Final Project Report

Estimating the health impacts among communities living in proximity to coal-fired power stations in South Africa

Final Version – 30 May 2025

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Disclaimer

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Executive Summary

Residents living in proximity to coal-fired power stations (CFPSs) and neighbouring communities are at risk of poor health outcomes and premature deaths associated to air pollution exposure from these CFPSs together with other air pollution sources. However, many of the studies conducted around the world on the health impacts of CFPSs are relatively old and present varying estimates of the magnitude of these health impacts. A re-assessment of the health risks of CFPSs, globally, together with an estimate of health effects presented by living in proximity to CFPSs in South Africa, is needed.

This project focused on reviewing and summarising the literature on the health impacts of CFPSs globally and for South Africa, as well as analysing actual health data in the district municipalities with CFPSs (compared to those district municipalities without CFPSs) to estimate mortality and morbidity risks for those living in proximity to CFPSs in South Africa.

We conducted a scoping review according to the Joanna Briggs Institute methodological framework and Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews guidelines.

We analysed the mortality and morbidity data for the district municipalities with CFPSs compared to control district municipalities. We used all-cause mortality as well as mortality outcomes known to be associated with exposure to air pollution (from CFPSs).

For morbidity, we determined pneumonia visits and case fatality numbers among children under 5 years of age, as well as tuberculosis (TB) prevalence for any age, for the district municipalities with CFPSs compared to district municipalities without CFPSs.

The main findings were as follows:

- Living in proximity to CFPSs poses a risk to human health (*finding from literature review*).
    - Typically studies consider living in proximity to CFPSs as being within 20 km distance to the CFPS (*finding from literature review*).
- In South Africa, there is observed evidence that people living in district municipalities with CFPSs are at greater risk of dying (mortality) from ischaemic

heart disease, hypertensive disease, diseases of the arteries, arterioles and capillaries, chronic lower respiratory infections, ‘other’ acute lower respiratory infections / respiratory diseases affecting the interstitium (fluid-filled space that connects organs and the skin) / diseases of the respiratory system, compared to people living in district municipalities without CFPSs (*statistically significant finding*).

- There was some evidence that pneumonia case fatality numbers in children under 5 years of age were greater in district municipalities with CFPSs compared to those without CFPSs (*not statistically significant finding*).

- There was evidence that the birth outcome, orofacial cleft lip and palate, occurred more in district municipalities with CFPSs compared to those district municipalities without CFPSs (*statistically significant finding*).

- There was a positive relationship between NO_2 and SO_2 concentrations with increasing pneumonia cases in children under 5 years of age (*statistically significant finding*).

- When adjusting for type of domestic fuel per district in the morbidity health, there was no significant change in the relative risk per increase in NO_2 and SO_2 concentrations.

Recommendations

- CFPSs should be decommissioned and replaced with alternative sources of electricity production that rely on renewable energy sources such as solar, wind, hydropower etc. Our study shows that exposure to pollution from coal-fired power stations has negative impacts on health, therefore eliminating this risk will also reduce the burden placed on health care facilities.

- The South African National Air Quality Standards are implemented in a more stringent manner to prevent mortality and morbidity, especially in district municipalities with CFPSs.

- Air quality management in Air Pollution Priority Areas is scaled up.

- Surveillance of air pollution-related health outcomes in district municipalities with CFPSs is scaled up.

- Health data (for example, mortality data, hospital admissions, ambulance call outs) are made available for tracking of air pollution exposure-associated health outcomes in district municipalities with CFPSs.

- Engagement with all stakeholders is made to ensure the severity of the situation regarding health impacts associated with living in proximity to CFPSs is made apparent.

- People living in proximity to CFPSs should be aware of the health threats that living in proximity to CFPSs present to their health. They should work together with NGOs to advocate for clean air in the environment.

- Researchers should continue to study the health and environmental impacts of living in proximity to CFPSs, especially in LMICs, to ensure that the baseline evidence exists to lobby and advocate for decommissioning of CFPSs.

- Children are most vulnerable to the health effects of exposure to air pollution from CFPSs due to their developing organs and body system. Therefore, energy transition could benefit children living near CFPSs.

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Background

Coal supplies approximately 36% of the world's electricity (International Energy Agency, 2023). According to the International Energy Agency (IEA) the global coal-fired power generation was about 10 400 terawatts-hours (Twh) in 2022 (International Energy Agency, 2023). There are more than 2 400 coal-fired power stations (CFPSs) in operation worldwide. The process of coal combustion for electricity generation releases sulphur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM) and fly ash into the atmosphere. Other emissions include arsenic, mercury, lead, selenium and other toxic elements. The release of the pollutants into the air has negative environmental and health impacts.

There is growing evidence of maternal exposure to particulate matter (PM) with a diameter smaller than 2.5 µm ($PM_{2.5}$) and adverse birth outcomes (Stieb et al., 2012; Pedersen et al., 2013; Chen et al., 2013). Air pollutants can significantly affect the neurocognitive development of children (Sears et al., 2020). Short-term exposure to air pollution in asthmatic children resulted in respiratory symptoms and school absence (Peters et al., 1997). Young children exposed to air pollution were at higher risk for hospital admission for respiratory diseases in Wuhan, China (Huang et al., 2022). A report on data from 22 European cohort studies showed that long-term exposure to $PM_{2.5}$ was associated with natural-cause mortality (Beelan et al., 2014). $PM_{2.5}$ has the potential to enter the bloodstream and can travel to the brain.

Residents living in proximity to CFPSs are at high risk of poor health outcomes and premature deaths attributable to emissions from CFPSs (Hii et al., 2021). Exposure to air pollution from CFPSs was associated with increased hospitalisation, respiratory effects, heart diseases, chronic obstructive pulmonary diseases, lung cancer and mortality (Chio et al., 2019; Karavus et al., 2002; Lin et al., 2019; Hagemeyer et al., 2019; Zierold et al; 2019; Kuo et al., 2014, Minichilli et al., 2019). Previous work observed that premature deaths were concentrated in districts where CFPSs were located (Barbhaya et al., 2022).

A recent study on the effects of the closure of three CFPSs in Chicago reported a decline in school absenteeism and emergency visits in areas (Komisarow and Pakhtigian et al., 2022). Other studies reported an association between long-term exposure to air pollution and lung function development in children living near CFPSs in Israel (Yogev-Baggio et al., 2010; Dubnov et al., 2007).

Furthermore, Karavus et al. (2002) reported that the stack emissions of the CFPSs reduced the pulmonary function of residents in villages located within 5 km of the station. The mean of the spirometer parameter FEV1 was lower in the individuals of the villages around the power station than individuals in control villages (more than 30 km away). Zhang et al. (2022) reported a significant and negative regression coefficient between nearest distance to CFPSs and four neurobehavioral symptoms in children. The distance of a child's residence to CFPSs ranged from 0.8 km to 16 km. Yang et al. (2017) observed that pregnant women living 32 km to 48 km away from a coal power plant were at greater risks of low birth weight in New Jersey, USA. Thus, air pollutants from coal combustion can travel long distances therefore communities living far from CFPSs can also be affected, however, there is less evidence on these aspects (Buchanan et al., 2014).

Few studies have investigated the health effects of air pollution in areas where CFPSs are located among children and adults particularly in low- and middle-income countries. The public health implications of relying on CFPSs in South Africa have been described in several reports (for example, the Holland report by groundWork (2017); Greenpeace (2014, 2019); and Centre for Research on Energy and Clean Air (2023) (Table 1). One study conducted a review of five health risk assessments that modelled the impacts of CFPSs on human health (Langerman and Pauw, 2018).

Table 1. Previous studies in South Africa that have assessed the impacts of CFPSs on health.

Study	Ambient air pollution concentrations modelled how?	CFPSs in South Africa that were considered	Power station emissions considered
Van Horen, 1996	EXMOD model's embedded air quality dispersion models	Arnot, Duvha, Hendrina, Kendal, Kriel, Lethabo, Matimba, Matla, Tutuka	PM, SO_2, NOx- 1994 annual emissions
FRIDGE, 2004	CALPUFF dispersion modelling suite	Arnot, Duvha, Hendrina, Kendal, Kriel, Lethabo, Matimba, Matla, Tutuka	PM, SO_2, NOx, CO, NO_2, benzene, lead, CH4, TNMOC, CO_2- 2002 annual emissions
Airshed and Infotox 2006	CALPUFF dispersion modelling suite	Arnot, Duvha, Hendrina, Kendal, Kriel, Lethabo, Majuba, Matla, Tutuka	PM, SO_2, NOx- 2003 annual emissions
Myllyvirta, 2014	Regression models derived from single-source CTM (CAMx and CALPUFF) model runs	Arnot, Camden, Duvha, Grootvlei, Hendrina, Kendal, Komati, Kriel, Lethabo, Majuba, Matimba, Matla, Medupi, Tutuka	PM, SO_2, NOx- 2012/13 annual emissions

Steyn and Kornelius, 2018	CALPUFF dispersion modelling suite	Arnot, Camden, Duvha, Grootvlei, Hendrina, Kendal, Komati, Kriel, Majuba, Matla, Tutuka and Sasol Synfuels steam plants	SO_2 only- difference 2012/13 annual emissions

The review by Langerman and Pauw (2018) found that the results differed by study depending on the input data and models applied (Table 2). All of these studies are relatively old – the latest used data from 2009 and 2014 (Steyn and Kornelius, 2018) – and the results are mixed, with studies reporting on different outcomes and even for those with the same outcome, the results are orders of magnitude different. For example, FRIDGE estimated 43 per 100 000 for cardiovascular mortality, and Airshed and Infotox estimated 204.9 per 100 000 people in relation to exposure to coal-fired power station emissions. All studies relied on modelling and not observed data (despite their shortcomings of observed data).

Given these differences, it seems that an appropriate exercise would be to re-assess the existing literature, including more recent studies / reports (if any) and analyse actual mortality and morbidity data in the district municipalities where CFPSs in South Africa exist.

Table 2. Population incidence of death / disease per 100 000 people used in the health risk assessments of South African coal-fired power stations.

Study / Reference	**Incidence of death / health outcome (**mortality and hospital admission rates are given per 100 000 population)	**Source of data**
Van Horen, 1996	Not published online.	-
FRIDGE, 2004	Total mortality: 1 235 (n) Cardiovascular mortality: 43 Respiratory mortality: 141 Respiratory hospital admissions: 3 100	Bradshaw et al 2003 StatsSA 2002 StatsSA 2002 Joburg 2000
Airshed and Infotox, 2006	Total mortality: 1 065 (n) Cardiovascular mortality: 204.9 Respiratory mortality: 93.7 Respiratory hospital admissions: 477	Bradshaw et al. 2004 (sum of provincial data) KZN DOH 2004
Myllyvirta, 2014	Lung cancer mortality: 9.1 IHD mortality: 34.6 COPD mortality: 11.8 Stroke mortality: 48.6 Lower respiratory infection (<5 years old): 12.2	Global Burden of Disease 2010

Steyn and Kornelius, 2018	Total mortality: 1 110 (n) Child mortality <5 years: 85.5 Respiratory hospital admissions: 1 500 Cardiac hospital admissions: 1 500	StatsSA 2014 StatsSA 2014 Da Costa 2009 Da Costa 2009

Aim and Objectives

Project aim

To examine and summarise the current body of literature on the health impacts of coal-fired power stations globally and specifically for South Africa, and to estimate health impacts (mortality and morbidity) in the district municipalities where CFPSs are located compared to district municipalities which do not have CFPSs but are similar to district municipalities in other aspects.

Project objectives

There were five project objectives:

1. To conduct a scoping review of the literature to assess the health impacts from exposure to emissions from CFPSs, globally, and specifically for South Africa.

2. To analyse all-cause and cause-specific (focusing on outcomes associated with air pollution exposure) mortality data, and morbidity data (pneumonia and TB) for all the district municipalities where CFPSs are located and compare the findings to ‘control’ district municipalities with similar geography and climate but no CFPSs.

3. To analyse the association between morbidity and mortality from objective 2 and air pollution concentrations in district municipalities where CFPSs are located and compare the findings to ‘control’ district municipalities with similar geography and climate but no CFPSs.

4. To collate all the outputs from the first three objectives that provide evidence of the health impacts in district municipalities with CFPSs compared to those with none and to summarise an estimate of the risk to human health from living in district municipalities with CFPSs versus those living in districts without CFPSs.

5. To disseminate the findings of the project via a workshop to be held in Gauteng in person and with virtual attendance possible.

Methods

Before elaborating on the methods, we have provided an overview of the different datasets that were applied in the project (Table 3).

Table 3. Data available for analyses in this project. All data were downloaded and prepared by the project team.

Data type	Source	Resolution / type of data	Time period
Mortality data	Statistics South Africa	Daily / cross-sectional	1997-2018
Morbidity data	National District Health Information System	Annual / longitudinal	2002-2024
Socio-economic data	Statistics South Africa	District / cross-sectional	2011 and 2022
Population data	Statistics South Africa	District / cross-sectional	2011 and 2022
Air pollution concentrations ($PM_{2.5}$, PM_{10}, SO_2, NO_2, CO)	South African Air Quality Information System	Hourly / cross-sectional	1997-2024

Below, the methods for the project activities are outlined, including for the scoping review and for the analyses that consider whether there were statistically significant differences in mortality and morbidity health outcomes, together with air pollution, in district municipalities without and with CFPSs.

Scoping literature review

The scoping review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines. A review protocol was developed in accordance with the Joanna Briggs Institute (JBI) methodological framework. Article searches were performed in the following databases: Google Scholar, PubMed, ScienceDirect, Scopus and Web of Science. We included studies published until 31 January 2024. Studies were restricted to the English language. For a complete presentation of the scoping review protocol, please see https://pubmed.ncbi.nlm.nih.gov/38508645/

The reference for the published protocol is as follows:

- Mahlangeni N, Kapwata T, Laban T, Wright CY. Health risks of exposure to air pollution in areas where coal-fired power plants are located: protocol for a scoping review. BMJ Open. 2024 Mar 19;14(3):e084074. DOI: 0.1136/bmjopen-2024-084074

The research questions for the scoping review were:

(i) What is the current evidence on the health risks associated with exposure to air pollution in areas where coal-fired power plants exist?
(ii) What is the relationship between health outcomes and proximity to coal-fired power plants?
(iii) What are the estimated mortality or morbidity risks of exposure to air pollution in areas where coal-fired power plants exist?

The eligibility criteria selected for the articles followed the PECOS (Participant, Exposure, Context, Outcome, Study design) framework to identify articles that are included and excluded (Table 4).

The search strategy of the review aimed to locate published and unpublished literature. Sources of grey literature included environment organisation reports such as the Centre for Environmental Rights and Environmental Defence Fund, as examples.

Table 4. PECOS together with eligibility criteria.

	Inclusion criteria	**Exclusion criteria**
Population	Studies reporting on individuals or groups of all ages (i.e. in utero, infants, children and adolescents, adults and the elderly) near CFPSs (as reported in the article, no km restriction).	Studies on animal models or in vitro studies.

Exposure	Studies that included exposure to air pollution in areas where coal-fired power plants exist such as SO_2, particulate matter, NO_x.	Studies not related to exposure to air pollution in areas where CFPSs exist.
Context	Studies from all geographical areas were considered.	There was no restriction on geographical area.
Outcome	Studies on health outcomes of communities located near to CFPSs such as respiratory illnesses and lung disease. Where possible, dose-response functions will be extracted. The health effects may be directly measured or estimated using models. All-cause or disease-specific mortality, hospital and emergency visits were considered. Studies on health risk assessment were also considered.	Health outcomes not associated with exposure to air pollution in areas where CFPSs exist.
Study design	Human epidemiological research articles published in peer-reviewed journals. Observational studies including cohort studies, case-control studies, time-series, ecological and cross-sectional studies. Experimental studies on humans on the health effects of air pollution in areas where coal-fired power plants exist. Reports that included health impacts from air pollution in areas where CFPSs exist.	Non-human studies (in vitro and in vivo) and studies on occupational exposure. Other forms of grey literature such as books, conference proceedings, letters to editor, newspaper articles, magazines, and blogs. Review articles were excluded but the list of references will be examined to identify relevant studies.

Data variables extracted from the included articles were emission and impact information and included details on the country of origin, study design, type and concentration of pollutants, sample size, proximity of CFPSs to the community, health outcomes, technical specifications and emission characteristics of the power stations, measures of effects, statistical approach, and key findings. A meta-analysis was not done due to the large range of health outcomes associated with exposure to emissions from CFPSs.

Morbidity and mortality analyses

Before discussing the morbidity and mortality data, we provide an explanation of how the district municipalities with CFPSs were selected versus those district municipalities without CFPSs but similar in other aspects.

Selection of district municipalities with and without CFPSs

The project focuses on the health effects in the district municipalities with and without CFPSs. The district municipalities with CFPSs were selected from those within the Highveld Air Pollution Priority Area since this is an area of intense air quality management by the Department of Forestry, Fisheries and the Environment. Additionally, district municipalities not in proximity to CFPSs were selected as ‘controls’ although it is important to acknowledge that all district municipalities have sources of air pollution including and beside CFPSs. We ensured that vital characteristics of residential households in all district municipalities, regardless of being in proximity to CFPs or not, were similar, for example, household living conditions such as main fuel source for heat/cooking, dwelling type etc. as well as population size were similar in the matched district municipalities including or excluding CFPSs.

The ratio of 1:1 for district municipalities with and without CFPSs was used as it is statistically more efficient than a ratio of 1:many and preferable when costs of the study are taken into consideration (Dumville, 2006). According to Setia (2016), the optimal case-to-control ratio is 1:1, however, if the number of cases is limited, a ratio of 1:2 or up to 1:4 will increase the statistical power. Moreover, the selection of district municipalities without CFPSs was made based on the location of the South African Air Quality Information System (SAAQIS) monitoring stations (Figure 1, Table 5).

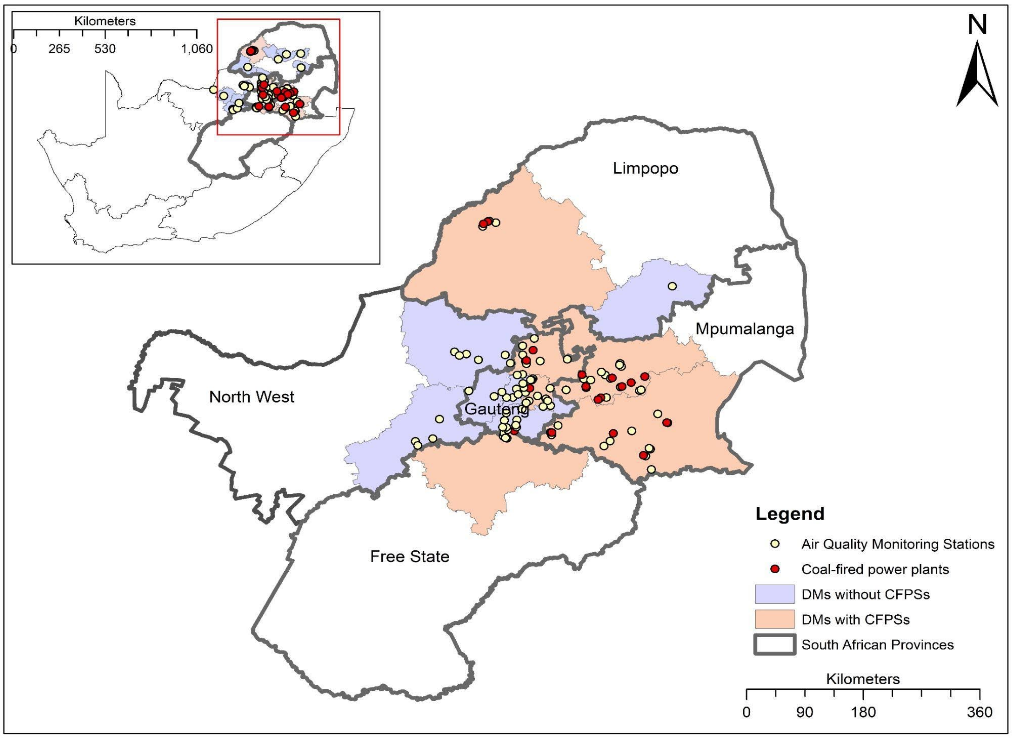


Figure 1. Map showing the location of the CFPSs, the SAAQIS monitoring stations, and the district municipalities with and without CFPSs.

Table 5. District municipalities with and without CFPSs for inclusion in the study.

District Municipalities without CFPSs	District Municipalities with CFPSs
Sekhukhune	Nkangala
Dr Kenneth Kaunde	Waterberg
Sedibeng	Gert Sibande
Bojanala	Ekurhuleni Metropolitan Municipality
West Rand	Fezile Dabi
City of Johannesburg	City of Tshwane Metropolitan Municipality

Mortality data
The mortality dataset that we used was provided by Statistics South Africa. The data was individual records of daily all-cause mortality with cause of death categorized according to the International Classification of Disease (ICD). These were then recoded according to the Global Burden of Disease list which aggregates ICD codes into three broad groups of cause of death. Group one are the pre-transitional causes: communicable diseases, maternal causes, perinatal conditions, and nutritional deficiencies. Group two are non-communicable causes and group three are injuries. Data was aggregated to daily totals for analysis at district municipality level. For the purposes of this study, we extracted Global Burden of Disease classifications for cause of death due to respiratory and cardiovascular diseases. The full list of ICD codes and Global Burden of Disease classifications is provided in the Appendix.

Morbidity data
Analyses using annual pneumonia prevalence and case fatality numbers in under 5-year-olds and annual reported TB prevalence numbers (new reported cases) for district municipalities with and without CFPSs were conducted. The data were obtained from the National District Health Information System (NDHIS) for years 2002 until 2023. Analyses were made at annual resolutions.

Statistical analyses
Independent *t*-tests were used to assess whether there were statistically significant differences between the means for pneumonia incidence in children under 5 and case fatality numbers in district municipalities with and without CFPSs.

Poisson regression models were used to assess the incidence rate ratios (IRRs) of mortality for air pollution-related causes of death between districts with and without CFPSs. The models included population as an exposure to account for differences in population size across the districts. Results were reported as incidence rate ratios (IRRs) and the corresponding 95%CI, p values less than 0.05 were considered statistically significant.

All of the analyses were conducted using STATA.

Air pollution data
We downloaded ground-based air quality data from the South African Air Quality Information System (SAAQIS) managed by the South African Weather Service, to estimate exposure to ambient air pollution. For districts with more than one monitoring station, the data from all stations were aggregated and then averaged to obtain a representative estimate.

Two district municipalities per region were analysed for an association between NO_2, SO_2 and the daily incidence of new cases of pneumonia in children under the age of 5 years (Figure 2). The first assumption for this study was that due to the monthly temporal scale of the analysis, the whole district municipality was exposed to the measurements as reported by SAAQIS. This is reasonable because these are ground monitoring stations measuring real-time concentration levels.

A total of 147 observations (months) from August 2008 to December 2023 were used (Table 6). The health data was aggregated per district municipality (Table 7). The two district municipalities (DM) with CFPSs were Fezile Dabi and Gert Sibande DM and the two DMs without CFPSs were Sedibeng and City of Johannesburg.

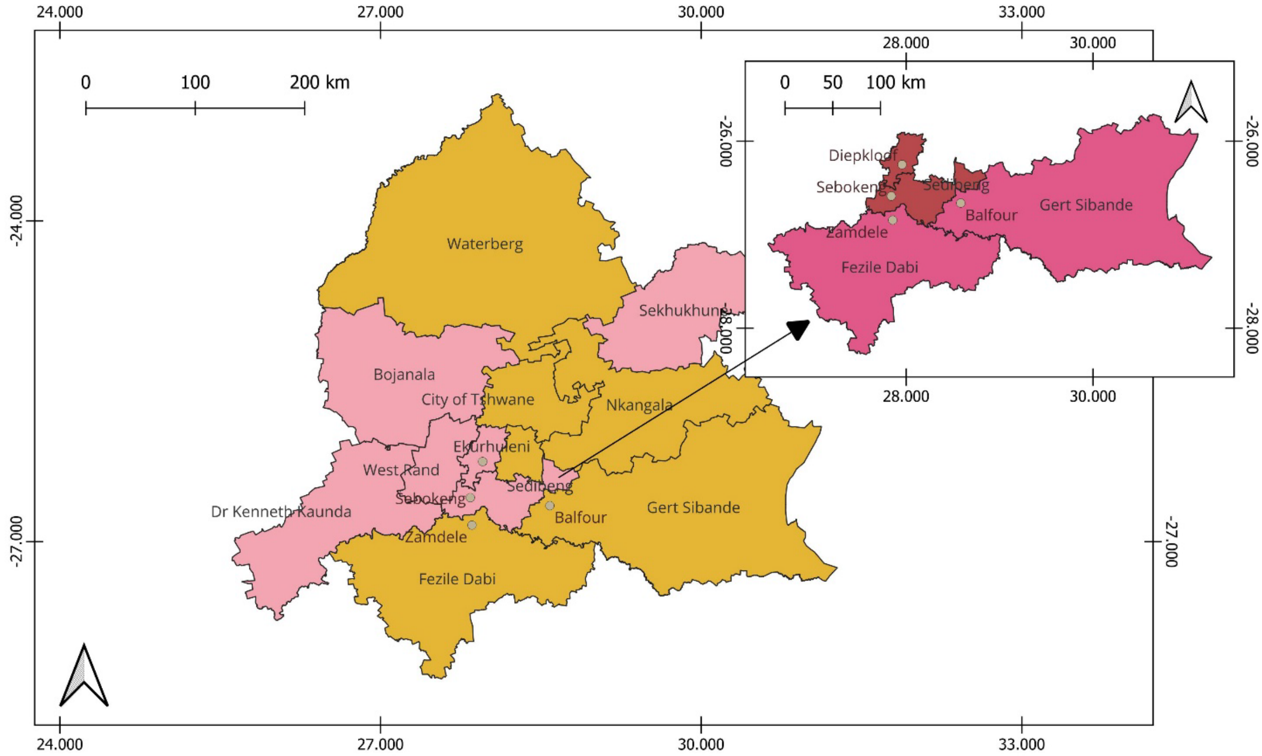


Figure 2. Layout map of the two district municipalities per study regions with the SAAQIS monitoring stations for the DLNM health study.

Table 6. Descriptive statistics for the air quality, with 147 observations from August 2008 to December 2023.

Variable	SAAQIS Monitoring station	Observations (months)	Mean	Std dev	Min	Median	Max
SO_2	Balfour	147	3,00	3,09	0	2,63	15,92
	Zamdele	147	7,24	3,12	0	7,30	14,97
	Sebelong	147	3,89	2,44	0	3,88	10,32
	Diepkloof	147	4,13	2,21	0	4,01	9,80
NO_2	Balfour	147	5,65	9,26	0	1,86	86,31
	Zamdele	147	8,13	6,51	0	9,00	25,77
	Sebelong	147	10,75	7,43	0	10,51	64,09
	Diepkloof	147	18,54	9,23	0	19,37	46,66

Table 7. Descriptive statistics for the new cases of pneumonia for under 5 children in district municipalities with and without CFPSs. Monthly observations of 147 from August 2008 to December 2023.

Variable (aggregated new cases of pneumonia < 5 years	**District Municipality**	**Observations (months)**	**Mean**	**Std dev**	**Min**	**Median**	**Max**
Regions with CFPS	Gert Sibande	147	123	96	6	103	355
	Fezile Dabi	147	181	128	4	152	523
Regions without CFPS	Sedibeng	147	149	103	4	123	462
	City of Johannesburg	147	1046	535	269	905	2895

Fezile Dabi and Gert Sibande district municipalities were aligned with the Zamdele and Balfour monitoring stations, respectively. For the region without CFPSs, the Sedibeng and City of Johannesburg, the Sebokeng and Diepkloof monitoring stations were selected. The selection was based on the 'fullness' of the air quality over the same period of time on order to ascertain not only a relative health effect but also a comparison with the neighbouring DM over the same time period.

Health and air pollution analyses

The association between exposure to air pollution and health outcomes is generally assumed to be non-linear. Therefore, a distributed-lag, nonlinear model (DLNM) and a Generalised Additive Model (GAM) based on the quasi-Poisson distribution will be used to model daily all-cause and cause specific mortality against air pollution variables (SO_2, NO_x, PM, O_3). Results were compared between districts with power stations and those without by reporting relative risks (RRs) with a 95% confidence interval (95% CI).

All analyses were conducted using R Software.

Birth outcomes

Since we had access to a birth outcomes dataset, we applied in a study published in 2023 (Wright at al., 2023) we thought it was a good opportunity to interrogate those data and consider the prevalence of the birth outcomes, i.e., orofacial cleft lip and palate (OFC), for the district municipalities with and without CFPSs.

The dataset comprised 2 525 cases of OFC from a Gauteng surgeon's database and data from South Africa Operation Smile. We extracted the cases for the district municipalities with and without CFPSs and compared the median CLP birth prevalence per 100,000 population.

Dissemination

The final phase of the project is to bring together all the findings from the previous phases in one comprehensive report.

We will communicate our key findings and messages to the public through a commentary/media release.

We will also host at least two workshops to share the findings of the research: workshop one with academics / researchers and workshop two with non-governmental organisations, the media and interested stakeholders, e.g., government departments, industry etc.

Limitations

While this is deemed to be the first study to assess the health impacts among communities living in district municipalities with and without CFPSs using observed data (i.e., not modelling health outcomes), there are some limitations. We cannot attribute the health outcomes to the CFPSs' emissions themselves as there are other sources of emissions in a district municipality (such as residential fuel burning and industrial emissions) so we compared the health outcomes of communities living in district municipalities with and without CFPSs, ensuring that the climate, geography and exposure sources were similar.

In 2025, we will adjust for confounding factors such as demographics, socio-economic status and other characteristics that could affect exposure at household level using census data for the district municipality. This includes information about residential household burning (see Appendix 1).

Ethical considerations

Ethics approval was granted by the South African Medical Research Committee EC007-5/2024. No participants or interviewees were recruited in this study.

We used mortality data and Demographic Health Information System data that was de-identified and anonymised when received from Statistics South Africa and the National Department of Health, respectively.

No communities were named.

We worked at the district municipality level in which there are several communities, so they are unlikely to be recognisable at an individual scale.

Results of the Scoping Review

Communities living in proximity to CFPSs may be at greater risk of negative health impacts from exposure to air pollution than communities living further away.

The aim of this scoping review was to provide an update on the evidence of the health risks of air pollution exposure associated with living in proximity to CFPSs and to evaluate the relationship between residential proximity to CFPSs and the extent of the health burden.

Fifty-six studies (summarised in the Appendix) were included in the review with most articles published from 2016 to 2023 (n=33, 59%) and 35 were in high income countries (63%). Figure 2 shows in which countries these studies were conducted.

Thirty-two studies included children (~3 to 14 years), mothers and newborns as the study population. Commonly investigated air pollutants included sulphur dioxide, particulate matter with diameter of 2.5 μm or less ($PM_{2.5}$), and polycyclic aromatic hydrocarbons.

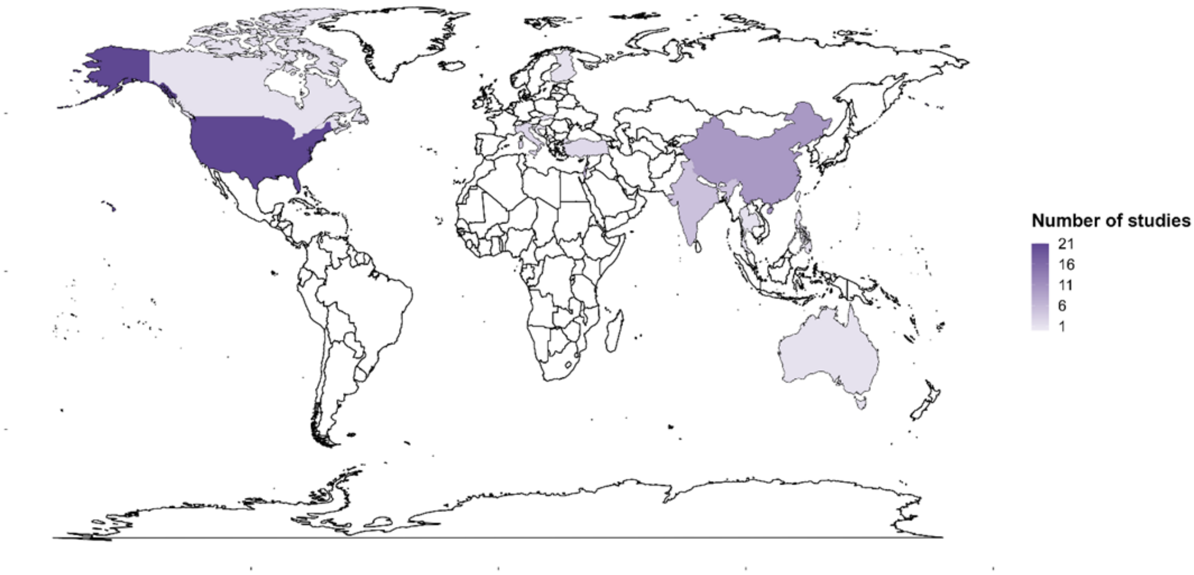


Figure 3. Map showing the distribution of included studies around the world.

Living close to CFPSs (0 - 20 km) was frequently associated with increased odds or likelihood of respiratory disorders, adverse birth outcomes and child developmental issues.

Interventions such as emission control systems or total shutdown of CFPSs led to improved health among communities living near CFPSs. It is important to note that other sources of air pollution in the areas near CFPSs may have also contributed to air pollution-related health impacts.

The review highlighted the health impacts from air pollution associated with living in proximity to CFPSs and the need for policy measures to enforce the CFPSs to reduce air pollution by installing emission control technologies or transitioning to cleaner energy sources especially for power generation.

Studies conducted in South Africa

Most of the studies conducted in South Africa focused on air quality impact of CFPSs only (i.e., did not measure health outcomes).

For example, the work by Ngamlana et al. (2024) who analysed a four year air quality data set from CFPSs in Mpumalanga province to determine the trends in SO_2, NO_2 and PM_{10} in communities near the CFPSs. Langerman and Pauw, (2018) evaluated the available data on health risk assessment of South African CFPSs emissions to obtain an accurate estimate of health effects from exposure to air pollution from CFPSs. Another study estimated premature mortality from exposure to $PM_{2.5}$ from CFPSs by applying the exposure-response function (Simelane et al., 2024). These were not ecological studies therefore they were not included in the review.

Results of the Data Analyses

Characteristics of district municipalities included in the study

The population numbers and characteristics of the district municipalities included in this study are provided in detail in the Appendix and they are summarised here.

Majority of the district municipalities were relatively large in population size with several 100 000s of people, except for Bela-Bela with around 65 000 and Ekurhuleni with over 3 million.

Regarding the main energy source for lighting and cooking, most district municipalities relied on electricity except for a few where gas was used. Coal was used in some district municipalities for cooking but among no more than 15% of the district municipalities' population.

Mortality outcomes in district municipalities with and without CFPSs

We found that the top three causes of mortality related to cardiovascular diseases (CVD) and cardiometabolic diseases that increase risk of CVD, were cerebrovascular disease (39.9%) hypertensive heart disease (23.9%) and ischaemic heart disease (20.7%).

Overall, lower respiratory infections, was the leading cause of death across all district municipalities (89%) followed by chronic obstructive pulmonary diseases (COPD) (7%) and asthma (4%) (Table 9).

Among the ten cardiovascular and cardiometabolic diseases that were analysed, hypertension had the highest statistically significant association with mortality in district municipalities with and without CFPSs (Figure 4). The incidence rate ratio of mortality from hypertension in district municipalities with CFPSs was 1.28 times higher than in district municipalities without CFPSs (IRR = 1.28, 95% CI = 1.11 – 1.49, p = 0.00[1]).

[1] A p-value or probability value is a number that measures how likely it is that observed data would occur if a null hypothesis were true. A p-value less than 0.05 means that there is a statistically significant finding at a 95% confidence interval.

Table 8. Total mortality (n) per district municipality for cardiovascular diseases (CVD) and cardiometabolic diseases that increase risk of CVD for all years from 1997-2018.

District	Status	Diabetes mellitus	Rheumatic heart disease	Hypertensive heart disease	Ischemic heart disease	Pericarditis, endocarditis and myocarditis	Cardiomyopathy	Cerebrovascular disease	Aortic aneurism	Peripheral vascular disorders	Congenital heart anomalies	Hypertension
Bojanala	DM without CFPSs	2938.00	52.00	9251.00	3131.00	138.00	1116.00	11680.00	90.00	68.00	109.00	21.00
		10.27	0.18	32.35	10.95	0.48	3.90	40.85	0.31	0.24	0.38	0.07
City of Johannesburg	DM without CFPSs	3564.00	209.00	8671.00	14772.00	549.00	2090.00	22472.00	661.00	164.00	493.00	331.00
		6.60	0.39	16.06	27.37	1.02	3.87	41.63	1.22	0.30	0.91	0.61
City of Tshwane	DM with CFPSs	5381.00	137.00	14957.00	13413.00	429.00	1773.00	19316.00	434.00	194.00	325.00	120.00
		9.53	0.24	26.48	23.75	0.76	3.14	34.20	0.77	0.34	0.58	0.21
Dr Kenneth Kaunda	DM without CFPSs	944.00	62.00	4039.00	4389.00	196.00	1176.00	7292.00	144.00	52.00	108.00	46.00
		5.12	0.34	21.89	23.79	1.06	6.37	39.53	0.78	0.28	0.59	0.25
Ekurhuleni	DM with CFPSs	4522.00	137.00	9146.00	12027.00	348.00	1722.00	20854.00	463.00	156.00	336.00	124.00
		9.07	0.27	18.35	24.13	0.70	3.46	41.85	0.93	0.31	0.67	0.25
Fezile Dabi	DM with CFPSs	1333.00	22.00	4192.00	3553.00	120.00	296.00	7258.00	162.00	39.00	73.00	33.00
		7.80	0.13	24.54	20.80	0.70	1.73	42.49	0.95	0.23	0.43	0.19
Gert Sibande	DM with CFPSs	2874.00	50.00	5712.00	3356.00	142.00	507.00	10098.00	124.00	39.00	101.00	20.00
		12.48	0.22	24.81	14.58	0.62	2.20	43.86	0.54	0.17	0.44	0.09
Nkangala	DM with CFPSs	2843.00	40.00	8421.00	4228.00	825.00	712.00	9411.00	104.00	51.00	107.00	30.00
		10.62	0.15	31.45	15.79	3.08	2.66	35.15	0.39	0.19	0.40	0.11
Sedibeng	DM without CFPSs	2925.00	52.00	6661.00	5908.00	183.00	712.00	10754.00	186.00	66.00	174.00	33.00
		10.58	0.19	24.09	21.36	0.66	2.57	38.89	0.67	0.24	0.63	0.12
Sekhukhune	DM without CFPSs	2742.00	38.00	8086.00	2918.00	220.00	1825.00	13027.00	40.00	30.00	61.00	24.00
		9.45	0.13	27.87	10.06	0.76	6.29	44.90	0.14	0.10	0.21	0.08
Waterberg	DM with CFPSs	1063.00	23.00	3211.00	2265.00	65.00	204.00	4136.00	83.00	34.00	48.00	18.00
		9.53	0.21	28.80	20.31	0.58	1.83	37.09	0.74	0.30	0.43	0.16
West Rand	DM without CFPSs	1293.00	35.00	3108.00	4247.00	132.00	455.00	6326.00	151.00	49.00	92.00	35.00
		8.12	0.22	19.52	26.67	0.83	2.86	39.73	0.95	0.31	0.58	0.22
Total		32422.00	857.00	85455.00	74207.00	3347.00	12588.00	142624.00	2642.00	942.00	2027.00	835.00
		9.06	0.24	23.87	20.73	0.94	3.52	39.85	0.74	0.26	0.57	0.23

*Denominator is total deaths districts per district

Other cardiovascular and cardiometabolic diseases that had high statistically significant risks of mortality in district municipalities with CFPSs compared to district municipalities without CFPSs were:

- pericarditis, endocarditis and myocarditis
    - (IRR = 1.22, 95% CI = 1.13 – 1.33, p = 0.00);

- aortic aneurism (a bulge in the wall of the aorta)
    - (IRR = 1.22, 95%CI=1.13 – 1.33, p = 0.00)

- congenital heart anomalies
    - (IRR = 1.10, 95%CI = 1.00 –1.21, p = 0.04); and

- hypertensive heart disease
    - (RR = 1.03,95% CI = 1.1.01 - 1.04, p = 0.00).

Table 9. Total mortality (n) per district municipality for diseases of the respiratory system.

District	Status	Lower respiratory infections (n and %)	Upper respiratory infections (n and %)	COPD (n and %)	Asthma (n and %)
Bojanala	DM without CFPSs	22744.00	112.00	1925.00	1553.00
		86.37	0.43	7.31	5.90
City of Johannesburg	DM without CFPSs	46175.00	104.00	4163.00	1477.00
		88.94	0.20	8.02	2.84
City of Tshwane	DM with CFPSs	33244.00	158.00	3167.00	2230.00
		85.68	0.41	8.16	5.75
Dr Kenneth Kaunda	DM without CFPSs	18682.00	73.00	1541.00	990.00
		87.77	0.34	7.24	4.65
Ekurhuleni	DM with CFPSs	45973.00	145.00	3943.00	1917.00
		88.45	0.28	7.59	3.69
Fezile Dabi	DM with CFPSs	21172.00	62.00	1074.00	892.00
		91.26	0.27	4.63	3.84
Gert Sibande	DM with CFPSs	29624.00	100.00	2000.00	1423.00
		89.37	0.30	6.03	4.29
Nkangala	DM with CFPSs	23465.00	77.00	1750.00	1437.00
		87.79	0.29	6.55	5.38
Sedibeng	DM without CFPSs	29021.00	63.00	1728.00	1418.00
		90.04	0.20	5.36	4.40
Sekhukhune	DM without CFPSs	28180.00	109.00	1325.00	1307.00
		91.14	0.35	4.29	4.23
Waterberg	DM with CFPSs	9257.00	26.00	618.00	649.00
		87.74	0.25	5.86	6.15
West Rand	DM without CFPSs	16976.00	49.00	1086.00	651.00
		90.48	0.26	5.79	3.47
Total		324513.00	1078.00	24320.00	15944.00
		88.70	0.29	6.65	4.36

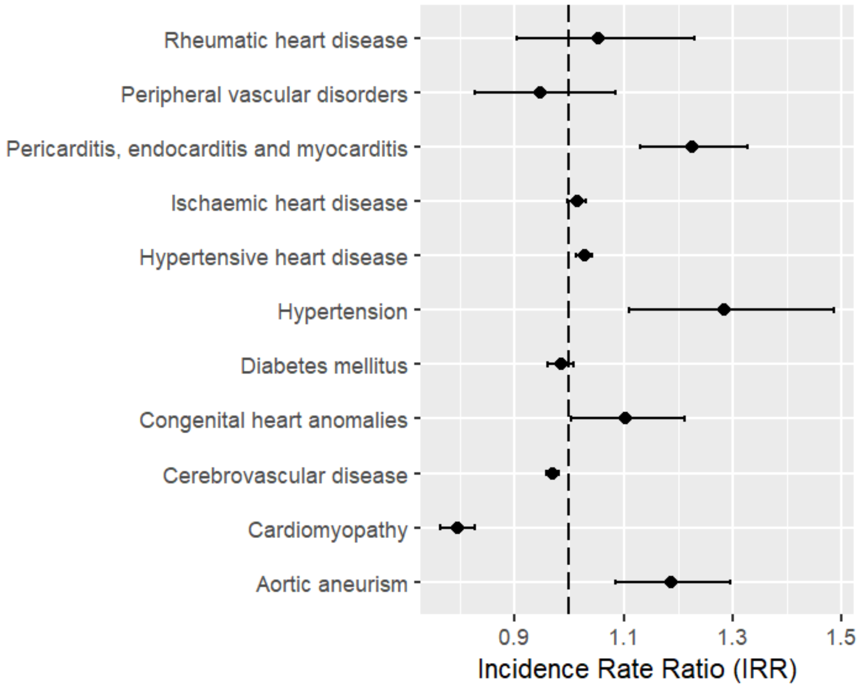


Figure 4. Incidence Rate Ratio (IRR) of cause-specific mortality for cardiovascular and cardiometabolic diseases in district municipalities with and without CFPSs. To interpret this plot, dots with lines and whiskers that sit to the right of the dashed line indicate increased risk.

Figure 5 shows that the rate of mortality due to (IRR=1.05, 95% CI = 1.03 – 1.08, p=0.00).

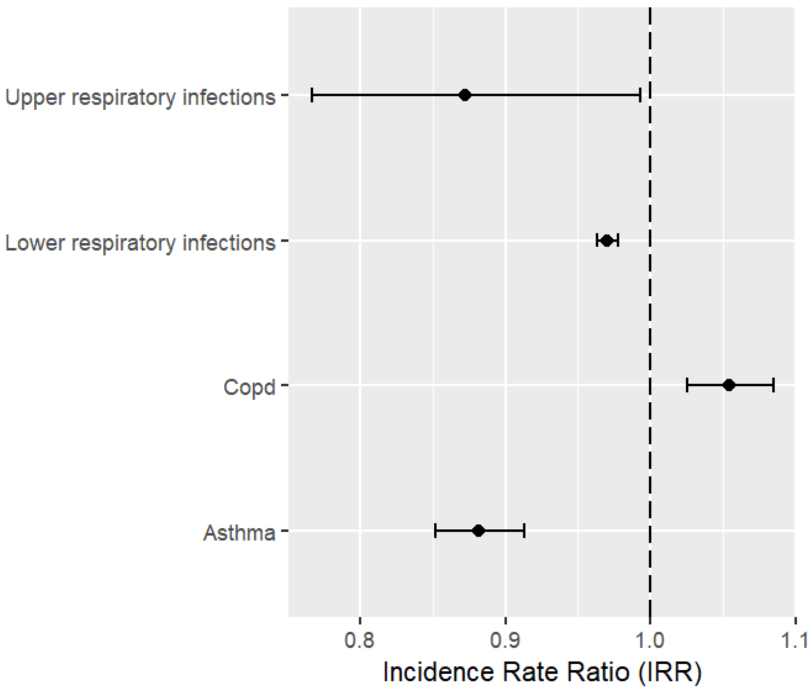


Figure 5. Incidence Rate Ratio (IRR) of cause-specific mortality for respiratory diseases in district municipalities with CFPSs compared to district municipalities without CFPSs. To interpret this plot, dots and lines that sit to the right of the dashed line indicate increased risk.

Morbidity outcomes in district municipalities with and without CFPSs

Definitions

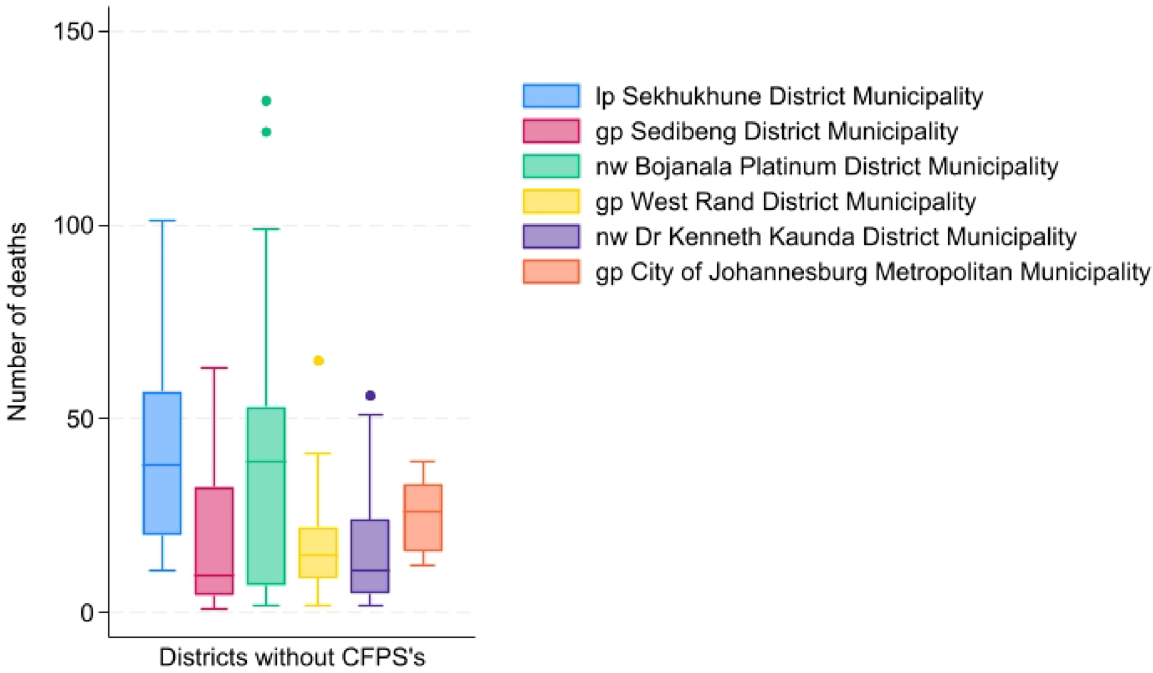
Pneumonia fatality: deaths resulting from pneumonia infection.

Pneumonia case fatality: Ratio of cases which resulted in death. Calculation= (number of pneumonia deaths/ number of pneumonia cases)

In Figure 6a, there is a visual of the distribution of number of pneumonia case fatalities in children under 5 years in the district municipalities without CFPSs and with CFPSs. District municipalities without CFPSs had a predominantly symmetrical distribution as the data was distributed relatively evenly around the middle, with a low range. Most of the data in the district municipalities without CFPSs was dispersed in the lower region of the graph.

A greater range was observed in the district municipalities with CFPSs (Figure 6b) with Ekurhuleni district having the greatest range without outliers. Overall, the distribution of data in the district municipalities with CFPSs was skewed to the right indicating that most of the outliers are present in the upper region of the graph.

a)



b)

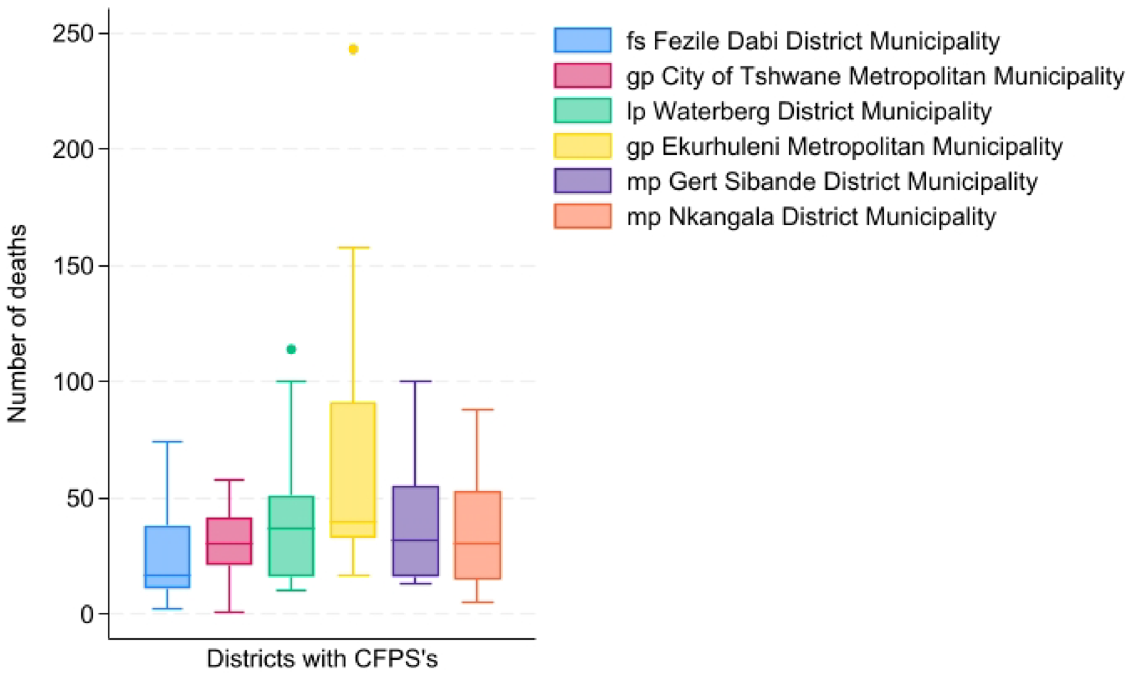


Figure 6. Graph summarising pneumonia fatality prevalence data for district municipalities a) with CFPSs; and b) without CFPSs.

Figure 7a and Figure 7b illustrate the pneumonia case fatality and incidence numbers in district municipalities with and without CFPSs from 2002 to 2018 and 2002 to 2022, respectively. Figure 7a shows an overall decline in the pneumonia case fatality ratios in all district municipalities. A peak in pneumonia case fatality for districts with and without CFPS's is observable in 2005, 2006 and 2007.

A steady decline in incidence cases (Figure 7b) was observed starting from 2009 in all districts. This decline is expected as the national rollout of antiretrovirals between 2004 and 2008 in South Africa reduced the risk of those with HIV from contracting and dying from pneumonia.

Peaks were observed in 2005 and 2009 in district municipalities without CFPSs with incidence cases (Figure 7b) of 7 841 and 7 507, respectively. District municipalities without CFPSs exhibited observable peaks in pneumonia infections in 2007 and 2009 at an incidence of 591 and 5 895 (fig 6B), respectively, as well as a third lower peak in 2017. Figure 7b illustrates the mean pneumonia incidence annually for districts with and without CFPSs.

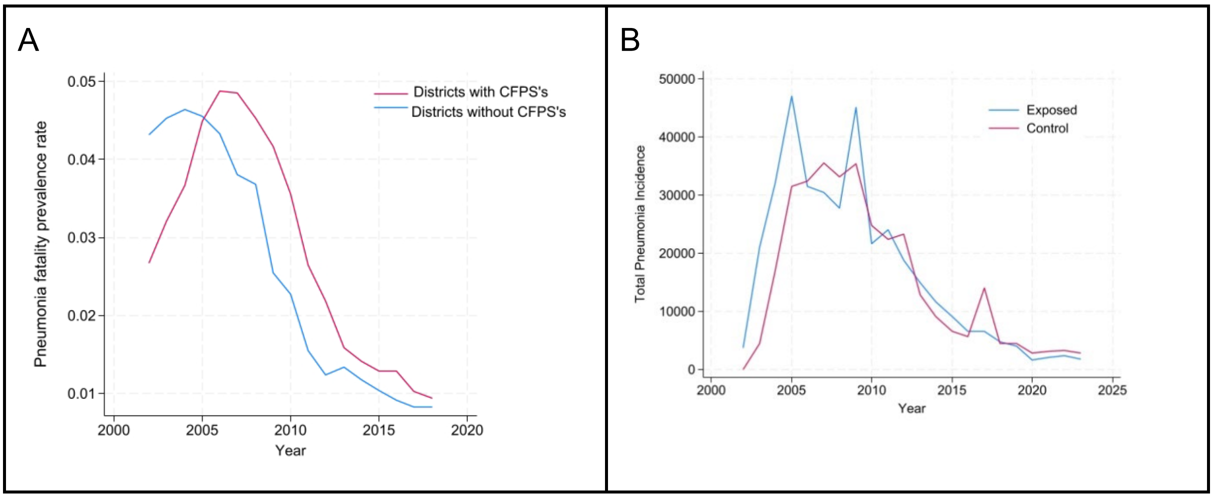


Figure 7. Line graph showing (a) annual pneumonia fatality prevalence; and (b) annual mean pneumonia incidence; in district municipalities with and without CFPSs from 2005 to 2022.

A t-test was conducted in order to assess whether there is a statistically significant difference between pneumonia health outcomes (incidence, new cases, fatality and fatality prevalence for pneumonia of children under 5). The results presented in Table 10 showed that the mean pneumonia incidence under 5 years of age (over the observed period of 2002-2018) was higher in district municipalities with CFPSs compared to district municipalities without CFPSs but the difference was not statistically significant ($p = 0.52$).

The results for pneumonia fatality prevalence showed that the mean fatality prevalence in children under 5 years of age was higher in district municipalities with CFPSs compared to district municipalities without CFPSs ($p < 0.805$).

Table 10. Difference between means for pneumonia outcomes of districts with CFPSs and districts without CFPSs.

		N	Annual mean (standard deviation)	95% Confidence Interval		p-value
Pneumonia incidence under 5 years of age	DMs without CFPSs	123	2673.07 (2588.75)	2210.99	3135.15	
	DMs with CFPSs	126	2896.38 (2889.23)	2386.97	3405.79	0.52
New cases under 5 years of age	DMs without CFPSs	124	4207.36 (4310.14)	3441.20	4973.53	
	DMs with CFPSs	126	4763.96 (4456.27)	3978.26	5549.67	0.32
Pneumonia deaths in under 5 years of age	DMs without CFPSs	99	28.26 (2.65)	23.01	33.52	0.010*
	DMs with CFPSs	108	39.13 (3.39)	32.80	46.22	
Pneumonia fatality prevalence in under 5 years of age (%)**	DMs without CFPSs	102	0.19 (0.14)	0.163	0.220	
	DMs with CFPSs	102	0.19 (0.013) (	0.160	0.214	0.81

Notes: ^ DMs means district municipalities. *Statistical significance is when p<0.05. ** Prevalence calculated as number of pneumonia deaths divided by population under 5 years x 100.

A regression analysis was conducted to identify if one variable changes based on another variable. The results presented in Table 11 indicated that for every 1 unit change in count of cases, the odds of pneumonia deaths in children under 5 years of age occurring in district municipalities with CFPSs compared to district municipalities without CFPSs increased by 1.01 (95% CI: 1.00-1.02, p=0.014).

Table 11. Results of regressions comparing health outcomes in district municipalities with and without CFPSs.

Health outcome	Odds Ratio	95% Confidence Interval		P-value
New pneumonia cases under 5 years of age	1.00	0.99	1.00	0.316
Pneumonia incidence	1.00	0.99	1.00	0.520
Pneumonia deaths under 5 years of age	1.00	1.00	1.02	0.014
Pneumonia death prevalence	1.04	0.66	1.66	0.842
Confirmed TB in under 5 years of age	0.99	0.99	1.01	0.733
TB death rate	1.00	0.92	1.10	0.767

Birth outcomes

Figure 9 shows that the median CLP birth prevalence per 100 000 population from 2006 to 2020 was higher in district municipalities with a median of 8 compared to 5 for district municipalities without CFPSs. The outlier CLP prevalence of 17 per 100 000 for City of Tshwane can be attributed to the fact that the majority of the data were from that district municipality.

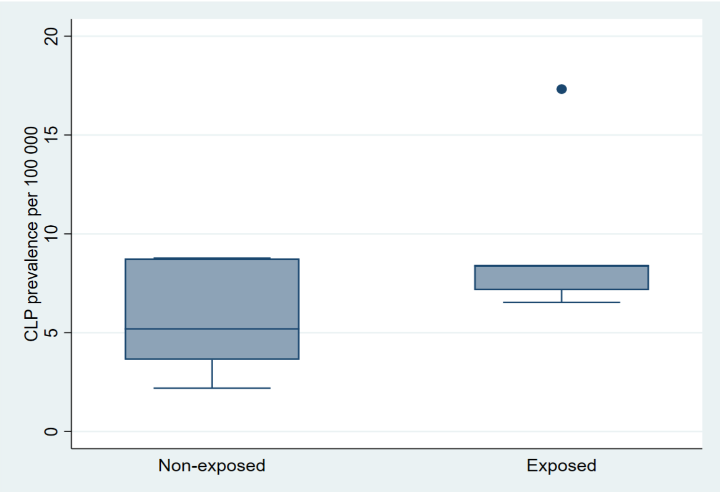


Figure 8. Boxplot of CLP birth prevalence per 100,000 population from 2006 to 2020.

Air pollution in the study area: NO_2 and SO_2 concentrations

Figures 9 and 10 show the NO_2 and SO_2 concentrations in the study area from 2009 to 2020. While there were exceedances of the NO_2 standard, this was not the case for SO_2.

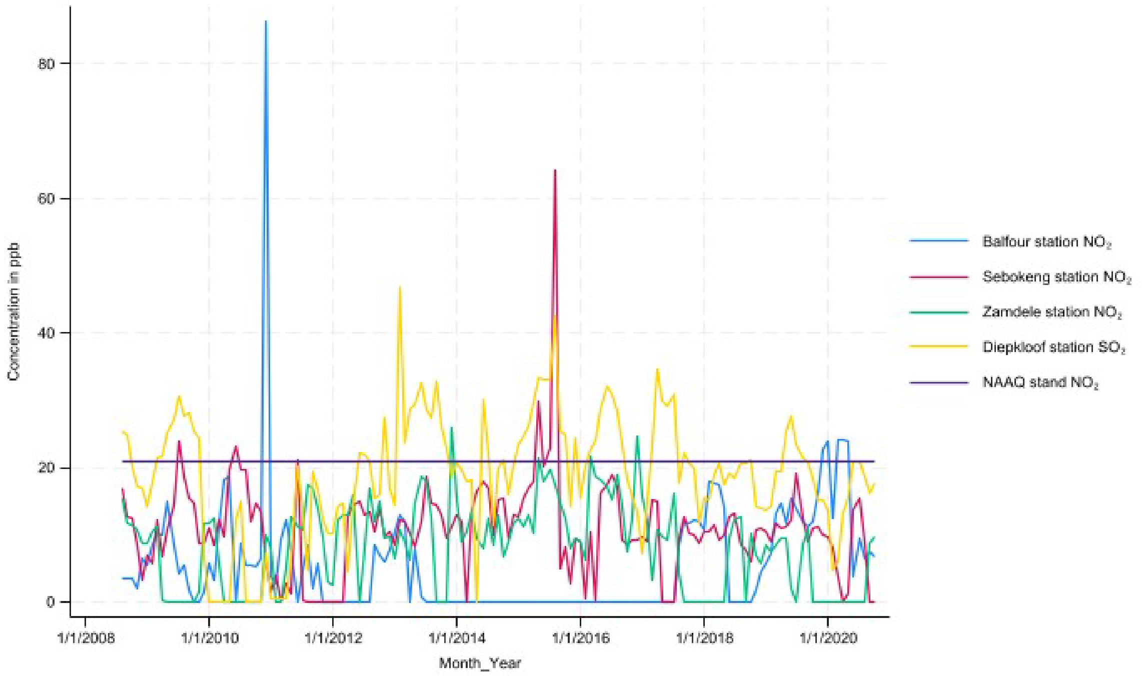


Figure 9. The timeseries for monthly concentration for NO2 against the annual standard for NO2 as per the South African National Air Quality Standards, 21 ppb.

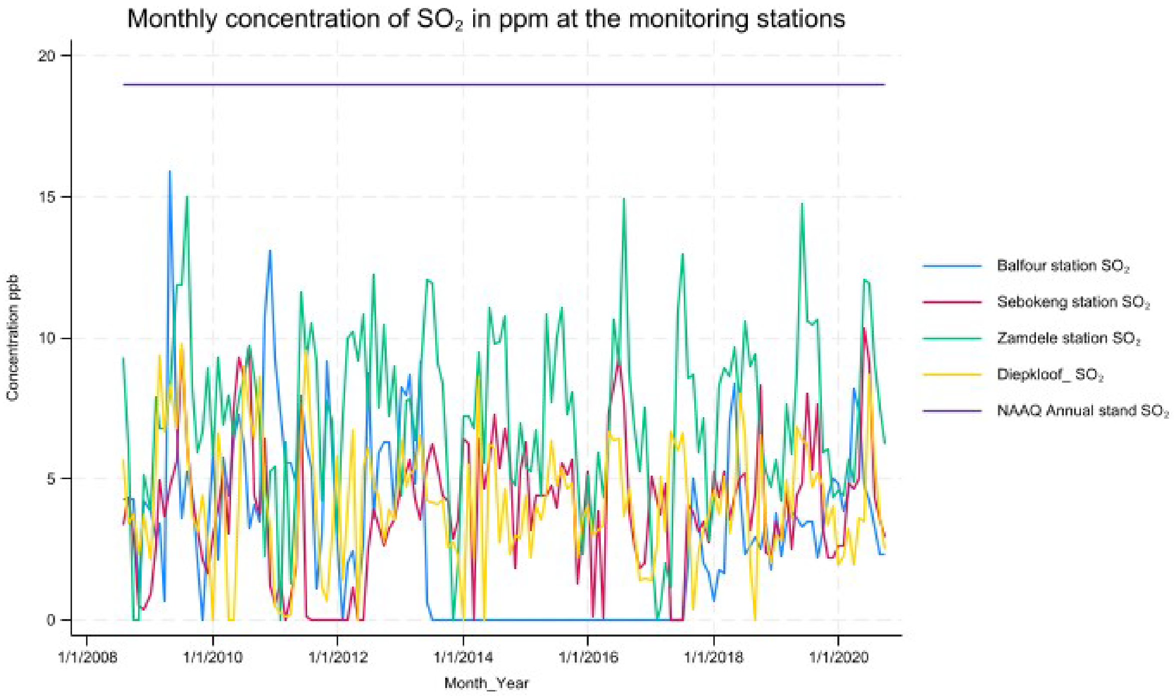


Figure 10. The timeseries for monthly concentration for SO2 against the annual standard for SO2 as per the South African National Air Quality Standards, 19 ppb.

Air pollution concentrations in district municipalities with and without CFPSs

Figure 11 shows the total monthly average concentration differences in concentrations (mean, minimum, median, maximum, summer mean, autumn mean, winter mean, spring mean) for district municipalities with and without CFPSs. The maximum pollution concentration values for stations in CFPSs was higher than those for stations located in district municipalities without CFPSs. The mean and median pollution concentration values for stations in CFPSs were higher than those for stations located in district municipalities without CFPSs.

There is a statistically significant (p<0.001) by Kruskal Wallis test, between seasons except for NO_2 in districts with CFPS. This implies a ubiquitous presence of NO_2.

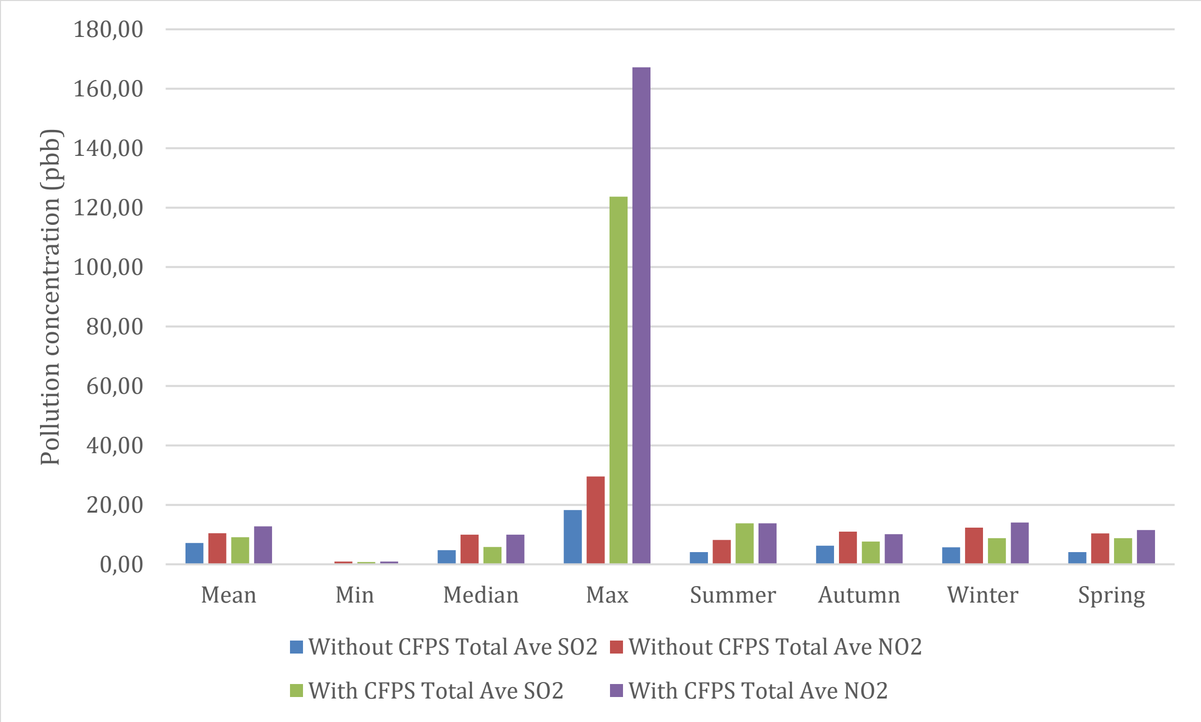


Figure 11: Descriptive statistics for total monthly and seasonal average concentration of NO_2 and SO_2 (ppb) between districts with CPFS and those without CFPS.

Air pollution, health outcomes and district municipalities with and without CFPSs

Distributed lag non-linear models (DLNMs) represent a modelling framework to describe simultaneously non-linear and delayed dependencies, termed as exposure-lag-response associations. The exposure data, in this case, is the NO_2 and SO_2 average monthly concentration (ppb) and the health outcome is the aggregated count data of new cases of pneumonia under the age of 5 per identified district municipality. The *dlnm* function in R software was used.

The output is the relative risk (RR) of an increase in new cases of pneumonia for children under the age of 5 years within the district municipality when an increase of 10ppb of SO_2 or NO_2 occurs (Table 12).

A lag of a month is also considered to determine the trend of pollutant in question. Although the sources of primary SO_2 and NO_2 are reported to be the same, the lifespan in the atmosphere (and over certain seasons) is different.

For all four district municipalities where the analyses were conducted, there was a linear increase in new cases of pneumonia in children under 5 years with every increase in 10ppb (Figures 12-15).

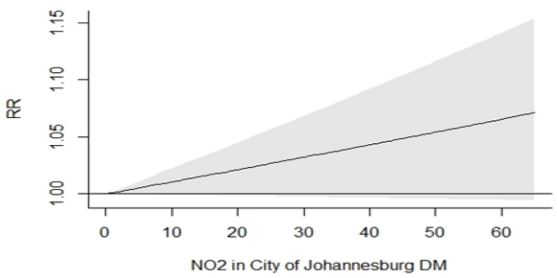
With the exception of Fezile Dabi district municipality, which demonstrates a high health effect due to the exposure to SO_2 at lag0 (the same month of the reported concentration of SO_2) and decreases over time, the other three districts reported the highest RR during the first month after exposure (Table 12).

With the exception of the Gert Sibande district municipality which demonstrates an increase in health effect over time, the other three district municipalities demonstrate an decrease in RR for every month after the initial exposure to the reported concentration of NO_2.

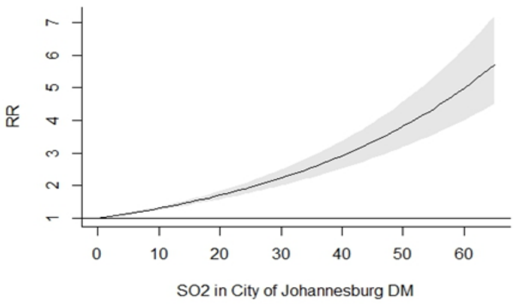
Table 12. The relative risk for the incidence of a new case of pneumonia under the age of 5 years for every following month (three months).

				Exposure to pollutant	
District Municipality	SO_2 (ppb)	NO_2 (ppb)	Lags (monthly)	SO_2	NO_2
City of Johannesburg	2,2(0-10)	18,5(0-46,7)	0	**1,005(1,001-1,009)**	**1,007(1,007-1,01)**
			1	0,994(0,986-0,002)	0,998(0,995-1,001)
			2	**1,021(1,009-1,033)**	**0,029(1,047-1,033)**
			3	**1,052(1,041-1,063)**	**0,966(0,962-0,969)**
Sedibeng	3,89(0-10,23)	1075(0-64,1)	0	0,998(0,991-1,002)	1,007(1,005-0,994)
			1	**0,967(0,959-0,976)**	0,992(0,989-1,012)
			2	**1,068(1,053-1,082)**	**1,008(1,004-1,012)**
			3	0,994(0,983-1,004)	0,997(0,993-1,000)
Fezile Dabe	7,24(0-15)	8,13(0-25,8)	0	1,06(1,05-1,07)	**1,1(1,01-1,2)**
			1	0,995(0,992-1,004)	0,993(0,982-1,004)
			2	0,999(0,992-1,004)	**0,96(0,948-0,977)**
			3	**1,0012(1,006-1,017)**	**1,038(1,038-1,061)**
Gert Sibanye	3,1(0-16)	5,65(0-86,31)	0	0,999(0,996-1,001)	0,999(0,996-1,001)
			1	**0,995(0,990-0,999)**	**0,995(0,990-0,999)**
			2	0,998(0,991-1,004)	0,998(0,991-1,004
			3	**1,012(1,006-1,017)**	**1,012(1,006-1,017)**

Note: * a lag is the equivalent of one month, i.e., lag1 is one month delay, lag2 is a two month delay and lag3 is a three month delay.

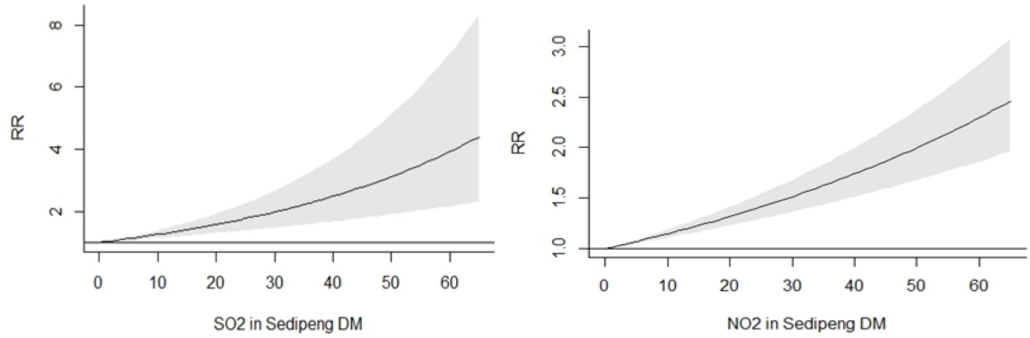


a)



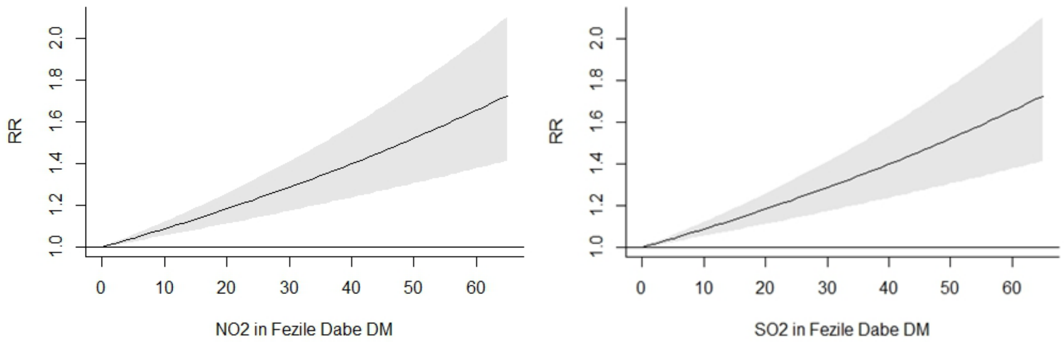
b)

Figure 12. The relative risk for the increase in incidence of new cases of pneumonia for under 5 children with every increase in 10ppb of NO_2 and SO_2, respectively. City of Johannesburg is within the region without coal fired power stations.



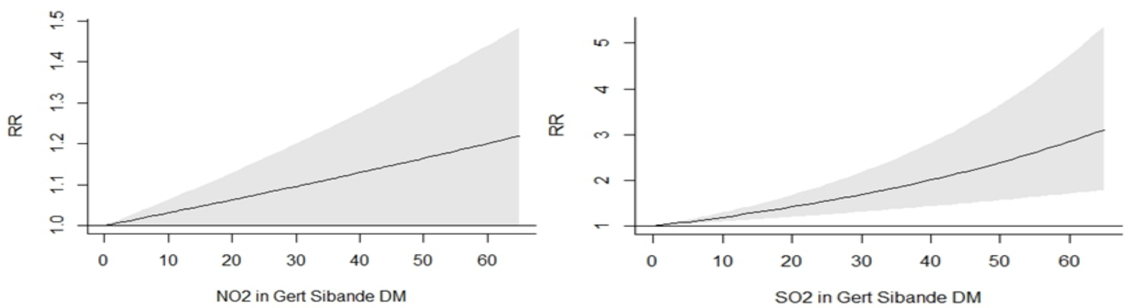
a) b)

Figure 13. The relative risk for the increase in incidence of new cases of pneumonia for under 5 children with every increase in 10ppb of NO_2 and SO_2, respectively. Sedibeng DM is within the region without coal fired power stations.



a) b)

Figure 14. The relative risk for the increase in incidence of new cases of pneumonia for under 5 children with every increase in 10ppb of NO_2 and SO_2, respectively. Fezile Dabi DM is within the region with coal fired power stations.



a) b)

Figure 15. The relative risk for the increase in incidence of new cases of pneumonia for under 5 children with every increase in 10ppb of NO_2 and SO_2, respectively. Gert Sibande DM is within the region with coal fired power stations.

We found that as air pollution concentrations, namely NO_2 and SO_2 concentrations, increase, so too do new cases of pneumonia in children under 5 years of age.

When adjusting for type of domestic fuel per district in the morbidity health, there was no significant change in the relative risk per increase in NO_2 and SO_2 concentrations (Table 13).

Table 13: The results of the analysis for the districts with and without CFPS when adjusting for the main domestic fuel type.

				Fuel use type for domestic fuel									
				Electricity		Wood		Coal		Solar		Gas and Parrafin	
District Municipality	SO2 (ppb)	NO2 (ppb)	Lags (monthly)	SO2	NO2	SO2	NO2	SO2	NO2	SO2	NO2	SO2	NO2
City of Johannesburg	2,2(0-10)	18,5(0-46,7)	0	**1,00(1,000**	**1,00(1,000**	1(1-1)	**0,64(0,63-**	**2,98((2,7-2**	**0,63(0,62-**	**2,90((1,7-2**	**0,55(0,54-**	**2,98((2,7-2**	**0,63(0,62-**
			1	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)
			2	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)
			3	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)	1(1-1)
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Discussion

Scoping review of the health impacts associated with living near CFPSs

What is the current evidence on the health risks associated with exposure to air pollution in areas where coal-fired power stations exist?

From the scoping review, evidence shows an association between exposure to air pollutants, namely NOx, SO_2, and $PM_{2.5}$ from CFPSs and increases in the prevalence of respiratory symptoms and diseases and a decline in pulmonary function among people living in proximity to CFPSs (Dubnov et al., 2007; Kamath et al., 2022; Rodriguez-Villamizar et al., 2018). Adults living near the CFPSs were significantly more likely to report having lung ($p < 0.0001$), muscular ($p = 0.004$), gingiva ($p = 0.009$) and skin symptoms ($p < 0.0001$) compared to the adults in the control group (Zierold et al., 2020).

Maternal exposure to air pollution from CFPSs was associated with preterm birth and low birth weight of neonates (Dauda et al., 2021; Ha et al., 2015; Mohorovic et al., 2004). Previous studies reported a link between exposure to PM_{10} and polycyclic aromatic hydrocarbons (PAHs) and neurodevelopmental disorders. A recent study reports association between PM_{10} from CFPSs and affective problems, anxiety issues, attention deficit hyperactivity disorders and depressive symptoms and social problems in children (6-14 years) living near CFPSs (Zhang et al., 2022; Zierold et al., 2022a, Zierold et al. 2022b, Hagemeyer et al. 2019). Another report showed that the prevalence rate of autism was greater in geographic areas of higher mercury levels where CFPSs exist.

What is the relationship between health outcomes and proximity to coal-fired power stations?

Previous studies have shown that particulates can travel up to 30 km from the CFPSs (Lordanidis et al., 2008). People in surrounding neighbouring areas where CFPSs exist are at higher risk of exposure to air pollutants from CFPS. According to findings from the review, the most common distance of exposure to air pollution studied was between 0 to 20 km from the CFPSs with control sites located at a distance above 20 km from CFPSs.

For example, respiratory function was compared in people living in areas within 12 km from the CFPS chimney in Bursa Province, Turkey, to people who were situated 22 km away (Pala et al., 2012). Lower respiratory function was reported in people living within 12 km from a CFPS chimney than those living away (Pala et al., 2012). Also, in Kütahya Province, Turkey, people above the age of 35 living in villages within a 5 km radius of a CFPS reported more frequent complaints of chest tightness than people in control villages (> 20 km away from the CFPS) (Karavus et al., 2002). Another study found that pregnant women living near 2 or more CFPSs within the 20 km radius had 12%, 20% and 23% increased odds of low birth weight, preterm delivery and very preterm delivery in the USA, respectively (Ha et al., 2015).

What are the estimated mortality or morbidity risks of exposure to air pollution in areas where coal-fired power plants exist?

People living in proximity to CFPSs are at risk for poor health outcomes. Studies investigating the respiratory effects of exposure to air pollution from CFPSs found lower mean forced expiratory volume in one second (FEV1) value and forced mid-expiratory flow (FE 25-75%) ($p = 0.0001$ and $p = 0.0001$, respectively), and increased emergency department visits ($p = 0.000$) for people living near CFPSs (Karavus et al., 2002; Rodriguez-Villamizar et al., 2018).

A cohort study investigating the association between residential proximity to CFPSs and risk of adverse birth outcomes found that pregnant women living near two or more CFPSs within a 20 km radius had a 12% increased odds (OR) of term low birth weight (OR = 1.12, 95% CI: 1.03, 1.22), 20% increased odds of preterm delivery (OR = 1.20, 95% CI: 1.14, 1.25), and 23% increased odds of very preterm delivery (OR = 1.23, 95% CI: 1.10, 1.36) (Ha et al., 2015).

Children living nearest to CFPSs were observed to suffer from four neurobehavioral symptoms: affective problems, anxiety problems, attention deficit hyperactivity disorders and social problems (Zhang et al., 2022). Inhaled fine particulates are transported to the brain by crossing the blood brain barrier thereby affecting brain health. Adults who lived near the CFPSs were significantly more likely to suffer from respiratory (AOR = 5.27, 95% CI: 2.16, 12), gingiva (AOR = 2.46, 95% CI: 1.46, 4.15), and skin symptoms (AOR = 3.37, 95% CI: 2.09, 5.43) compared to adults living further away (Zierold et al., 2020). This further shows that people living within 20km radius of CFPSs are at greater risk of higher exposure to air pollutants and negative health outcomes.

Mortality, morbidity and birth outcomes in district municipalities with and without CFPSs

A recent Global Burden of Disease (GBD) study estimated that in 2019, environmental air pollution was responsible for 6.7 million deaths globally (GBD 2019 Risk Factors Collaborators, 2020; Roth et al., 2020). Coal-burning power plants are a significant contributor to air pollution (Wang et al., 2020). Our results show that mortality due to cardiovascular and respiratory diseases was significantly higher in districts with CFPSs compared to those without. This corroborates findings from a national study conducted in the United States which observed that between an estimated 460,000 deaths could have been avoided if there were no emissions from coal power plants between 1999 – 2020 (Hennemen et al., 2023). In addition, more than 5000 deaths were associated with coal fired power plants located close to the Mississippi River (Hennemen et al., 2023).

Similarly, in Taiwan an estimated 576 deaths (95% CI: 537–619) and 145 premature deaths (95% CI: 136–155) were attributed to $PM_{2.5}$ from a CFPS (Chio et al., 2019). Another study that investigated the impacts of emissions from CFPSs on annual excess mortality for cardiovascular and respiratory diseases across 28 European Union member states observed that at least 9 500–12 100 excess deaths were related to air pollution exposure (Khusta et al., 2021).

Our cause-specific analysis found that the incidence rate of mortality due to hypertension was 28% higher in districts with CFPSs compared to those with no CFPSs and this association was statistically significant. Numerous studies have demonstrated positive associations between long and short term exposure to air pollution and elevated bloop pressure and increased incident hypertension (Tykhonova et al., 2022). In a large American cohort study, exposure to $PM_{2.5}$ was associated with excess burden of mortality due to several diseases including hypertension (30 696.9 deaths [95% Uncertainty Interval: 27 518.1, 33 881.9 deaths]) (Bowe et al., 2019). In China, each 10 µg/m3 increase in NO_2 and each 1 mg/m3 increase in CO, increased the relative risk (RR) for hypertension hospitalization (lag 0-3, RR: 1.04; 95% CI: 1.02, 1.07) and (lag 3, RR: 1.10; 95% CI: 1.04, 1.17). In addition, evidence from several studies suggests that air pollution is associated with an increased risk of cardiovascular disease and mortality related to cardiovascular disease (Aryal et al., 2021; Alkindi et al., 2020; Martins et al., 2006).

Our results also showed that the mortality rate of mortality due to COPD was higher in exposed districts compared to non-exposed districts. Previous studies have reported increased risk of COPD mortality due to exposure to pollutants such as PM_{10}, SO_2 and NO_2 (Li et al., 2016) . Evidence from a meta-analysis found that a 10 µg/m_3 increase in $PM_{2.5}$ is associated with increased incidence of COPD (pooled HR 1.18, 95% CI 1.13–1.23).

Previous research also supports the association between air pollution and increased risk and prevalence of tuberculosis (Liu et al., 2018). There was some evidence that pneumonia case fatality numbers in children under 5 years of age were greater in district municipalities with CFPSs compared to those without CFPSs, however, the differences were not that large and these data are challenged by some uncertainties. Yussef et al. (2024) saw an increase in respiratory function alteration in a large coal region in Brazil and pneumonia was the most common respiratory problem in children.

There was some evidence that the birth outcome, orofacial cleft lip and palate, occurred more in district municipalities with CFPSs compared to those district municipalities without CFPSs. Exposure between prenatal exposure to power plants and adverse birth outcomes has been seen in the USA (Schneider et al., 2023) specifically, a significant interaction (both $p < 0.01$) showed that a 10% increase in fuel consumption was associated with infants born to White women having slightly lower birth weights (1.76 g; 95% confidence interval = −2.87, −0.65) and higher risk of being born small for gestational age (0.0002; 95% confidence interval = 0.0002, 0.0002). Moreover, a Chinese study found that there were molecular and neurodevelopmental benefits to children when a CFPS was closed down (Tang et al., 2014).

We also found a statistically significant positive relationship between NO_2 and SO_2 concentrations with increasing pneumonia cases in children under 5 years of age. Several studies have found similar associations in other parts of the world, including China (Zhou et al., 2023) and Taiwan (Liu et al., 2022).

Study limitations and what we did not do

- We did not do source apportionment to identify all the sources in the district municipalities or to identify how much pollution came from each source.
- We did not do any modelling.
- All the data are actual data. Such data have their own challenges including missing data and outliers. We removed all of these problems from the datasets prior to using them in the analyses.
- We did not consider the regional effect of emissions from CFPSs. These emissions may have gone into district municipalities without CFPSs but were likely less concentrated when this did occur compared to within the district municipality where the CFPSs were located.

Recommendations

From the global literature, it is clear that health risks to mortality and morbidity associated with living in areas where CFPSs are located **do exist**.

We recommend that:

- CFPSs should be decommissioned and replaced with alternative sources of electricity production that rely on renewable energy sources such as solar, wind, hydropower etc. Our study shows that exposure to pollution from coal-fired power stations has negative impacts on health, therefore eliminating this risk will also reduce the burden placed on health care facilities.

- People living in proximity to CFPSs should be aware of the health threats that living in proximity to CFPSs present to their health. They should work together with NGOs to advocate for clean air in the environment.

- Researchers should continue to study the health and environmental impacts of living in proximity to CFPSs, especially in LMICs, to ensure that the baseline evidence exists to lobby and advocate for decommissioning of CFPSs.

- Children are most vulnerable to the health effects of exposure to air pollution from CFPSs due to their developing organs and body system. Therefore, energy transition could benefit children living near CFPSs.

Specifically for South Africa, we recommend that:

- The South African National Air Quality Standards are implemented in a more stringent manner to prevent mortality and morbidity, especially in district municipalities with CFPSs.
- Air quality management in Air Pollution Priority Areas is scaled up.
- Surveillance of air pollution-related health outcomes in district municipalities with CFPSs is scaled up.
- Health data (for example mortality data, hospital admissions, ambulance call outs) are made available for tracking of air pollution exposure-associated health outcomes in district municipalities with CFPSs.
- Engagement with all stakeholders is made to ensure the severity of the situation regarding health impacts associated with living in proximity to CFPSs is made apparent.

Main take-away messages

- Living in proximity to CFPSs poses a risk to human health.
    - Typically studies consider living in proximity to CFPSs as being within 20 km distance to the CFPS.
- There are notable differences in the health and wellbeing of people living in districts with CFPSs compared to those that live in districts without CFPSs.
- In South Africa, there is observed evidence that people living in district municipalities with CFPSs are at greater risk of dying (mortality) from cardiovascular and cardiometabolic diseases causes including pericarditis, endocarditis and myocarditis, aortic aneurism, congenital heart anomalies, hypertensive heart disease, hypertension compared to people living in district municipalities without CFPSs.
- The mortality rate of COPD was the only respiratory outcome that was higher in district municipalities with CFPSs compared to those without.
- While other factors likely play into these findings, it does not discredit that there is a difference in the mortality rates in district municipalities with and without CFPS.
- There was some evidence that pneumonia case fatality numbers in children under 5 years of age were greater in district municipalities with CFPSs compared to those without CFPSs, however, the differences were not that large and these data are challenged by some uncertainties.
- There was evidence that the birth outcome, orofacial cleft lip and palate, occurred more in district municipalities with CFPSs compared to those district municipalities without CFPSs.
- There was a statistically significant positive relationship between NO_2 and SO_2 with increasing pneumonia in children under 5 years of age.

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Appendices

Table 14. Population size of district municipalities with and without CFPS.

Local District Municipality	Census 2022 population(n)	Census 2011 population(n)	**Local District Municipality**	Census 2022 population(n)	Census 2011 population(n)
District municipalities without CFPSs			**District municipalities with CFPSs**		
Sedibeng	1 190 688	916 484	Fezile Dabi	509 912	488 036
West Rand	998 466	821 191	Gert Sibande	1 283 459	1 043 194
City of Johannesburg Metropolitan	4 803 262	4 434 631	Nkangala	1 588 684	1 308 129
Sekhukhune	1 336 805	1 076 840	Waterberg	762 862	679 336
Bojanala	1 624 144	1 507 505	Ekurhuleni Metropolitan	4 066 691	3 178 470
Dr Kenneth Kaunda	743 203	695 933	City Of Tshwane Metropolitan	4 040 315	2 921 488

Table 15. Energy source for lighting and cooking, and dwelling type of district municipalities with and without CFPSs.

Local District Municipality	Main Energy Source For Lighting (%)				Main Energy Source For Cooking (%)				Dwelling Type (%)		
Without CFPS's	**Electricity**	**Solar**	**Candles**	**Gas/Paraffin**	**Electricity**	**Wood**	**Gas**	**Coal**	**Formal**	**Informal**	**Traditional**
Bojanala	93.9	0.4	3.7	1.0	88.3	4.4	2.9	0.0	84.5	14.8	0.7
Dr Kenneth Kaunda	92.4	0.8	4.0	2.2	86.9	0.7	5	0.0	89.7	10.0	0.3
Sedibeng	91.2	2.0	4.8	1.3	87.4	0.7	7.6	0.4	91.1	8.5	0.3
West Rand	94.2	0.7	3.2	1.3	90.1	0.5	5.4	0.0	88.3	11.4	0.3
City of Johannesburg	92.2	1.3	4.5	1.2	88.1	0.2	6.6	0.1	90.0	9.8	0.2
Sekhukhune	93.8	0.9	3.6	0.8	65	29.8	1.9	0.4	95.8	2.6	1.5

Local District Municipality	Main Energy Source For Lighting (%)				Main Energy Source For Cooking (%)				Dwelling Type (%)		
With CFPS's	**Electricity**	**Solar**	**Candles**	**Gas/Paraffin**	**Electricity**	**Wood**	**Gas**	**Coal**	**Formal**	**Informal**	**Traditional**
Fezile Dabi	94.8	1.0	3.0	0.9	88.3	1.3	7.2	0.4	89.9	9.5	0.6
Waterberg	94.4	1.2	3.2	0.6	65	27.3	5.3	0.1	91.8	7.6	0.6
Gert Sibande	89.3	1.0	7.3	1.8	66.5	23.1	3.1	5.3	88.2	8.1	3.6
Ekurhuleni	93.4	1.0	3.7	1.3	89.6	0.3	4.4	0.2	88.5	11.2	0.3
City of Tshwane	90.5	1.6	5.1	1.5	84	0.7	8.2	0.0	86.5	13.2	0.3
Nkangala	91.7	1.6	5.2	0.9	80.4	7.5	5.3	2.9	91.5	7.6	0.9

Source: 2022 Census Stats SA

Figure 16. PRISMA flow diagram of the study selection.

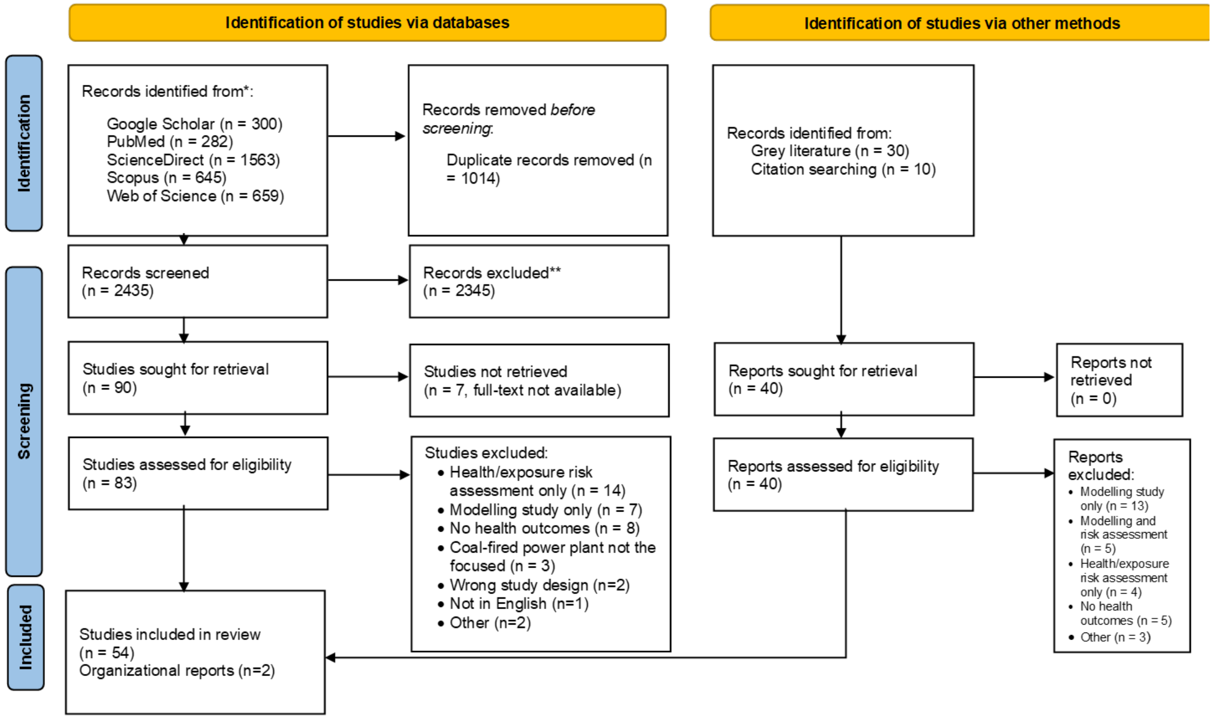

Table 16. Proximity to coal-fired power plants and health outcomes.

Study ID	Distance from CFPS	Health outcome	Key findings linked to exposure to air pollution and health outcomes	Statistical model(s) used to measure association
Aekplakorn et al. 2003	7-8 km	Pulmonary function	A weak association was observed between reduced pulmonary function and changes in the ambient concentration of SO_2	General linear mixed
Amster et al. 2014	20-30 km	Respiratory symptoms	Data did not support an association between CFPSs emissions and prevalence of chronic obstructive pulmonary disease or asthma. However, nearly all of the respiratory symptoms studied were associated with NO_x power plant emissions.	Logistic regression
Barbhaya et al. 2022	NR	All-cause mortality	47,000 premature adult deaths in India were attributable to CFPSs in 2014 and were concentrated in the 10% of Indian districts that housed these CFPSs.	Linear regression
Barik et al. 2021	≤20 km	URTI	Increased average annual prevalence of URTI was observed in the central Indian population residing near coal-fired TPPs.	None
Barrows et al.2019	0-50 km	Infant mortality	Impact of infant mortality rate was reported to be larger for older plants, located in districts with higher baseline pollution levels and burning domestic rather than imported coal. Urban areas within districts were more exposed to coal-powered capacity than rural areas as CFPSs were located in urban areas.	Panel regression
Bencko et al.1977	NR	Hearing loss	Higher rate of enlarged and large tonsils and adenoids and concomitant phlegm-pus flow in the posterior nasopharynx was found in the exposed group compared to the control group. Higher incidence of repeated rhinitis was observed in the exposed group.	None
Blanchard et al. 2011	NR	Autism	Higher levels of ambient mercury were geographically associated with point sources of mercury emission, such as CFPSs and cement plants with coal-fired kilns. School districts in closest proximity to these areas had the highest autism rates in the county.	None

Casey et al. 2018	≤20 km	Preterm birth	The prevalence of preterm birth decreased near CFPSs after retirement, with larger reductions closer to CFPSs.	DID linear mixed
Casey et al. 2020	NR	ER Asthma visits and hospitalization	The reductions in CFPS air pollution exposure after retirements and SO_2 control installations translated to fewer asthma-related ERVs and hospitalizations, as well as fewer average daily short-acting beta-agonists (SABA) uses.	Generalized linear, DID, 1st difference & quasi-Poisson
Chen et al. 2017	7-13 km (high exposure), 16-27 km (low exposure)	Urinary metabolomic biomarkers linked to oxidative stress	Ambient concentration of vanadium and PAHs were significantly higher in high exposure groups that lived closer to the CFPS when compared to the low exposure group, for both children and elderly participants.	Multiple linear regression
Chen et al. 2021	≤50 km	Respiratory and cardiovascular diseases mortality	The spillover effects of air pollution from CFPSs had consistent and stable effects on CVD and respiratory mortality at 30 km to 70 km.	Fixed effect
Chen et al. 2018	NR	Respiratory disease and lung cancer mortality	SO_2 emissions resulted in 230,000 extra deaths every year which increased economic costs.	OLS and 3SLS regressions
Collarie et al. 2017	NR	Lung and bladder cancer	An excess risk of lung and bladder cancer was associated with high residential exposure to benzene and NO_2 in women aged ≥75 years old.	None
Daouda et al. 2021	NR	Preterm birth	The spatial distribution of preterm birth showed that the rate of PTBs among Black women was higher than that of White women in most counties.	Poisson generalized additive mixed
Datt et al. 2023	NR	Anaemia	The increase of coal units closer to residential areas had a stronger effect on the likelihood that the child was anaemic. A negative correlation was observed between distance from the coal primary sampling unit and the magnitude of the harmful impact of coal on women's health.	OLS regression
Dubnov et al. 2007	≤10 km	Pulmonary function	A strong negative association between pulmonary function and the estimated level of air pollution in the vicinity of the child's residence was observed.	Stepwise multiple regression & OLS regression
Fan and Wang, 2020	≤50 km	Mortality	DID regression approaches found that power plant retirements lead to reductions in $PM_{2.5}$ levels and consequently decreased monthly mortality among older adults. The mortality effects were higher among males	DID regression

			than females and its impact was the greatest among people >75 years.	
Goren and Hellmann, 1997	≤19 km	Asthma and related respiratory conditions	The rise in prevalence of asthma was not related to any residential area. Air pollution levels were very low and previous health studies in the area around the CFPS did not find any negative health effects.	Logistic regression
Goren et al. 1995	≤10 km	Respiratory diseases	The air pollution levels in both 1980 (before CFPS operation) and 1983 (when CFPS was in operation) were highest in the community located in the city (closer to CFPS). Air pollution levels measured around the CFPS were low and did not seem to cause adverse health effects.	Multiple regression
Goren et al. 1988	≤19 km	Pulmonary function	No negative health effects among children residing in areas expected to be affected by the operation of CFPS as compared to the expected low-pollution areas. The respiratory symptoms among children were linked to age, epidemics and background variables rather than air pollution levels.	None
Ha et al. 2015	<5 to ≥20 km	Preterm delivery, very preterm delivery, and low birth weight	Proximity to power plants increased the odds of all adverse birth outcomes in the adjusted model. A decrease in 5 km in the distance to any power plant increased the odds of low birth weight, preterm delivery and very preterm delivery.	Logistic regression
Hagemeyer et al. 2019	<1 km (exposed), ~97 km (non-exposed)	Respiratory symptoms	The exposed population was more likely to report having a poorer perception of health and experienced several respiratory symptoms and infections than non-exposed group.	Logistic regression
Henneman et al. 2019	NR	Cardiac, respiratory health and all-cause mortality	Rates reductions in six cardiac and respiratory health outcomes decreased with decreases in $PM_{2.5}$ and coal exposure. A secondary analysis found that nonlinearities in relationships between changing health outcome rates and coal exposure may explain differences in their associations.	DID regression
Henry et al. 1991	≤5 km (exposed area), ~80 km (control area)	Asthma	The asthma symptoms were similar in exposed and control areas and the frequency of asthma was low on both areas. SO_2 and NO_x concentrations were within	Logistic regression

			recommended guidelines, air quality had no effect on asthmatic symptoms.	
Hii et al. 2022	≤35 km (within), >35 km (away)	Pulmonary function	Adults living within 35 km from one of the 11 CFPSs were more likely to have worse pulmonary function (FEV1/FVC≤0.8) compared those living 35 km away from a CFPS.	Survey regression
Kamath et al. 2022	>5 km to <10 km	Respiratory function	There was significant association between abnormalities in pulmonary function tests and those living in the vicinity of the CFPS ($p<0.05$). Those living near the CFPS had higher abnormal lung function test compared to those residing far.	Bivariate and multivariate logistic regression
Karavuş et al. 2002	≤5 km (exposed villages), >30 km (control villages)	Respiratory complaints and function	A higher percentage of individuals living in villages around the CFPS had complaints of chest tightness and coughing attacks compared to individuals in control villages and the difference was found to be statistically significant ($P=0.001$ and $P=0.024$, respectively).	None
Komisarow and Pakhtigian, 2021	≤10 km	Asthma-related conditions	After closure of CFPSs in 2012, ZIP codes in close proximity to the three CFPSs experienced reductions in emergency department visits for asthma-related conditions among children.	DID regression
Komisarow and Pakhtigian, 2022	≤10 km (treatment group), >10 km (control group)	Asthma-related conditions	After closure of CFPSs, school-level absence rates decreased by around 6% in schools located near the CFPSs. A decline in rates of emergency department visits for asthma-related conditions was observed among school-age children in ZIP codes near the CFPSs compared to ZIP codes farther away.	DID regression
Lee et al. 2017	≤2.5 km	Neurodevelopment outcomes	An inverse association between prenatal exposure to PAH, measured by PAH-DNA adducts in cord blood, and LINE1 methylation status in both cohorts combined; and a direct correlation between LINE1 methylation status and child IQ scores at 5 years of age in the 2002 cohort was observed.	Multivariate linear regression
Minichilli et al. 2019	NR	Natural and all-cause mortality	Exposure to SO_2 from CFPS and ISDI were significantly correlated ($P<0.001$). An association was found in males and females between increasing exposure to SO_2 and diseases of the nervous system, and sense organ circulatory and respiratory system.	Cox regression

Mohorovic, 2004	3.5-12 km	Preterm delivery and low birth weight	A greater and longer exposure to SO_2 emissions during the initial 2 months of pregnancy resulted in a significantly shorter gestation at the end of the 1st and 2nd month of pregnancy (p=0.008, p=0.016, respectively) and in lower birthweight of newborns (p=0.016, p=0.026, respectively).	None
Pala et al. 2012	1.5-12 km (study group), ~22 km (control group)	Respiratory function	FEV1 and FVC values of the study group were significantly lower than those of the control group, and residents directly wind of the power plant's smokestack showed greater impairment of respiratory functions compared with residents upwind.	Logistic regression
Perera et al. 2012	≤2.5 km	Child IQ	CFPS was the major source of environmental PAHs. After adjusting for potential confounders, neither PAH-DNA adducts nor exposure to ETS had significant main effects on IQ.	Multiple linear regression
Perera et al. 2008	≤2.0 km	Child neurodevelopment	PAH–DNA adducts in cord blood were significantly associated with DQ decrements in the motor area and in the average DQ among children who were in utero during the operation of the CFPS (2002 cohort), however these significant associations were not seen among children who were in utero after the CFPS had been shut down (2005 cohort). In the 2002 cohort, PHA-DNA adducts were associated with an ~2-fold increased odds of developmental delay in the motor area.	Multiple linear and logistic regression
Perera et al. 2018	≤2.5 km	Neurodevelopment outcomes	Mean telomere length (TL) was significantly higher in the 2005 cohort compared to the 2002 cohort. PAH-DNA adducts were significantly and inversely correlated with TL (p=0.018). A significant association between adducts and TL after adjusting for key covariates and cord Hg was observed (p =0.001).	Multiple linear regression
Pershagen et al. 1986	NR	Respiratory symptoms	Plant A had the largest dust emissions. In area A there was a greater proportion of respondents reporting annoyance due to soot, dust, or fly ash in the subareas less than 2 km from plant A than in the subareas further away. Respiratory symptoms and diseases were more prevalent in areas with CFPSs (with more industries and roads) than in the reference areas.	None

Quizon et al. 2016	NR	Respiratory symptoms and pulmonary function	There was no difference on the 8-hr average for PM_{10} between the 'near' barangays (near CFPSs) and the 'far' barangays (far from CFPSs)	Multiple logistic regression
Rodriguez-Villamizar et al. 2017	NR	ED Asthma visits	There was an inverse association of the distance to the CFPS with asthma visits.	Negative binomial multivariable spatial regression
Sears et al. 2020	≤16 km	Cognitive control	Female adolescents living near two CFPSs with coal fly ash storage facilities may be more susceptible to impaired cognitive control associated with indoor particulate matter exposure.	Linear regression
Severnini, 2017	NR	Low birth weight	The shutdown of the TVA nuclear power plants in 1985 induced increases in coal-fired power generation and air pollution. Average birth weight declined ~134 g, or 5.4 log points, after the nuclear shutdown.	Linear regression models & DID regression
Shabani Isenaj et al. 2022	NR	Respiratory diseases	An increase in $PM_{2.5}$ led to significant increases in ambulatory visits on the first and second day after the pollution episode. Stationary hospital admissions only increased on the day following the pollution episode	Linear regression
Tang et al. 2014	≤2.5 km	Neurodevelopment outcomes	In the two cohorts combined, PAH-DNA adducts were inversely associated with mBDNF as well as scores for motor ($p = 0.05$), adaptive ($p = 0.022$), and average DQ ($p = 0.014$). BDNF levels were positively associated with DQ scores. Closure of a CFPS resulted in the reduction of PAH-DNA adducts in newborns and increased mBDNF levels.	Multiple linear regression and logistic regression
Tang et al. 2014	≤2.5 km	Foetal and child development	A decrease in detectable PAH-DNA adducts in the umbilical cord was observed in the 2005 cohort compared to the 2002 cohort. The percentage of infants categorized as delayed for the motor area was significantly lower in 2005 than in 2002. Initial birth weight, height and head circumference for infants in the 2002 cohort were lower or reduced than for those in the 2005 cohort.	Multiple regression
Tang et al. 2006	≤2.5 km	Foetal and child development	Among females, high cord blood adduct level was significantly associated with smaller birth head circumference, as well as lower weight and shorter length. Cord PAH-DNA adduct level was negatively but not significantly associated with distance ($p=0.190$). Longer	Multiple linear regression

			distance from the CFPS was significantly associated with greater birth length (p=0.03).	
Tang et al. 2008	≤2.5 km	Child neurodevelopment	Increased adduct levels were associated with decreased motor area development quotients (DQ), language area DQ and average DQ. Decrements in one or more DQs were significantly associated with cord blood levels of PAH–DNA adducts and lead, but not mercury.	Multiple linear regression and logistic regression
Wilkie et al. 2023	≤24 km	Preterm birth	SO_2 emission reduction interventions were associated with a decrease in preterm birth for gestational parents living within 4–<10 miles (6.4 km-<16 km) compared with 10–<15 miles (16 km-<24 km) away, especially among those living near CFPSs that installed scrubbers on coal electricity generating units.	DID regression
Yang et al. 2017	32-48 km	Low birth weight and very low birth weight	Babies born to mothers who live as far as 20 to 30 miles (32-48 km) away downwind from the power plant during the final stage of pregnancy were at greater risks of low birth weight and very low birth weight. Also, an increase of 1,000 tons of SO_2 monthly emissions that come from upwind directions during the final stage of pregnancy could increase the likelihood of low birth weight.	OLS regression
Yogev-Baggio et al. 2009	NR	Pulmonary function	There was substantial decrease in the number of heathy children in the cohort in the most air polluted areas. Analysis of variance also confirmed that the interaction between air pollution levels and the children's health status was associated significantly with the children's PFT change.	Multivariate regression analysis
Zhang et al. 2022	≤16 km	Neurobehavioral problems	Significant and inverse associations were observed between distance to the nearest CFPS and four neurobehavioral symptoms: affective problems, anxiety problems, ADHD, and social problems.	Multiple linear regression
Zierold et al. 2020	97 km (non-exposed group)	Health symptoms	Adults who lived near the coal-burning power plant were significantly more likely to suffer from respiratory symptoms and skin symptoms compared to non-exposed comparison group.	Logistic regression
Zierold et al. 2023	≤16 km	School and social competency	Children with fly ash in their homes scored an average 2.63 points lower on school competency compared with children who did not have fly ash in their homes.	Univariable and multivariable linear regression

Zierold et al. 2022	≤16 km	Internalizing behaviour disorders	Exposure to zinc and imputed zirconium were associated with internalizing behaviours in children.	Multivariate logistic regression
Zierold et al. 2022	≤16 km	Depression	Children with fly ash indoors had more depressive problems compared to non-exposed children.	Univariate and multivariate linear regression
Am. Lung Assoc., 2011	NR	CVD, asthma and other lung diseases	The EPA proposed a new requirement that all coal and oil-fired power plants that produce 25 MW of power for sale will be required to install cleanup technology such as scrubbers, as required by the Clean Air Act. This was done to reduce harmful air pollutants that make breathing difficult and causes asthma attacks and increase the risk of emergency room or hospital visits.	NR
HEAL, 2013	NR	CVDs, respiratory symptoms and diseases, heart disease, and cancer	Significant evidence exists on how long-term exposure to air pollutants affects the lungs and the heart. Recent research suggests that air pollution may also result in low birth weight and pre-term delivery because of maternal exposure during pregnancy.	NR

Note - Abbreviations: 3SLS-three stage least squares, BDNF-brain-derived neurotrophic factor, CVD-cardiovascular diseases, DID-difference-in-difference, DQ-developmental quotient, EDV/ERV–emergency department visits/ emergency room visits, ETS-environmental tobacco smoke, FVC-forced vital capacity, FEV1-forced expiratory volume at 1 second, ISDI-Individual socioeconomic deprivation index, NA-not applicable, NR-Not reported, OLS-ordinary least squares, PFT-pulmonary function test, URTI-upper respiratory tract infection.

Table 17. Global Burden of Disease categories.

Respiratory		Cardiovascular (CVD) and cardiometabolic diseases that increase risk of CVD diseases	
Code	**Cause of death**	**Code**	**Cause of death**
91	COPD	88	Aortic aneurism
11	Lower respiratory infections	89	Peripheral vascular disorders
93	Asthma	84	Pericarditis, endocarditis and myocarditis
12	Upper respiratory infections	114	Congenital heart anomalies
		83	Ischaemic heart disease
		86	Cerebrovascular disease
		56	Diabetes mellitus
		82 and 147	Hypertensive heart disease/hypertension
		81	Rheumatic heart disease
		85	Cardiomyopathy

Table 18. Statistics South Africa Cause of Death.

Respiratory causes of death (ICD codes)	Cardiovascular and cardiometabolic causes of death (ICD codes)
J00	E10
J01	E100
J018	E101
J019	E102
J02	E105
J029	E109
J03	E11
J039	E110
J04	E111
J040	E112
J042	E115
J05	E116
J050	E117
J051	E119
J06	E12
J09	E13
J10	E135
J100	E14
J101	I00
J108	I01
J11	I019
J110	I02
J111	I05
J118	I050
J12	I058
J120	I059
J121	I06
J128	I061
J129	I068
J13	I07
J14	I071
J15	I08
J150	I080
J151	I089
J152	I09
J154	I10
J155	I11
J156	I110
J157	I119
J158	I12
J159	I120
J16	I129
J160	I13

J168	I20
J173	I200
J18	I209
J20	I21
J208	I210
J209	I211
J21	I212
J210	I214
J218	I219
J219	I22
J22	I23
J40	I24
J41	I248
J418	I249
J42	I25
J43	I30
J439	I31
J44	I33
J45	I38
J459	I40
J46	I42
	I60
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	Q273
	Q278
	Q279
	Q28