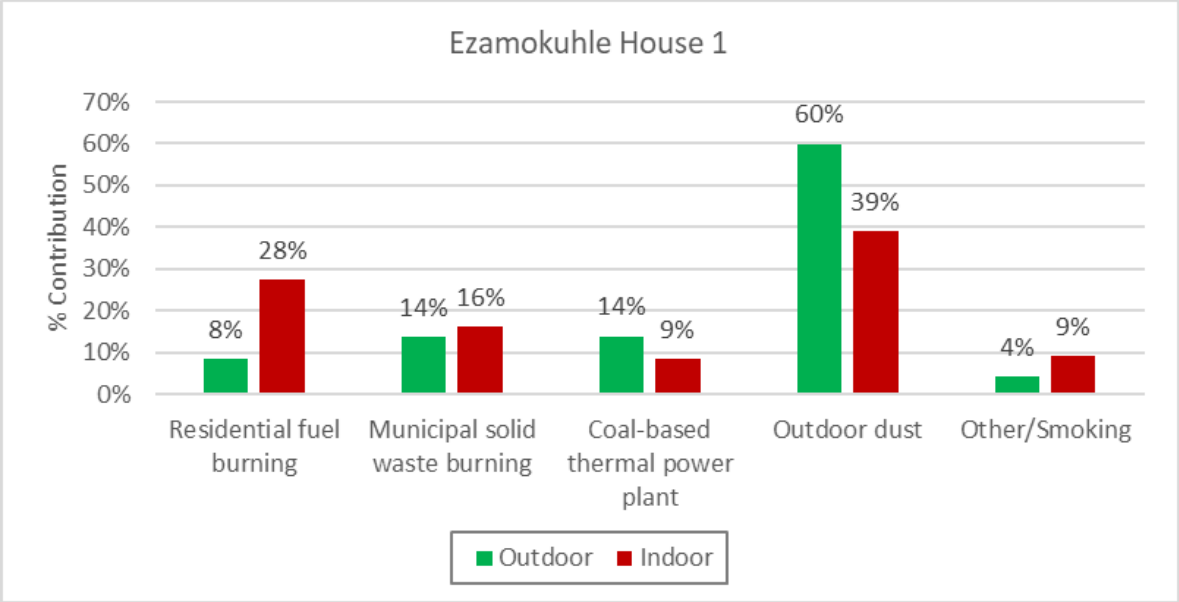

Figure 23: A comparison of the source contributions of particulates found in both outdoor and indoor air at Ezamokuhle house 1

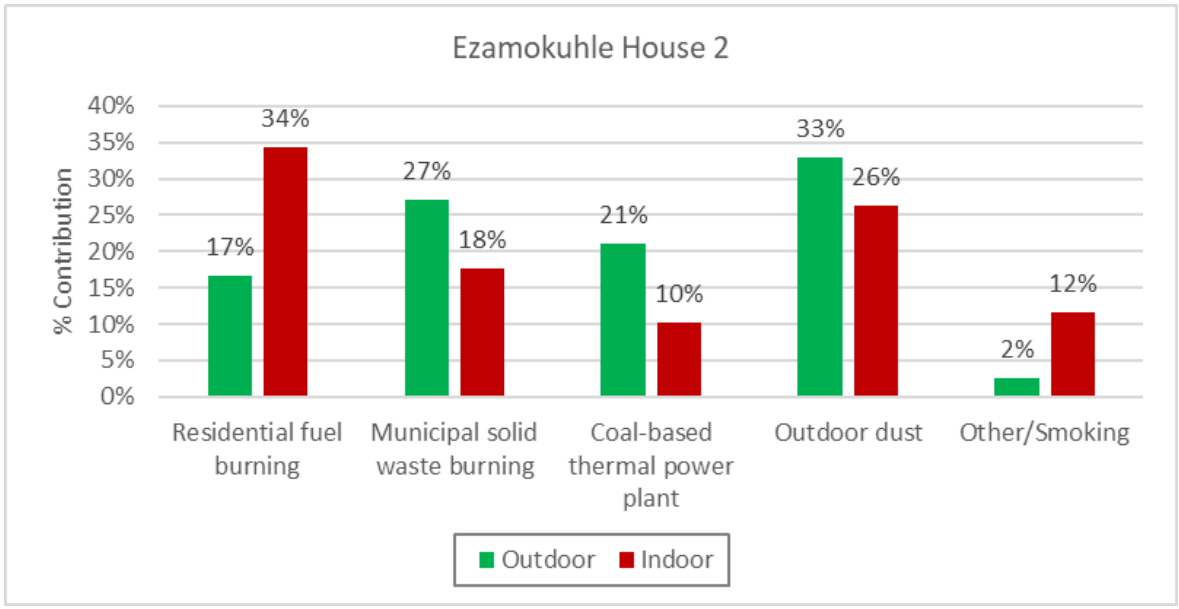

Figure 24: A comparison of the source contributions of particulates found in both outdoor and indoor air at Ezamokuhle house 2

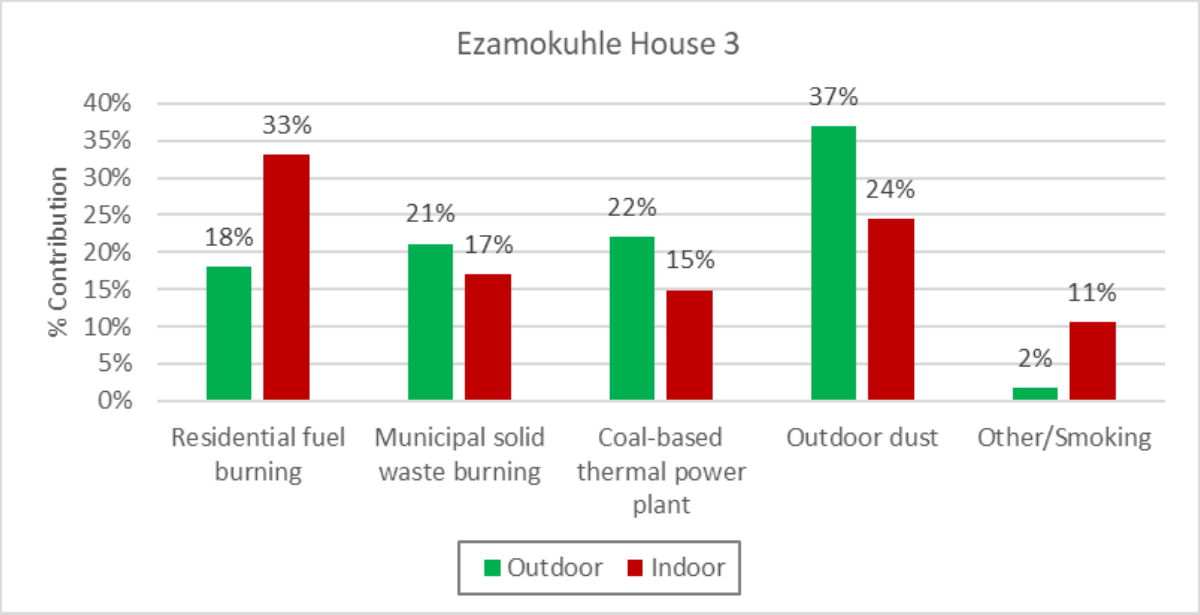

Figure 25: A comparison of the source contributions of particulates found in both outdoor and indoor air at Ezamokuhle house 3

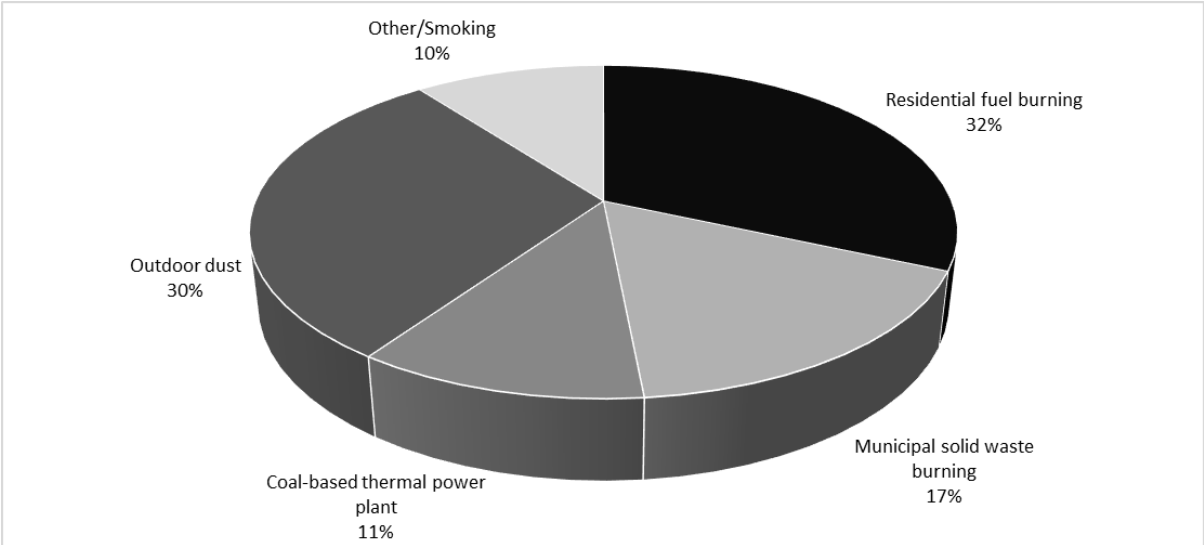

Figure 26: Particulate source contribution average in indoor air for all sampled households in Ezamokuhle

4.2.5 Interpretation Of Source Apportionment Contribution Results

Overall, while sources with the largest contributions are certainly important to consider in source apportionment studies, the significance of their impacts depends on a variety of factors beyond just their contribution (Figure 17) to measured ambient PM pollutant concentrations.

The sources with the largest PM contributions in source apportionment studies may or may not have the most significant impacts, and this depends on several factors:

4.2.5.1 Toxicity and health impacts:

Coarse particles are those of size between 10 and 2.5 μm ($PM_{10-2.5}$); fine particles are those with an equivalent aerodynamic diameter of 2.5 μm and less (denoted as $PM_{2.5}$) and ultrafine particles are those of size less than 0.1 μm (Schwela, 2010). Re-suspension of soil and road dust by wind, pedestrians, vehicles, as well as construction work, and agricultural activities have been attributed in the formation of coarse particles (PM_{10}) (Newby *et al.*, 2015). Whereas residential pollution, mostly from cooking and heating, and generating electricity from fossil fuels, and transport tail-pipe emissions, are the main human-made sources of fine particles globally (WHO, 2021). The Harvard Six Cities cohort study found that fine-particulate ($PM_{2.5}$) pose a greater risk to human health because this can penetrate deep into the lungs and is more toxic than larger particles (PM_{10}) (Dockery et al., 1993).

Thus whilst, the study results have demonstrated that outdoor dust (Figure 17) are the largest source contributor in in Ezamokuhle, its noted that these are coarser fraction particles. Whereas residential fuel burning although a smaller source contribution pose a greater risk to human health of to the community as they are finer-particulates.

4.2.5.2 Meteorology and Dispersion

Atmospheric constituents follow a series of steps from the time of their introduction into the atmosphere until their eventual removal from it (Figure 27). The main processes that comprise the atmospheric pathway are emissions, transformation, transport, and deposition (Figure 27). Furthermore, air quality is strongly influenced by meteorology which covers this array of atmospheric processes. Tall stack sources are transported over large distances and undergo significant dilution as opposed to low-level non buoyant ground level emissions which result in elevated ground level conditions.

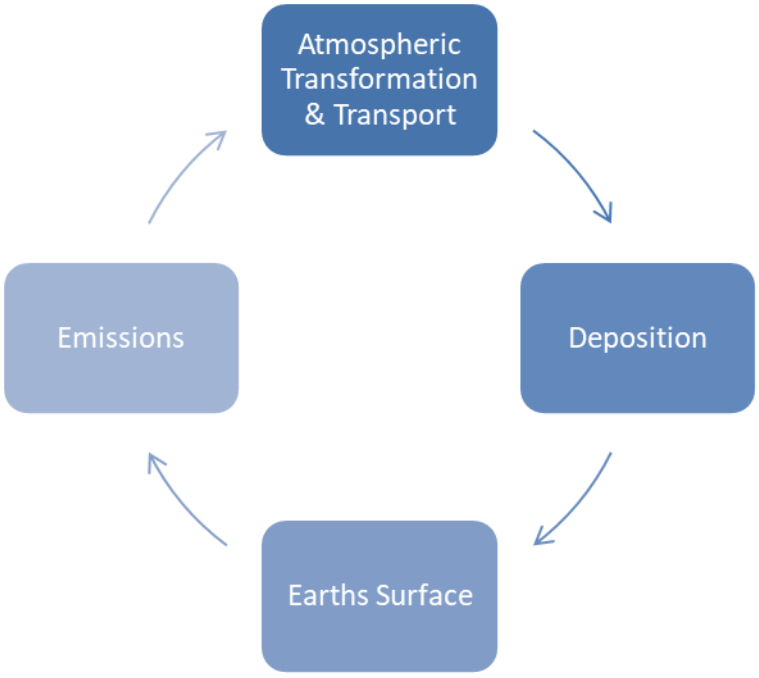

Figure 27: Atmospheric cycle and its component processes

The study results have demonstrated that the ambient PM contribution of both coal-based thermal and residential emissions are of a similar magnitude (Figure 17) however their air

quality impact is not necessarily the same. Residential fuel burning is a significant contributor to ambient PM concentration measured at Ezamokuhle (Figure 17). Both the 2022 and 2023 survey campaigns have consistently demonstrated that elevated short-term PM in the winter months is clearly attributable to residential fuel burning signature in Ezamokuhle (ARM, 2024). Residential fuel burning has a higher air quality impact in Ezamokuhle than coal-based thermal sources due it low release height in adverse and unfavourable meteorological conditions in winter that inhibit dispersion which results in elevated PM concentrations (ARM, 2024).

4.2.5.3 Exposure period to PM

Epidemiological studies are often used to evaluate the increased risk due to air pollution, as the studies evaluate the impact on humans in real-world conditions (WHO 2000b). The WHO recommends a procedure to be followed to calculate health impacts that can be attributed to the exposure of air pollution in the Environmental Burden of Disease Series (WHO 2004). The higher exposure period to a PM pollutant, the higher the risk of adverse human health impacts (WHO, 2005).

In South Africa, indoor air pollution poses a serious threat to public health, particularly in impoverished areas where respiratory illnesses are exacerbated by prolonged exposure to subpar cooking appliances and fuels (DOH, 2019). The indoor source PM contribution results show that the dominant source is residential fuel burning. This prolonged indoor exposure to PM, particularly from the domestic use of solid fuels, has significant health implications, plausibly leading to respiratory diseases and other health conditions for the Ezamokuhle households.

5. CONCLUSIONS

A scientifically credible source apportionment was undertaken to identify the potential sources of the particulate matter during the winter baseline for Ezamokuhle. The main contributing sources to PM in Ezamokuhle include dust; coal-fired thermal power stations; residential fuel burning and municipal waste burning. Overall, while sources with the largest contributions are certainly important to consider in source apportionment studies, the significance of their impacts depends on a variety of factors beyond just their contribution to measured ambient PM pollutant concentrations. This includes inter alia: toxicity and health impacts; meteorology and dispersion & exposure period to PM. Taking these factors into consideration an analysis of the Ezamokuhle source apportionment results demonstrate that the residential fuel burning sources poses the greatest risk to human health of to the community. It is evident that the interventions put in place have the potential to reduce indoor PM concentrations and ultimately reduce ambient concentrations due to the reduction in use of solid fuels for space heating and for cooking. Thus, supporting the roll-out of Eskom's PMV air quality offset household intervention project in Ezamokuhle.

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8. ANNEXURE 1: CALCULATION OF MASS CONCENTRATIONS FROM PARTICLE SHAPE FACTORS

To determine the average mass concentration of dust in the air over the sample period, in a micrograms per cubic meter (µg/m^3) equivalent the following steps were then conducted.

From the work of Wagner and Leith (2001a) the deposition velocity, V_{dep}, was estimated for each particle, *i*, as

$$V_{dep,i} = V_{amb,i}\gamma_{mesh,i} \quad \textbf{0.1}$$

Where $V_{amb,i}$ is the particle (*i*) settling velocity and $\gamma_{mesh,i}$ is an empirical modifier to account for the presence of the mesh cap[1]. $V_{amb,i}$ and $\gamma_{mesh,i}$ were calculated as;

$$V_{amb} = \tau g \quad \textbf{0.2}$$

$$\gamma_{mesh} = 0.00595\left(\frac{d_{PA}\tau g}{v}\right)^{-0.439} \quad \textbf{0.3}$$

Where τ is the relaxation time of the particle, *g* is the gravitational constant, and *v* is the kinematic viscosity of air. The relaxation time, was calculated as;

$$\tau = \frac{\rho_p {d^2}_a}{18\eta} \quad \textbf{0.4}$$

[1] A mesh cap is an annual cap attached to the top of the stub that has a hole on its centre to allow the diffusive settling of particles that go through the size selective mesh. The mesh cap holds the substrate onto the small stub and prevents it from falling when handling.

where ŋ is the dynamic viscosity of air. A Cunningham slip correction factor was not included in the calculation of due to its minor influence on the calculation for particles of the coarse size range. Particle aerodynamic diameter, d_a, was assumed equal to the projected area diameter, d_{pa}, obtained from microscopy to eliminate the need to estimate the aerodynamic shape factor, S_D. This assumption is supported by (Davies, 1979) work that showed that d_a/d_{pa} was equal to one for sand and near one for most other coarse mineral dusts (Wagner & Macher, 2003). It is also supported by the fact that S_D has a relatively minor influence on mass calculation (Wagner & Leith, 2001a).

The mass of a single particle, m_i, was then calculated using Equation 0.2. For field tests, particle density was assumed to be 1.1gcm^{-3} following (Heyduk, 2016). The volume shape factor S_V is a dimensionless constant that can be used to correct for the relative circularity of the particle and was determined for each particle from particle circularity, C_p, output by ImageJ as:

$$S_{V,i} = \frac{1}{C_{p,i}} = 1/[4\pi]\left(\frac{A_i}{P^2{}_i}\right) \qquad \textbf{0.5}$$

where P is the perimeter and A is the projected area of the particle. A circularity of unity indicates that the particle is a perfect sphere, while circularity progressively decreases from unity the more irregularly shaped a particle appears. The contribution of a single particle to mass concentration, C, was calculated as:

$$C_i = \frac{F_i}{V_{dep,i}} = (\frac{m_i}{A_T t})\frac{1}{V_{dep,i}} \qquad \textbf{0.6}$$

where F is the mass flux of the particle to the deposition surface translating to the particles collected per area time, A_T is the total area of the sample that was imaged (A_T is the

number of images times the area of one image), and *t* is the sample time. $PM_{10\text{-}2,5}$ was calculated as:

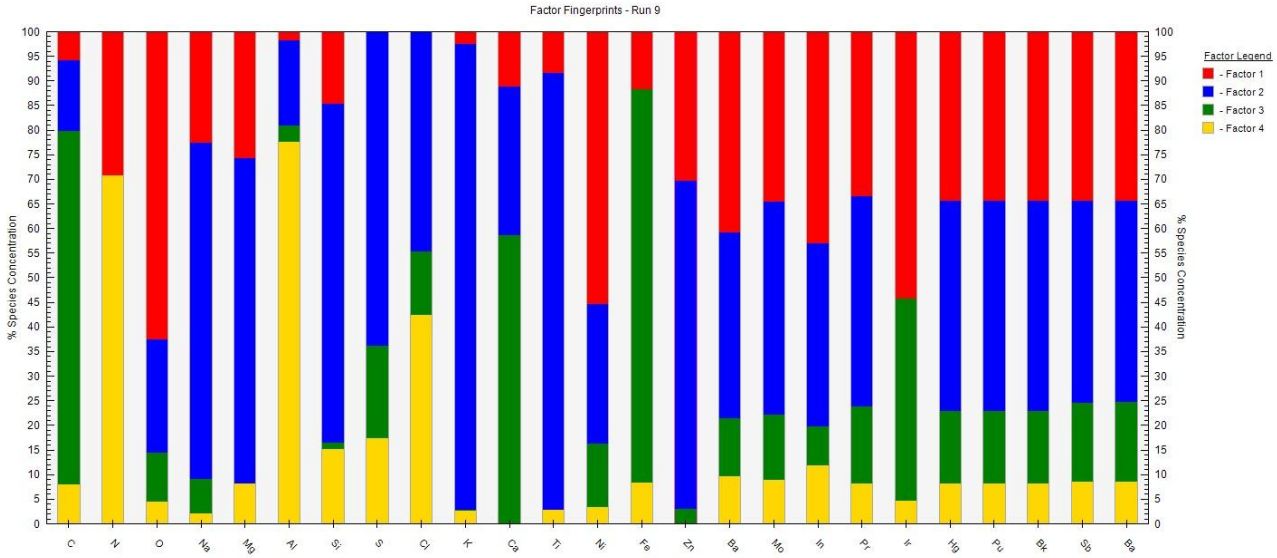
$$PM_{10-2.5} = \sum_{i=1}^{n} C_i E_i \ \ (if\ d_a > 2.5\ \mu m) \quad \textbf{0.7}$$

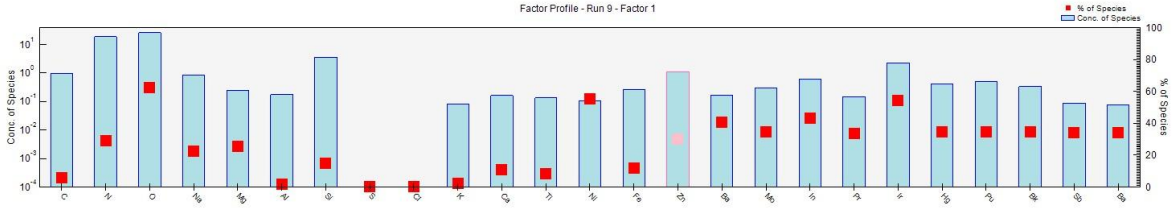
where *E* is the PM_{10} curve as defined by Hinds (1999):

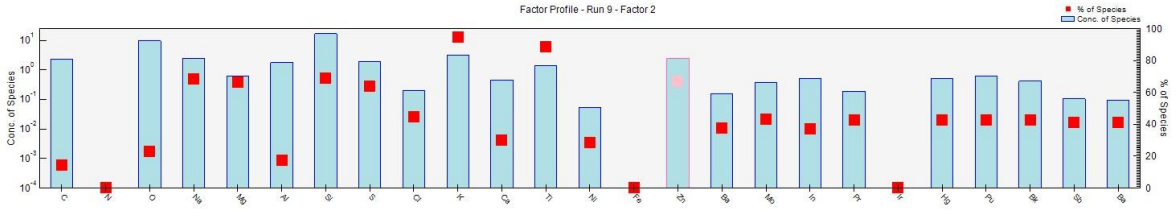
$$E_i = 0.9585 - 0.00408{d_{a,i}}^2 \ \ for\ d_{a,i} < 15\mu m \quad \textbf{0.8}$$

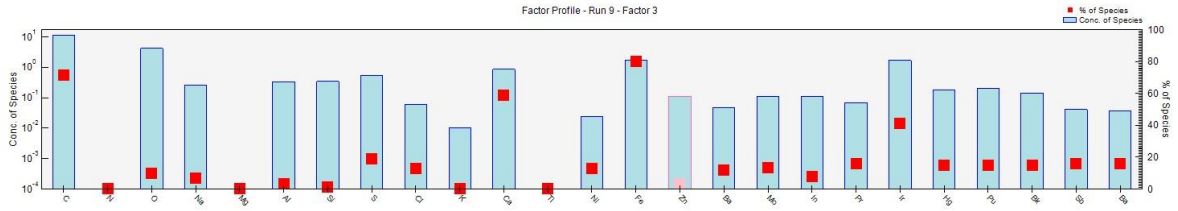
$$E_i = 0 \ \ for\ d_{a,i} > 15\mu m \quad \textbf{0.9}$$

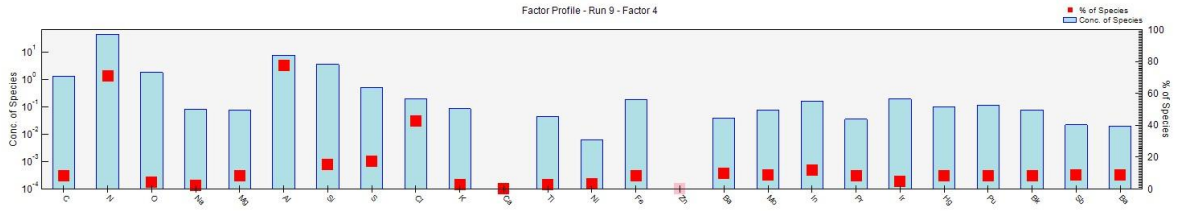
9. ANNEXURE 2: FACTOR SPECIES AND VARIABILITY DURING PMF MODELLING

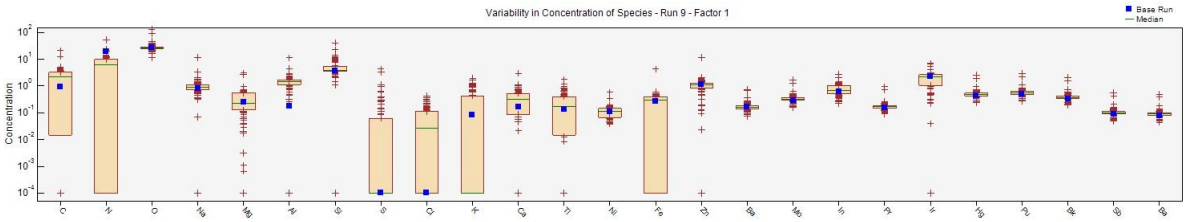


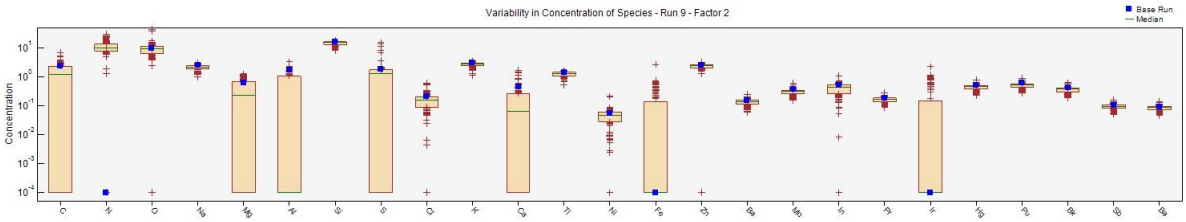


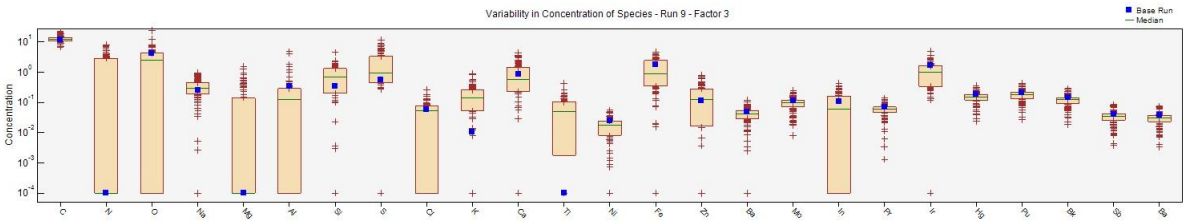


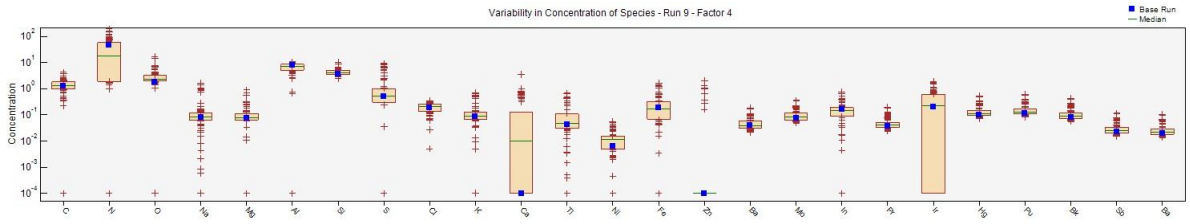

Factor Profile - Run 9 - Factor 3
% of Species
Conc. of Species
Conc. of Species
% of Species

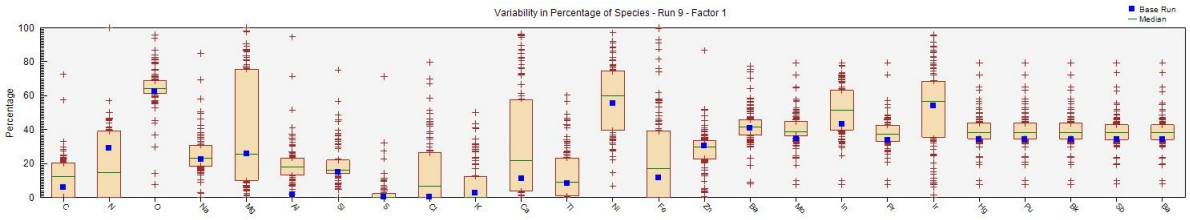

Factor Profile - Run 9 - Factor 4
% of Species
Conc. of Species
Conc. of Species
% of Species

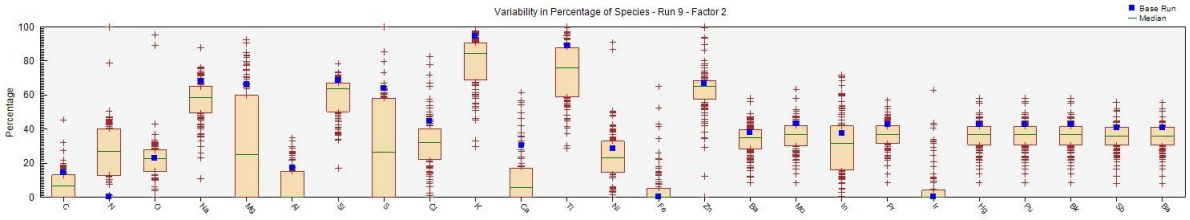

Variability in Concentration of Species - Run 9 - Factor 1
Base Run
Median
Concentration

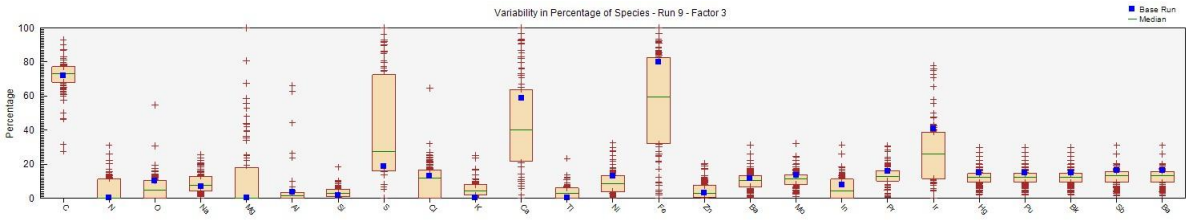

Variability in Concentration of Species - Run 9 - Factor 2
Base Run
Median
Concentration

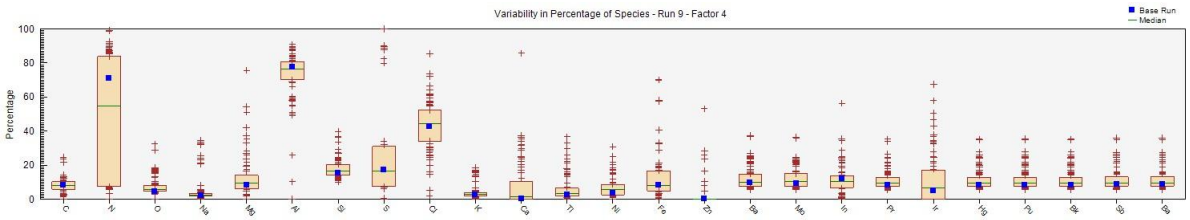

Variability in Concentration of Species - Run 9 - Factor 3
Base Run
Median
Concentration


Variability in Concentration of Species - Run 9 - Factor 4
Base Run
Median
Concentration


Variability in Percentage of Species - Run 9 - Factor 1
Base Run
Median
Percentage


Variability in Percentage of Species - Run 9 - Factor 2
Base Run
Median
Percentage


Variability in Percentage of Species - Run 9 - Factor 3
Base Run
Median
Percentage


Variability in Percentage of Species - Run 9 - Factor 4
Base Run
Median
Percentage

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