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# Human Health Risk Assessment of $PM_{2.5}$, $NO_2$, and $SO_2$ and its Impact on Mortality in Nkangala and Gert Sibande, South Africa

ORIGINAL RESEARCH

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## ABSTRACT

*Introduction:* Located in Mpumalanga's Highveld Priority Area (HPA), Nkangala and Gert Sibande are well-known for sustained exposure to high levels of air pollution, which is linked to adverse health effects. We aimed to carry out a comprehensive health risk assessment to determine to what extent air pollution impacts mortality rates in Nkangala and Gert Sibande.

*Methods:* A standardized US EPA health risk assessment (HRA) protocol was used to calculate hazard quotients (HQs), using pollutant concentration, average body mass and inhalation rates, and pollutant concentrations (2009–2018) for $PM_{2.5}$, $SO_2$, and $NO_2$ from three air quality monitoring stations in Nkangala and three in Gert Sibande. Cause-specific mortality rates were compared with the HQs.

*Results:* The study findings revealed frequent exceedances of WHO air quality guidelines for $PM_{2.5}$, $NO_2$, and $SO_2$ in Nkangala and Gert Sibande, despite compliance with less stringent South African NAAQS reference standards. Gert Sibande consistently had higher pollutant levels and associated hazard quotients (HQs) and greater attributable mortality, particularly for lower respiratory infections (LRIs), stroke, and chronic obstructive pulmonary disease (COPD). Secunda, in Gert Sibande, showed especially high short-term $PM_{2.5}$ exposure risks.

*Discussion:* Continued exposure to air pollution has been associated with the development of multiple health concerns, as well as increased mortality. This study suggests that $SO_2$ and $NO_2$ exposure is not as great a concern for populations living in the HPA. However, continuous monitoring is needed to ensure these pollutants' concentrations do not increase in the future.

*Conclusions:* These findings highlight the history of inadequate South African national reference standards in protecting public health and the need for stricter air quality regulations that align with international standards. $PM_{2.5}$ is a major health concern for people living in the HPA, South Africa. Air quality management should be bolstered to decrease the amount of $PM_{2.5}$ in the area.

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## INTRODUCTION

In 2021, air pollution was responsible for 8.1 million deaths, accounting for more than 1 in every 8 deaths globally [1]. Moreover, there is substantial scientific evidence that air pollution is a significant global public health risk factor, with statistically significant links between air pollution and a range of health effects and diseases affecting people in every demographic [1].

Acute air pollutant exposure exacerbates respiratory diseases and symptoms, which include chronic obstructive pulmonary disease (COPD), coughing, breathlessness, wheezing and asthma, among others [2, 3]. Evidence indicates that hospitalization rates rise during times of heightened air pollutant exposure [3, 4]. Chronic exposure to pollutants such as nitrogen dioxide ($NO_2$) and fine particulate matter ($PM_{2.5}$) has been associated with cardiovascular disorders, such as heart attacks and strokes [5, 6]. In addition, air pollution negatively impacts reproductive health, cognitive function, and general well-being [7]. Several studies have shown associations between air pollution exposure and impaired neural development, which raises the risk of mental health disorders, developmental delays, and birth defects [8]. There is ever-growing evidence that chronic exposure to air pollutants is a significant risk factor in the development of cancer [9–11].

In regions like the Highveld Priority Area (HPA) in South Africa, mining and industrial activities give rise to high levels of air pollutants [12]. Thus, understanding and mitigating public health risks are paramount [13]. In 2023, the HPA had a reported unemployment rate of 34.9%, higher than the national rate of 32.1% [13, 14]. The population of the Mpumalanga Highveld faces acute and chronic exposure to air pollutants such as $NO_2$ and $PM_{2.5}$ stemming largely from industrial and mining activities [15]. A study in eMalahleni, situated in the Highveld area, showed the presence of $SO_2$, $NO_2$, and ozone ($O_3$) within and outside classrooms at varying concentrations [16]. $SO_2$ concentrations within classrooms ranged from 3 to 38 µg/m$^3$, whereas outside the classrooms, levels were significantly higher, ranging from 17 to 84 µg/m$^3$. Our previous investigation into adolescent health unveiled a concerning correlation between acute and chronic respiratory symptoms and criteria pollutants [13]. Furthermore, we identified a statistically significant association between prolonged residence in Secunda or eMbalenhle and the prevalence of chronic respiratory illnesses, emphasizing the urgency for targeted intervention measures in these areas [13].

Human health risk is a measure of the probability that an individual / population exposed to an unhealthy substance may develop adverse health outcomes [17]. There are several indices that have been developed to measure human health risk, including evaluating the potential for adverse effects of air pollutants on individuals and populations. Human health risk assessments (HRA) play a crucial role in guiding regulatory efforts, public health interventions, and urban planning strategies aimed at reducing air pollution and protecting human health [18]. By identifying high-risk areas and populations, implementing targeted interventions, and promoting pollution control measures, these assessments contribute to improving air quality and mitigating the adverse health effects of air pollution [18].

Recently, there have been several human HRA studies related to air pollution in several low-income communities in the High Priority Areas in South Africa [19–23]. These studies provide valuable insights into the specific health risks faced by local communities, the distribution of pollutants, and the effectiveness of mitigation measures. By leveraging scientific evidence and community engagement, these studies contribute to evidence-based policymaking and public health interventions tailored to local contexts.

The purpose of this study was to determine to what extent air pollution may have an impact on the health of indigent communities in the Nkangala and Gert Sibande municipalities located in the HPA. An HRA was conducted using total concentrations of air pollutants ($PM_{2.5}$, $SO_2$, and $NO_2$) from 2009 to 2018. In addition, the attributable cause-specific mortality from $PM_{2.5}$ exposure was determined in response to these risks posed by air pollution. The findings are imperative for informing targeted interventions in those low-income areas with high levels of air pollution that are aimed at preserving public health amidst environmental challenges.

# METHODS

## STUDY AREA

The Highveld region of South Africa spans 31,106 km$^2$ and covers parts of Gauteng and Mpumalanga provinces [15]. It comprises three district municipalities, which host various industrial and non-industrial sources of air pollution [15]. The study investigated the Nkangala District Municipality and the Gert Sibande District Municipality. Air quality data were collected from air quality monitoring stations situated in Hendrina, Middelburg, and eMalahleni to indicate the air quality status of the Nkangala municipality, and Ermelo, Secunda, and eMbalenhle to indicate the air quality status of the Gert Sibande municipality (Figure 1, Table 1). The six air quality monitoring stations were in areas near coal-fired power stations, mines, and a coal liquefaction plant [13].

## MORTALITY DATA ANALYSIS

Mortality data was sourced from Statistics South Africa (Nkangala and Gert Sibande). In total, death counts included 101,246 deaths in Nkangala and 104,971 deaths in Gert Sibande (International Classification of Disease (ICD) A00-R99), recorded over nine years (2009–2018) (Figure 2; Table 2). There were 4,672 more male deaths in Nkangala and 4,293 more male deaths in Gert Sibande. For cause-specific mortality (Table 3), we focused on cardiovascular diseases (I10-I70), ischemic heart diseases (IHD) (I20-I25), lower respiratory infections (LRIs) (J00-J99), stroke (I64), and COPD (A16).

To assess the health impacts of exposure to $PM_{2.5}$, we used the Integrated Exposure Response (IER) functions developed as part of the Global Burden of Disease [26] study. The IER functions estimate relative risks (RRs) for specific health outcomes across a wide global range of $PM_{2.5}$ exposure levels and represent the most accurate estimates from large global datasets. These curves were developed by integrating a large body of epidemiological evidence from ambient air pollutant exposure and are used to calculate attributable mortality from ambient air pollution in several populations. However, the evidence has only been made available for a selection of the most relevant health outcomes, including IHD and stroke in adults aged ≥25 years as well as LRI and

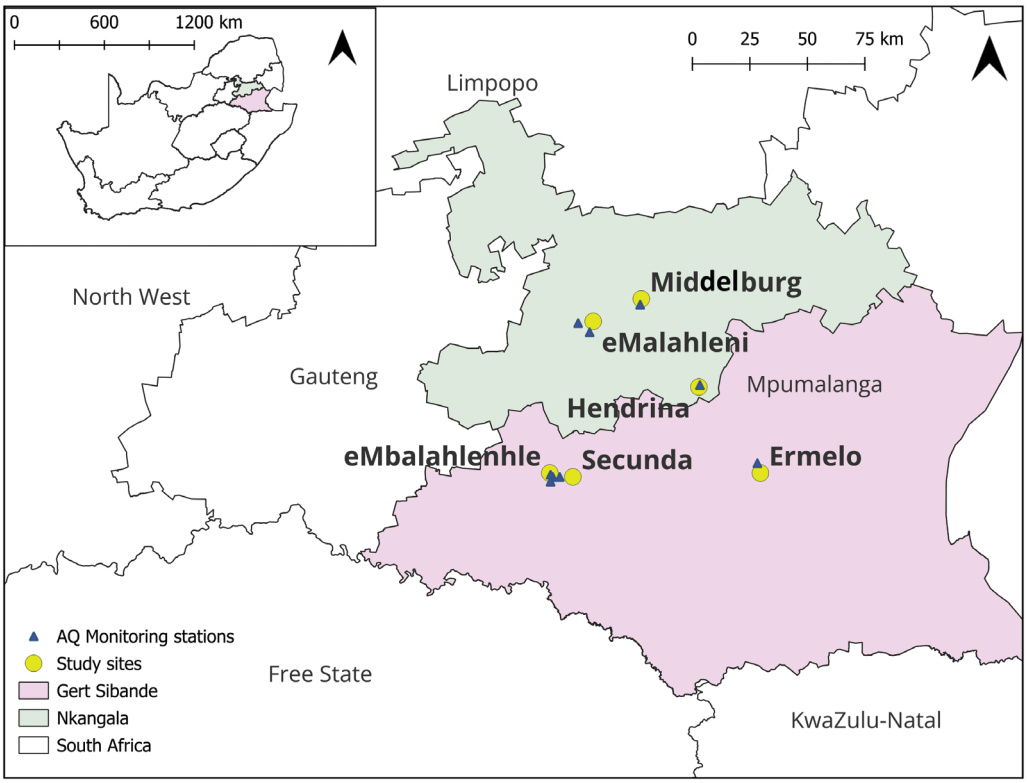


**Figure 1** Map illustrating study sites Nkangala and Gert Sibande and the air quality monitoring stations within these sites.

| DISTRICT | AQ MONITORING STATION | POLLUTANT SOURCES | NUMBER OF STATIONS SAMPLED | SAMPLING PERIOD |
|---|---|---|---|---|
| Nkangala | Hendrina | Middle-income residential; not in the vicinity of direct pollutant sources and no local domestic burning [24]. | 1 | 2010–2018 |
| | Middelburg | Middle-income residential; large industrial sources: Columbus Steel and Middelburg Ferrochrome, industries to the south and mine dumps to the northwest, no domestic fuel burning [24]. | 2 (MP and SAWS) | 2009–2018 |
| | eMalahleni | Low-income site; domestic fuel burning, transport, and industrial and mining emissions [24]. | 1 | 2009–2018 |
| Gert Sibande | Ermelo | Low-income site; coal transportation trucks and domestic fuel burning [24]. | 1 | 2010–2018 |
| | Secunda | Low-income site; domestic fuel burning in the vicinity and Sasol plant to the east [24]. | 1 | 2009–2018 |
| | eMbalenhle | Low-income site; domestic burning, secondary aerosols, wood and biomass burning, and industrial emissions [25]. | 3 | 2016–2018 |

**Table 1** Summary of district municipality study sites, putative pollutant sources near air monitoring stations, and sampling periods.

*Note*: MP: Mpumalanga Province; SAWS: South African Weather Service.

| | NKANGALA | | GERT SIBANDE | |
|---|---|---|---|---|
| | DEATH COUNTS | MEAN ± SD | DEATH COUNTS | MEAN ± SD |
| All-cause mortality | 101,246 | 27.8 ± 7.2 | 104,971 | 28.8 ± 8.4 |
| Male | 52,959 | 3.9 ± 2.4 | 54,632 | 3.9 ± 2.5 |
| Female | 48,287 | 3.6 ± 2.1 | 50,339 | 3.7 ± 2.3 |
| 0–18 years old | 11,609 | 1.9 ± 1.1 | 14,219 | 2.3 ± 1.4 |
| 19–45 | 32,893 | 4.68 ± 2.5 | 37,988 | 5.3 ± 2.9 |
| 46–65 | 29,603 | 4.2 ± 2.2 | 28,666 | 4.0 ± 2.1 |
| >65 | 27,470 | 3.9 ± 2.0 | 24,384 | 3.5 ± 1.9 |

**Table 2** Descriptive statistics of the daily mean death counts for Nkangala and Gert Sibande from 2009 to 2018.

| HEALTH OUTCOME | NKANGALA | | | GERT SIBANDE | | |
|---|---|---|---|---|---|---|
| | TOTAL | MALE | FEMALE | TOTAL | MALE | FEMALE |
| IHD* | 2,104 | 1,298 | 806 | 1,527 | 883 | 644 |
| Stroke* | 3,540 | 1,581 | 1,959 | 3,732 | 1,506 | 2,226 |
| LRI | 12,763 | 6,544 | 6,219 | 12,363 | 6,414 | 5,949 |
| COPD | 420 | 313 | 107 | 624 | 458 | 166 |

**Table 3** The cause specific mortality counts for Nkangala and Gert Sibande from 2009 to 2018.

*Numbers given are for those >25 years old.

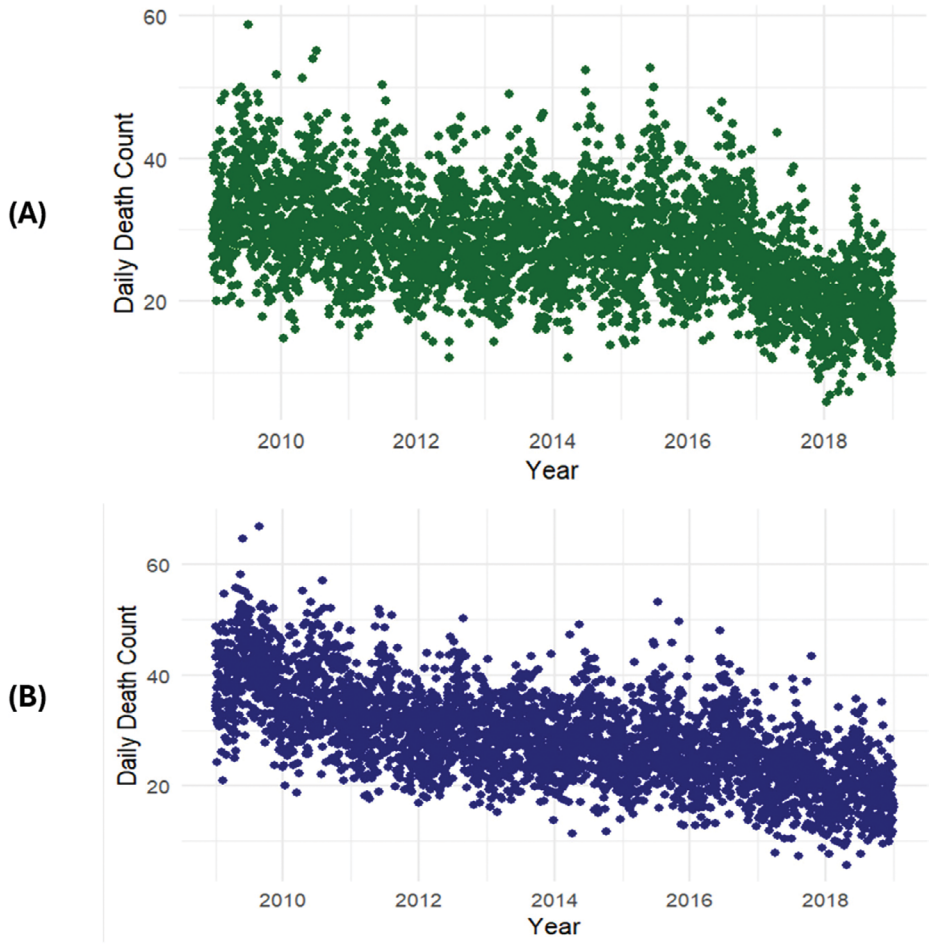


**Figure 2** Daily death count from 2009 to 2018 in **(A)** Nkangala and **(B)** Gert Sibande.

COPD in all age groups. The population attributable fraction was calculated using guided published methods, considering disease burden [27] and statistical rigor [28].

$$PAF = \frac{P(RR-1)}{P(RR-1)+1}$$

where:

- RR = relative risk at the observed annual average $PM_{2.5}$ concentration,
- P = proportion of the population exposed (assumed to be 1 using population-weighted $PM_{2.5}$ averages per site).

The total attributable burden and the percentage of the total attributable burden were then calculated for each year and health outcome. Uncertainty was incorporated using the lower and upper bounds of IER parameter estimates, where the 95% uncertainty range around the theoretical minimum risk exposure level was used as part of the [26] study, resulting in lower and upper bounds for RRs and PAFs and corresponding to the lower and upper estimates of the attributable burden.

## AIR POLLUTANT MEASUREMENTS

Hourly ambient air quality data collected from six air quality monitoring stations, three from Nkangala and three from Gert Sibande, were sourced from the South African Air Quality Information System (SAAQIS) for the period 2009–2018 [29]. The analysis focused on three criteria pollutants, namely $PM_{2.5}$, $SO_2$, and $NO_2$. The annual average per monitoring station was calculated. A data availability threshold of 70% was applied for finding the 99th percentile 24-hour and the average annual pollutant concentrations.

| POLLUTANT | AVERAGING PERIOD | SA NAAQS* | | | WHO* | | | | | WHO 2021 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2009 | 2012 | 2016 – 2029 | AQG 2005 | IT-1 | IT-2 | IT-3 | IT-4 | |
| $PM_{2.5}$ | 24-hour | -# | 65 | 40 | 25 | 75 | 50 | 37.5 | 25 | 15 |
| | 1 year | - | 25 | 20 | 10 | 35 | 25 | 15 | 10 | 5 |
| $NO_2$ | 1-hour [a] | 200 | nc | nc | 200 | - | - | - | - | - |
| | 1 year | 40 | - | - | 40 | 40 | 30 | 20 | - | 10 |
| $SO_2$ | 24-hour | 125 | - | - | 20 | 125 | 50 | - | - | 40 |

**Table 4** South African National Ambient Air Quality Standards (SA NAAQS) and World Health Organization (WHO) air quality reference standards for $PM_{2.5}$, $NO_2$, and $SO_2$.

* All pollutant reference concentrations are in $\mu g/m^3$.

#South Africa was only assigned a formal reference standard to fine particulate matter in 2012 [15].

[a] South Africa has a 1-hour $NO_2$ reference standard and does not have a 24-hour reference standard [35], and even though WHO has a 24-hour standard, the 1-hour reference standard is used in this study as a comparison with the SA-NAAQS as the 99th percentile at 4 exceedances per year [32]. 'nc' denotes 'no change' in regulations in the subsequent year.

## HUMAN HEALTH RISK ASSESSMENT

The HRA framework used in this study is outlined by the United States of America Environmental Protection Agency (US EPA) [30]. The pollutants of interest ($PM_{2.5}$, $NO_2$, and $SO_2$) were identified from previous studies, and exposure to these pollutants results in significant detrimental health effects (Table 4). The reference standards are derived from the South African National Ambient Air Quality Standards (SA NAAQS) [15, 31] and the World Health Organization (WHO) [32] (Table 4). The WHO AQG and SA NAAQS standards and guidelines are taken from reliable sources and are delimited based on evidence of adverse health effects. In terms of decision-rule uncertainty, this study focused on short- and long-term exposure to three criteria pollutants. Exposure to these air pollutants by means of inhalation was considered due to their chemical phase nature. It was decided to consider three criteria pollutants, firstly for their known association with adverse health outcomes, and secondly, due to their differing methods of action. $SO_2$ is soluble in water, causing it to become an irritant in the airway almost immediately [33]. By contrast, $NO_2$ is less soluble in water, taking it longer to dissolve and therefore making it a deep-lung irritant [34]. The differing methods of action of each pollutant activate different physiological pathways in different timeframes, necessitating research that considers multiple pollutants simultaneously.

A Hazard Quotient (HQ) was calculated for non-cancer effects. The HQ is the ratio of a single substance's exposure level over a specified period, relative to a reference concentration or dose for that substance and is derived from a similar exposure period. The HQ describes the potential for developing adverse effects (other than cancer) from exposure to a hazardous substance. In this study, the focus was on $PM_{2.5}$, $NO_2$, and $SO_2$. The overall risk was quantitatively assessed by calculating HQs to evaluate adherence to exposure limits. Data were compared with WHO AQGs and the South African NAAQS and at specified averaging periods to provide a comprehensive characterization of the risk.

Hazard quotients were calculated using the following equation [36]:

$$HQ = \frac{EC}{RfC}$$

where:

$HQ$ = Hazard quotient

$EC$ = Exposure air pollutant concentration

$RfC$ = Reference air pollutant concentration

The resulting HQ value represents the likelihood of an increased risk of adverse health outcomes. An HQ exceeding 1 suggests a heightened risk of adverse health effects, whereas an HQ below 1 typically denotes a lower, often negligible, risk of such outcomes [30]. Since the pollutant concentrations were gathered from air quality monitoring stations, where equipment is routinely calibrated and maintained at the proper temperature and humidity, variable uncertainty is reduced in this study. Furthermore, a 70% data availability threshold was applied to the data collected from air quality monitoring stations. This meant when looking at the daily and annual datasets, any dataset that contained less than 70% data availability was excluded to ensure sufficient and reliable data for the study.

# RESULTS

## AMBIENT AIR QUALITY

An analysis of ambient air quality data was undertaken to assess pollutant concentrations on both an average 24-hour and average annual basis. The large variations of $PM_{2.5}$, $NO_2$, and $SO_2$ ranged from well below 20 µg/m$^3$ to more than 100 µg/m$^3$. Box plots of average 24-hour $PM_{2.5}$ concentrations revealed significant variability throughout each year, with frequent exceedances of both the WHO 2005 reference standard and the South African NAAQS set in 2016 (Figure 3). The earlier 2012 NAAQS for $PM_{2.5}$ was aligned between the WHO Interim Targets 1 and 2 (IT1 and IT2), indicating that South Africa was not yet prepared to adopt more stringent air quality limits at the time. However, data from 2016 and 2017 show that even this less stringent 2012 standard could not be adhered to at 65µg/m$^3$ (Figure 3). This suggests that the adopted standards were insufficient to protect public health from the risks posed by elevated $PM_{2.5}$ levels as air quality was considered safe even though they exceeded levels considered dangerous in other parts of the world.

In terms of annual averages, the annual $PM_{2.5}$ reference standards were exceeded multiple times across the 10-year period across both districts (Figure 4). The annual average $PM_{2.5}$ levels in Gert Sibande were higher than Nkangala across most of the 10-year period, notably in 2009, 2010, and 2018 (Figure 4).

## RISK ASSESSMENT RESULTS

The HQs that were calculated from the pollutant exposure levels show that there is a significant discrepancy between health risk assessments based on the WHO reference standard versus the

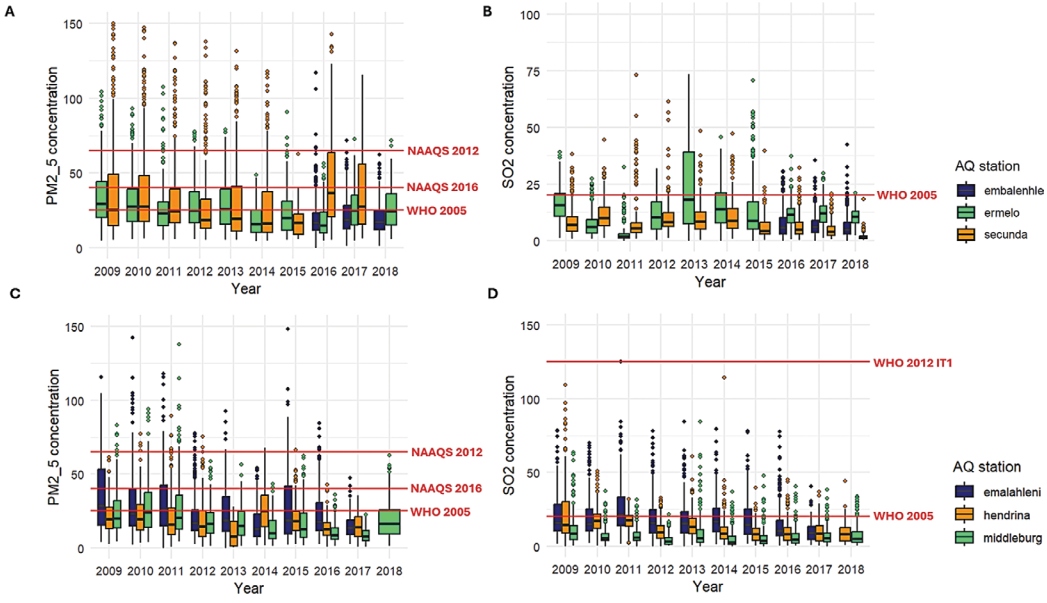


**Figure 3** Box plots of the average 24-hour pollutant concentrations from air quality monitoring stations from 2009 to 2018 in Gert Sibande: **(A)** $PM_{2.5}$ concentrations with reference standards shown in red lines, **(B)** $SO_2$ concentrations and reference standards shown in red lines and Nkangala: **(C)** $PM_{2.5}$ concentrations and reference standards shown with red lines **(D)** $SO_2$ concentrations and the reference standards shown in red lines.

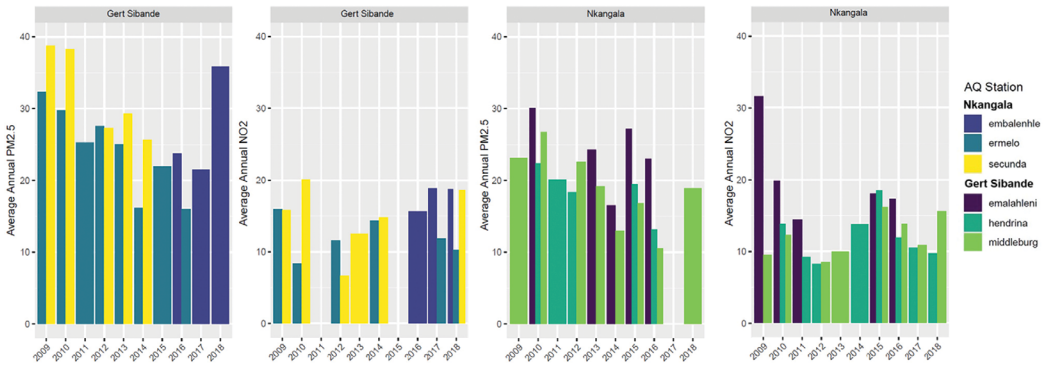


**Figure 4** Annual average pollutant concentrations for $PM_{2.5}$ and $NO_2$ at AQ stations from Gert Sibande and Nkangala (2009–2018). Missing columns denote years that did not pass the data availability threshold of 70%.

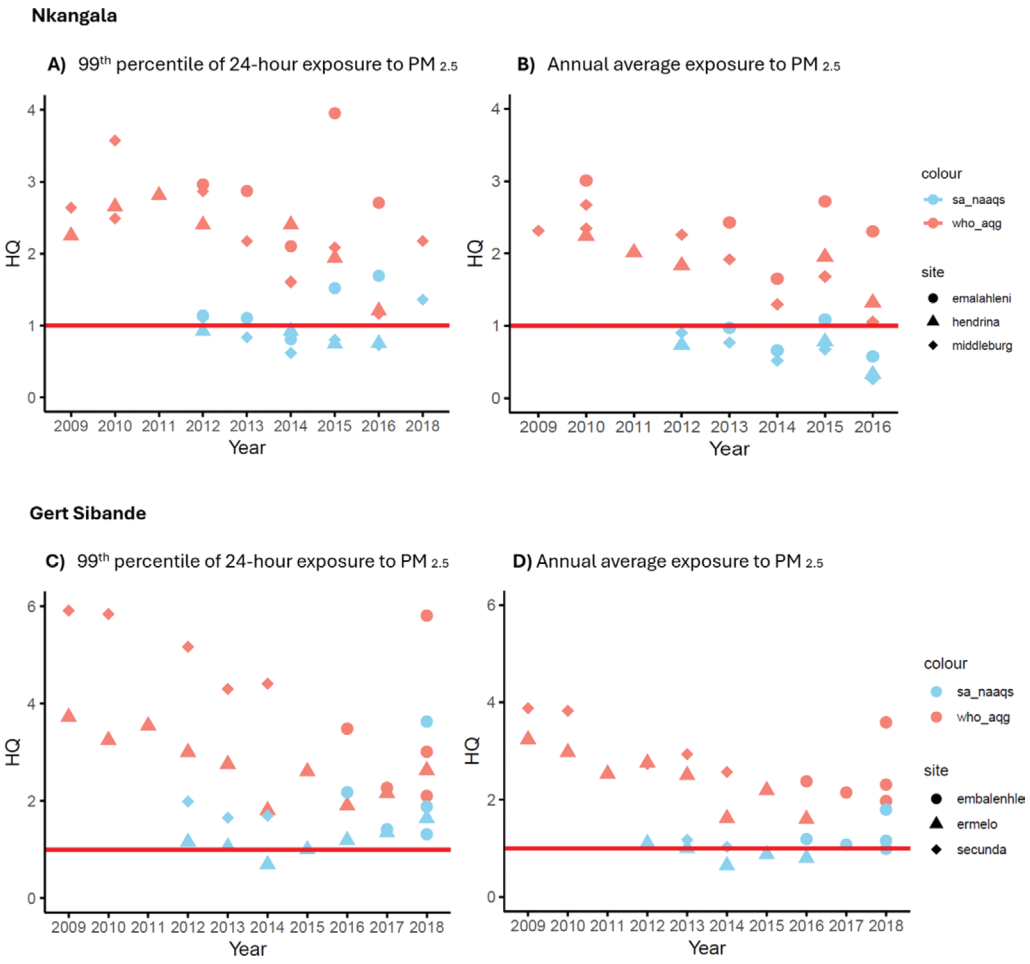


**Figure 5** Hazard quotients (HQ) for Nkangala with **(A)** 99th percentiles of the 24-hour average exposure and **(B)** annual average $PM_{2.5}$ exposure. Hazard quotients (HQ) for Gert Sibande with **(C)** 99th percentiles of the 24-hour average exposure, and **(D)** annual average $PM_{2.5}$ exposure, based on South African National Ambient Air Quality Standards (SA NAAQS) and WHO Air Quality Guidelines (WHO AQG).

South African NAAQS reference standard. (Figure 5) In the population in Nkangala, particularly around eMalahleni, there is a more significant chance of being chronically exposed to higher $PM_{2.5}$ levels that exceed WHO health-based thresholds. The temporal patterns show little improvement over time, suggesting persistent air quality challenges. In Gert Sibande, $PM_{2.5}$ exposure consistently exceeds WHO guidelines (red), with HQ values well above 1, indicating significant health risks. Interestingly, HQ values based on South African standards (blue) are generally below or near 1, but more frequently exceeded 1 than in Nkangala. This highlights a likely difference in air quality

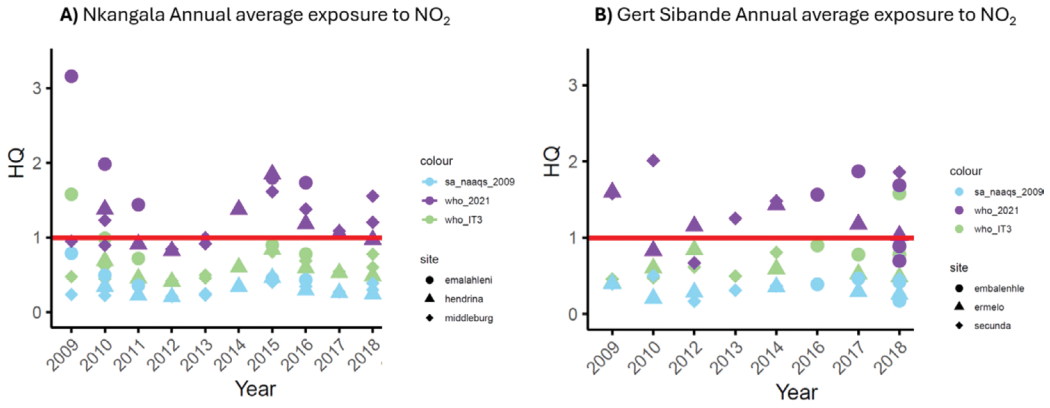


**Figure 6** Hazard quotients (HQ) for **(A)** annual average $NO_2$ exposure in Nkangala and **(B)** Gert Sibande based on South African (2009) and WHO [32], (IT3) air quality guidelines.

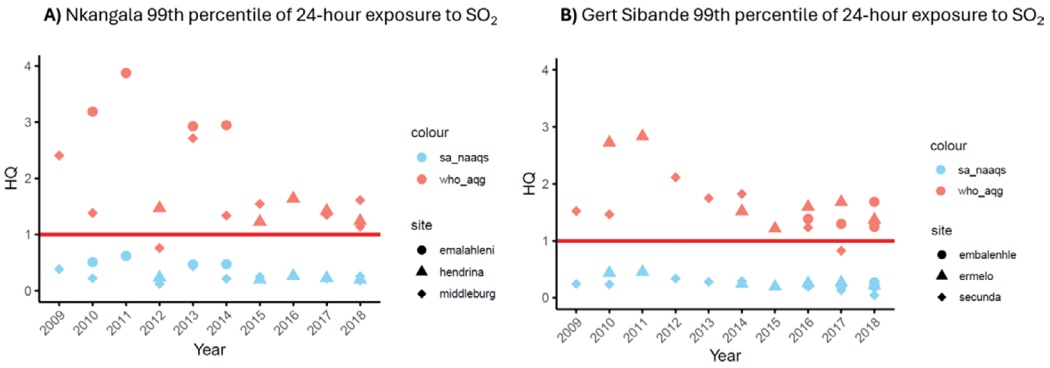


**Figure 7** Hazard quotients (HQ) for **(A)** 99th percentiles of the 24-hour average exposure to $SO_2$ in Nkangala with and **(B)** 99th percentiles of the 24-hour average exposure to $SO_2$ in Gert Sibande.

exposure levels between the two sites, with Gert Sibande exceeding HQs more often. There are persistent air quality challenges that, when assessed against stricter international health benchmarks, require more stringent air quality reference standards. For the annual $NO_2$ exposure in both Nkangala (A) and Gert Sibande (B), there were frequent exceedances according to the WHO guideline thresholds (2021 and IT3), with HQ > 1, especially between 2009 and 2014 (Figure 6). Most values remain below the older South African standard (2009), highlighting the difference in risk depending on the benchmark used. Finally, the HQs for $SO_2$ show a significantly higher association with risk when the WHO AQG reference standards are used to assess risk (Figure 7).

### ATTRIBUTABLE MORTALITY

Between 2009 and 2018, Gert Sibande consistently showed higher attributable fractions (AF%) and more deaths across all four health outcomes compared to Nkangala (Table 5). LRI was the most significant burden in both districts, though deaths and total burden steadily declined over time. IHD had a low and stable burden (under 1%) in both areas, with Gert Sibande showing a slightly higher percentage attributable fraction. Stroke accounted for a moderate and stable burden (around 1.8%–2.2%), again higher in Gert Sibande. COPD contributed the smallest burden overall, but Gert Sibande experienced consistently higher mortality and percentage attributable fraction, particularly from 2011 onward. These results correspond well with the HQs and pollutant levels in Gert Sibande compared to Nkangala.

## DISCUSSION

This study assessed the extent to which air pollution exacerbated health risks in Nkangala and Gert Sibande municipalities located in the HPA. While earlier studies considered the HQs that may be associated with an increased risk of detrimental health outcomes, these studies did not explore

**Table 5** Summary of the attributable mortality burden to outdoor air pollution in Nkangala and Gert Sibande.

| OUTCOME | YEAR | NKANGALA | | | | | GERT SIBANDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AF (%) | DEATHS (FEMALE) | DEATHS (MALE) | TOTAL | % TOTAL BURDEN (% UI) | AF (%) | DEATHS (FEMALE) | DEATHS (MALE) | TOTAL | % TOTAL BURDEN (% UI) |
| LRI | 2009 | 14 | 146 | 148 | 293 | 2.4 (1.3–3.3) | 19 | 204 | 206 | 410 | 3.3 (2.0–4.5) |
| | 2010 | 17 | 138 | 140 | 279 | 2.5 (1.4–3.4) | 19 | 206 | 213 | 419 | 3.7 (2.2–5.0) |
| | 2011 | 14 | 98 | 112 | 210 | 1.9 (1.1–2.7) | 19 | 146 | 169 | 315 | 2.9 (1.7–4.0) |
| | 2012 | 14 | 106 | 107 | 213 | 2.0 (1.1–2.8) | 19 | 134 | 138 | 272 | 2.6 (1.5–3.6) |
| | 2013 | 11 | 81 | 85 | 166 | 1.6 (0.9–2.3) | 14 | 96 | 106 | 202 | 2.0 (1.1–2.7) |
| | 2014 | 14 | 99 | 111 | 210 | 2.0 (1.1–2.8) | 14 | 75 | 85 | 160 | 1.5 (0.8–2.1) |
| | 2015 | 14 | 87 | 97 | 184 | 1.8 (1.0–2.4) | 14 | 68 | 77 | 146 | 1.4 (0.8–1.9) |
| | 2016 | 14 | 83 | 88 | 171 | 1.6 (0.9–2.3) | 14 | 57 | 65 | 123 | 1.2 (0.6–1.6) |
| | 2018 | 14 | 57 | 53 | 109 | 1.5 (0.9–2.2) | 17 | 51 | 54 | 105 | 1.5 (0.9–2.1) |
| IHD (>25 years old) | 2009 | 27 | 23 | 40 | 63 | 0.5 (0.5–1.0) | 35 | 26 | 40 | 66 | 0.5 (0.4–0.7) |
| | 2010 | 31 | 17 | 42 | 59 | 0.5 (0.5–0.9) | 35 | 27 | 37 | 64 | 0.5 (0.5–0.8) |
| | 2011 | 27 | 24 | 45 | 69 | 0.6 (0.6–1.3) | 35 | 25 | 35 | 61 | 0.5 (0.5–0.9) |
| | 2012 | 27 | 26 | 41 | 67 | 0.6 (0.6–1.3) | 35 | 23 | 31 | 54 | 0.5 (0.5–0.8) |
| | 2013 | 21 | 19 | 32 | 51 | 0.5 (0.5–1.0) | 27 | 13 | 24 | 37 | 0.4 (0.4–0.7) |
| | 2014 | 27 | 33 | 40 | 72 | 0.7 (0.7–1.3) | 27 | 19 | 23 | 42 | 0.4 (0.4–0.8) |
| | 2015 | 27 | 25 | 43 | 68 | 0.6 (0.6–1.3) | 27 | 15 | 23 | 38 | 0.4 (0.4–0.8) |
| | 2016 | 27 | 27 | 35 | 63 | 0.6 (0.6–1.3) | 27 | 24 | 27 | 51 | 0.5 (0.5–1.0) |
| | 2018 | 27 | 17 | 26 | 43 | 0.6 (0.6–1.3) | 31 | 27 | 35 | 61 | 0.9 (0.9–1.5) |
| Stroke (>25 years old) | 2009 | 46 | 118 | 88 | 206 | 1.7 (1.1–1.9) | 54 | 170 | 117 | 287 | 2.0 (1.5–2.2) |
| | 2010 | 50 | 102 | 89 | 191 | 1.7 (1.1–1.9) | 54 | 142 | 105 | 248 | 1.9 (1.4–2.1) |
| | 2011 | 46 | 109 | 89 | 198 | 1.8 (1.3–2.1) | 54 | 150 | 106 | 256 | 2.2 (1.6–2.5) |
| | 2012 | 46 | 92 | 76 | 169 | 1.6 (1.1–1.9) | 54 | 135 | 71 | 206 | 1.9 (1.4–2.1) |
| | 2013 | 40 | 81 | 64 | 145 | 1.4 (0.9–1.7) | 46 | 116 | 76 | 192 | 1.8 (1.3–2.1) |
| | 2014 | 46 | 109 | 88 | 197 | 1.9 (1.3–2.2) | 46 | 112 | 78 | 189 | 1.8 (1.3–2.1) |
| | 2015 | 46 | 111 | 84 | 194 | 1.9 (1.3–2.2) | 46 | 105 | 71 | 176 | 1.8 (1.3–2.1) |
| | 2016 | 46 | 103 | 85 | 188 | 1.8 (1.3–2.1) | 46 | 110 | 63 | 172 | 1.8 (1.3–2.1) |
| | 2018 | 46 | 68 | 59 | 127 | 1.8 (1.3–2.1) | 50 | 79 | 69 | 148 | 2.1 (1.5–2.4) |

(Contd.)

| OUTCOME | YEAR | NKANGALA | | | | | GERT SIBANDE | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AF (%) | DEATHS (FEMALE) | DEATHS (MALE) | TOTAL | % TOTAL BURDEN (% UI) | AF (%) | DEATHS (FEMALE) | DEATHS (MALE) | TOTAL | % TOTAL BURDEN (% UI) |
| COPD | **2009** | 19 | 2 | 6 | 9 | 0.07 (0.05–0.08) | 26 | 4 | 13 | 17 | 0.11 (0.08–0.13) |
| | **2010** | 22 | 3 | 8 | 11 | 0.09 (0.07–0.11) | 26 | 4 | 12 | 16 | 0.12 (0.08–0.14) |
| | **2011** | 19 | 2 | 7 | 9 | 0.08 (0.05–0.10) | 26 | 6 | 13 | 19 | 0.16 (0.11–0.19) |
| | **2012** | 19 | 2 | 8 | 10 | 0.09 (0.07–0.11) | 26 | 6 | 14 | 21 | 0.19 (0.13–0.22) |
| | **2013** | 15 | 1 | 7 | 8 | 0.08 (0.05–0.10) | 19 | 2 | 11 | 13 | 0.13 (0.09–0.15) |
| | **2014** | 19 | 2 | 7 | 9 | 0.09 (0.07–0.11) | 19 | 3 | 9 | 13 | 0.12 (0.08–0.15) |
| | **2015** | 19 | 3 | 6 | 9 | 0.08 (0.05–0.10) | 19 | 4 | 12 | 16 | 0.16 (0.11–0.19) |
| | **2016** | 19 | 3 | 5 | 8 | 0.08 (0.05–0.10) | 19 | 2 | 8 | 11 | 0.11 (0.08–0.13) |
| | **2018** | 19 | 2 | 3 | 5 | 0.08 (0.05–0.10) | 22 | 5 | 9 | 14 | 0.20 (0.14–0.23) |

the link between the HQs and the likely attributable mortality estimates from pollutant exposure. This study demonstrated an association between the high levels of pollutants in Nkangala and Gert Sibande and the attributable mortality due to the health outcomes of IHD, stroke, COPD, and LRIs. In this study, the great variability in the data indicates that, while exceedances of SA NAAQS are rare, the risk of exposure-related mortality still exists due to the higher reference standard compared to the WHO AQG. Despite limitations in data availability, the study spans an extensive period and adds important evidence to the understanding of air pollution's health impacts in the HPA. Notably, when comparing HQs based on the 99th percentile 24-hour average $PM_{2.5}$ concentrations and the SA NAAQS reference standards, Ermelo recorded the lowest HQ while Secunda recorded the highest, both within the Gert Sibande municipality. The findings suggest a high likelihood of adverse health effects from $PM_{2.5}$ exposure across the study sites and timeframe. Secunda's pollutant levels are particularly concerning as even the lowest HQ suggests a 2.69-fold increased risk of adverse health effects. At peak concentrations, individuals in Secunda were nearly 10times more likely to experience adverse health effects, underscoring how strongly actual exposure levels exceeded what may be considered "safe" by SA NAAQS reference standards. This discrepancy raises important questions about the adequacy and protective value of existing regulatory thresholds. While HQs for long-term (annual) $PM_{2.5}$ exposure were not as extreme as those for short-term (24-hour) exposure, the health implications remain significant and short-term 24-hour peaks are more likely to exacerbate existing conditions, whereas long-term exposure is associated with disease development and progression [37]. These findings demonstrate that more action is needed to lower pollutant levels to protect the populations from both the long-term and short-term health effects.

The results of this study support the evidence that air pollution is high in the Highveld region of South Africa [38–42]. The HPA is characterized by intense mining, coal-fired power plants, industries, agricultural activity, motor vehicles, and domestic fuel burning. This combination of industrial and domestic activities contributes to the poor air quality in the area, emphasizing the decision to declare it a high-priority air pollution area [42]. In addition, the area is subjected to dry winter climate with sub-zero temperatures at night, and rain in the summer months [38, 41, 22]. The mortality outcomes of the study are similar to findings of previous South African epidemiological studies that have assessed the link between attributable mortality due to adverse health outcomes such as cardiovascular diseases, stroke, IHD, COPD, and respiratory diseases, among others, that likely occurred from high concentrations of long-term or short-term $PM_{2.5}$ exposure [43, 27, 44–48]. Taken together, these factors contribute to fluctuations in the air pollution levels in the Highveld region, often resulting in exceedances of NAAQS.

Pollutant levels in Nkangala seemed to decrease slightly throughout the 10-year period. The pollutant levels in Gert Sibande did not decrease much during the 10-year period. The study findings underscore the persistent challenges in maintaining safe air quality levels and the need for more effective regulatory and enforcement mechanisms to reduce pollutant exposure and protect public health.The decreases in pollutant levels seen in Nkangala may be attributed to the implementation of the changes in the SA NAAQS in 2012 and 2016, which progressively became more stringent to ideally align with the WHO AQG, which has been shown in two other studies that assessed air pollution in the Vaal triangle and HPA and in Richards Bay [49, 23]. However, more actions need to be taken in Gert Sibande that still has a higher HQ index and higher occurrence of attributable deaths due to all three pollutants. More stringent NAAQS mean a decrease in the acceptable reference concentration for an air pollutant, over a specific period. For example, the NAAQS for $PM_{2.5}$ for a one-year averaging period went from 120 $\mu g/m^3$ between 2012 and 2014, to 75 $\mu g/m^3$ from 1 January 2015. It has subsequently decreased to 20 $\mu g/m^3$, from 2016, and will decrease further from 2030. These regulations are a concentration at which air pollution exposure will not negatively impact human health [15]. Adherence to these adjusted NAAQS forces industry and companies to lessen their emissions.

The underlying source of toxicity from air pollution exposure has been linked to the activation of multiple redox signaling pathways in the human body, leading to oxidative stress [50, 51]. Exposure to $PM_{2.5}$ has been associated with increased morbidity and mortality from cardiovascular

and respiratory diseases and disorders, even at low concentrations [52, 53]. Short-term (24 hours) exposure to $PM_{2.5}$ has been found to be associated with increased hospital admissions [54], increased PM-related mortality [55], and increased all-cause mortality [56]. These effects have also been associated with long-term $PM_{2.5}$ exposure [55, 57], even at concentrations well below the WHO AQG [58]. Hazard quotients >1 is an indication of an increased risk of developing non-cancerous health effects, with children and adolescents at a greater risk of an increased risk of chronic adverse health effects [59]. Our results showed HQs >1 for both short- and long-term $PM_{2.5}$ exposure. These results are in keeping with other studies in South Africa [19–21, 23]. Constant exceedances of NAAQS will add to the burden of non-communicable diseases in South Africa, as well as causing a massive financial cost to the government [60, 61].

Conversely, the results for $NO_2$ and $SO_2$ showed no exceedance of the SA NAAQS at these sites. These results are in keeping with another study in the HPA which showed that the HQ for these pollutants did not exceed the SA NAAQS, despite diurnal and seasonal fluctuations [22]. Interestingly, one-year average $NO_2$ HQs did intermittently exceed the WHO AQG, highlighting the discrepancy in stringency in the air quality reference values used. Moreover, South Africa, particularly the HPA, has been considered an $NO_2$ hotspot based on satellite data [41]. These data are not in keeping with ground-based data: $NO_2$ is predominantly associated with traffic-related air pollution emissions and is typically focused on city centers, peaking during high traffic times [41], and the concentrations measured by satellite are heavily influenced by long-range transport of air masses [62].

Short-term exposure to $SO_2$ has been significantly associated with respiratory mortality, and long-term exposure to $SO_2$ has been significantly associated with all-cause mortality, per 1 µg/$m^3$ increase in $SO_2$ [63]. Similarly, per 10 ppb increase in $NO_2$ concentration, short- and long-term exposure to $NO_2$ has been associated with increased all-cause, cardiovascular, and respiratory mortality [64, 65]. Several studies have investigated the health risks associated with long-term exposure to $SO_2$, particularly its relationship with different causes of mortality. However, the findings have been inconsistent. Some studies report strong associations between long-term ambient $SO_2$ exposure and increased mortality, while others find insignificant or no associations with the same mortality outcomes [66]. These broad differences in reported RRs may be influenced by factors such as the size of the study population and the spatial resolution used in exposure assessments [66]. Additionally, evidence suggests that females may be more susceptible to the health effects of long-term $SO_2$ exposure [66]. In this study, death counts among females were higher for stroke at both sites, but lower for IHD. Similar findings of attributable mortality were found in the entire population of South Africa for 2000, 2006, and 2012 [44].

## CONCLUSIONS

Addressing human health risks from air pollution in the Mpumalanga HPA, especially in impoverished populations in low-income communities such as those in Nkangala and Gert Sibande requires a multifaceted approach, integrating scientific research, regulatory frameworks, and community participation. Human health risk assessments play a central role in this endeavor by providing actionable insights into the nature and extent of health impacts, guiding interventions to mitigate risks, and fostering collaborations between stakeholders. By prioritizing public health and environmental sustainability, policymakers can work toward ensuring cleaner air and healthier communities in South Africa's industrial regions like the HPA.

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The authors have no competing interests to declare.

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