Research article

Factors affecting particulate matter concentrations in Gauteng province, South Africa: A systematic review

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Abstract

Gauteng is South Africa's largest urban and manufacturing hub and most populous province. There is widespread non-compliance with national ambient particulate matter (PM) standards in the province. This review aims to comprehensively assess strengths and weaknesses in the existing body of knowledge on the factors that affect PM concentrations in Gauteng. A systematic literature review of relevant studies is performed based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis) method, to synthesise our understanding of local and regional sources of PM ($PM_{2.5}$ andPM_{10}) and its precursors, the transport mechanisms, and the spatial and temporal variations. While it is known that the major sources of PM in Gauteng are industrial and mining emissions, domestic fuel use, vehicular emissions, aeolian dust, and biomass burning, their relative contributions to ambient PM concentrations have not been satisfactorily quantified. Long-range transport of pollutants is governed by the position of the continental anticyclone, but it is not known how this will change in association with climate change, or how urban heat islands over built-up areas affect pollution transport. The lack of availability of consistent PM measurements at ambient air quality monitoring stations hampers the understanding of long-term trends in PM concentrations. Satellite observations, atmospheric dispersion models and chemical transport models offer great promise in assessing temporal and spatial variations in PM concentrations. It is recommended that data availability at a core subset of Gauteng's ambient air quality monitoring network be improved; source apportionment studies be conducted in densely populated areas where exposure levels are high; PM and precursor emissions from vehicles be quantified; and the environmental justice implications of the high spatial variability in PM concentrations be investigated. Prioritisation of these areas of research will aid the design of evidence-based interventions to reduce population exposure to harmful pollution levels in southern Africa's most densely populated region.

Keywords

particulate matter, nitrogen oxides, sulphur dioxide, Gauteng province, source apportionment

Introduction

Particulate matter (PM) pollution is a significant environmental concern worldwide, with well-documented adverse effects on human health and the environment (Burnette et al., 2014; WHO, 2021; Health Effects Institute, 2024). Fine particulate matter ($PM_{2.5}$) concentrations are generally higher in areas with higher population density and, to a lesser extent, larger populations (Kim et al., 2021). The Gauteng province in South Africa is characterised by dense urban areas and industrial activities and is particularly susceptible to high levels of PM pollution (Hersey et al., 2015; Jury, 2017; Ross et al., 2017; Arowosegbe et al., 2021; Muyemeki et al., 2021; Howlett-Downing et al., 2022). South African national ambient $PM_{2.5}$ (fine particulates with an aerodynamic diameter of ≤2.5 micrometers) and PM_{10} (coarse particulates with an aerodynamic diameter of ≤10 micrometers) air quality standards are widely exceeded across the province (Gwaze, 2024).

Local sources, including vehicle emissions, domestic fuel combustion, and industrial activities, make significant contributions to the province's air pollution (Hersey et al., 2015; Arowosegbe et al., 2021; Muyemeki et al., 2021; Howlett-Downing et al., 2022). Air pollutants are also transported into Gauteng from regional sources like biomass burning and large industrial complexes in neighbouring provinces (Tyson and D'Abreton, 1998; Held et al., 2004; Piketh and Walton, 2004; Mafusire et al., 2016; Adeyemi et al., 2022a; Howlett-Downing et al., 2022). High exposure levels to PM pollution has resulted in Gauteng being selected as one of the twelve Priority Target Areas for the National Aeronautical and Space Agency (NASA)-Italian Space Agency's Multi-Angle Imager for Aerosols (MAIA)

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investigation, which aims to understand how different types of particulate matter affect human health using satellite-based observations (Averett, 2023).

This review aims to comprehensively assess the existing body of knowledge on the factors that affect PM concentrations in Gauteng. By synthesising findings from previous studies, this review seeks to identify the major emission sources, their contribution to ambient PM levels, air pollution transport, dispersion dynamics, and spatial and temporal variations in PM concentrations in Gauteng.

Study area

With an area of 18 176 km^2 and a population of approximately 15.9 million in 2024, Gauteng is home to a quarter of the country's total population of 63 million (StatsSA, 2024). The province is the economic hub of the country, generating 40% of the national GDP (Nkomo- Ralehoko, 2022).

Gauteng is located in the sub-tropics between 25.1 and 26.9°S. Situated on the southern African plateau, most of Gauteng is at an altitude of over 1 400 m. The atmospheric circulation over the province is dominated by anticyclonic conditions (Tyson and Preston-Whyte, 2000), associated with calm, clear, warm weather and elevated absolutely stable layers (Cosijn and Tyson, 1996). The anticyclone weakens in the austral summer (November-February), and rain occurs when moist air is advected over the province by the tropical easterlies.

Apartheid era segregation policies further transformed the urban landscape when high-density residential areas were established

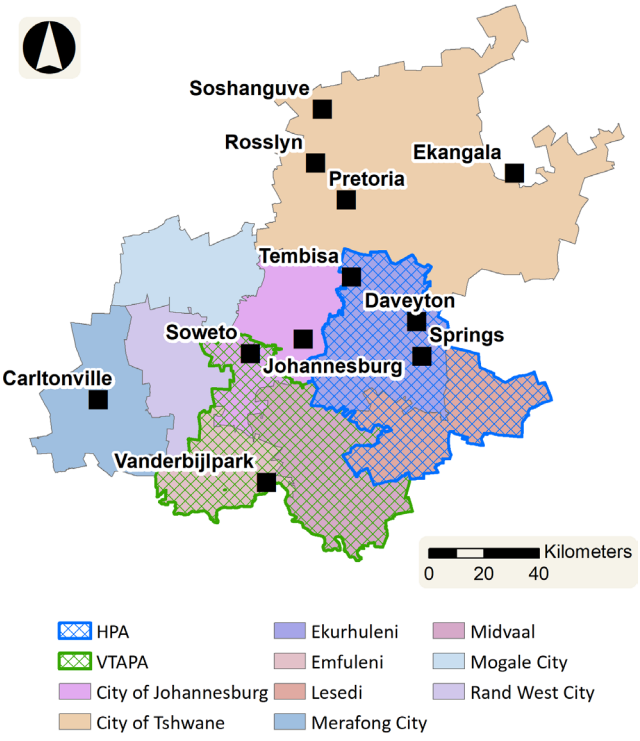


Figure 1: *Municipal boundaries and city and town centres in Gauteng. HPA = Highveld priority area (HPA), VTAPA = Vaal Triangle airshed priority area.*

for non-white people. Soweto (population of around 1.9 million) to the south-west of Johannesburg, Tembisa in the north, and Katlehong on the East Rand (each with a population of over 400 000) are the three largest townships in Gauteng (Figure 1).

Although mining only occurs on the periphery of Gauteng today, the mine tailings and industrial activities that developed adjacent to the mines are local sources of pollution in Gauteng. Vehicles and the residential burning of paraffin, wood, and coal are other sources of emissions. Long-range transport is a significant contributor to Gauteng's pollution, importing PM and precursor gases (SO_2 and NO_x) from industrial areas in the Highveld and Vaal-Triangle priority areas as well as regional biomass burning. (Hersey et al., 2015; Kuik et al., 2015; Arowosegbe et al., 2021; Muyemeki et al., 2021; Howlett-Downing et al., 2022). As of November 2025, Gauteng includes portions of two of the three designated national air quality priority areas (Figure 1): the City of Ekurhuleni was included in the Highveld Priority area in 2007 (DEA, 2012), while the entirety of the City of Johannesburg was recently included into the Vaal-Triangle Airshed Priority Area (DEFF, 2020, DFFE, 2025a). The City of Tshwane is proposed to be included in the Waterberg-Bojanala Priority Area (DFFE 2025b).

Methodology

A systematic literature review was performed to synthesise current understanding of the sources contributing to PM and PM precursor gases in Gauteng; the transport of pollutants in and out of Gauteng; along with spatial and temporal trends in ambient PM concentrations. The literature review was supplemented with new analysis, including the compilation of an area source map, a graphical summary of source apportionment results, and a synthesis of trajectory studies.

The systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 methodology (Figure 2) (Page et al., 2021). During the search stage, keywords were employed to narrow down the geographical focus of the documents to Gauteng and identify studies focusing on PM and its precursor gases (see Supplementary Table 1 for the search terms). The time frame of the review is studies published between 1988 and 2023. The search was limited to articles written in English. Relevant scholarly literature was identified using the Scopus database and supplemented with Google Scholar. Grey literature, including air quality management plans, air quality impact assessments, and industry reports, was found using Google's search engine. A total of 1 219 documents were collected, of which 1 162 were from the Scopus database, 29 were found using Google Scholar, and another 28 were grey literature.

The identified articles were screened to assess their relevance (Figure 2). Screening included scanning through titles and abstracts to identify and remove obviously irrelevant studies that do not address the research questions. There were 397 duplicate articles from Scopus. A further 666 articles were excluded due to not meeting the screening criteria, i.e., full-text

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available; and Gauteng-relevant. Nineteen articles from Scopus were omitted because they could not be retrieved electronically. The eligibility assessment involved four successive phases of assessment: title, keywords, abstract, and full text. A total of 1 163 articles from Scopus were excluded because they were not relevant to this study, were out of the study domain, or the full text could not be accessed. A total of 42 documents were included in the review (Supplementary Table 2).

The selected studies focused on three main areas. Firstly, studies that assessed the sources of air pollution affecting Gauteng. Secondly, articles that examined atmospheric transport, looking at the effects of seasonal changes on wind direction, stable layers, and local temperature inversions. Lastly, papers that investigated the spatial and temporal variation of pollution. Analytical techniques included station-based ambient measurements, remotely sensed data, modelling approaches, and PM chemical sampling.

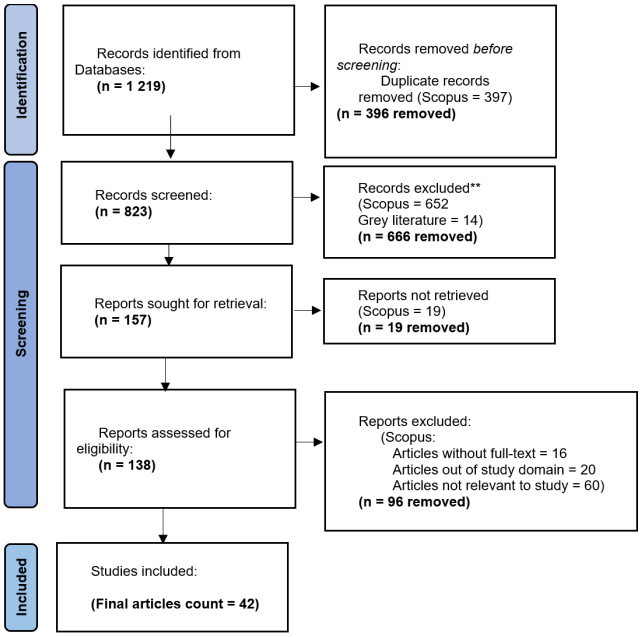


Figure 2: *PRISMA flow diagram showing the process followed to identify studies to include in the systematic literature review of factors affecting PM concentrations over Gauteng.*

Descriptive statistics were calculated to present an overview of the studies included in the review. This includes a summary of the number of studies in each year, the method of analysis used, the emission source(s) of interest, and pollutants assessed. Studies using more than one method were counted once for each method used. To supplement the systematic literature review, a map was created to show the location of sources of PM and its precursors in Gauteng, using socio-economic and land use datasets (Table 1) (StatsSA, 2016; The World Bank, 2022; DFFE, 2023). The sources included industrial areas, landfills, mining operations, mining tailings, and residential areas that rely on fossil fuels for cooking, space heating and lighting requirements.

To evaluate the challenges in assessing long-term PM trends, we analysed data availability from the South African Air Quality Information System (SAAQIS) for ambient monitoring stations between 2019-2023. We assessed the number of stations that had ≥70% in each year for $PM_{2.5}$ and PM_{10} measurements. This 70% threshold was applied to data post-quality control, meaning it reflects the proportion of valid, quality-assured measurements available for analysis. Ideally, we needed a 75% data availability threshold as recommended by the South Africa's regulatory reporting on ambient air quality measurement (DEA, 2004). We have relaxed this threshold to find a balance between ensuring sufficient temporal coverage for representativeness and maximising the number of sites included in the analysis. Use of a completeness threshold reduces the risk of bias in annual or season PM estimates arising from temporally sparse data, while still acknowledging the limitation inherent in real world monitoring in resource-constrained settings. Data cleaning included removal of measured hours with negative or zero concentrations.

Table 1: *Datasets used to compile a map of PM source areas in Gauteng.*

Data (date data captured for)	Source
Socio-economic ward-level data (2016)	
Population count Percentage of households with no income Percentage of households using coal/wood for heating Percentage of households classified as informal	(StatsSA, 2016)
Land cover data (2018)	
Land fills Dry pans Industrial Mine: tailings and resource dumps Mine: extraction pits, quarries, surface structure	(DFFE, 2023)
Roads data (2017)	(The World Bank, 2022)

To identify domestic fuel-using low-income areas, wards satisfying the following conditions were extracted and overlapped based on an "AND" operation: 10% or more households with no income, 10% or more households utilising coal/wood for heating, and 10% or more households classified as informal. These wards were further intersected with areas with a population density greater than 1 000 people.km^{-2}, revealing the locations of densely populated low-income areas relying on domestic fuel.

The delineation of industrial and mining zones was achieved using landcover data in conjunction with a kernel density function that assessed the number of features per unit area (Dehnad, 1986). The output depicts the spatial distribution of zones characterised by a dense cluster of industrial areas, mine tailings and resource dumps, and mine operations (extraction pits, quarries and surface structures). To delineate industrial and mining zones, land cover pixels (30 m × 30 m) classified as industrial or mining were first converted to point features. The kernel density analysis was performed using a 10 km search radius, which calculates the spatial concentration of these points. The output represents the density of industrial and

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mining features per square kilometer. The resulting density surface was simplified by applying a threshold contour value of 0.2. This value was determined through iterative comparison with a 2019 basemap to ensure it captured most industrialised areas while excluding isolated features points. A density value of 0.2 indicates that within any 10 km radius inside the contour, there is an estimated concentration of at least 0.2 industrial/mining points per square kilometer, equivalent to approximately one point every 5 km^2.

A map of predominant transport trajectories was synthesised from trajectory modelling studies performed by Hersey et al. (2015) for Johannesburg for the period 01 January 2000 – 31 December 2009 and Adeyemi et al. (2022b) for Pretoria for the period 18 April 2017 – 17 April 2018.

To systematically analyse the source apportionment results, the results from each study were tabulated to record the sample sites or study areas and the percentage contribution of each source to ambient concentrations of PM and PM precursor gases. The results of different studies conducted in the same region were averaged. The source apportionment studies were conducted using both chemical analysis of short-term aerosol samples and apportionment of sources based on known source profiles and dispersion modelling. The studies included span from 1993 to 2018 and employed diverse methodological approaches. These included chemical mass balance (Engelbrecht et al., 1996; DEA, 2013), positive matrix factorisation (Muyemeki et al., 2021; Lourens et al., 2016; Jaars et al., 2018; DEA, 2019b; DEFF, 2020; Adeyemi et al., 2022a), analysis of stable nitrogen isotopic composition in aerosol nitrate (Altieri et al., 2022), and particle-induced x-ray emission (Formenti et al., 1998). Several studies utilised integrated approaches combining emission inventories, dispersion modelling, and receptor modelling (Liebenberg-Enslin & Hurt, 2009; DEA, 2009; DEA, 2012). Sampling durations varied substantially, ranging from two-week campaigns (Formenti et al., 1998), through seasonal studies (Engelbrecht et al., 1996; Altieri et al., 2022; Lourens et al., 2016; Muyemeki et al., 2021), to comprehensive full-year monitoring (Liebenberg-Enslin & Hurt, 2009; DEA, 2009; DEA, 2012; DEA, 2013; Jaars et al., 2018; DEA, 2019b; DEFF, 2020; Adeyemi et al., 2022a). This summary is simply exploratory and serves to highlight the range provided by the different techniques and averaging periods.

Results

An overview is provided of the focus, methods of analysis, and year of publication of studies included in this review. Then a synthesis is presented of our state of knowledge of compliance with ambient PM standards, emission sources and source apportionment, horizontal transport and vertical dispersion of pollutants, and finally temporal and spatial variations in PM concentrations.

Overview of PM studies in Gauteng

There has been a steady increase in the number of studies

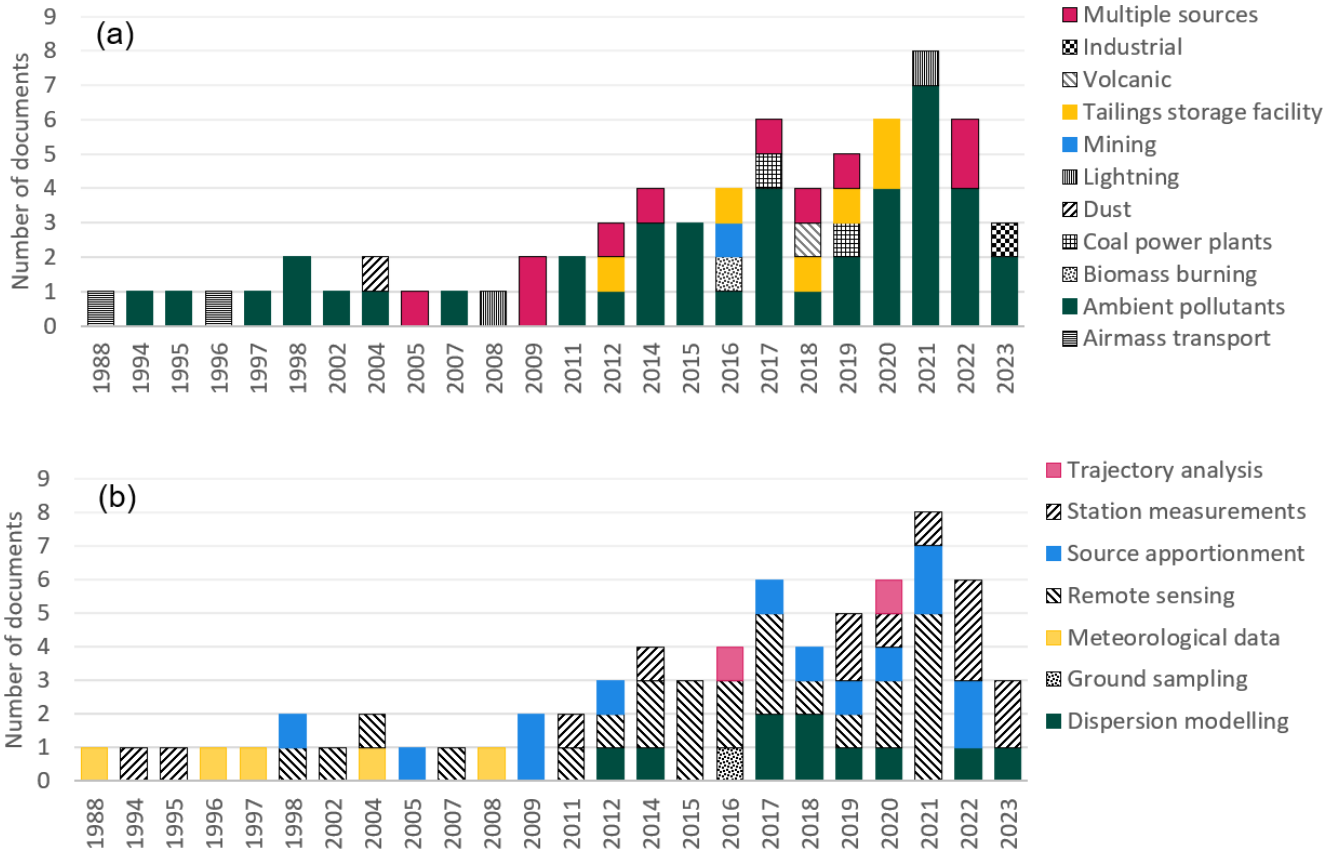


Figure 3: *(a) Year of publication and emission sources of focus for studies on PM in Gauteng, and (b) main method of analysis used in each study.*

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on Gauteng's particulate matter pollution since 2009 (Figure 3). Before 2009, more than half of the studies focused on the transport of pollution, using meteorological data. Since the air quality management policy and ambient standards were implemented in 2009, there has been a dramatic increase in studies using satellite observations (33%, n = 23), atmospheric dispersion modelling (14%, n = 10), continuous ambient measurements (18%, n = 13) and studies conducting source apportionment (16%, n = 11). Most studies have focused on ambient particulate matter (53%, n = 37), with tailings storage facilities and coal-fired power plants being the sources specifically studied.

Ambient PM concentrations in Gauteng

Our analysis of SAAQIS data confirms that an assessment of ambient PM concentrations in Gauteng is hampered by the poor availability of data at ambient monitoring stations. Although there are more than 30 ambient air quality monitoring stations in Gauteng, only 8-15 had more than 70% of PM_{10} data and only 7-13 had more than 70% of $PM_{2.5}$ data available annually between 2019 and 2023 (Table 2).

Table 2: *Number of ambient air quality monitoring stations in Gauteng with more than 70% data availability from 2019-2023.*

Year	PM_{10}	$PM_{2.5}$
2019	8	7
2020	15	13
2021	13	11
2022	12	11
2023	14	9

Nevertheless, it is evident from the ambient air quality measurements collected between 2019-2023 (Table 2) that there is widespread non-compliance with the South African National Ambient Air Quality Standards for $PM_{2.5}$ and PM_{10} across residential and industrial areas in the province. The $PM_{2.5}$ annual average standard of 20 mg/m^3 was exceeded at all of the analysed monitoring stations between 2019 and 2023 (with the exception of Diepsloot in Soweto in 2022). The PM_{10} annual standard of 40 $\mu g.m^{-3}$ was exceeded at 8 or 9 of the analysed monitoring stations between 2019 and 2023 (Supplementary table 1) (Gwaze, 2024). Concentrations in low-income areas are approximately 130% and 60% higher than those in industrial and urban/suburban areas, respectively (Hersey et al., 2015; Arowosegbe et al., 2021; Howlett-Downing et al., 2022; Muyemeki et al., 2021). The low availability of consistent PM measurements from ambient monitoring stations and sporadic coverage means that it is very difficult to determine long-term trends in ambient PM concentrations from ground-based measurements in the province.

Emission source areas

Studies have focused on industrial, mining and domestic fuel-burning activities as major sources of emissions in Gauteng. There is a dearth of studies on vehicle emissions.

Industrial areas

Gauteng's mining legacy has shaped the location of industrial areas in the province (Figure. 4). Industries are clustered along the Witwatersrand gold-bearing reef that runs from the West Rand, through central Johannesburg, and to the East Rand. Industries are also located in the Vereeniging-Vanderbijlpark region in the south of Gauteng, adjacent to the coal deposits. The 3 700 MW coal-fired Lethabo Power Station is located just south of Gauteng in the northern Free State Province. There is also an industrial area near Rosslyn, north-west of Pretoria.

Most of the gold-mining operations, except for a few on the far West Rand, are no longer in operation, but mine tailings remain along the Witwatersrand Ridge (Bobbins et al., 2018). Tailings storage facilities located near communities in Carletonville, Benoni, Brakpan, Soweto, and Johannesburg contribute to localised dust emissions, especially during windy and dry periods (in the late winter and early spring) (Ojelede et al., 2012; Kumar et al., 2014; Shackleton, 2016; COJ, 2017; Petzer, 2018; Andraos et al., 2019; Mpanza et al., 2020; Petzer, 2020). Tailings storage facilities are mainly a source of coarse aerosols (PM_{10}), and the windblown dust can contain cyanide and heavy metals, which further increase the potential health risks (Ojelede et al., 2012; Shackleton, 2016; Venter et al., 2016; Matandirotya et al., 2023).

Under the Apartheid-era legislature, non-white people were only allowed to live in designated townships on the periphery of urban centres, often adjacent to industrial or mining areas (Christopher, 1990). Today, lower-income and informal residential areas are still on the outskirts of the cities, and it is in many of these areas that communities rely on dirty fuels. Low-income households in Gauteng typically use paraffin and wood for space heating in winter (Liebenberg-Enslin and Hurt, 2009; StatsSA, 2016). Domestic coal use used to be high in Ekurhuleni during the early 2000s due to the region's proximity to collieries, but has declined significantly since then (van Niekerk et al., 2021).

Domestic fuel using communities

Domestic fuel-burning emissions have localised but severe impacts on ambient pollution levels (Hersey et al., 2015; Arowosegbe et al., 2021). In the large townships of Soweto south-west of Johannesburg, Daveyton near Benoni on the East Rand, and Tembisa in Midrand, it is estimated that domestic fuel burning emissions contribute about 60-70% of ambient PM_{10} concentrations (Scorgie et al., 2005; Liebenberg-Enslin and Hurt, 2009). In the Vaal, domestic burning contributes between 37% and 65% of PM_{10} in winter (Liebenberg-Enslin and Hurt, 2009). Around 83% of households in Gauteng are electrified (StatsSA, 2025), and the household use of dirty fuels continues because rapid urbanisation and growth of informal settlements strain the distribution of basic services such as electricity, and due to their cost-effectiveness compared to electricity.

Traffic emissions

Gauteng has about 40% of the country's vehicle fleet (4.5 million

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registered vehicles in 2020), and the number of vehicles increases annually (eNaTIS, 2021). Vehicle emissions are concentrated in the major urban centres of the City of Johannesburg, City of Tshwane, and Ekurhuleni (Scorgie et al., 2005) and on the major highways and arterial roads in the province. The main vehicle emissions are NO_x, CO, volatile organic compounds (VOCs), non-methane VOCs, and PM from exhaust (DEA, 2013). In addition, vehicle entrainment of dust from unpaved roads in high-density low-income areas represents a significant non-exhaust PM source, particularly contributing to coarse particulate matter (PM_{10}) emissions (DEA, 2019b). More than 95% of diesel sold in South Africa has a sulphur content of 50 ppm (Xie et al., 2022). Although this is an improvement over older, higher-sulphur fuels, the sulphur emitted remains a precursor to secondary $PM_{2.5}$.

Landfills and waste burning

Open waste burning and landfill operations are emerging as significant contributors to air pollution in Gauteng, particularly in densely populated urban are--as where waste management infrastructure is strained. While not as extensively studied as industrial or vehicle emissions, recent research highlights their role in degrading local air quality and impacting public health.

Studies conducted at landfill sites in Gauteng have documented elevated particulate matter exposures among workers and nearby communities. Research at the Onderstepoort landfill site in Pretoria found that waste reclaimers were exposed to high levels of PM_4, with personal exposures exceeding occupational exposure limits of 5 $mg.m^{-3}$ (5000 $\mu g.m^{-3}$), as per the Regulations for Hazardous Chemical Agents (Maeteletja, 2018; Maeteletja et al., 2019; Department of Employment and Labour, 2021). Similarly, Tlotleng et al. (2019) reported a high prevalence of respiratory symptoms, including wheezing and chronic bronchitis, among waste recyclers at Johannesburg landfills, directly linking occupational exposure to adverse health outcomes.

The contribution of waste burning extends beyond formal landfill sites. Inadequate waste collection services in many of Gauteng's townships and informal settlements lead to the common practice of open waste burning for volume reduction and pest control (Njewa et al., 2025). This uncontrolled combustion releases a complex mixture of pollutants, including fine particulate matter ($PM_{2.5}$), black carbon, and toxic volatile organic compounds (Njewa et al., 2025). The health risk impacts are compounded by open burning of plastic waste. When burned, plastic releases a suite of highly toxic carcinogenic chemicals (furans, hydrochloric acid, dioxins, benzene, styrene and heavy metals) which can be components of, or associated with the released PM (UNEP, 2023). Mazhandu et al. (2023) identified open plastic burning as the worst-case scenario for

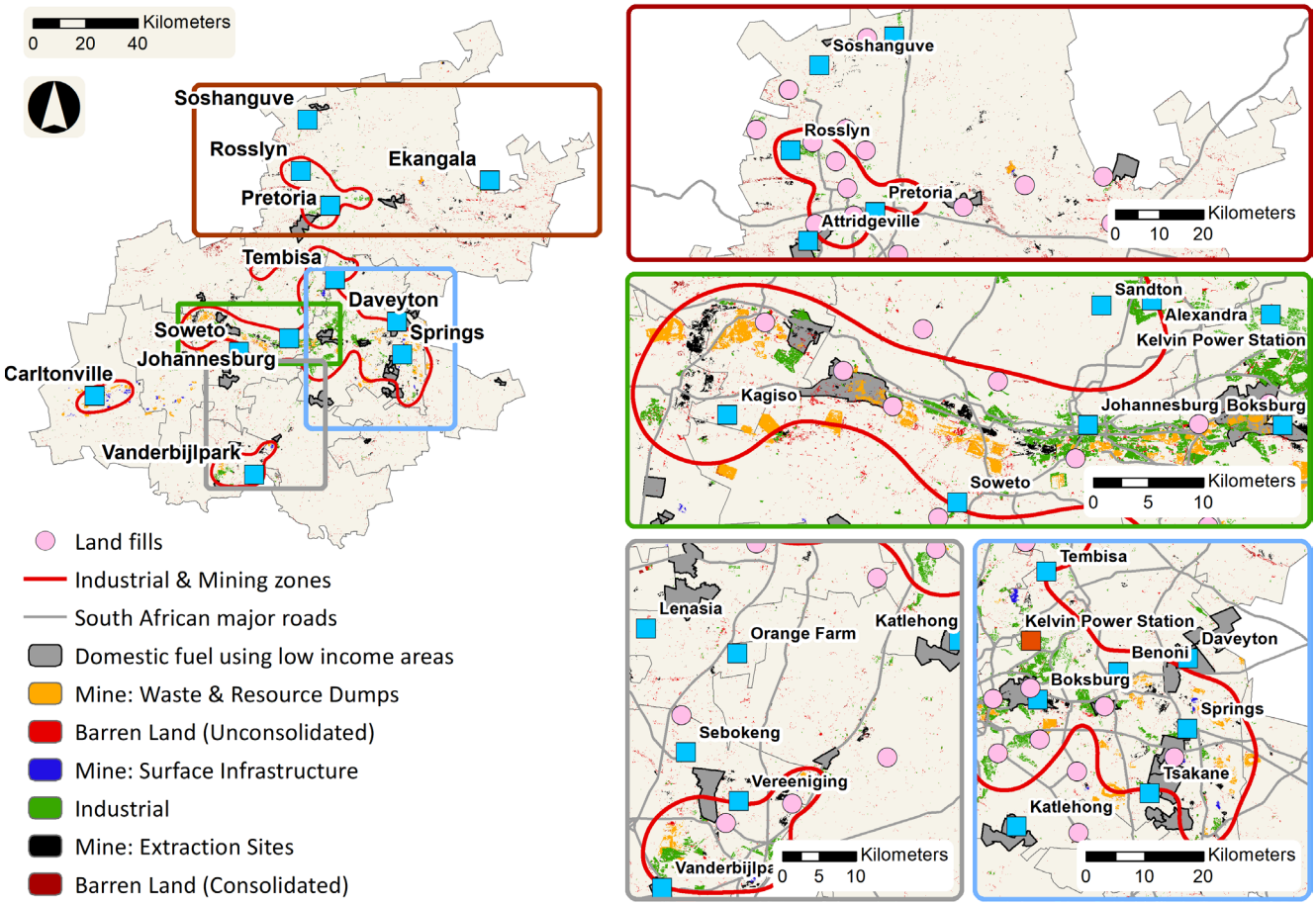


Figure 4: *Area source map of PM and PM precursors in Gauteng (compiled from datasets from StatsSA, 2016; The World Bank, 2022; DFFE, 2023).*

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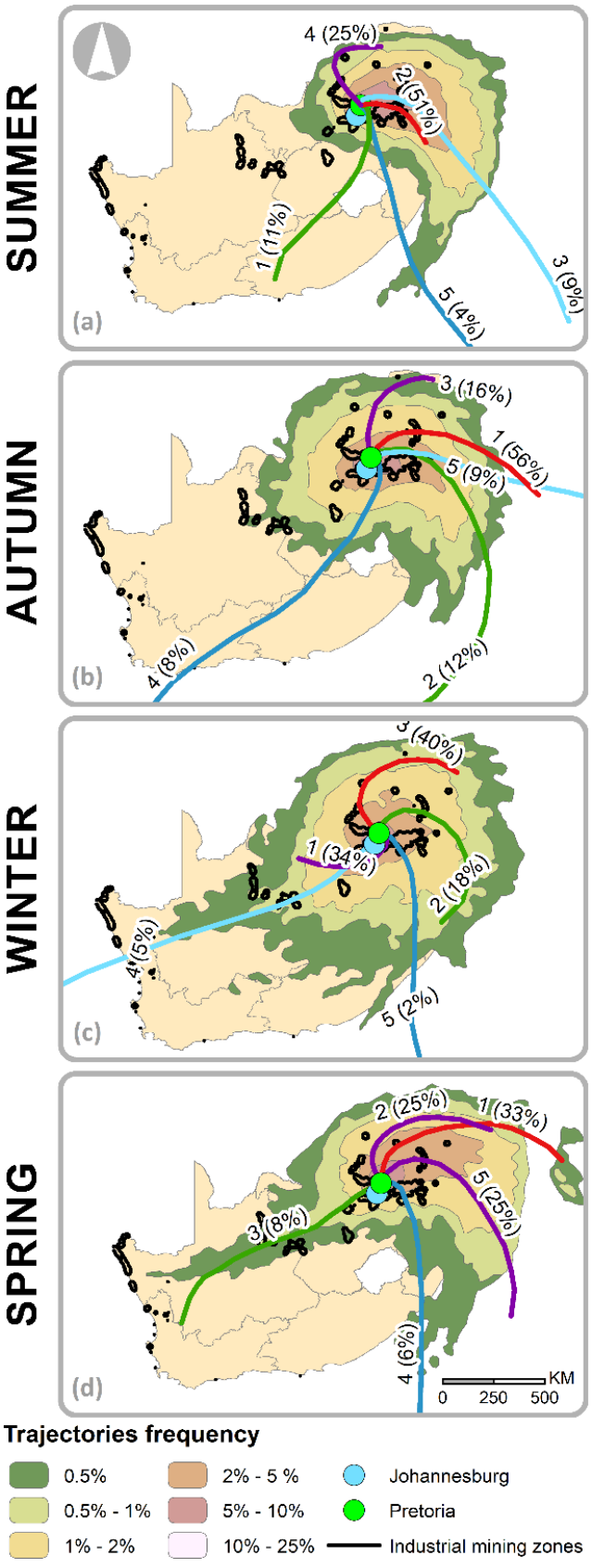


Figure 5: *Daily airflow back trajectories by season showing the origin of airflow into Gauteng adapted from Adeyemi et al. (2022b) for Pretoria (18 April 2017 – 17 April 2018) and Hersey et al. (2015) for Johannesburg (1 January 2000 – 31 December 2009). Summer (DJF), autumn (MAM), winter (JJA), spring (SON).*

environmental and health impacts in Johannesburg's waste management system.

The proximity of many low-income settlements to landfill sites creates environmental justice concerns, as these communities experience a double burden of exposure to both landfill emissions and domestic solid fuel burning. A regional review by Njewa et al. (2025) emphasises that dumping sites in Southern Africa, including those in Gauteng, significantly contribute to air, soil, and water pollution, with inadequate enforcement of regulations exacerbating the problem.

Airflow over Gauteng

The long-range transport of PM and its precursors into and out of Gauteng is determined by synoptic circulation patterns that govern both the direction and speed of airflow, and the occurrence of rain that effectively removes pollution from the atmosphere. Emissions from outside of Gauteng, especially from the Mpumalanga Highveld and the Vaal industrial complexes and from biomass burning, are sometimes advected over Gauteng due to synoptic circulation patterns.

Pollution transport into Gauteng

In all seasons, airflow into Gauteng is determined by the position of the continental anticyclone (Adeyemi et al., 2022a) (Figure 5). Except in winter, airflow is predominantly from the easterly direction, specifically from the south-easterly, easterly, and north-easterly directions. The airflow is often slow-moving, and especially during winter, it spends several days traversing the subcontinent before reaching Gauteng. Primary industrial source areas affecting Gauteng include the Mpumalanga Highveld, Vaal, and the mining regions in the North West and Limpopo (Swap, et al., 1996; Hersey et al., 2015; Jury, 2017; Adeyemi et al., 2022a, Howlett-Downing et al., 2022).

During the summer, airflow typically arrives in Gauteng from the south-east (Figure 5a) due to the weakening and increase in altitude of the continental anticyclone. This easterly flow consists of moist air originating over the Indian Ocean (Freiman and Piketh, 2002). It passes over the industrialised Mpumalanga Highveld before reaching Gauteng and may contribute to elevated air pollution in the Ekurhuleni and Pretoria regions (Adeyemi et al., 2022a). Approximately 25% of the airflow in summer arrives from a north-westerly direction. It is slow-moving and passes through the mining regions in Limpopo and the North West before reaching Gauteng (Adeyemi et al., 2022a). The third most frequent airflow arrives from a southerly direction, carrying emissions from the densely industrialised Vaal area. The presence of airflow arriving from a south-westerly and south-south-easterly direction, as observed in Adeyemi et al. (2022b), is not apparent in Hersey et al. (2015), possibly due to the trajectories being performed for different dates and time periods.

Autumn is a transitional season, but airflow is still predominantly from the east. In winter, the continental anticyclone deepens and the pressure belts move northwards (Tyson and Preston-

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Whyte, 2000). Slow-moving airflow from the north is most prevalent, potentially transporting dust and emissions from mining activities and biomass burning in Limpopo and North West provinces over Gauteng. The trajectories exhibit greater curvature compared to other seasons, potentially associated with the recirculation of pollutants from source areas within Gauteng.

Spring is another transitional season, with the continental anticyclone rising and weakening. Pressure belts migrate southward, and the predominantly easterly airflow pattern re-establishes itself.

Pollution transport out of Gauteng

Air most commonly exits Gauteng to the east. Pollutants accumulated in the air are either exported to the south-west and southern Indian Ocean (estimated to occur around 45% of the time by Freiman and Piketh (2002)) or may recirculate back over southern Africa in anticyclonic flow (around 33% of the time) (Tyson et al., 1988; Freiman and Piketh, 2002; Resane et al., 2004).

Surface winds

Surface wind flow patterns in Gauteng are influenced by a combination of synoptic conditions and local topography (Liebenberg-Enslin and Hurt, 2009). Most parts of Gauteng typically experience winds from the north-easterly to south-easterly directions (Liebenberg-Enslin and Hurt, 2009). Conversely, in the Vaal region in the south of Gauteng, north-westerly winds occur during the day and north-easterly winds occur at night (Liebenberg-Enslin and Hurt, 2009). This diurnal wind direction change is closely linked to mountain-valley winds in the Vaal River valley.

These local wind patterns have implications for airflow into and out of Gauteng. Easterly airflow can transport pollution from industrial sources in the Mpumalanga Highveld into Gauteng (Hersey et al., 2015; Adeyemi et al., 2022b). Local topography and the built environment can also hinder the transport of pollutants out of the province. In the Johannesburg CBD, for example, vehicle and other local emissions may be trapped due to calm conditions and obstructed surface wind flow caused by dense urban buildings (Liebenberg-Enslin and Hurt, 2009). Understanding these complex interactions between synoptic conditions, topography, and local land cover is crucial for effective air quality management and urban planning in Gauteng.

Vertical transport

Vertical transport over Gauteng is affected by different factors at regional and local scales. On a regional scale, absolutely stable layers trap pollutants in defined haze layers. On a local scale, nocturnal surface inversions confine pollutants close to the surface, and urban heat islands prevent the dispersion and mixing of local pollutants with the surrounding atmosphere.

Absolutely stable layers

Air pollutants over the Highveld tend to become trapped beneath the frequently occurring 700 hPa and 500 hPa absolutely stable layers (Tyson et al., 1988; Tyson and D'Abreton, 1998; Freiman and Tyson, 2000; Freiman and Piketh, 2002). Absolutely stable layers occur where the observed lapse rate exceeds the wet (saturated) adiabatic lapse rate, suppressing vertical motion. The 700 hPa and 500 hPa layers occur at altitudes of roughly 3 km and 5 km above sea level, respectively (Garstang et al., 1996; Cosijn and Tyson, 1996; Tyson and D'Abreton, 1996; Freiman and Tyson, 2000). Over Gauteng, the 500 hPa layer occurs 96% of the time in summer and 88% of the time in winter. The 700 hPa layer occurs 79% of the time in summer and 98% of the time in winter (Freiman and Tyson, 2000).

The lifting of the elevated stable layers in summer allows air pollution to diffuse through the depth of the mixed layer, and there is minimal recirculation. Moist air from the Indian Ocean is also able to reach the interior, allowing the development of rain (the main air pollution sink), resulting in cleaner ambient air during summer. During winter, the stable layers deepen (Freiman and Tyson, 2000). This restricts moist airflow from the Indian Ocean, limits vertical turbulent mixing, and results in minimal to no rainfall over Gauteng in winter (Tyson et al., 1988). It also results in higher ambient air pollution concentrations during this season.

Urban heat islands

Urban heat islands develop due to alterations in the energy balance of the surface and the atmosphere above urban areas and the release of anthropogenic heat into the air, resulting in higher temperatures over the urban areas than over the neighbouring rural areas, particularly at night (Tyson and Preston-Whyte, 2000). Urban heat islands have been frequently recorded in Tshwane, Johannesburg, Ekurhuleni, Emfuleni, and Midvaal (Hardy and Nel, 2015; Shikwambana et al., 2021). This is mainly due to the density of built-up areas and minimal vegetation cover compared to their surroundings (Shikwambana et al., 2021).

Urban heat islands usually co-exist with urban pollution islands due to the concentration of pollution-emitting activities in cities (Ulpiani, 2021). Wind patterns at the onset of urban heat islands, particularly the inward flow that converges and ascends in the urban centre while diverging and subsiding in adjacent rural areas islands, sharpens the pollution gradient between urban and rural areas (Santamouris et al., 2012), However, higher temperatures in urban areas increase turbulent mixing and raise the boundary layer height, promoting dispersion (Ulpiani, 2021).

The urban heat island and the urban pollution island interact in complex ways that have not been explored in the South African context to date. There are gaps in information regarding the degree to which urban heat islands increase PM concentrations within the islands and how seasons may affect the depth of the urban heat islands in Gauteng.

Source apportionment

Ambient PM in Gauteng is a mixture of fresh, locally emitted/formed particulates and aged particulates transported from

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further afield (Adeyemi et al., 2021; Howlett-Downing et l., 2022). While sources of PM and precursor gases have been identified, the relative contribution of these sources to ambient PM concentrations is poorly quantified. The PM source apportionment studies have analysed the chemical composition of ambient PM samples and performed source apportionment using various methods including the positive matrix factorisation model, chemical mass balance, surrogate tracing techniques and a Bayesian isotope mixing model (Engelbrecht et al., 1996; Formenti et al., 1998; DEA, 2009; Liebenberg-Enslin and Hurt, 2009; DEA, 2012; Lourens et al., 2016; Jaars et al., 2018; DEFF, 2020; Muyemeki et al., 2021; Adeyemi et al., 2022b Altieri et al., 2022). The characterisation of sources of the trace gases was conducted using atmospheric dispersion modelling to assess the emission, transport, and chemical transformation of the precursor gases (Engelbrecht et al., 1996; Formenti et al., 1998; DEA, 2009; Liebenberg-Enslin and Hurt, 2009; DEA, 2012, 2013; Lourens et al., 2016; DEA, 2020; Muyemeki et al., 2021; Adeyemi et al., 2022b; Altieri et al., 2022). Due to the use of different methodologies in studies and the short periods for sampling campaigns, there is poor agreement between the studies.

Only 14 source apportionment studies in Gauteng have been published (Figure 6 and 7). Many only identify three or four sources. Domestic fuel burning (of wood, coal, and to a lesser extent paraffin) and soil dust have been identified as the main sources of PM_{10} (Lourens et al., 2016; DEFF, 2019a; Adeyemi et al., 2022b; Muyemeki et al., 2021). In addition to these sources, industrial and vehicle emissions contribute to $PM_{2.5}$ concentrations (Liebenberg-Enslin and Hurt, 2009; DEFF, 2019a; Muyemeki et al., 2021). The main sources of NO_x and SO_2 are industrial emissions, vehicle emissions, and coal-fired power stations, with domestic coal burning contributing somewhat to SO2 concentrations (DEA, 2009, 2012; Lourens et al., 2011, Lourens et al., 2012; DEFF, 2019a; Muyemeki et al., 2021; Adeyemi et al., 2022b; Altieri et al., 2022; Liebenberg-Enslin and Hurt, 2009). The two studies assessing the sources of benzene (Liebenberg-Enslin and Hurt, 2009; Jaars et al., 2018) do not agree on what the sources are.

Given the large number of petrol vehicles on the roads in Gauteng, it is likely that they significantly contribute to ambient benzene levels (Liebenberg-Enslin and Hurt, 2009). It is also likely that vehicles contribute to toluene, ethylbenzene, and xylene (TEX) concentrations (Jaars et al., 2018).

Temporal variations

Trends in annual PM concentrations

Continuous measurements of PM have been collected at ambient monitoring stations in Gauteng for almost 20 years. Unfortunately, there is insufficient accurate PM data at most monitoring stations to identify long-term trends.

According to report from DEFF (2019a), PM concentrations have decreased over the years at some monitoring stations in the province, and there is no discernible trend at the other



Figure 6: *A comparison of source apportionment results from different studies for different sources contributing to $PM_{2.5}$ and PM_{10}, adopted from studies between 1996 and 2022. In square brackets is the sampling period.(Engelbrecht et al., 1996; Formenti et al., 1998; DEA, 2009; Liebenberg-Enslin and Hurt, 2009; DEA, 2012, 2013; Lourens et al., 2016; DEFF, 2020; Muyemeki et al., 2021; Adeyemi et al., 2022b; Altieri et al., 2022).*

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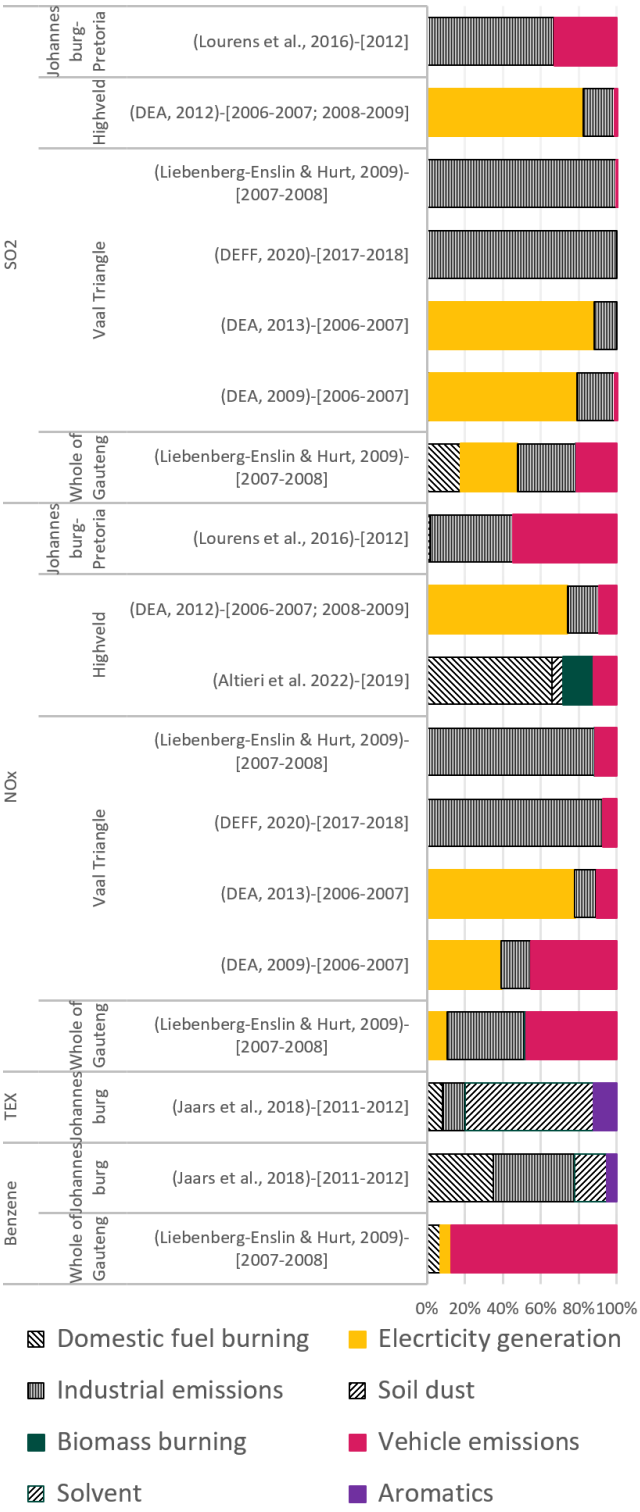


Figure 7: *A comparison of source apportionment results from different studies for different sources contributing to precursors of PM, adopted from studies between 1996 and 2022. In square brackets is the sampling period. TEX = toluene, ethylbenzene and xylenes. (Engelbrecht et al., 1996; Formenti et al., 1998; DEA, 2009; Liebenberg-Enslin and Hurt, 2009; DEA, 2012, 2013; Lourens et al., 2016; DEFF, 2020; Muyemeki et al., 2021; Adeyemi et al., 2022b; Altieri et al., 2022).*

stations. The most reliable ambient PM measurements were reported to be in the Vaal Triangle Airshed Priority Area in the south of Gauteng. According to the DEFF (2019a) report and, Govender and Sivakumar (2019), decreasing trends in $PM_{2.5}$ concentrations have been observed at Diepkloof, Sebokeng, and Sharpeville. There was no trend at Kliprivier. During this timeframe, PM_{10} levels declined in Diepkloof, Kliprivier, Sebokeng, and Sharpeville. There was no discernible trend in PM_{10} concentrations in Three Rivers (DEFF, 2019a; Govender and Sivakumar, 2019).

The DEFF (2019a) report for Johannesburg, indicates that Ivory Park, and Alexandra have displayed a decreasing trend in PM_{10} concentrations, while other stations showed no clear trend (DEFF, 2019a). In Pretoria, Rosslyn exhibited a decreasing trend in PM_{10} concentrations, while other stations showed no apparent trend over the years (DEFF, 2019a). In Ekurhuleni, the available data is too limited to identify PM_{10} trends.

Most decreasing PM trends were discernible in stations located within priority areas. This may indicate the impact of emissions reduction policies targeted at industrial activities and the introduction of emissions standards (Arowosegbe et al., 2021). The fluctuations in PM over the years may be related to several factors that may be anthropogenic (different emission rates from sources) and natural (prevailing synoptic conditions, rainfall, and wind occurrences), which vary from year to year.

Seasonal variations

Ambient PM concentrations typically increase from May, peak in August, and decrease after that (Govender and Sivakumar, 2019; Arowosegbe et al., 2021). The lowest concentrations occur from October until March (Arowosegbe et al., 2021). PM is highest in winter due to the prevailing anticyclonic conditions, the deepening of the 700 and 500 hPa absolutely stable layers, which limit the vertical mixing of air pollution, and minimal rainfall. Emissions from some sources, like domestic burning, are also higher in winter due to space heating requirements. The low PM concentrations from spring until early autumn (November-April) result from the lifting of the 700 and 500 hPa stable layers and the encroachment of the tropical easterlies, allowing rainfall over the interior, which removes particulates via wet deposition (Freiman & Tyson, 2000).

Diurnal variations

Diurnal variations in PM concentrations across the province show peak levels during early mornings and late afternoons/evenings, coinciding with traffic rush hour, domestic fuel use, and unfavourable conditions for the dispersion of air pollutants (development of nocturnal surface inversions and stable meteorological conditions) (Arowosegbe et al., 2021; Matandirotya et al., 2023). Furthermore, concentrations are typically higher on weekdays than at weekends due to reduced industrial activities and vehicle traffic over weekends (Govender and Sivakumar, 2019; Arowosegbe et al., 2021).

Spatial variability

Only two studies using remote sensing data to explore spatial variations in PM concentrations in Gauteng were found

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(Arowosegbe et al., 2022; Zhang et al., 2021), suggesting there is still considerable scope for further studies. These studies estimated PM concentrations from satellite aerosol optical depth (AOD) and meteorological, land use and socioeconomic factors associated with PM using machine learning. These studies both report high PM levels in the eastern (Ekurhuleni), central (Johannesburg), and southern (Vaal) regions of Gauteng. The differing findings on the location of areas with low PM concentrations are primarily due to the studies' distinct study area focus and methodology. Zhang et al. (2021), in their regional $PM_{2.5}$ model, link low concentrations in southwestern Gauteng to less industrial and mining activity. In contrast, Arowosegbe et al. (2022), using a national PM_{10} model, identify more extensive low concentration zones on the northwest, southwest, and southeast of Gauteng, which they associate with non-urban land uses like agriculture. The key distinguishing factors are thus the pollutant fraction analysed and the model's spatial scale, which alter the influence of emission sources and land-use variables.

Ambient measurements of PM concentrations show high spatial variability in PM concentrations across the province. The highest annual average PM_{10} concentrations (>100 $\mu g.m^{-3}$) and $PM_{2.5}$ concentrations (>50 $\mu g.m^{-3}$) in Gauteng were recorded before 2013 in low-income areas, often adjacent to industrial areas, where some households practise domestic fuel burning, especially during winter: Sharpeville, Sebokeng, Diepkloof, Alexandra, Diepsloot, Etwatwa, Thokoza and Wattville (DEFF, 2019a; DEFF, 2019b; Govender and Sivakumar, 2019).

Discussion on the state of knowledge

The strengths and weaknesses in our knowledge of factors controlling PM concentrations in Gauteng that have emerged from this review are evaluated here. Recommendations are made for future research directions.

PM over Gauteng is derived from local and regional sources. Regional sources include industrial and power generation activities on the Mpumalanga Highveld, mining activities to the north-west, biomass burning, and aeolian dust. The influence of coal mining activities in Mpumalanga and platinum mining and smelting activities in the North West and Limpopo provinces on Gauteng's air quality has not been comprehensively assessed. Local sources of emissions in Gauteng are the industries clustered on the Witwatersrand ridge and in the south of Gauteng (Vereeniging), motor vehicles, and domestic burning of wood and paraffin. The relative strength of these emission sources and their contribution to ambient PM levels have not been convincingly assessed. No PM source apportionment has been conducted in Ekurhuleni or dense low-income settlements, and no source apportionment for $PM_{2.5}$ has been conducted in Johannesburg.

At the synoptic scale, there is a good understanding of the transport of pollutants. Trajectory modelling has shown that the pervasive continental anticyclone dominates long-range transport. Transport into Gauteng is from the eastern quadrant in most seasons, except in the winter when it is mainly from the north. Transport out of Gauteng is mainly to the east, some of which recirculates back over the sub-continent. However, it is not known how transport pathways will be affected by circulation changes associated with climate change. Moreover, atmospheric transport at the micro-scale is often controlled by local topography. Site-specific assessments need to be made when information is needed about local wind fields. The effect of the urban form and the pronounced urban heat islands over the built-up areas on pollution dispersion is poorly understood.

The poor availability of PM concentration data at ambient air quality monitoring stations in the province has hampered the understanding of long-term trends in PM concentration. Improving the quality of data available and number of ambient monitoring stations in the province should be a priority for the government and all other stakeholders. Satellite measurements offer considerable potential to aid in understanding long-term trends, but they have limited spatial resolution (for an urban environment), and it is difficult to derive surface concentrations with confidence.

At a regional scale, there is a clear understanding that there are PM hotspots over Johannesburg, Ekurhuleni, and the Vaal. However, at a ward-level, PM levels vary significantly over short distances. This finer-scale can identify the most vulnerable communities for prioritised action. Documentation at this scale is insufficient to capture the dynamics and patterns of PM spatial variations in detail. Satellite observations are unlikely to provide the fine spatial resolution needed to assess spatial variability in PM in an urban environment (Chudnovsky et al., 2013). A chemical transport model, like CAMx, is more useful in identifying localised PM hotspots in the province.

The following research is needed to assist with aiding our understanding of PM dynamics, and ultimately its effect on health, in Gauteng:

- The maintenance and operation of a core subset of ambient monitoring stations needs to be prioritised in order to enable long-term trend analysis and meaningful comparisons across diverse environments. This network should include stations in low-income, middle- and or high-income suburbs, key source areas (industrial zones, major roads), heavily congested transport corridors (e.g., National (N), regional (R) and metropolitan (M) roads (SANRAL, 2012), especially those located close to residents, schools and hospitals), and regional background sites unaffected by anthropogenic sources. This design will allow for the quantification of urban pollution and provide insights into the contribution of non-anthropogenic sources.
- The deployment of low-cost sensor networks (calibrated with reference monitors) to fill critical spatial and temporal data gaps, particularly in high-exposure areas such as townships and areas adjacent to tailings storage facilities.

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- An analysis of long-term trends in PM concentrations should be conducted in the most densely populated areas using satellite observations.
- A coordinated PM source apportionment programme based on long-term samples should be initiated. The Pretoria and Johannesburg sites in the SPARTAN monitoring network (Liu et al., 2024) are a good start.
- The interactions between urban form, the urban heat islands and urban pollution islands should be investigated.
- Knowledge is needed on the spatial variability of PM at a fine scale to have an in-depth understanding of community-level spatial variability of health impacts.
- The environmental justice implications of vastly different exposure levels of people living in different geographical areas, with varying socio-economic status and land use types (high density informal settlements and low-cost housing areas compared with affluent suburbs) should be investigated, particularly as it pertains to the health impacts of PM inhalation.
- The magnitude and location of vehicle-related emissions of PM and its precursors should be monitored using on-road measurements (remote sensing/portable emissions measurement systems). This data is important for validating and refining vehicle emission inventories and for assessing the effectiveness of control strategies, such as those in the City of Johannesburg's vehicle control emissions strategy and action plan (COJ, 2021).

Conclusion

A systematic literature review of studies on the sources, transport and ambient concentrations of PM in Gauteng, South Africa's most populous and industrialised province, has revealed significant shortcomings in the knowledge base. These pertain to the highly variable and often conflicting quantifications of source contributions to ambient PM; a poor understanding of how changing weather patterns and climate uncertainties such as how the intensification of synoptic systems may alter pollution transport recirculation, and deposition, and a lack of reliable data to determine long-term trends in PM concentrations.

There is considerable opportunity to improve the availability of data collected at the ambient air quality monitoring stations in Gauteng, and to use satellite and the chemical transport model data already available in the VTAPA, HPA and AQMP baseline assessments, to investigate temporal and spatial trends in PM concentrations. Publishing studies conducted privately for funding bodies would also aid in disseminating the knowledge accumulated.

The health risks of air pollution exposure in Gauteng, although not yet comprehensively assessed, are likely to be considerable given the high exposure levels and the large number of people living in the province. Filling the gaps in our knowledge base, particularly quantifying the contribution of sources to ambient PM levels, is urgently needed to enable the design of interventions to most effectively reduce exposure levels.

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Supplementary material

Supplementary material can be accessed at https://cleanairjournal.org.za/article/view/23693

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