

Research article

Air Pollution and Health Studies in the Highveld Priority Area, South Africa: A Scoping Review

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Received: 25 November 2025 - Reviewed: 6 March 2026 - Accepted: 27 May 2026

<https://doi.org/10.17159/caj/2026/36/1.24710>

Abstract

Air pollution remains a major environmental health concern in South Africa, particularly in the Highveld Priority Area (HPA), where multiple coal-fired power stations, heavy industry, and household solid fuel use contribute to sustained poor air quality. This review systematically assessed the peer-reviewed evidence on air pollution and health in the HPA to establish a baseline of research, identify gaps, and inform future policy and scientific priorities. Following PRISMA guidelines, we searched four bibliographic databases and key journals for English-language studies published up to October 2024. A total of 130 papers met inclusion criteria: 98 focused on air quality only, 19 on health only, and 13 addressed both air quality and health outcomes. Air quality studies span more than four decades, documenting trends in criteria pollutants such as SO₂, NO₂, PM₁₀, PM_{2.5}, and O₃, with recent analyses highlighting the HPA as one of the world's NO₂ and O₃ hotspots. Health studies, mostly post-2014, primarily investigated respiratory outcomes, and extending to cardiovascular disease and congenital anomalies. Most relied on self-reported health data, while only one study used objective spirometry. Studies combining air quality and health data are few, methodologically limited, and largely unable to establish causal relationships. Nevertheless, evidence consistently suggests that HPA residents, focusing on children, adolescents, and the elderly, are at heightened risk of respiratory morbidity. The review highlights critical research gaps, including insufficient use of personal exposure monitoring, limited objective health assessments, and a narrow focus on respiratory outcomes. We recommend coordinated, large-scale, interdisciplinary studies leveraging the HPA as a natural laboratory to advance understanding of air pollution–health linkages. Strengthening ambient monitoring networks, integrating indoor and outdoor exposure data, and expanding research beyond respiratory effects are essential to guide effective interventions and uphold the constitutional right to a healthy environment in South Africa.

Keywords

air quality; Highveld Priority Area; environmental health; South Africa; public health

Introduction

Air pollution is increasingly recognised as a serious threat to human health by the World Health Organization (WHO) (WHO 2021). It is estimated that 4.2 million people die annually due to ambient air pollution, with an additional 3.8 million deaths attributed to indoor air pollution mainly from emissions by cookstoves and fuels (Bhat et al. 2021). South Africa, with its heavy reliance on coal-fired power stations and the use of coal and kerosene as a domestic fuel in some areas, coupled with urban-industrial activities, has a long history of air pollution problems. Consequently, potential human health impacts are not unexpected.

The declaration of air quality priority areas in terms of Section 18 (1) of the National Environmental Management: Air Quality

Act (No. 39 of 2004) is the mechanism used by the South African national government to focus efforts and manage air pollution levels in these targeted areas. Through Air Quality Management Plans (AQMPs) that aim to ensure that the constitutional rights of all citizens to a clean and healthy environment are upheld (RSA 1996), air quality levels are closely monitored and managed.

To date, three national air quality priority areas have been declared in the country on the basis that air pollution levels in these areas were exceeding or were expected to exceed national ambient air quality standards (NAAQSs). The first to be declared was the Vaal Triangle Airshed Priority Area (VTAPA) in April 2006, followed by the Highveld Priority Area (HPA) in November 2007, and the Waterberg-Bojanala Priority Area (WBPA) in June 2012.

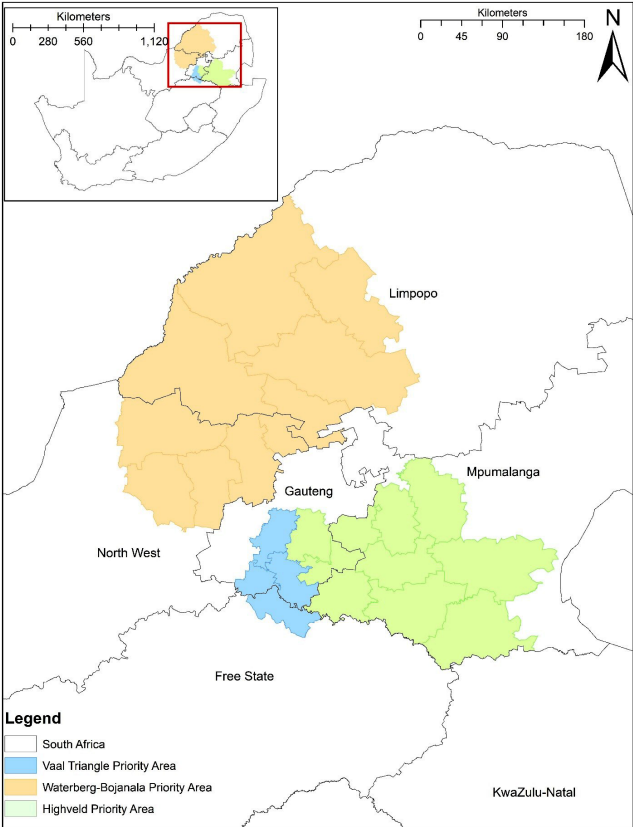


Figure 1: Map illustrating the location of the three air pollution priority areas in South Africa.

A study in the WBPA was conducted by Wernecke et al. (2023), however, this is the first such review for the HPA. This paper presents a scoping review of air pollution and health studies in the HPA. The aim is to map the existing peer reviewed evidence, identify gaps, and provide a baseline for future research. This approach is particularly timely given the development of the second generation HPA Air Quality Management Plan and the growing emphasis on health centred air quality management in South Africa.

Study area

The HPA, an area of over 31 000 km² in the provinces of Gauteng and Mpumalanga, comprises one metropolitan municipality (Ekurhuleni), three district municipalities (DMs) (Gert Sibande, Nkangala and Sedibeng), and nine local municipalities (Lesedi in Sedibeng DM, Victor Khanye, Steve Tshwete, and eMalahleni in Nkangala DM, and Govan Mbeki, Dipalaseng, Msukaligwa, Lekwa, and Pixley ka Seme in Gert Sibande DM (Fig. 1). There are 12 Eskom coal-fired power stations and Sasol’s coal to liquids refinery in the area, as well as the towns of eMalahleni, Middelburg, Secunda, Standerton in Mpumalanga and Edenvale, Boksburg and Benoni in Gauteng.

The HPA AQMP was gazetted in March 2012 (No. 35072) (termed AQMP 2011) and aimed to implement interventions to improve air quality in the area. Measured data showed that there had not been significant improvement in air quality and that there were

still a significant number of exceedances of NAAQS. In total, less than 50% of the planned interventions had been achieved and only 29% of industry and low-income settlement interventions had been accomplished. It was noted that the number of ambient air quality monitoring stations reporting to the South African Air Quality Information System (SAAQIS) had increased from 20 to 31, but that there were technical and other challenges that hampered data availability.

The draft Second-Generation Highveld Priority Area Air Quality Management Plan was published for public comment in July 2024 (Gov. Gazette 26 July 2024, No. 50985) and contained a far greater emphasis on human health. At the time of writing, it had not been finalised.

Methods

The review followed the PRISMA ScR (Preferred Reporting Items for Systematic Reviews and Meta Analyses Extension for Scoping Reviews) principles to ensure transparency in the search and selection process. As a scoping review, the objective was to describe the breadth of available evidence and identify research gaps; therefore, no risk of bias assessment, dual reviewer screening, or meta analysis was undertaken. Key word search terms were categorised into three groups as summarised in Table 1.

Table 1: Key words and search strategy applied in the systematic review

Group 1	Group 2	Group 3	Combinations
Air pollution OR air quality AND	Health OR respiratory health OR respiratory health outcomes AND	Highveld OR Mpumalanga OR Ekurhuleni	Term from Group 1 plus term from Group 2 plus term from Group 3 until all combinations were exhausted

Four bibliographic databases (PubMed, Web of Science, ScienceDirect, and Google Scholar) and two journals (Clean Air Journal and BMC Public Health) were searched for English language papers published up to 31 October 2024. Search terms were grouped into three categories relating to air pollution, health, and the HPA (Table 1). Boolean operators were used to combine terms across categories.

Eligibility criteria

Included studies met the following criteria:

- peer reviewed journal articles
- written in English
- included data from the HPA (either exclusively or as part of a broader study area)
- focused on air quality, health outcomes, or both

Excluded sources:

- student theses
- government reports and AQMPs
- grey literature

Grey literature was excluded to maintain a consistent standard of peer reviewed evidence; this is acknowledged as a limitation

Screening and selection

Titles and abstracts were screened to identify potentially relevant papers, followed by full text review. Duplicates were removed manually. Papers were categorised as:

1. air quality only
2. health only
3. combined air quality and health

A PRISMA ScR flow diagram summarises the search and selection process (Figure 2).

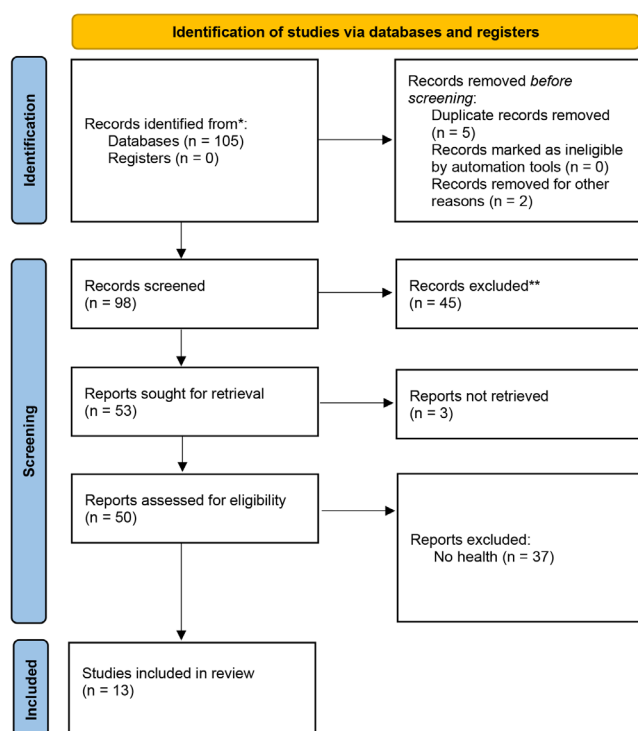


Figure 2: PRISMA 2020 flow diagram for new systematic reviews which included searches of databases and registers only

Overview

Air Pollution Monitoring and Studies in the HPA

The Mpumalanga Highveld (now comprising much of the HPA) has long been identified as a potential air pollution hotspot as a result of the concentration of heavy industries and multiple coal-fired power stations. An early paper by Louw et al. (1982) reported on near-surface sulphur dioxide (SO₂) concentrations at five sites, including two in the Mpumalanga Highveld, based on data for winter 1980. Although none of the prevailing international ambient air quality standards of the time were exceeded, the authors recommended continued air pollution monitoring as a result of industrial expansion. The potential for future deterioration of air quality was recognised.

The most extensive ambient air quality monitoring network in the region is that operated by Eskom, which reports its data

to SAAQIS. A chronological overview of the Eskom-operated ambient ground-based network in the region was provided by Mkhathshwa (2008). It commenced with mobile SO₂ monitors in 1978, was expanded over time to include 22 SO₂ monitoring stations, and was rationalised in 1989 to five stations monitoring SO₂, nitrogen oxides (NO_x) and particulate matter with a diameter less than 10 µm (PM₁₀). Today the suite of pollutants monitored has expanded, with Collette et al. (2010) reporting that at the station of Elandsfontein, nitrogen dioxide (NO₂), nitric oxide (NO), nitrate (NO₃), ammonia (NH₃), ozone (O₃), carbon monoxide (CO), hydrogen sulphide (H₂S) and black carbon (BC) are monitored. The Eskom data have formed the basis of many analyses. The station of Elandsfontein located in the central Highveld, has the longest data record commencing in 1985.

Early papers based on these data by Held et al. (1994) for particulates and Rorich and Galpin (1998) for SO₂, NO_x, O₃ and fine particulate matter (FPM) did not identify the Mpumalanga Highveld as a potential air pollution hotspot. Held et al. (1994), based on data from May 1985 to March 1990 and 15 monitoring stations, concluded that while ground level particulate concentrations were generally not 'unacceptable', stagnant atmospheric circulation patterns and air mass recirculation could result in episodic occurrences of high sulphate and nitrate particulate concentrations, particularly at elevated sites, but they rarely exceeded international air quality standards.

Another early study by Zunckel et al. (1996), which investigated dry and wet deposition of sulphur on the central Mpumalanga highveld based on winter and summer pilot studies noted that the dry deposition rate exceeded the wet deposition rate and drew heavily on the region's location in the subtropical high-pressure belt as explanation for the diurnal and seasonal patterns observed. They concluded that the deposition rates were comparable with those found in other studies in the United States and did not draw attention to the region as an air pollution hotspot.

As trend studies began to be undertaken, a picture emerged of a region where air pollution concentrations were generally rising and reference was made to the Mpumalanga Highveld as one of the top five NO₂ emission hotspots in the world (Laakso et al. 2012). For example, Mkhathshwa (2008) analysed long term trends in SO₂, NO_x and PM₁₀ at three stations and found a slight increase in SO₂ at Elandsfontein over a 20-year time period (1986-2005) and increased PM₁₀ at two stations. Feig et al. (2019), on the other hand, found that PM₁₀, PM_{2.5} and SO₂ concentrations were generally improving over a 15-year period. However, they noted that PM levels were non-compliant with NAAQS as were SO₂ levels at the station of Witbank.

Surface O₃ was the focus of two studies by Zunckel et al. (2004; 2006) as part of the Cross Border Air Pollution Impact Assessment project (CAPIA) which focused on impacts on maize across the southern African region, including the Mpumalanga Highveld. The former was based on observational data, with highest O₃ concentrations occur over Botswana and

the Mpumalanga Highveld. In both regions, the springtime maximum was between 40 and 60 ppb, but reached a mean of more than 90 ppb in October 2000. The latter paper was based on modelled estimations and indicated large areas on the sub-continent where surface O_3 concentrations exceeded 40 ppb for up to 10 hours per day. Maximum concentrations exceeded 80 ppb, particularly in the winter when mean ozone concentrations were higher. The areas where the 40 ppb threshold was exceeded coincided with maize growing areas in South Africa and Zimbabwe. The authors concluded that neither anthropogenic emissions nor biogenic emissions were dominant in the production of surface ozone over southern Africa, rather the formation of surface O_3 over the region was attributed to the combined contribution of precursors of anthropogenic and biogenic origin. Laban et al. (2018) also focused on O_3 and its relationship with precursor species, noting that the interior of South Africa was volatile organic compound (VOC) limited as a result of high NO_x emissions and suggested that the most effective way to reduce O_3 was to reduce CO and VOCs, which were mainly associated with combustion of domestic fuels and biomass burning respectively.

Over time, surface-based measurements of ambient air pollutants in the HPA and the surrounding region were supplemented by aircraft measurements (e.g. Broccardo et al. 2018; Kirkman et al. 2000), vertical profile measurements (Campbell et al. 2003) and satellite observations (Broccardo et al. 2018; Cogho et al. 2022; Hersey et al. 2015; Kneen et al. 2016; Lourens et al. 2012; Ross et al. 2007; Sangeetha et al. 2019; Sibiya et al. 2024; and Shikwambana et al. 2020; 2024). While satellite observations, in particular, helped to define the spatial extent of elevated pollution levels and confirmed the existence of a regional NO_2 and O_3 hotspot in Mpumalanga, Hersey et al. (2015) drew attention to some limitations of satellite data, such as their inability to capture trends in ground PM levels. They argued that they could not be considered as a replacement for a ground-based network of air pollution monitors. Modelling studies also contributed to our knowledge of the spatial configuration of the pollution hotspot and improved spatial resolution of data, and in disaggregating source contributions (Arowsegbe et al. 2021a, 2021b, 2022; Chihindi et al. 2019; De Lange et al. 2021; Hersey et al. 2015; Josipovic et al. 2010a; Zhang et al. 2021; Zunckel et al. 2006) and investigating emission mitigation strategies (De Lange et al. 2021).

Collett et al. (2010) investigated the nitrogen budget using data from Eskom's Elandsfontein station aiming to characterise the conversion, transport and removal of atmospheric nitrogen species. While NO_2 and NO_3 concentrations were higher in winter months, it was concluded that levels did not pose a significant threat to the natural environment (human health was not mentioned) as between 4% and 15% was deposited to the ground as wet and dry deposition, the remainder being transported out of the region.

A series of papers (Josipovic et al. 2010a; 2010b; 2011; Swartz et al. 2020) reported on the analysis of monthly mean

concentrations of near-surface SO_2 , NO_2 and O_3 based on data from a network of 37 passive sampling sites over the Mpumalanga Highveld. The data were part of a field campaign conducted between August 2005 and Sept 2007, in which the primary aim was to evaluate whether acidic atmospheric pollutants posed a threat to the natural environment. Risks to human health were not mentioned. Only in the central Highveld (vicinity of Elandsfontein) were pollution levels above critical thresholds for environmental damage.

Although the criteria air pollutants of SO_2 , NO_2 and PM were the early focus of attention, over time, interest emerged in the characteristics of other species, such as BC (Chiloane et al. 2017; Feig et al. 2015; Shikwambana and Tsoeleng 2019; Xulu et al. 2020), brown carbon (BrC) (Xulu et al. 2020), H_2S (Cogho et al. 2023), methane (CH_4) (Sibiya et al. 2024), asbestos (Moja et al. 2016; Kwata et al. 2017, 2018; Vorster et al. 2018), mercury (Hg) (Belelie et al. 2019a; True et al. 2010), lead (Olufemi et al. 2019), radon (Le Roux et al. 2021; Le Roux 2022), sulphate (Scheifinger 1992; Snyman et al. 1987), the BTEX (benzene, toluene, ethylbenzene and xylene) group (Lourens et al. 2011; Pone et al. 2007), and metals such as lead (Pb), chromium (Cr), nickel (Ni), manganese (Mn), vanadium (V), cobalt (Co) and iron (Fe) (Monna et al. 2006; Žibret et al. 2013). There were also studies that reported on the chemical composition and size of atmospheric aerosols or particulates in an attempt to identify sources (Annegarn et al. 1983; Held et al. 1993, 1994; Khumalo et al. 2020; Laakso et al. 2012; Maenhaut et al. 1996; Piketh et al. 1995; Scheifinger and Held 1997; Walton et al. 2021; Xulu et al. 2020).

Besides for industrial air pollutants, a few studies reported on levels of pollen and fungal spores which are also known to impact human health (Berman 2007; Ordman 1963) and biogenic VOCs (BVOCs) because of their influence on the formation of O_3 (Sowden et al. 2007).

In general, early papers were focused on documenting levels of ambient air quality, describing the observed seasonal patterns, and in some cases on understanding the seasonal climatological and meteorological influences. There was no mention of potential health risks posed by what was clearly recognised as an air pollution hotspot.

By the mid-2010s, potential health impacts were increasingly being mentioned as justification for the studies of various air pollutants (e.g., Chihindi et al. 2019; Chiloane et al. 2017; Feig et al. 2015; 2019; Kneen et al. 2016; Kumar et al. 2014; Language et al. 2016a) and in some cases there was reference to relevant ambient air quality standards. The shift to a central focus on health impacts commenced a few years later, towards the end of the decade.

Another trend that began to emerge around the same time (mid-2010s) was the increased attention on indoor air quality measurements as a result of the combustion of domestic fuel sources, usually coal, in informal dwellings (e.g., Adesina et al.

Table 2: Overview of papers on air quality and/or health-related research in the Highveld Priority Area

Geographical area	Number of papers on air quality only	Number of papers on health only	Number of papers on both air quality and health	Total
Highveld Priority Area	51	11	10	72
Broader region but including HPA	47	8	3	58
Total	98	19	13	130

2020a; 2020b; Language et al. 2016a, 2016b; Le Roux 2022; Le Roux et al. 2021; Madonsela et al. 2024; Nkosi et al. 2017; Olufemi et al. 2019; Rodney et al. 2024; Segakweng et al. 2022; Wernecke et al. 2015). Comparisons between indoor and outdoor pollution levels have yielded variable results that are influenced by, *inter alia*, season and pollutant species, but a body of evidence is emerging that points to generally higher pollution levels in indoor environments. Monitoring stations have been set up specifically to monitor air quality in low-income communities, for example, KwaZamokuhle established in September 2014, and Ezamokuhle in July 2017.

Results

The 130 included studies were categorized according to their primary focus (air quality only, health only, or combined), data sources, and methodological approaches to facilitate synthesis and identification of research gaps.

Table 2 summarises the number of papers on air quality and/or health-related research in the HPA. The entries are broken down into those that were focused exclusively on the HPA and those that had a broader geographic focus, either on neighbouring urban-industrial areas or South Africa as a whole. As mentioned earlier, only papers that included data from the HPA were included.

The number of papers on both air quality and health (n=13) in the HPA exceeds the number found in the WBPA (n=7) by Wernecke et al. (2023), who included a broader catchment of papers and not just peer-reviewed journal publications as was the case in the current study. The number of ‘air quality only’ papers (n=98) far exceeds the number of ‘health only’ papers (n=19) and ‘health and air quality’ papers (n=13). There is a long history of air quality studies dating back to 1980 (e.g. Kemeny 1980; Louw et al. 1982), evidence of a renewed focus in the 1990s linked to the Southern-Africa Fire-Atmosphere Research Initiative (SAFARI) and increased activity from 2006 onwards, with a solid focus on air quality research since 2015. With few exceptions (n=5), most of the health only papers tend to be post-2014. Studies linking air quality and health and reflecting a shift from delineating and understanding the nature of the air pollution hot spot to a focus on impacts, are also mainly confined to the last ten years.

Health Studies in the HPA

Poor air quality is often cited as the reason for many health-related studies being conducted in the HPA, even though there was no attempt to link health outcomes directly to ambient air pollution levels. In some cases (e.g., Albers et al. 2015; Bidassey-Manilal et al. 2019; Mashalane et al. 2006; Mudau et al. 2024), surveys elicited information on associated risk factors such as domestic fuel use and/or tobacco smoking to inform conclusions on the relationship with health outcomes. In other cases, comparisons between disease prevalence in urban and rural areas or disease prevalence in communities close to gold mine tailings dumps (exposed) and unexposed communities (Nkosi et al. 2015a; 2015b; 2016; 2017; 2020; Olajide-Ibiejugba et al. 2021) enabled inferences to be made about the role of air pollution. Most of the studies focused on respiratory health, although allergic and non-allergic rhinitis, cardiovascular disease and eczema were also studied. Target populations also varied from children to adolescents to the general population. Few studies relied on objective health-related measurements such as spirometry; the vast majority utilised self-administered questionnaires to elicit health information, which may impose bias due to lack of recall on the part of participants.

Key findings from the various studies are higher prevalence of self-reported respiratory illnesses among children from households relying on non-electrical fuels versus electricity for cooking (43.9% compared with 31.6%) and for heating (37.8% compared with 29.0%), with the highest prevalence (45.5%) amongst those using coal for cooking (Albers et al. 2015). Bidassey-Manilal et al. (2019), in a cross-sectional study across households in four different locations, found that the prevalence of allergic rhinitis ranged between 23% and 64%, with a significant association between higher prevalence and households that relied on coal, wood and kerosene as fuel.

Several studies compared health outcomes of residents living close to gold mine tailings dumps (exposed) and those living further away (unexposed). Although the results are applicable to a broader region than just the HPA, it was concluded that elderly (> 55 years) persons living in exposed areas had significantly higher prevalence of chronic respiratory symptoms and diseases than those in unexposed areas. The Odds Ratio (OR) for asthma was 1.57, chronic bronchitis (1.74), chronic cough (2.02), emphysema (1.75), pneumonia (1.38) and wheeze (2.01) (Nkosi et al. 2015a; 2015b). A study by Nkosi et al. (2020) focusing on non-allergic rhinitis amongst the elderly found the overall prevalence to be 23.99%, compared with 27.08% in exposed and 18.82% in unexposed communities. Another study by Nkosi et al. (2021) compared the prevalence of high blood pressure in exposed versus unexposed communities, concluding that blood pressure levels were higher in exposed communities. In a similar study, investigating the comorbidity of respiratory and cardiovascular diseases amongst the elderly, Nkosi et al. (2016) found a higher prevalence in exposed versus unexposed communities. Comparing disease outcomes amongst adolescents in exposed and unexposed communities, Nkosi et al. (2015a) reported increased likelihoods of wheeze (OR of

Table 3: Categorisation of health and air pollution papers according to sources of air pollution and health data

Nature of health data	Nature of pollution data						
		Sourced from published studies	Sourced from SAAQIS ambient air quality database	Targeted ambient air quality campaign	Targeted indoor air quality campaign	Personal air sampling	Modelled air quality data
	Comparisons with NAAQS	-	Millar et al (2022) Olutola et al (2018)	-	-	-	-
	Data from questionnaire	Zwi et al (1990)	Millar et al (2022) Olutola et al (2018)	John et al (2014) Wright et al (2011)	-	-	-
	Hospital admission data	-	Olutola & Wichman (2021)	-	-	-	-
	Cohort of physician-diagnosed participants	-	Wright et al (2023)	Nkosi et al (2017)	Nkosi et al (2017)	-	-
	Estimates based on activity patterns	-	-	Wernecke et al (2021)	-	Wernecke et al (2021)	-
	Statistical estimates	Norman et al (2007b)	Simelane & Langerman (2024) Altieri & Keen (2019) Lindeque et al (2021)	-	-	-	Simelane & Langerman (2024) Lindeque et al (2021)
Health administered tests	Zwi et al (1990)	-	-	-	-	-	-

1.38) and rhino conjunctivitis (OR of 1.54). Olajide-Ibiejugba et al. (2021) focused on the presence of allergies in adolescents in exposed and unexposed communities and although the prevalence of doctor-diagnosed allergies was higher in exposed communities (26.97%) than unexposed communities (22.69%), the difference was small.

The 13 papers that reported on studies of both air quality and health were further categorised according to the nature of the air pollution data, specifically whether the data were sourced from SAAQIS and/or whether a specific short-term monitoring campaign (ambient, indoor and/or wearable passive samplers) was designed and/or whether air quality data were sourced from the literature and/or from the application of air quality models (Table 3). Health data categories included those that compared air pollution levels with NAAQS, those that collected health-based data based on questionnaires, those based on hospital admission data, those that focused on a cohort of participants with physician-diagnosed illnesses, those that used activity patterns to estimate intake doses, those based on statistical estimates, and finally, those that administered health tests (Table 3). It is noted again that health risk assessment studies that focused solely on comparison of air quality levels with NAAQS were excluded from this analysis. The breakdown facilitated easy identification of gaps.

Most studies (n=7) relied on air quality data from SAAQIS. Four relied on data from targeted air quality measurement campaigns, of which only one (Nkosi et al. 2017) was focused on the indoor environment. The source of health data varied widely, with questionnaires being the most commonly used method. It was noteworthy that only one of the studies (Zwi et al. 1990) relied on objectively determined health tests, such as spirometry, to derive health data.

An overview of the air quality and health studies, including air quality and health data, and target population is provided in Table 4. Table 5 summarises the study aims, findings and significance of the study for each of the air quality and health studies.

Discussion

An early, groundbreaking paper that considered air quality and health simultaneously was by Zwi et al. (1990). Despite its limitations (see Table 5), it is still the only study in the HPA that has included objective measurements of health status. Perhaps because the results revealed small differences in respiratory health between exposed and control groups, there were no follow-up studies, which is unfortunate. Another pioneering study by Norman et al. (2007b), and its companion paper (Norman et al. 2007a), which focused on indoor air quality impacts on health, were limited to gross estimates and their focus was not specifically on the HPA.

It is only in the last five years or so that study designs have explicitly addressed both air quality and health. Notwithstanding these investigations, these studies have failed to advance definitive cause-effect relationships between air quality and health and hence have not advanced the knowledge frontier in any meaningful way. In each case, study design limitations are cited, for example, limited data set, reliance on self-reported health data, failure to consider extraneous influences etc.

There is sufficient evidence from health risk studies (not included here) to suggest that air quality in the HPA presents a serious risk to human health. What is lacking is the quantification of impact in terms of mortality and morbidity statistics, and precise

Table 4: Overview of input data and target population for air quality and health studies in the HPA

Author/title	Air quality data	Health data	Target population
Altieri & Keen (2019) Public health benefits of reducing exposure to ambient fine particulate matter in South Africa.	PM ₁₀ and PM _{2.5} SAAQIS data for 2012. PM ₁₀ data set includes 60 stations within 7 provinces, while PM _{2.5} data set includes 21 stations in 5 provinces.	Population statistics and published concentration response (C-R) functions from international studies were used to estimate excess mortalities at a municipal level.	SA population in general.
John et al (2014) Environmental health outcomes and exposure risks among at-risk communities living in the Upper Olifants River Catchment, South Africa.	Monitored ambient air quality (PM, SO ₂ , NO ₂ , Pb, Hg, Mn) at one site for one month (Sept – Oct 2010).	Questionnaire administered to 1003 randomly selected households about exposure to air pollutants and health status.	Local communities living in informal dwellings and low-cost housing.
Lindeque et al (2021) The health and economic benefits of reduced residential solid fuel burning on the South African Highveld.	SAAQIS data for PM ₁₀ and PM _{2.5} for all monitoring stations in the study area from 1998 to 2012.	Used C-R functions from epidemiological study by Krewski et al (2009) to estimate premature all-cause mortality.	Population ≥ 30 yrs in low-income communities.
Millar et al (2022) Respiratory health among adolescents living in the Highveld Air Pollution Priority Area in South Africa.	SAAQIS data (2005-2019) (PM _{2.5} , PM ₁₀ , SO ₂ , NO ₂ , O ₃) from Secunda in a middle to high-income area and 2 stations in eMbalenhle in low-income areas. Note: O ₃ data were only available from one low-income station.	Self-administered questionnaire on health status, medical history, socio-economic status and fuel type used in the home.	233 adolescents (13-17 yrs) in Grades 8-10 at 4 schools in 2 areas. Only those who had lived in the study areas for more than 12 months were recruited.
Nkosi et al (2017) Indoor and outdoor PM ₁₀ levels at schools located near mine dumps in Gauteng and North West provinces, South Africa.	Personal respirable dust measured in breathing zone of participants from 08:00 to 15:00. Mobile monitoring station in school premises measured ambient PM ₁₀ and SO ₂ between 08:00 and 15:00.	Only physician-diagnosed asthmatics included in study.	13-14-year-old physician-diagnosed asthmatics. 10 randomly selected from each of 5 exposed (1-2 km from gold mine dumps) and 5 unexposed (≥5 km from gold mine dumps) schools.
Norman et al (2007b) Estimating the burden of disease attributable to urban outdoor air pollution in South Africa in 2000.	Included annual mean PM ₁₀ levels for 6 metropolitan areas. Ekurhuleni data sourced from Scorgie et al (2004). Estimated PM _{2.5} levels based on an assumed PM _{2.5} /PM ₁₀ ratio.	Estimated mortality risks based on method used by Cohen et al (2004).	Children <5 yrs and adults ≥ 30 yrs.
Olutola et al (2018) Factors associated with parent-reported wheeze and cough in children living in an industrial area of Gauteng, South Africa.	Mobile monitoring station operated by Ekurhuleni Metropolitan Municipality. Measured PM ₁₀ , SO ₂ , NO _x , O ₃ & benzene.	Questionnaire administered to 550 mothers and their children who attended Olifantsfontein clinic for immunisation from Feb-Dec 2016. Response rate was 89.6%. Also asked questions about fuel use in home and smoking.	Children (aged 1 to 26 months).
Olutola & Wichman (2021) Does apparent temperature modify the effects of air pollution on respiratory disease hospital admissions in an industrial area of South Africa?	Hourly ambient air pollution data (NO ₂ , SO ₂ , PM ₁₀ & PM _{2.5}) obtained from SAAQIS for Jan 2011 to Oct 2016.	14568 hospital admissions, approx. equal number of males and females.	People admitted to 2 private hospitals in Secunda with respiratory disease (RD) from Jan 2011-Oct 2015. Used the case-crossover epidemiology study design.
Simelane & Langerman (2024) The sensitivity of health impact assessments of PM _{2.5} from South African coal-fired power stations.	Annual average ambient PM _{2.5} data from 38 SAAQIS stations (2010-2013). Data were interpolated across all wards using a regression model based on household socio-economic factors. Also, regression model developed for 2011 PM _{2.5} concentrations derived from coal-fired power stations emissions.	Exposure-response functions used to estimate premature mortalities attributable to PM _{2.5} on a ward basis using 3 methods. Illnesses considered were ischaemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD), lung cancer and lower respiratory infection (for children <5 years).	Average South African population.
Werneck et al (2021) Quantifying potential particulate matter intake dose in a low-income community in South Africa.	Ambient PM _{2.5} and PM ₁₀ monitored at one site for 8 days in August 2013. Personal PM ₄ monitored on 1 adult for the same period.	Linked PM exposure to microenvironments based on participants wearing GPA trackers and determined direct.	Low-income community on Mpumalanga Highveld.
Wright et al (2011) Air quality and human health among a low-income community in the Highveld Priority Area.	Monitored ambient PM, SO ₂ , NO ₂ , Pb, Hg, Mn for 1 month (Oct 2010) at one location in community.	Questionnaire survey. Asked participants about exposure to air pollutants & health & healthcare.	Participants in informal/low-income households in 3 suburbs within KwaGuga. 334 households in each. Final number of households was 1003, with 4190 respondents.
Wright et al (2023) The risk of orofacial cleft lip/palate (CLP) due to maternal ambient air pollution exposure: A call for further research in South Africa.	SAAQIS PM _{2.5} and PM ₁₀ data for all monitoring stations in the geographical area for 2006 to 2020.	Patients were included if they had CLP and the mother's place of residence was known. Total number of participants was 2515. Details on the nature of CLP, classified into eight categories, were also included.	A retrospective cohort of patients with CLP for the period 2006-2020 sourced from two databases: (1) records of CLP patients at a Pretoria hospital; (2) patients supported by Operation Smile.
Zwi et al (1990) Respiratory health status of children in the Eastern Transvaal Highveld.	Published smoke and SO ₂ statistics were used to identify exposed and unexposed schools.	Data on past and present respiratory illnesses obtained from a questionnaire answered by child's mother and spirometry lung function tests administered.	1031 school children from 11 schools in 6 towns in the polluted area (exposed children) and 978 children in 11 schools in 10 towns in unpolluted areas (unexposed children).

Table 5: Overview of study aim, findings, limitations and significance for air quality and health studies in the HPA

Author/title	Study aim	Study findings	Study limitations	Significance of study
Altieri et al (2019)	To determine avoided premature mortalities and associated economic benefits of reducing PM _{2.5} concentrations for all municipalities in SA.	14 000 and 28 000 avoided premature mortalities in 2012 in SA if all areas met NAAQS PM _{2.5} annual average standard and the more stringent WHO guideline value respectively. Comparative figures for the HPA are 1670 and 3240 avoided premature mortalities respectively.	Statistics are given for SA as a whole. There are no C-R functions available for SA, necessitating the use of global C-R functions.	The study attached a monetary value to the number of avoided premature mortalities. By increasing the spatial resolution of input data, they were able to show that previous studies had vastly underestimated the number of mortalities.
John et al (2014)	To understand potential impacts of air and water pollution on local communities in a potentially high-risk area.	None of the 24-hr standards for criteria air pollutants were exceeded. Mn concentrations had the highest potential to exceed the annual guideline of the WHO. Sinus-related problems were the most prevalent (average of 42.3% across all households). The household prevalence of asthma was 10%.	Errors may be introduced when relying on self-reported health outcomes.	By considering impacts of both air and water pollution on health of residents, able to show that it is not just one factor that poses a health risk and that the poor environmental conditions may expose them to other risks that increases their vulnerability and affects their ability to cope.
Lindeque et al (2021)	To estimate health and economic benefits of thermal insulation as an intervention measure to reduce solid fuel burning in low-income settlements on the Highveld.	Compared pre-intervention and post-intervention PM ₁₀ levels and related difference to avoided premature mortalities. Concluded that large-scale implementation of intervention would result in 143 avoided premature mortalities.	Used the C-R functions derived from epidemiological studies in developed countries and not SA.	Exposure to household emissions poses a significant risk to human health. Insights into effectiveness of intervention measures provides guidance to air quality management policies.
Millar et al (2022)	To investigate the prevalence of adverse respiratory health outcomes among adolescents in the HPA air pollution hotspot.	Did not find strong evidence for an association between air pollution and respiratory health, but found a statistically significant association between number of years living in the environment and presence of respiratory illnesses. PM and O ₃ are the pollutants most frequently exceeding national standards.	Sample size was relatively small (233) and relied on self-reported health outcomes. The survey asked for 'ever' occurrence of respiratory health outcomes, rather than 'in the past 2 weeks or past year' and hence may have over-reported occurrence. Household characteristics such as ventilation and roof type which can influence exposure were not included.	Study was the first of its kind and provided valuable baseline data. Children and adolescents are at greater risk to air pollution because their organs (lungs and brain, etc.) are still developing.
Nkosi et al (2017)	To measure exposure of asthmatic children to indoor and outdoor air pollution at exposed and unexposed schools.	Significantly higher 8-hr mean concentrations of PM ₁₀ , SO ₂ and respirable dust in exposed schools compared with unexposed schools.	Small sample size which prevented generalisation of findings to the whole community. The only gaseous pollutant considered was SO ₂ . Results are aggregated across 2 provinces and so are not specifically for HPA.	Focus on school children, and particularly on asthmatics, is important as they are a vulnerable group. Children spend approximately one-third of their total time inside a school building. No previous studies have investigated whether proximity to mine dumps affects indoor and outdoor respirable dust.
Norman et al (2007b)	To estimate the mortality burden attributed to urban ambient air pollution in South Africa.	Ambient air pollution is responsible for 3.7% of national mortality from cardiopulmonary disease; 5.1% from cancers of trachea, bronchus and lung in adults ≥ 30 yrs; 1.1% from acute respiratory infections in children < 5 yrs.	Statistics for SA as a whole based on limited mean annual PM ₁₀ values in urban areas, including Ekurhuleni.	Drew early attention (2007) to hitherto under-recognised negative health impacts of air pollution in SA and to the need for an air quality monitoring network.
Olutola et al (2018)	To examine the factors associated with mother-reported wheeze and dry cough in children living in Tembisa, a low-income area.	The prevalence of wheeze ever was 16.4% while the prevalence of dry cough ever was 37.7%. Children had a higher probability of wheezing if their mother had lived in the area for longer periods and children who had trucks passing their houses frequently were more likely to have had dry cough ever compared to those with no trucks passing.	Study relied on mother-reported information and the study design precluded inferences about causality.	Focus on young children is important as they are particularly vulnerable.
Olutola & Wichman (2021)	To investigate the effect of temperature on the association between air pollution and human health as estimated by respiratory disease (RD) hospital admissions.	Risk of RD hospital admissions due to ambient air pollution exposure is different on cold, normal and warm days. SO ₂ was associated with increased RD hospital admissions on warm days, with females showing greater susceptibility. On cold days, children aged 0-14 yrs experienced greater hospital admissions due to increased SO ₂ .	Patient records from private hospitals were used and the results cannot be extrapolated to the general SA population. Air quality and temperature were assumed to be homogenous for the study area. Potential lag effects among participants who were not admitted immediately were not considered, nor were other contributing factors such as physical activity or pre-existing diseases.	It is important to explore the modification effects of ambient temperature on the association between respiratory morbidity and air pollution because mean annual temperature is expected to increase as a result of climate change.

Table 5: Overview of study aim, findings, limitations and significance for air quality and health studies in the HPA continued...

Author/title	Study aim	Study findings	Study limitations	Significance of study
Simelane and Langerman (2024)	To improve on previous assessments of premature mortality attributed to exposure to PM _{2.5} from coal-fired power stations in SA.	It is estimated that there are 802 attributable premature mortalities p.a. due to PM _{2.5} from coal-fired power stations. Of these, 414 are due to IHD, 240 to stroke, 104 to COPD, 40 to lung cancer, and 4 to lower respiratory illness (LRI) in children < 5 yrs.	Methods used to estimate PM _{2.5} concentrations at ward level, and amount contributed by power stations are rough approximations. Exposure-response functions have not been validated on the SA population, nor have the prevalence of HIV or other diseases, been considered.	Addresses the large uncertainties in premature mortality numbers by comparing various methods. Concludes that the average emitter approach, which assigns health impact based on proportion of PM _{2.5} contributed to total ambient PM _{2.5} is the most equitable way of attributing health impacts.
Wernecke et al (2021)	To link potential PM exposure of individuals to micro-environments in which they spend their time, by monitoring ambient, indoor and personal PM.	Highest PM concentrations were measured inside and directly outside the dwelling. Directly measured (personal monitors) potential intake doses were higher than indirectly measured (stationary monitors) potential intake doses. Individuals have a high risk of negative health impacts as most time is spent indoors.	Personal sampling was done for only eight days. To better understand personal exposure, time-activity patterns of individuals, their biology (e.g. weight and breathing rate) and chemical characteristics of the pollutant are needed.	First study in SA to link PM exposure to micro-environments, to enable identification of high exposure environments for risk mitigation. First study to compare potential exposure derived from direct measurements to indirect measurements.
Wright et al (2011)	To understand the potential human health impacts of air pollution on a low-income community in the HPA.	Ambient air quality concentrations, monitored for one month, did not exceed national standards. The prevalence of self-reported health outcomes was low. 77% of participants perceived health to be good. Sinus-reported symptoms were the most frequent (42% of households had at least one case).	Study was based on a limited ambient air quality monitoring campaign. Health outcomes are self-reported and not objectively derived.	Drew attention to the need to quantify the relationship between respiratory health and air pollution in highly polluted areas.
Wright et al (2023)	To investigate air pollution levels in geographic locations of orofacial cleft lip/palate (CLP) cases.	Results showed statistically significant positive correlations between CLP birth prevalence and PM ₁₀ and PM _{2.5} levels.	Data sourced from only one doctor and one organisation. Personal characteristics (e.g. age, smoking, alcohol and drug history etc.) of mothers were not investigated.	Maternal exposure to air pollution is known to impact the foetal environment and increase CLP risk. This is the first such study in SA. Sufficient evidence was discovered to warrant a more extensive study across the whole of SA.
Zwi et al (1990)	To determine if the respiratory health of children living in the Eastern Transvaal Highveld (ETH) is affected by comparing them with children in less polluted areas.	Children in the ETH experience more respiratory symptoms and chest illnesses and are shorter than those in the control areas but the differences are small. Lung function as assessed by spirometry does not differ between the two areas.	Air quality data were limited at the time the study was undertaken. Study focused only on white school children.	One of the few studies to objectively assess respiratory health by using spirometry.

identification of which interventions work and where policy interventions should be directed. The study by Lindeque et al. (2021), which compared pre-intervention and post-intervention PM₁₀ levels is a useful starting point.

There is also a need to quantify definitively the relative contributions from indoor and outdoor pollution to health impacts through greater reliance on personal air samplers. It is time to move beyond numerous small, low-budget, short-term projects. The HPA presents an ideal laboratory to focus efforts aimed at quantifying the relationship between ambient and indoor air quality and health by bringing the air pollution and health research communities together. While there is an extensive ambient air quality monitoring network that dates back over a long period, it is hampered by technical issues, which must be addressed. It is recommended that greater use be made of models to improve the spatial resolution of ambient air pollution data.

There are major gaps in the collection of health data that should be addressed in future studies. For example, there is a need for better quantification of personal exposure to air pollutants through personal monitoring and the collection of data on time-

activity patterns, and a need for greater reliance on objectively determined health outcomes through direct measurements, such as spirometry. Improved study designs should also seek to shift from descriptive to more analytical approaches that allow for cause-effect relationships to be investigated.

Synthesis of evidence

Air quality studies consistently identify the HPA as a hotspot for NO₂, O₃, and particulate matter, with both ground based and satellite observations supporting this conclusion. However, health studies remain fragmented, often cross sectional, and heavily reliant on self reported outcomes. Only one study used objective spirometry, and no longitudinal cohort studies were identified. Exposure assessment is generally limited, with few studies incorporating personal monitoring, indoor-outdoor comparisons, or high resolution spatiotemporal exposure models.

Methodological limitations in the evidence base

Across the literature, several limitations constrain the strength of conclusions including reliance on self reported health outcomes, short term or single season monitoring campaigns,

limited integration of meteorological and dispersion processes, ecological exposure estimates with potential misclassification, absence of personal exposure monitoring and limited cardiovascular and non respiratory endpoints. These limitations underscore the need for more rigorous, interdisciplinary approaches.

Policy relevance

The findings are directly relevant to the second generation HPA Air Quality Management Plan, which places greater emphasis on health. The review highlights the need for strengthened ambient monitoring networks, integration of indoor and outdoor exposure data, improved exposure assessment methods, routine linkage of air quality and health datasets, and evaluation of interventions and policy measures.

Research gaps and priorities

Key gaps identified include lack of objective health measurements (e.g., spirometry, biomarkers), limited personal exposure monitoring, absence of longitudinal cohort studies, narrow focus on respiratory outcomes, limited assessment of vulnerable populations and insufficient integration of meteorology, emissions, and exposure modelling. Addressing these gaps will require coordinated, large scale, interdisciplinary research efforts.

This scoping review highlights substantial air quality research in the HPA but limited and methodologically constrained health research. Strengthening exposure assessment, expanding health endpoints, and integrating environmental and health datasets are essential to advance understanding of air pollution–health linkages in this region. The HPA remains a critical natural laboratory for interdisciplinary research that can inform policy, guide interventions, and support the constitutional right to a healthy environment.

Conclusion

This study conducted a systematic review of air pollution and health studies following the PRISMA guidelines for the HPA of South Africa. It is the first such review for the HPA. It was based on published and peer-reviewed journal papers written in English. Student theses, reports and AQMPs were excluded. Keyword search terms were categorised into three groups as follows: Group 1 – Air pollution OR air quality; Group 2 – Health OR respiratory health OR respiratory health outcomes; Group 3 – Highveld OR Mpumalanga OR Ekurhuleni. Papers included needed a term from Group 1 plus a term from Group 2 plus a term from Group 3 until all combinations were exhausted.

The number of ‘air quality only’ papers (98) far exceeds the number of ‘health only’ papers (19) and ‘health and air quality’ papers (13). There is a long history of air quality studies dating back to 1980 (Kemeny, 1980; Louw et al., 1982), evidence of a renewed focus in the 1990s and increased activity from 2006 onwards, with a solid focus on air quality research since 2015. With few exceptions (5), most of the health only papers tend

to be post-2014. Studies linking air quality and health and reflecting a shift from delineating and understanding the nature of the air pollution hot spot to a focus on impacts, are also mainly confined to the last ten years.

The 13 papers that reported on studies of both air quality and health were further categorised according to the nature of the air pollution data and the nature of health data. It was found that most studies (7) relied on air quality data from SAAQIS. Four relied on data from targeted air quality measurement campaigns, of which only one (Nkosi et al. 2017) was focused on the indoor environment. The source of health data varied widely, with questionnaires being the most commonly used method. It was noteworthy that only one of the studies (Zwi et al. 1990) relied on objectively determined health tests, such as spirometry, to derive health data.

Based on the analysis undertaken it is recommended that it is important to bring the air pollution and health communities together and to use the HPA as a laboratory to mount a large-scale air pollution and health study that overcomes many of the limitations of previous low-budget, short-term research projects. Gaps to be addressed include quantifying the relationship between ambient and indoor air quality and health; ensuring that technical problems associated with the ambient air quality monitoring network are addressed; better quantification of personal exposure to air pollutants through personal monitoring and the collection of data on time-activity patterns; greater reliance on objectively determined health outcomes through direct measurements; and a need to expand research beyond respiratory outcomes.

Acknowledgements

We thank the late Professor Roseanne D Diab (University of KwaZulu-Natal) for support with identifying, screening and summarising the research articles to include in the review.

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