Chapter 3

An approach to identifying reasonable health-oriented air quality interventions in a data-constrained context

Christiaan J. Pauw
Nova Institute NPC, Pretoria, South Africa
University of Pretoria
christiaan.pauw@nova.org.za

Bianca Wernecke
Independent Researcher
(Previous: South African Medical Research Council)
wernecke.bianca@gmail.com

Rirhandzu Novela
Nova Institute NPC, Pretoria, South Africa
rirhandzunovela@nova.org.za

Hendrik. J. Smith
Nova Institute NPC, Pretoria, South Africa
hendriksmith@nova.org.za

Abstract

Decreasing industrial emissions receives significant attention and funding. Non-industrial sources from within residential areas are relatively neglected, despite potentially having a higher impact on human health. Implementing evidence-based air quality interventions to improve health in low-income households is a complex endeavour. This is especially true when targeting local, non-industrial sources. Complexity is apparent in (i) measuring air quality, (ii) quantifying source-specific exposure, (iii) establishing exposure-response, (iv) identifying and prioritising key micro-environments and meso-airsheds that are amenable to intervention, (v) developing and selecting interventions within the reality of low-income households and settlements, and (vi) measuring intervention success in a dynamic context. Some sources have not been researched in depth from the perspectives of air quality and health. This includes sources that are prevalent in low-income settings but not in high-income countries. A lack of high confidence results from air quality and health research about such sources hampers decision-making regarding some intra-community interventions in low-income settings. To make progress with improving health through air quality interventions, we propose (i) considerations regarding the selection of pollutants to target, (ii) considerations regarding exposure reduction, (iii) proceeding with sufficiently positive interventions where sufficient knowledge is available, (iv) an evidence-based[1] method for intervention development and selection in particular communities or subgroups of households, (v) an appropriate approach to air quality impact evaluation in dynamic environments, (vi) actively avoiding zero-impact interventions, (vii) targeted research regarding specific topics, (viii) respecting the intended beneficiary, (ix) considering the impact of green policies that potentially increase pollutant exposure suffered by members of low-income households by increasing energy cost, and (x) clarifying *ambient air*.

Keywords: air quality interventions, decision-making under uncertainty, environmental pragmatism, exposure assessment, exposure-response relationships

---

[1] Editors' note: The policy background is extensively discussed in Chapter 10, which includes a discussion of *evidence-based*.

1. Background

The Atmospheric Pollution Prevention Act (APPA) (Act 45 of 1965)[2] (RSA, 1965)[3] represented an early effort to address air pollution control in South Africa. Its primary focus was on industrial sources of pollution. However, the Act's scope did not extend to noise, dust, or vehicle emissions. As a result, the APPA's effectiveness in comprehensively mitigating air quality problems was limited. The emergence of the idea of localised areas with concerning levels of pollutants, often termed "hotspots", necessitated a modernised approach to air pollution control in South Africa. The National Environmental Management: Air Quality Act (NEM: AQA) (Act 39 of 2004)[4] (RSA, 2004) was enacted in 2005 to address this issue. This Act introduced air quality management as the core control strategy. The NEM: AQA incorporated various legislative measures, including establishing ambient air quality standards, minimum emission standards, and decentralising air quality management responsibilities. The Act required the identification, quantification, and mitigation of all significant pollution sources. It recognised source-based controls alongside alternative measures such as market incentives, voluntary programmes, as well as public education and awareness initiatives. The NEM: AQA promoted cost-effective mitigation and management practices and mandated air quality management planning by authorities and emissions reduction planning by polluters. Public access to air quality information and participation in consultation processes were also emphasised by the Act (RSA, 2004).

The National Environmental Management: Air Quality Act (NEM: AQA) of 2004 provided for South Africa's Minimum

---

[2] APPA No. 45 OF 1965 assented to 17 April 1965, commenced by 21 April 1965 as amended by APPA No. 17 of 1973, as amended by APPA No. 21 OF 1981, as amended by APPA No. 15 of 1985.

[3] 'RSA' refers bibliographically to South African government publications since 1961.

[4] NEM: AQA (No. 39 of 2004) was first published in the Notice 163 in the government Gazette 27318 of 24 February 2005, and amended by NEM: AQA No. 20 of 2014 in the Notice 390 in Gazette 37666 of 19 May 2014.

Emissions Standards (MES)[5]. The MES applies to various listed activities, including combustion installations, petroleum refineries, and facilities involved in carbonisation, metallurgical processes, and waste treatment. The NEM: AQA adopted a phased implementation approach. Existing sources were initially required to meet less stringent emissions limits by 2015. This provided a grace period for industries to adapt and implement air pollution control measures. By 2020, existing facilities had to comply with the stricter emissions standards that had already been applied to new facilities from 2015. A key aspect of the 2020 MES update was the mandatory installation of controls for criteria pertaining to air pollutants from coal-fired facilities. These controls included flue gas desulfurisation for sulfur dioxide (SO_2), filters for particulate matter, and low NOx burners to reduce nitrogen oxides (NOx).

Retrofitting existing coal-fired power stations with pollution control equipment to reduce emissions of particulate matter, NOx, and SO_2 presents challenges. The original design of some older plants may not be easily modified to accommodate new equipment. Additionally, the cost of retrofits can be substantial. Eskom (2019) estimated the cost to be R187 billion for South Africa’s coal-fired power stations. Eskom applied for a postponement to comply with the MES until 2025 and a suspension for power stations due for decommissioning by 2030. Eskom has invested in pollution control technologies to comply with stricter air quality regulations. These advancements target various air pollutants:

- Flue gas desulfurisation (FGD) technology can reduce SO_2 emissions by over 90%. Medupi was built ready for FGD installation and Kusile already has the technology.
- Pulse-jet fabric filters are being employed to capture approximately 99% of particulate matter, significantly improving air quality.

---

[5] The MES was first published in Notice 893 in Government Gazette 37054 of 22 November 2013 and amended by Notice 551 in Gazette 38863 of 12 June 2015 and Notice 1207 in Gazette 42013 of 31 October 2018. As we write, the last update was in Gazette 42472 of 22 May 2019.

- Low-NOx burners are being installed to reduce NOx emissions and to ensure compliance with minimum emissions standards (Eskom, 2019).

Sasol, South Africa's energy and chemical giant, has embarked on a significant air quality improvement programme since 2015. Between 2015 and 2023, Sasol invested more than R7 billion in emissions reduction initiatives, achieving MES compliance for 98% of its emissions sources at Secunda, Sasolburg, and Natref facilities (Sasol, 2023b). Sasol reported plans to invest an additional R4 billion by April 2025 to ensure all that remaining emissions sources (excluding a solution for a specific SO_2 issue) comply with even stricter new plant standards (Sasol, 2023a). A common challenge for both Sasol and Eskom was the difficulty in implementing technology to achieve full compliance with MES for SO_2. They both applied for the postponement of or alternative compliance arrangements.

Despite targeted emission reduction efforts by some industries, achieving the desired air quality improvements remains technically and financially difficult. Additional tools, such as offsets, are required to assist in attaining the overall objectives envisioned by the standards. An offset is an intervention, specifically implemented to counterbalance the adverse and residual environmental impact of atmospheric emissions to deliver a net ambient air quality benefit within, but not limited to, the affected airshed where ambient air quality standards are being or have the potential to be exceeded and whereby opportunities and need for offsetting exist. The Minister published the Air Quality Offsets Guideline under section 24 J (a) of the National Environmental Management Act, 1998 (Act 107 of 1998) (RSA, 1998; 2016). Several industries were required to submit air quality offset plans. These included Sasol and Eskom. The Department of Environmental Affairs (DEA) (and subsequently the successor Department of Forestry, Fisheries and the Environment (DFFE)) did not keep a public registry of air quality offset requirements, plans, or reports. This severely limits the public's and experts' understanding, participation and analysis.

While industrial sources are doubtlessly important, local air quality is often more strongly determined by ground-level sources within or near residential areas. Studies have shown that although power stations affect nearby communities, a high proportion of particulate matter in low-income settlements near power stations is from within these low-income settlements (Chidhindi et al., 2019). The introduction of new small-scale industries and the ongoing challenges of domestic burning, waste burning, biomass burning, and vehicle emissions all impede air quality improvements (Tshehla & Wright, 2019). These diverse sources of pollution require a comprehensive approach that combines industry-specific regulations with clean energy solutions, effective household waste management strategies, local dust control, and stricter controls on open burning practices to meet the desired air quality in low-income settlements.

The importance of these local air pollution sources in terms of health outcomes is demonstrated by several studies. A cross-sectional study carried out by the Nova Institute, the CSIR (Council for Scientific and Industrial Research) and the University of Cape Town for the Department of Environmental Affairs and Development Planning of the Western Cape, Olaniyan et al. (2019) investigated the association between asthma and common indoor exposures amongst school children from four informal settlements located in two municipalities in the Western Cape province (Masiphumelele, Khayelitsha, Marconi Beam, and Oudtshoorn). The study provided circumstantial evidence that the use of paraffin for cooking and heating was associated with an increased risk of rhinitis and airway inflammation (Olaniyan et al., 2019). A study by Buthelezi et al. (2019) in an informal settlement in Umlazi, KwaZulu-Natal province, found that upper respiratory tract infections were prevalent in respondents who used non-electric sources compared to electric sources for heating and cooking. A reasonable health-oriented air quality intervention needs to account for local sources and not only industrial sources.

Unsurprisingly, more than one economic analysis identifies interventions addressing local, ground-level, or indoor sources as cost-effective targets for intervention. The so-called FRIDGE study is a well-known example (Airshed Planning Professionals and Bentley West Management Consultants, 2004). Another South African economic analysis of air quality initiatives identified that technological interventions within homes represent the most efficient strategy for reducing healthcare costs linked to air pollution (Leiman et al., 2007). This suggests that prioritising advancements in household appliances or technologies for cleaner fuel use could yield significant health benefits while remaining cost-effective.

Air pollution has both human health and environmental impacts, and the regulation of ambient standards focuses on concentrations that directly impact human health. The chapter will emphasise this aspect and not discuss other environmental effects. The chapter is divided into six sections. Section one is the introduction; Section two addresses the complexity of designing evidence-based air quality interventions, focusing on epistemic and practical difficulties; Section three presents the state of knowledge regarding air pollution sources within low-income residential areas; Section four discusses the state of action; Section five explores the relationship between the knowledge and action; and lastly, Section six answers the question of how to identify reasonable health-oriented air quality interventions in a data-constrained context.

2. The complexity of designing evidence-based air quality interventions

There is a need for intervention to decrease people's exposure to harmful airborne pollutants. However, designing and implementing evidence-based air quality interventions to improve health in low-income households is a complex endeavour. This is especially true when targeting intra-community sources. Developing, implementing, and measuring air quality interventions present both epistemic and practical difficulties.

The epistemic difficulties are apparent in at least the following:

- Measuring air quality is difficult.
- Estimating the contribution of sources to the total air pollutant load is difficult.
- Estimating an individual's or population's exposure to air pollution from a particular source is difficult.
- Quantifying the effects of exposure is difficult.

Bearing in mind these complexities, there are also practical questions to resolve:

- How should one identify where an intervention should be conducted?
- How should one go about identifying and prioritising intervention options?
- How should interventions be developed and implemented?
- How should the outcomes be measured and reported?

The epistemic difficulties are elaborated under subsection 1, and the practical questions under subsection 2.

2.1 Epistemic difficulties

2.1.1 Measuring air quality

The measurement of air pollutants represents one of the first steps towards the development of evidence-based air quality interventions designed to reduce air pollution-related health impacts. Air quality monitoring can provide prima facie evidence that an air quality problem exists and can provide clues as to the sources of the problem.

Monitoring air quality in ambient or indoor environments in low-income settings is riddled with challenges. These challenges are related to:

- high temporal and spatial variability of pollution concentrations
- the presence of a wide range of pollutants
- the presence of multiple pollution sources

- the cost and maintenance requirements of air quality monitoring equipment
- logistical challenges such as unreliable access to electricity or limited Internet connection.

It is somewhat naïve to expect that ambient air quality measurements before an intervention is implemented and then again after the intervention has been implemented will provide a firm indication of whether an intervention has contributed to a reduction of the targeted pollutants. Although this may be the case in an environment that is dominated by a single pollution source on which the intervention has a dramatic effect, most low-income households are exposed to a mixture of local and regional pollution sources that are somewhat stochastic and show large spatial and temporal variances.[6]

Although complex from an environmental health[7] perspective, the measurement of air quality in low-income settings is important. Resource constraints, however, prevent this from occurring at the required scales. In data- and resource-constrained environments, traditional methods of air quality measurement, which often rely on expensive and sophisticated equipment, may not be present or feasible. Alternative possibilities include, either on their own or in combination, satellite data, dispersion modelling, low-cost sensors, pollutant-specific exposure proxies (including fuel-use patterns or the use of indicator plants) or citizen science approaches, where community members are trained to collect air quality data using simple tools. All these approaches have their limitations. Combinations of monitoring approaches that complement one another can at least provide an estimation of the level of pollution that people are exposed to.

---

[6] Editors' note: These themes are also discussed in Chapter 12 of this book.

[7] Environmental Health is a discipline that examines human health effects from exposures to harmful agents in the environment. The 'environment' may include the outdoors, home, workplace, or public buildings.

2.1.2 Quantifying source-specific contributions

Measuring air pollution and identifying concentration hotspots to inform interventions for reduced health impacts is the logical first step, but this alone is insufficient. Greater understanding and quantification of the various sources of air pollution are crucial for developing and enforcing efficient strategies to mitigate and control air pollution (Mathuthu et al., 2019). Identifying the sources of an air pollutant of interest in low-income areas can be a challenge. Often, a combination of indoor sources (such as cooking and heating) and outdoor sources (such as traffic, waste burning, and industrial emissions) together with industrial and regional backgrounds creates a complex mixture of air pollutants, to which people are exposed and which ultimately, either in isolation but also in combination, cause negative health impacts.

Source apportionment has been used for the identification of air pollution sources as well as the quantification of their contribution to air pollution levels (Engelbrecht et al., 2002; Tshehla & Djolov, 2018; Walton et al., 2021; Alfeus et al., 2024; Van Der Westhuizen et al., 2024). Source-oriented models and receptor models are the two main types of models used to identify sources of pollution (Cogho, 2019). Source-oriented models are typically preceded by emissions inventory exercises. They require knowledge of all emissions from the contributing sources (Pant & Harrison, 2012). As a result, the use of source-oriented models is limited in South Africa because the required detailed emissions inventories for input into the models are not always readily available (Alfeus et al., 2024). Detailed emissions inventories in low-income settlements are expensive and difficult to create because the source landscape often contains a myriad of small, sometimes intermittent or sporadic, pollution sources of different kinds.

Receptor models use receptor concentrations as input to calculate the source's contributions (Van den Berg, 2015). The receptor models include the analysis of pollution data collected on the receptor sites and the subsequent identification of the chemical composition of the measured pollutant. Inductively coupled plasma–mass spectrometry (ICP-MS) or Wavelength Dispersive X-ray Fluorescence (WD-XRF) has been used to identify elemental composition and ionic elements using ion chromatography. The study by Van Loggenberg (2020) compared elemental composition readings from XRF and ICP-MS and reported that lower trace metal concentrations determined with WD-XRF compared to ICP-MS are caused by fine-size particles penetrating deeper into the substrate medium, which can increase X-ray scattering and background noise, whereas higher concentrations of trace metal species associated with crustal sources determined with WD-XRF were attributed to the nitric acid digestion underestimating silicate minerals in the dust. The choice of instrument in practice depends on the availability and the cost of analysis and not the limitation or underestimation of certain elements which might result in the underestimation of contributions of certain sources.

The most common unsupervised analysis technique for elemental or chemical composition data obtained in this way includes principal component analysis (PCA) and positive matrix factorisation (PMF) (which is sometimes, more correctly, referred to as non-negative matrix factorisation, NNMF). These techniques require minimal prior knowledge of emissions profiles. Other techniques, such as the US EPA (United States Environmental Protection Agency)'s chemical mass balance (CMB) model, require more detailed information about the emissions sources (Van den Berg, 2015; Walton, 2021) but have distinct advantages. The CMB model does not require large datasets for input into the model as well as further source interpretation (Walton, 2021). However, it is not widely used in South Africa because local source profiles are still lacking (Muyemeki et al., 2021); and readily available source profiles are not always indicative of the properties of a specific source at different airsheds (Walton, 2021). Although PCA has been used for source apportionment, Van den Berg (2015) noted that PCA is a good method for ascertaining which typical chemicals originate from which source, but it cannot be used for source apportionment analyses and for quantifying source contributions in the way that CMB can. PMF is also not without limitations. Some limitations stem from assumptions that the model is based on, such as that the composition of the emissions sources is constant over the sampling period at the receptors (Walton, 2021). The PMF is commonly used because, compared to the CMB model, it does not require source profile data; compared to PCA it uses a point-by-point minimisation scheme which allows the profiles to be directly compared to the input matrix without any transformation (Van den Berg, 2015).

Source apportionment approaches can also take on more qualitative approaches such as the direction-based receptor models (Carslaw & Beevers, 2013) or identification of main pollution sources based on time-specific activities (e.g., in domestic settings, cooking takes place at specific times); if specific pollutant concentrations continuously peak at times during which meals are prepared, it is safe to assume that domestic cooking could represent an important source of the pollution. In addition, a combination of trajectory models and satellite data can help to assign pollutant concentrations in given areas to specific source categories (e.g., residential or traffic-related sources). Similarly, questionnaire data and information received from community members may indicate which pollution sources are most critical to consider in exposure work.

2.1.3 Quantifying source-specific exposures

In air pollution studies, *exposure* is commonly understood as the pollutant concentration that a person "comes into contact with", which is typically measured by air quality instrumentation. It can, however, more comprehensively refer to the amount or the dose of a pollutant that enters the human body (e.g., in the case of air pollution, mostly through inhalation) and then continues to react within the body, causing specific health impacts (US-EPA, 2023). Quantifying source-specific exposure is considered important in exposure research because it tells us more about the potential toxicity of a pollutant as well as the associated physiological implications. This is a way in which one can identify high health risk air pollution sources in low-income settings for intervention prioritisation. Exposure should also be defined when assessing the impact of an intervention so that the impact of the intervention can be correctly isolated. It is important to distinguish whether the exposure is being quantified on the basis of a community, a targeted group, or on individuals.

While quantifying source-specific exposure is key, understanding and identifying the duration and the physical location in which the exposure is taking place is a crucial step that cannot be omitted, especially for individual exposure studies.

When designing an intervention, the complexities of exposure must be considered. A study by Wernecke et al. (2021) in a low-income community in the Mpumalanga Highveld identified five main locations where people spend time: inside their homes, directly outside their homes, on dirt roads, on tar roads, and in open fields. They then measured the concentration of pollutants in each of these micro-environments. Based on the time spent in each environment and the corresponding pollution levels, the researchers estimated how much particulate matter the participants may have inhaled. The most concerning finding was that the highest concentrations of pollutants were measured inside and directly outside the participants' dwellings.

Some interventions do not modify pollution sources but only introduce behaviours or technologies that reduce people's exposure to pollutants (Ballard-Tremeer & Mathee, 2000). For such interventions, it is especially important to adequately quantify the behaviours associated with exposure. Many interventions, however, aim to reduce emissions from a specific pollution source. For example, the installation of flue gas desulfurisation by Eskom (Eskom, 2024) and Sasol (Sasol, 2023b). During the design of such interventions, an exposure assessment functions to demarcate the group of people most impacted by the source and help to quantify the expected benefits of reducing emissions from that source.

Over and above "simply" measuring the concentration of a given pollutant in the air, the source from which the pollution stems tells of the composition of the pollutant

(Fisher et al., 2021). In a low-income community context for instance, the air pollution developed by burning domestic waste in the ambient environment could represent a mix of volatile organic compounds (VOCs), particulate matter (PM) (including heavy metals such as lead and mercury), polycyclic aromatic hydrocarbons, various gaseous pollutants (e.g., SO_x, NO_x, CO), highly toxic chemical compounds and also greenhouse gases (Wang et al., 2023). Similarly, the practice of domestic wood burning could create a different amalgamation of pollutants.

2.1.4 Establishing exposure-response relationships

The related concepts of *concentration-response*, *exposure-response* or *dose-response* function within environmental health studies and are used to understand the impact of air pollutants on human health. *Exposure-response* refers to the correlation between external intensity, duration, and nature of the exposure to a specific pollutant and the realisation of specific health outcomes (Cox, 2023). For example, average ambient $PM_{2.5}$ concentrations derived by either stationary measurements and/or remote sensing can be related to the incidence of specific respiratory diseases in a given population.

The concept *dose-response* involves a more nuanced assessment. It includes identifying how much of a given pollutant enters the body and how it incrementally interacts with the physiology of the individual, ultimately causing specific health impacts. For this, it is not only important to define the pollutant of interest, but in the case of PM, for example, it is important to understand the relevant chemical composition and physical attributes of the pollutant (as identified through source-apportionment work) and to understand how the pollutant (or in this case toxicant) is absorbed and metabolised by the body, causing a specific biological effect (US-EPA, 2023). The dose-response approach is fundamental in toxicology and is essential for setting exposure limits and safety standards.

The heterogeneous nature of air pollution, in terms of pollutants and sources, necessitates a careful definition of an intervention study's scope. Understanding the health effects associated with varying levels of specific pollutants is crucial for prioritising interventions. A key decision is the selection of the target population: Will the intervention aim to improve community-wide health outcomes, or will it focus on improving the well-being of a specific exposed group of individuals?

From a health point of view, the most studied pollutants are $PM_{2.5}$, O_3 and NO_2 (Yazdi et al., 2021). These pollutants have historically been associated with morbidity and mortality incidences related to respiratory and cardiovascular disease, and a range of other negative health impacts (Lancet Planetary Health, 2022). Acute exposure to $PM_{2.5}$, which represents particulates smaller than 2.5 microns in diameter that can be inhaled deeply into the lungs, has been linked to the prevalence, morbidity and exacerbation of, as well as mortality related to, respiratory ill health problems. This includes asthma and chronic obstructive pulmonary disorder (COPD) (Wang & Liu, 2023; Wen & Gao, 2018; Guo et al., 2018).

For a long time, response functions were derived to model relationships between chronic exposures and specific health outcomes at a population scale in developed countries. More recently, exposure-response functions have been derived using data from studies conducted around the world, including in low- and middle-income countries (LMICs) (Xue et al., 2023). For example, a non-linear exposure-response function showed that chronic exposure to ground-level ozone levels contributes substantially to the mortality of children under five years of age in LMICs (Xue et al., 2023). Another LMIC study showed that incremental increases in $PM_{2.5}$ levels are associated with a significant increase in deaths from all causes amongst the population studied (Li et al., 2018). Importantly, more research is being conducted at a physiological level. For example, research into the dose-response relationship between air pollutants and reactive oxygen species in the human respiratory tract shows that breathing in air pollution directly causes oxidative stress and triggers the body's immune response, exacerbating health effects (Lakey et al., 2016). Chemical exposure-response relations provide a quantitative basis for assessing the relative importance of specific air pollutants in different environments (Lakey et al., 2016).

Deriving these functions for specific air pollutants and health outcomes involves epidemiological studies, toxicological research, and exposure assessments, all of which require the necessary resources, which are sparse in low-income settings. Given that ambitious research may not always be possible in data-constrained contexts, utilising existing epidemiological studies and adapting their findings to the local contexts might be necessary.

The lack of local and area-specific exposure-response or dose-response functions represents a critical gap in air pollution and health studies. This complicates the assessment of the possible effects of air quality interventions in lower-income settings and thus makes the selection of appropriate interventions more difficult. Ideally, more should be invested in the derivation of more context-specific and localised exposure-response and even dose-response functions. The dilemma remains that the resources required to do this are not available in resource-constrained environments. Careful consideration of the benefits of exposure-response or dose-response studies is needed.

2.2 Practical questions

2.2.1 Identifying and prioritising key micro-environments and meso-airsheds that are amenable to intervention.

Pollutant concentrations show substantial spatial variation. Though ambient air pollution levels in low-income settings often exceed safe-to-breathe levels over large spatial areas, measurements taken around households burning dirty fuels or around waste dumps may demonstrate exceptionally high concentrations. The indoor environments can see especially high pollutant concentrations in low-income settings because of high reliance on the use of dirty fuels for cooking or heating activities (Language et al., 2016; Segakweng et al., 2022; Adesina et al., 2020).

The key to impactful air quality interventions is finding the environments with the highest concentrations and where people spend most of their time which thus have the largest health impacts. That means determining the exposure hotspots within micro- or meso-airsheds (i.e., localised areas within a community setting or communities within a larger region that share similar air pollution characteristics and sources).

In a resource-constrained environment, a lack of prioritisation can lead to inefficient use of limited resources. This is often why stationary air quality monitoring stations, though considered an acceptable proxy for air quality exposure, should not be used in isolation when designing interventions targeting human health. The cost-efficiency of interventions will be increased when key micro- and meso-airsheds in which interventions can be implemented are identified and prioritised.

2.2.2 *Developing and selecting interventions within the reality of low-income households and settlements*

Intervention strategies need to be effective and feasible within the economic constraints of low-income settings. Commonly, interventions in such settings include promoting affordable clean cooking technologies, enhancing natural ventilation in homes, or community-based tree planting initiatives and other nature-based solution approaches to improve air quality through affordable purification methods. Engaging with the community to understand their needs and capacities is vital for the success of the interventions[8] reported in this book. Thus, developing and selecting air quality interventions require a nuanced understanding of the socioeconomic and cultural context of a given location to cater for specific needs and constraints so that interventions are not only good on paper but also in practice (Burns et al., 2019).

Building on the concept of micro-environments identifying micro-airsheds / micro-environments with high pollutant concentrations in which "vulnerable" people who are most susceptible to air pollution exposure impacts (for example the elderly, children, women and those with pre-

---

[8] Editors' note: This is illustrated by the case studies discussed in Chapters 5 and 6. Chapter 9 discusses theory in this regard.

existing health conditions known to be exacerbated by or sensitive to air pollution exposure) spend most of their time, and then targeting those environments for improved air quality, represents an effective way to ensure those most at risk receive the greatest protection.

It is important to understand that in many resource-constrained environments, survival is “more important” than clean air. In such settings, efforts are geared towards putting food on the table and a roof over one’s head, rather than breathing air that is not detrimental to one’s health. Interventions need to take this into account. As poor air quality is a fundamentally systemic issue related to energy poverty, the best interventions would ideally target not only the source of the pollution but also the source of the problem, i.e., the socioeconomic disparities and circumstances forcing the reliance on polluting fuels and practices. This means implementing comprehensive strategies that include access to clean and affordable energy, economic development programmes, education, and affordable healthcare services (Burns et al., 2019). By addressing these root causes, interventions can contribute to sustainable improvements in air quality while also enhancing overall community resilience and well-being, and additionally improving the health of the environment.

The thought that the implementation of a single intervention may lead to evidence-based improvements in health is challenged by the fact that sustainable and long-term impacts are more likely achieved through multi-pronged intervention approaches over time (Burns et al., 2019; Avis & Bartington, 2020).

2.2.3 *Measuring intervention success in a dynamic context*

The complexities mentioned above suggest that the success of air quality interventions to improve health in dynamic low-income settings is challenging to measure. The complexity of the situation necessitates a flexible and robust monitoring and evaluation framework. This framework should incorporate quantitative and qualitative indicators to assess changes in air quality and health outcomes over time.

This requires the definition of the baseline scenario that would exist if the intervention were not implemented. It furthermore requires a decision on the parameters to be monitored and metrics and indicators used to track those parameters. This includes the determination of what it means to have a ‘successful intervention’. A suite of measures is needed to assess the immediate, medium-term, and long-term impacts of air quality interventions. The exact configuration of measurements will be determined by the nature of the intervention.

The effects of air pollution interventions occur over different time scales and (potentially) across the whole impact pathway. The Driving-Force-Pressure-State-Exposure-Effect-Action (DPSEEA) Framework is used to depict the impact pathway. Air quality *drivers* (the first position on the impact pathway) are long-term phenomena and can be assessed using long-term or periodic monitoring. Emissions (an environmental *pressure* - position two on the impact pathway) result from activities and events. It is often easier to measure indicators of activities and events than the emissions themselves. Ambient air quality is the relevant environmental *state* (position three on the impact pathway) for the sake of this discussion. This is measured using intermittent or continuous air quality monitoring and relevant monitoring locations. Monitoring *exposures* (position four on the impact pathway) means monitoring the time and location of people in relation to varying ambient states. In sophisticated cases, a differential intake rate (i.e., breathing rate in the case of air) can be quantified to estimate dose and not just exposure. Health *effects* constitute the fifth position on the impact pathway. The period over which health effects can be monitored is determined by the nature of the dose-response relationship itself. Some effects occur shortly after exposure (e.g., an asthmatic response to high SO_2 concentrations), while some develop over the long term (e.g., COPD from long-term PM exposure).

Figure 2 presents the WHO (World Health Organization)’s DPSEEA framework with examples of the impact pathway of domestic fuel burning for space heating, adapted by the authors from Friedl and co-authors (Friedl et al., 2008).

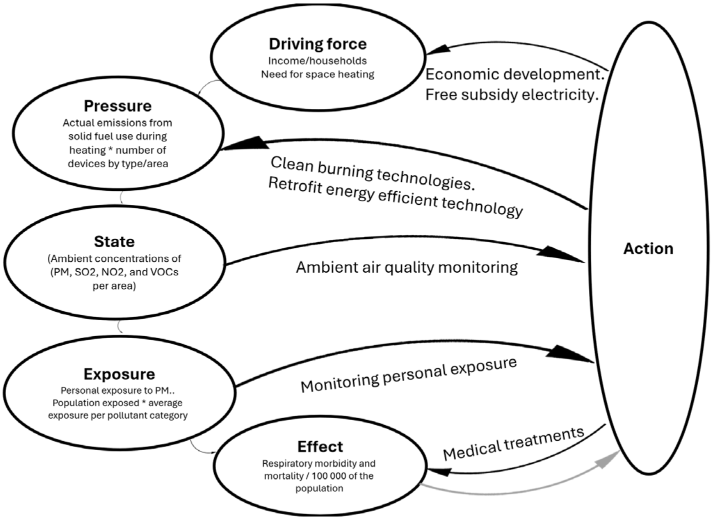

Figure 2: The WHO's DPSEEA framework with an example of biomass burning for space heating.

Success could also be measured by the capacity to scale and adapt interventions across different contexts, ensuring that strategies remain relevant and effective in improving public health amid evolving challenges. Targeting the reduction of short-term higher air pollution concentrations below pollutant levels established in exposure-response functions as important health thresholds may be easier to accomplish than the reduction of long-term pollutant exposure, which is typically lower. Similarly, targeting a micro-airshed such as an old-age home or single homes in which elderly people live and are exposed to high pollution concentrations may be ways in which the health impacts of interventions could more easily be isolated from confounding factors. This same rationale could apply to a micro-airshed in which vulnerable groups spend most of their time and/or are exposed to the highest pollution concentration or the most toxic pollutants.

Evaluating the impact of interventions is challenging, especially in dynamic environments where multiple factors influence air quality. A combination of continued air quality monitoring, health outcome tracking, and community feedback can provide insights into the effectiveness of the interventions.

3. State of knowledge regarding air pollution sources within low-income residential areas

3.1 Solid fuel burning

A great deal of research has been done regarding solid-fuel burning in low-income residential settings. This is because of reliance on burning solid fuels for cooking and heating in low-income settlements. Even though 89.3% of South African homes had electricity in 2021 (StatsSA, 2022), many low-income families cannot use electricity for all their energy needs because of the cost and, in recent years, load shedding. Instead, families use a mix of energy carriers, called fuel stacking, for activities such as cooking and heating that require a lot of energy (Langerman & Pauw, 2018). The type of solid fuels used varies based on availability, cost and the utility required (e.g., how much space heating is needed). Friedl et al. gave a systematic overview of solid fuel use in dense, low-income settlements in South Africa before 2008 (Friedl et al., 2008). More recently, Pauw et al. (2022) reviewed solid fuel use on the Highveld and described types and formats of fuels used, the fuel-burning devices used, the utilities for which solid fuels are used, as well as their spatial distribution. They also describe the historic actions undertaken to combat the inappropriate use of domestic solid fuel.

A study conducted at KwaZamokuhle, the Nova Institute and North-West University on behalf of Eskom (Adesina et al., 2020) has shown that most households in that settlement used coal or wood to meet their energy demands. In Umlazi, a coastal low-income settlement in KwaZulu-Natal, South Africa, households use electric- and non-electric (coal, wood, gas, paraffin) energy sources for cooking and heating (Buthelezi et al., 2019). Naidoo et al.(2015) conducted a study in Zenzele, a settlement near Johannesburg without access to electricity. It was found that households in un-electrified areas typically rely on paraffin and liquid petroleum gas for cooking and lighting during warmer months, while solid fuels such as wood and coal are preferred during winter by those with limited means (Naidoo et al., 2015). Nationally, solid fuels are used as a primary energy carrier for heating rather than for cooking (Friedl et al., 2008; StatsSA, 2022).

The combustion of these fuels releases pollutants such as carbon monoxide (CO), particulate matter (PM), sulfur dioxide (SO_2) and volatile organic compounds (VOCs) into the air, contributing to local air pollution. Residential ambient air concentrations are highly variable in time and space. Adesina et al. (2020) carried out continuous monitoring of particulate matter (PM_4) in two houses in KwaZamokuhle: a solid fuel-burning house (coal) and a non-solid fuel-burning house. The solid fuel-burning house had higher concentrations than the non-solid fuel-burning house (Adesina et al., 2020). Similar findings were observed by Moletsane et al. (2021). The study measured ambient fine particulate matter ($PM_{2.5}$) in distinct microenvironments (at four sites) of KwaZamokuhle between March and June 2018. It was further found that the highest concentrations of hourly averaged ambient $PM_{2.5}$ were recorded at a site with wide concentrations of informal dwellings and solid fuel-reliant houses (Moletsane et al., 2021). Hersey et al. (2015) conducted a study on the five major metropolitan areas in South Africa: Cape Town, Bloemfontein, Gauteng province, Industrial Highveld Air Quality Priority Area, and Durban. The study categorised each metropolitan area into four categories: township areas with proximity to domestic burning, urban / suburban residential areas, industrial areas, and traffic sites directly adjacent to major on-road sources. Low-income township sites in Gauteng experience by far the worst particulate air quality in South Africa, with monthly averaged PM_{10} concentrations as much as 78% higher in townships than in industrial areas (Hersey et al., 2015).

In addition, extreme $PM_{2.5}$ concentrations that exceeded the 24-hour $PM_{2.5}$ National ambient air quality standard (NAAQS) of 40 $\mu g.m^{-3}$ were seen during the cold period (May and June); meanwhile, the warm period (March and April) recorded relatively lower $PM_{2.5}$ episodes across different sections of KwaZamokuhle (Moletsane et al., 2021). A study conducted by Matandirotya et al. (2022) at the low-income urban settlement of Jabavu, located within the City of Johannesburg, South Africa, during 2018 observed similar trends of high concentrations during winter. This is because there is an increase in the use of solid fuels by households in the settlement to keep warm during winter (Matandirotya et al., 2022). Several studies (Adesina et al., 2020; Nkosi et al., 2017; Wernecke et al., 2015) have reported two burning events per day that have been observed with an increase in particulate matter, a morning burning event between 06:00 and 12:30, and an evening burning event from 16:00 to 22:00. It is worth noting that the burning event and seasonal pattern occur during the period of poor atmospheric dispersion potential (Lindeque et al., 2021), hence the high concentration.

Furthermore, in addition to being an outdoor source of air pollution, solid fuel combustion increases indoor air pollution. High indoor concentrations are observed even in households that do not burn solid fuels themselves. Adesina et al. (2020) observed that indoor concentrations were higher than outdoor during morning and evening; these periods coincide with the fuel-burning pattern at KwaZamokuhle. Similar results were observed by Language et al. (2016) at KwaDela. Concentrations of respirable particulate matter within indoor environments were significantly higher than those of PM_{10} and $PM_{2.5}$ found in the ambient environment (Piketh, et al., 2016). A study by Segakweng et al. (2022) collected outdoor (ambient) and indoor aerosols in different size fractions during summer and winter in four low-income urban settlements located in the north-eastern interior of the South African Highveld, i.e. KwaDela, KwaZamokuhle, Zamdela, and Jouberton. The highest concentrations of particulates were measured indoors, with the highest mass concentration determined in the indoor $PM_{2.5\text{-}10}$ (coarse) size fraction (Segakweng et al., 2022).

3.2 Waste burning[9]

Some sources of air pollution, such as waste disposal and burning, industrial activities, traffic emissions, and transboundary pollutants in low-income settlements, have not been researched in-depth from the perspectives of air quality and health. In South Africa, low-income residential areas are mainly rural areas, informal settlements, and government-subsidised formal settlements. Waste service delivery in rural areas and informal settlements ranges from no service at all (Rodseth et al., 2020) to minimum service. In rural areas, 86,4% of households discard their refuse themselves (StatsSA, 2022). Haywood et al. (2021) found that the waste bins supplied by the municipality are insufficient to handle the amount of waste generated in dense, low-income formal settlements with additional backyard dwellings. The unequal distribution of waste collection services can be partly explained by the challenging and currently unsolvable conditions in informal settlements. These settlements often lack proper road access, often have a high population density, poor spatial planning and layout, and illegal land ownership. These factors make it difficult or impossible to provide waste collection services in these areas. Solid wastes are produced at a faster rate than any other environmental pollutant (Yadav et al., 2019) and in larger quantities than local municipalities can handle. The residents resort to unregulated waste 'management' practices such as illegal dumping and uncontrolled burning (Rodseth et al., 2020), which release harmful pollutants into the air, including PM, heavy metals, and toxins from burning plastics and other materials. According to the results obtained by Rodseth et al. (2020), 29% (3.67 million tonnes per annum) of domestic waste generated in South Africa is not collected or treated through formal management options. It is estimated that the proportion of household waste disposed of illegally ranges from 5% for unserviced rural households to 27% in metropolitan areas (Rodseth et al., 2020).

---

[9] Editors' note: See chapter 5.

The study by Haywood et al. (2021) conducted in four provinces in South Africa, Limpopo, Gauteng, Mpumalanga, and North West, reported that households who used non-electric sources of energy for heating or cooking, those who lacked proper sanitation, and those who did not have access to piped water inside the dwelling were more likely to dispose of waste by dumping it in the street or yard, or by burying it. The burning of waste within the yard was reportedly less common in families who reported living in a shack and were more likely to dump waste in the street, possibly because of a lack of yard space.

3.3 Adjacent industries

Some low-income residential areas are located near areas where industrial facilities emit pollutants into the air (DEA, 2009). These pollutants can include sulfur dioxide (SO_2), nitrogen oxides (NOx), PM, and other harmful substances, depending on the type of industrial processes taking place. Proximity to stationary sources of pollution deteriorates air quality in low-income settlements. The study by Belelie et al. (2019) evaluated the dispersion of $PM_{2.5}$, $SO_{2,}$ and NO_X emissions from Eskom power plants (Arnot, Hendrina, and Komati) located close to KwaZamokuhle Township. The simulations show that KwaZamokuhle Township receives SO_2 and NOx from the power plants' emissions (Chidhindi et al., 2019). Emissions from industrial point sources have a different temporal pattern than that of domestic sources. Several studies, for example, the one conducted by Matandirotya et al. (2022) at KwaZamokuhle, show elevated SO_2 concentrations during the middle of the day. This is the time of the day when dispersion conditions permit tall stack emissions to be mixed down into the surface. Even though this is a detectable phenomenon, it is worth noting that the SO_2 did not exceed the National Ambient Air Quality Standards.

3.4 Traffic

Particular low-income residential areas also experience high levels of air pollution caused by traffic emissions. These emissions come from gasoline or diesel vehicles and include pollutants such as NOx, CO, PM, and VOCs. Unpaved roads in low-income settlements have been linked to an increase in coarse particulate matter (Matandirotya et al., 2022). Bokamoso, a low-income residential area within the Rustenburg Municipality, has a paved road network of 19%, and 81% unpaved roads (Nkosi et al., 2023). This study has shown that an increase in vehicle speed and vehicle weight increases the amount of non-exhaust traffic PM_{10} emitted (Nkosi et al., 2023). The majority of the houses in low-income settlements are poorly ventilated. Pollutants infiltrate into households from the outdoor air, leading to elevated concentrations of pollutants indoors (Mutahi et al., 2021).

3.5 Commercial cooking

Commercial cooking in low-income settlements refers to street vendors making fires using "dirty fuels" on roadsides either to cook meals or roast meat for selling. The Department of Environmental Affairs (DEA) identified commercial cooking as a source of air pollution in low-income settlements (DEA, 2019). Sepadi and Nkosi (2023) conducted a health risk assessment of informal food vendors in Johannesburg. The study recorded higher concentrations of air pollutants at the outdoor markets compared to indoor markets. In addition, they reported that outdoor cooking vendors have a higher risk of developing respiratory diseases. The use of 'dirty fuels' by street vendors has not been addressed. This could be a lack of comprehensive research into intervention strategies or a lack of funding to implement the interventions.

3.6 Regional sources

In addition to local sources, transboundary pollution further contributes to the problem of air quality in low-income settlements. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model has been used to trace the sources and paths of transboundary pollutants by running backward trajectories. The HYSPLIT makes assessments of air parcel trajectories based on Lagrangian models to identify sources, pathways of pollutants, and transportation within the atmosphere over time. A study by Muyemeki et al. (2021)

reported that air mass originating from Mozambique and passing through mining and industrial areas in the Mpumalanga region contributes to high concentrations of $PM_{2.5}$ observed during the summer and autumn in low-income settlements at the Vaal Triangle Highveld priority area (Kliprivier, Sebokeng, Sharpeville, and Zamdela). The study further reported that air mass originating in northern South Africa and passing through Botswana and the mining areas of the North West province were reported to contribute to high concentrations of $PM_{2.5}$ observed during the winter at the Vaal Triangle Highveld priority area (Kliprivier, Sebokeng, Sharpeville, and Zamdela) (Muyemeki et al., 2021). The Indian Ocean air mass passing through Mozambique and Limpopo, as well as the Atlantic Ocean air mass passing through Northern Cape and Gauteng, has been observed by Matandirotya et al. (2022) as contributing to air pollution in low-income settlements at an Mpumalanga highveld priority area (KwaZamokuhle).

4. State of action

4.1 Interventions to address solid fuel burning

Over the years, numerous attempts have been made to eliminate or decrease the health impact of air pollution in South Africa. These actions were directed at air pollution from different sources and were undertaken at different positions along the impact pathway (IER, 2012; IAEA, 1995). Some actions attempt to reduce the *drivers* of air pollution, some limit emissions (i.e., *pressures*), some attempt to modify atmospheric *states*, some modify *exposure,* and some treat the *effects*.

Solid fuel use has historically received a lot of attention (see Pauw et al., 2022, and Friedl et al., 2008, for additional sources). To address solid fuel use, one can either replace the functionality of the solid fuel burning device with another usage pattern or modify the device or the fuel or the operational technique. The first way of replacing a functionality is to make it unnecessary (i.e., remove the *driver*, to use the DPSEEA terminology).

Formalisation of houses and electrification are two government interventions that have reduced solid fuel use significantly. The primary objective of these was not, in the first place, air quality, but to raise the general standard of living. Improved air quality is a benefit of an improved standard of living. Electricity is an economical source of energy for lighting and cooking and therefore readily replaces the liquid and solid fuels used for these utilities when the opportunity arises. Although the thermal properties of most subsidy houses in South Africa are inefficient in colder areas, these houses still provide better protection than a corrugated iron shack. The formalisation of housing (which includes electrification) on the whole was therefore associated with a reduction in solid fuel use.

Smokeless stoves that use bituminous coal made for South African conditions were developed and tested as far back as the 1960s (Sorgnit, 1968a; 1968b; Van Doornum, 1965). In the 1980s, an attempt was made to enforce the use of smokeless stoves. This largely failed (Pauw et al., 2022). The attention moved to fuel in the 1990s with the low-smoke coal programme of the then Department of Minerals and Energy (see for example, Asamoah et al., 1998, and Dickson et al., 1995). Experiments with different low-smoke fuels never lead to a solution that could be implemented *en masse*.

The improved top-down ignition technique (*Basa Magogo!* or *Basa njengo Magogo*)[10] was implemented widely and had mixed success, depending on the quality of implementation. In areas with high implementation quality, high adoption rates and reasonable attrition rates were achieved. Still, the initial implementation by the Nova Institute on behalf of Sasol had positive results (Wagner et al., 2005). Nova's implementation of the technique, using climate finance, scaled in impact drastically. The government's Clean Fires Campaign was a damp squib. All things considered, the implementation of the top-down ignition technique offered a cost-effective but temporary

---

[10] Editors' note: See, amongst others, Section 6 of Chapter 9.

solution because the proportion of people who use the technique wanes with time after implementation.

The subsidy houses built under the RDP (Reconstruction and Development Programme) after 1994 were thermally inefficient (Nel, 2023). The adoption of thermal performance standards for these houses was an important step towards avoiding this problem in future. For existing structures, different retrofit solutions have been tried. The most thoroughly tested and most widely implemented solution involves applying spray polyurethane foam (SPF) combined with a fire-retardant paint to the inside of roofs and fitting a standard gypsum ceiling below that. This is combined with a coal for liquid petroleum gas (LPG) stove swap. The development of this solution was started by the Nova Institute and TIASA in 2004 and developed in partnership with Sasol and Eskom through at least five rounds of in-use testing until the first large-scale implementation was undertaken by Sasol in eMbalenhle and Lebohang (Murray et al., 2023). Murray et al. (2023) reported on a follow-up study that determined that the implementation by Sasol was extremely successful.

Eskom's pilot project involving this technology took place in KwaZamokuhle between 2015 and 2017. Several alternatives were evaluated. The interventions tested included: installing insulated ceilings and insulation on three walls, replacing the coal stoves with low-emission coal stoves, replacing the coal stoves with LPG heaters and stoves, and an electricity subsidy in the winter months. Each household was given an insulation retrofit and either a low-emission coal stove, an LPG heater and stove, or an electricity subsidy (Eskom, 2024). The intervention finally selected was the installation of thermal insulation and swapping the coal stove for an electric / LPG hybrid stove and an LPG heater (Langerman et al., 2018).

Recently, the idea to build a smokeless coal stove suited to the needs of low-income households has gained momentum with the development of a low-emission semi-continuous coal stove at the North-West University (NWU, 2024)[11]. An evaluation

---

[11] Editors' note: See chapter 9 below.

of end user satisfaction following an in-use evaluation by households was conducted in Zamdela, South Africa, in 2022 by the Nova Institute. Overall, the evaluation of households was very positive.

4.2 Miscellaneous interventions in the context of air quality offsets

Air quality offsets lead to a proliferation of interventions aimed at reducing harmful emissions in communities. A project by Sasol's Sasolburg Operations and Natref, aimed at removing grass and waste material, resulted in significant reductions in air pollution estimates. Sasol claims that cutting and removing 4.4 million square metres of grass and 1,040 tonnes of biomass avoided an estimated 6.6 tonnes of PM_{10}, 5.2 tonnes of $PM_{2.5}$, and 0.62 tonnes of SO_2 emissions. The methodology on which this calculation is based is not publicly available. Similarly, Sasol claimed that removing 3,080 tonnes of waste prevented an estimated 21.27 tonnes of PM_{10}, 22.5 tonnes of $PM_{2.5}$ (this is reported as such but appears to be wrong because the $PM_{2.5}$ to PM_{10} ratio exceeds 1), and 2.95 tonnes of SO_2 emissions. These findings highlight the potential air quality benefits of managing biomass and waste effectively.

Additionally, to curb dust pollution, Sasol's Sasolburg Operations embarked on a road construction project within the Zamdela area. This initiative specifically targeted particulate matter emissions caused by vehicle traffic. To achieve this, they have paved approximately 1.6 kilometres of the access road. The impact of the reduction of particulate concentrations over the residential area resulting from this intervention is unclear.

In recent years, the proliferation of interventions, caused by the inception of air quality offset policies, included interventions with no clear impact on air pollution, nevertheless being implemented as part of air quality offset programmes. Sasol also implemented a comprehensive education and awareness campaign with two key components. One is a general public campaign where field officers engage directly with residents in eMbalenhle and Lebohang through door-to-door interactions. Local newspapers publish these topics in three languages to broaden outreach. There was also a school awareness campaign that involved 26 primary schools in Govan Mbeki Local Municipality in 2022. Around 27,060 learners participated in engaging activities such as puzzle-building, colouring books, dramas, debates, and quizzes. A post-assessment confirmed a positive impact, with learners gaining a deeper understanding of air quality concepts (Sasol, 2023b). It is unclear if or how this awareness translates to air quality outcomes.

4.3 Emission control technology

Experimentation with new technological interventions is continuing. Researchers are actively exploring various technologies to curb air pollution from household fuel combustion. These technologies include the use of a catalyst inserted into the flue of the stove. However, implementing these solutions has proven challenging. For example, although wood boiler catalysts reduce air pollutants, they struggle to function at low flue gas temperatures during startup and shutdown (Ozil et al., 2009), and some residential heaters may not have sufficiently high flue gas temperatures to activate the catalyst (Hukkanen et al., 2012). The study by Steyn et al. (2023) used a manganese active catalyst and was successful in the laboratory; however, in a real-life setting, particulate matter increased when the catalyst was used.

5. Relationship between knowledge and action[12]

The most impactful changes in people's exposure to harmful air pollution resulted from improvements in the material standard of living[13]. This emphasises that general economic development is the long-term solution that must be pursued, and that approaches that detract from this should be viewed with the

---

[12] Editors' note: It will be instructive to compare this section with chapter 6, where caution is advised against a certain kind of knowledge in specific contexts.

[13] Editors' note: This may underlie some of the sentiments expressed in Chapter 14.

strongest suspicion. Langerman et al. (2018) demonstrated the marked contrast between air quality in a low-income (KwaZamokuhle, an apartheid-era township) and an adjacent middle-income town (Hendrina). While both share the same background sources of the industrialised Mpumalanga Highveld, KwaZamokuhle has markedly higher PM concentrations and noticeably articulated peaks that apparently derive from the internal sources inside the township – mainly domestic coal burning and dust sources (Qhekwana, 2019).

The most successful intervention implemented specifically to curb air pollution was triggered by an air quality offset requirement and resulted from research, development, and testing over longer than a decade. A key factor was the combination of rigorous technical evaluation, combined with qualitative and quantitative research into end user requirements, behaviours, and perceptions.

This thermal insulation retrofit and stove swap intervention that was implemented by Sasol at scale and performed exceedingly well (see Murray et al., 2023). It succeeded because it addressed the correct driver. It also worked on a technical level. It was implementable and improved the quality of life of end users. The reduction in PM_{10} and $PM_{2.5}$ emissions from this project has been quantified, but the final impact on human exposure has not been quantified through dispersion modelling.

At the same time, interventions have been implemented where the relationship between the intervention and even the reduction of emissions is not clear at all. The air pollution awareness campaign implemented by Sasol is an example of this.

There are no cases in South Africa where the health effects of an air quality intervention in a low-income settlement have been directly measured. At best, some interventions calculated the reduction in pollutant emissions, but none of those projects made their assumptions, calculation methods, or data collection and quality procedures public. As far as we could ascertain, none of this is open to public scrutiny.

5.1 How to identify reasonable health-oriented air quality interventions in a data-constrained context

5.1.1 Requirements for high-quality, evidence-based interventions

A high-quality, evidence-based intervention requires that an air quality monitoring network that is spatially representative of the settlement be operated for a sufficient time to understand the temporal variation in pollutant concentrations. This network could consist of either conventional compliance-grade monitoring equipment or a combination of alternative instruments and methods, such as low-cost sensors and remote sensing.

After understanding pollutant concentrations, the sources contributing to these concentrations need to be understood. This implies the need for an emission inventory of background and foreground sources.

After understanding the spatial and temporal variability in pollutant concentrations and the sources involved, and the sources contributing to these, the contributions from the identified sources need to be more accurately quantified. Different source apportionment models can be used to estimate the contributions of each identified source. Typically, methods that can accurately identify individual sources, such as CMB, should be used; but these should be cross-checked with other receptor models so that unexpected and unknown sources can also be detected. The spatial and temporal resolution of the sampling campaign needs to be adequate to resolve the number of sources.

With an understanding of pollutant concentrations and source contributions in hand, an assessment of how the population is exposed to these pollutants must follow. This assessment should consider the frequency and the magnitude of exposure over the population.

Ideally, one would have already established the exposure-response relationships for the most important pollutants and health outcomes derived from comparable populations. This can then be used to calculate the source-specific impact of exposure on the population. This knowledge can be used to prioritise the sources to address for each airshed in which exposure takes place (be that micro-, mini- or meso-airsheds) and identify sources to address, and possibly the required emissions reduction from each.

With a source and an emissions reduction target, the development or selection of interventions that meet the needs and fit the constraints of low-income households can commence. This presupposes a detailed understanding of the usage patterns, requirements, and constraints of households that will participate in the intervention.

Part of the development of an intervention is the development of the quantification methods for baseline emissions, exposures, and effects (emissions, exposures, and effects in the absence of the project activity) and project emissions, exposures, and effects (emissions, exposures, and effects when the project activity is implemented).

5.2 Proposal for a pragmatic approach to intervention development

We conclude this chapter by proposing a broad approach towards air quality intervention programmes. As industrial sources are managed via the MES, we limit this section to interventions in residential areas.

The phased approach that we describe below is predicated on the supposition that (i) interventions must meet three key criteria: sufficient impact on experienced air quality, positive or neutral impact on quality of life, and feasibility; (ii) activities and measurement should be informed by relevant and sound science; (iii) interventions that are supported by stronger knowledge should be given preference, all things being equal; and (iv) a staged approach to intervention development and implementation should be followed. A full description of the staged approach to intervention development is not attempted here: however, we signal the stages to include evaluation and scoping, pre-feasibility, feasibility testing, pilot, launch, scaling, and exit or maintenance.

We propose a four-phased approach to air quality intervention programme execution. The phases include (i) preparation, (ii) baseline establishment, intervention development and selection, (iii) implementation, and (iv) monitoring and evaluation.

Preparation could include a rapid in situ assessment by a multi-disciplinary team of experts and a formal assessment of readily available documented area intelligence. The preparation should be designed to inform the requirements of subsequent activities, such as baseline establishment and intervention development.

Baseline establishment, intervention development and selection are put together as a phase. In this context, baselines would include information regarding demographics[14], intra-community emissions activity, air quality, household practices and quality of life. Intervention development includes the identification of the airshed of concern, the pollutant of concern and addressable sources, followed by an assessment of source impact on the pollutant of concern within the airshed(s) of concern. The addressable sources are then evaluated in combination with potential avenues of intervention to estimate the potential efficacy of various interventions, ultimately to arrive at an estimate of the potential impact of intervention(s) on the human-experienced pollutant of concern. This is followed by a detailed design of candidate interventions, in-community feasibility testing at a scale likely to produce statistically significant results, extensive feasibility performance monitoring, and evaluation of the intervention in terms of emissions reduction achieved, air quality benefit expected, impact on quality of life, and implementability in terms of the funding and resource context. For interventions that pass the three key hurdles – sufficient air quality benefit, positive or neutral impact on quality of life, and implementability, one can

---

[14] In countries or locations where national statistics are of poor quality, it may be key to conduct an enumeration survey early in the process to establish key demographic variables such as population, number of households, and number of stands.

proceed to propose roll-out design and costing, followed by the selection of intervention(s) for implementation.

Implementation should be aligned closely to the intervention and local interaction that was successfully tested – one should not assume that minor variations would not have a meaningful and potentially detrimental impact on intervention uptake, intervention use, emissions impact, intervention longevity, and the like. Also note that in low-income settings, implementations that optimise the employment of local unemployed individuals, while judiciously using expert service providers, national suppliers, and local suppliers, are likely to enjoy greater support and greater success.

During monitoring and evaluation, data is collected again regarding the use of the intervention, the emissions impact, the quality-of-life impact[15] (including cost and utility impacts experienced by households), whether intervention use is sustained, and whether the intervention artefacts have suitable durability and are maintained by users. Air quality modelling or highly targeted air quality monitoring (such as indoors) can be conducted to describe the impact. Ultimately, the data is analysed, and the intervention is evaluated with a view to describing real-world costs and the benefits of implementation at scale.

5.3 Dealing with knowledge constraints

From sections one to four of this chapter, we can conclude that the ideal high-quality, evidence-based intervention development described in the preceding subsection cannot be developed in South Africa at present. We have shown that specific and comprehensive data relevant to South Africa is hard or impossible to obtain for every step. We outlined a pragmatic framework for decision-making that takes a realistic view of the quality and quantity of data available to the decision-maker.

The limitations will mean that one will not always be able to provide direct or full evidence for a specific decision taken at

---

[15] Editors' note: See Chapter 12 on measuring impact.

a particular step in the process. For example, it is difficult to obtain a full year's air quality data to make a definite conclusion about compliance with the NAAQS. The conclusion of whether an area is compliant with the NAAQS or not is necessary for one to decide whether to include or exclude the area in the target areas for an intervention. Even if this can be undertaken at one point, it will remain unclear how air quality varies over the rest of the target area. Regardless, a decision must be made. That decision must necessarily be taken based on a balance of probabilities and not beyond reasonable doubt.

Viewing a phenomenon from different positions along the impact pathway is, in our view, a reasonable way to make decisions amid the inevitable limitations in knowledge. When one observes the *drivers* for certain behaviours through household surveys, quantifies the emissions (*pressures*) or at least the activity rates leading to those emissions through household measurements or direct observation and observes the temporal, spatial and compositional signature of that source through some form of ambient air quality monitoring (*states*), one can formulate a reasonable hypothesis of the impact of a source in a particular environment, even though each one of the measurements is subject to uncertainty. Dispersion modelling is useful in this undertaking as it elucidates the relationship between pressures and states in a particular environment, but the results should be viewed in context. It is important to incorporate the fact that there are different types of airsheds where people are exposed to particular sources into the decision-making process.

Given the limitations, the metrics used to evaluate the success of an intervention cannot be the health effects that constitute its ultimate aim. As one moves right on the impact pathway towards exposures and effects, complexity and uncertainty accumulate and the time scales over which causes and effects are linked increase. This is especially true for the effects of chronic exposure. The best that can be undertaken in most circumstances is to formulate the target of an intervention as an emissions reduction (and possibly a modelled concentration reduction). Monitoring an intervention then means collecting data on the activities causing the emissions and estimating the reduction based on the difference between a counterfactual baseline scenario and an actual project scenario. Dispersion modelling can provide an estimate of the implication of this estimated emissions reduction on ambient pollutant concentrations.

List of Sources

Adesina, J.A., Piketh, J., Qhekwana, M., Burger, R., Language, B. & Mkhatshwa, G. 2020. Contrasting indoor and ambient particulate matter concentrations and thermal comfort in coal and non-coal burning households at South Africa highveld. *Science of the Total Environment*, 699(2020), 134403. https://doi.org/10.1016/j.scitotenv.2019.134403

Airshed Planning Professionals and Bentley West Management Consultants. 2004. *Study to Examine the Potential Socio-Economic Impact of Measures to Reduce Air Pollution from Combustion*. Final Report. Johannesburg: Trade and Industry Chamber / Fund for Research into Industrial Development, Growth and Equity (FRIDGE).

Alfeus, A., Molnar, P., Boman, J., Hopke, P.K. & Wichmann, J. 2024. PM2.5 in Cape Town, South Africa: Chemical characterization and source apportionment using dispersion-normalised positive matrix factorization. *Atmospheric Pollution Research,* 15(3), 102025. https://doi.org/10.1016/j.apr.2023.102025

Asamoah, J., Lloyd, P., Hoets, P. & Grobbelaar, C. 1998. Low-smoke fuel programme: Preliminary results of the macro-scale experiment. *Clean Air Journal*, 10(1), 19–22. https://doi.org/10.17159/caj/1998/10/1.7100

Avis, W. & Bartington, S. 2020. *Interventions in LICs and LMICs to improve air quality and/or mitigate its impacts*. K4D Helpdesk Report. Brighton, UK: Institute of Development Studies

Ballard-Tremeer, G. & Mathee, A. 2000. *Review of Interventions to Reduce the Exposure of Women and Young Children to Indoor Air Pollution in Developing Countries*. Washington DC: WHO/USAID Global Consultation. [Online]. Available at: https://www.energia.org/assets/2015/06/11-Review-of-interventions-to-reduce-the-exposure-of-women-and-young-children.pdf

Belelie, M.D., Piketh, S.J., Burger, R.P., Venter, A.D. & Naidoo, M. 2019. Characterisation of ambient total gaseous mercury concentrations over the South African Highveld. *Atmospheric Pollution Research*, 10(1), 12–23. https://doi.org/10.1016/j.apr.2018.06.001

Burns, J., Boogaard, H., Polus, S., Pfadenhauer, L.M., Rohwer, A.C., van Erp, A.M., Turley, R. & Rehfuess, E. 2019. Interventions to reduce ambient particulate matter air pollution and their effect on health. *Cochrane Database Syst Rev.,* 205(5). https://doi.org/10.1002/14651858.cd010919.pub2

Buthelezi, S., Kapwata, T., Wernecke, B., Webster, C., Mathee, A. & Wright, C. 2019. Household fuel use for heating and cooking and respiratory health in a low-income, South African coastal community. *International Journal of Environmental Research and Public Health*, 16(4), 550. https://doi.org/10.3390/ijerph16040550

Carslaw, D.C. & Beevers, S.D. 2013. Characterising and understanding emission sources using bivariate polar plots and K-means clustering. *Environmental Modelling & Software,* 40(2013), 325-29. https://doi.org/10.1016/j.envsoft.2012.09.005

Chidhindi, P., Belelie, M., Burger, R., Mkhatshwa, G. & Piketh, S.J. 2019. Assessing the impact of Eskom power plant emissions on ambient air quality over KwaZamokuhle. *Clean Air Journal,* 29(1), 29–37. https://doi.org/10.17159/2410-972X/2019/v29n1a2

Cogho, E. 2019. *Source Apportionment of Hydrogen Sulphide at Elandsfontein in Mpumalanga Highveld.* Master of Science Thesis, Potchefstroom: North-West University.

Cox, L.A. 2023. What is an exposure-response curve? *Global Epidemiology,* 6(2023), 7-11. https://doi.org/10.1016/j.gloepi.2023.100114

DEA (Department of Environmental Affairs). 2009. *State of Air Report 2005*. DEA. [Online]. Available at: https://www.gov.za/sites/default/files/gcis_document/201409/state-air-report-2005.pdf

DEA (Department of Environmental Affairs). 2016. National Environmental Management Act, 1998 (Act No. 107 of 1998): Air Quality Offsets Guideline. *Government Gazette, No. 39833*. [Online]. Available at: https://cer.org.za/wp-content/uploads/2010/03/National-Environmental-Management-Act-107-1998-Air-quality-offsets-guideline-20160318-GGN-39833-00333.pdf

DEA (Department of Environmental Affairs). 2019. National Environmental Management: Air Quality Act, 2004 (Act No. 39 of 2004): Strategy to Address Air Pollution in Dense Low-Income Settlements. *Government Gazette, No. 42464*. [Online]. Available at: https://www.gov.za/sites/default/files/gcis_document/201905/42464gon666.pdf

Dickson, B., Van Horen, C. & Williams, A. 1995. *Low Smoke Fuels as a Solution to Household Air Pollution Problems: A Synthesis of Current Research.* Cape Town: Energy for Development Research Centre. University of Cape Town.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G. & Egami, R.T. 2002. The comparison of source contributions from residential coal and low-smoke fuels, using CMB modeling, in South Africa. *Environmental Science & Policy,* 5(2), 157–67. https://doi.org/10.1016/S1462-9011(02)00029-1

Eskom. 2019. *Applications for Suspension, Alternative Limits and/or Postponement of the Minimum Emissions Standards (MES) Compliance Timeframes for Eskom's Coal and Liquid Fuel Fired Power Stations*. ENV18-R245 rev 2.1. Eskom.

Eskom. 2024. *Air Quality Offsets Programme.* Eskom. [Online]. Available at: https://www.eskom.co.za/eskom-divisions/gx/air-quality-offsets-programme/

Fisher, S., Bellinger, D.C., Cropper, M.L., Kumar, P., Binagwaho, A., Biao Koudenoukpo, J., Park., Y., Taghian, G. & Landrigan, P.J. 2021. Air pollution and development in Africa: Impacts on health, the economy, and human capital. *The Lancet Planetary Health,* 5(10), e681-e688. https://doi.org/10.1016/s2542-5196(21)00201-1

Friedl, A., Holm, D.J.J., Kornelius, G., Pauw, C.J., Oosthuizen. R. & Van Niekerk, A.S. 2008. *Air Pollution in Dense, Low-Income Settlements in South Africa*. NOVA Institute for the DEAT on behalf of the Royal Danish Embassy.[16]

Guo, C., Zhang, Z., Lau, A.K.H., Lin, C.Q., Chuang, Y.C., Chan, J., Jiang, W.K., Tam, T., Yeoh, E.K., Chan, T.C., Chang, L.Y. & Lao, X.Q. 2018. Effect of long-term exposure to fine particulate matter on lung function decline and risk of chronic obstructive pulmonary disease in Taiwan: A longitudinal, cohort study. *The Lancet Planetary Health*, 2(3), e114-e125. https://doi.org/10.1016/s2542-5196(18)30028-7

Haywood, L.K., Kapwata, T., Oelofse, S., Breetzke, G. & Wright, C.Y. 2021. Waste disposal practices in low-income settlements of South Africa. *International Journal of Environmental Research and Public Health,* 18(15), 8176. https://doi.org/10.3390/ijerph18158176

Hersey, S.P., Garland, R.M., Crosbie, E. Shingler, T., Sorooshian, A. Piketh, S.J. & Burger, R. 2015. An overview of regional and local characteristics of aerosols in South Africa using satellite, ground, and modeling data. *Atmospheric Chemistry and Physics,* 15(8), 4259-78. https://doi.org/10.5194/acp-15-4259-2015

Hukkanen, A., Kaivosoja, T., Sippula, O., Nuutinen, K., Jokiniemi, J. & Tissari, J. 2012. Reduction of gaseous and particulate emissions from small-scale wood combustion with a catalytic combustor. *Atmospheric Environment,* 50(2012), 16–23. https://doi.org/10.1016/j.atmosenv.2012.01.016

---

[16] Throughout this book, there are references to unpublished Nova reports. Not all reports are public. Readers are advised to contact Nova should they need to consult these. Go to Nova.org.za for contact details.

IAEA (International Nuclear Information System). 1995. *Europäische Kommission. 1995. ExternE: Externalities of Energy: Vol. 2: Methodology:* [Method for Estimation of Physical Impacts and Monetary Valuation for Priority Impact Pathways]. *EUR 16521*. Luxembourg: Off. for Official Publ. of the Eur. Communities. [Online]. Available at: https://inis.iaea.org/records/3mhy4-42d26

IER (University of Stuttgart Institute of Energy Economics and Rational Energy Use). 2012. *IEHIAS - Integrated Environmental Health Impact Assessment System: The DPSEEA Framework*. IER. [Online]. Available at: https://www.ier.uni-stuttgart.de/en/research/projects/integrated-assessment/

Lakey, P.S., Berkemeier, T., Tong, H., Arangio, A.M., Lucas, K., Pöschl, U. & Shiraiwa, M. 2016. Chemical exposure-response relationship between air pollutants and reactive oxygen species in the human respiratory tract. *Scientific Reports*, 6(2016), 32916. https://doi.org/10.1038/srep32916

Lancet Planetary Health. 2022. The air that we breathe (editorial). *The Lancet Planetary Health*, 6(1), e1. https://doi.org/10.1016/S2542-5196(21)00350-8

Langerman, K.E. & Pauw, C.J. 2018. A critical review of health risk assessments of exposure to emissions from coal-fired power stations in South Africa. *Clean Air Journal,* 28(2), 68–79. http://dx.doi.org/10.17159/2410-972X/2018/v28n2a19

Langerman, K.E., Pauw, C.J., Smith, H.J. & Piketh, S.J. 2018. *Moving households to cleaner energy through air quality offsets*. Proceedings of the IEEE 2018 International Conference on the Domestic Use of Energy (DUE):1-8.

Language, B., Piketh, S.J., Wernecke, B. & Burger, R. 2016. Household air pollution in South African low-income settlements: A case study. In: S. Syngellakis (ed.) *WIT transactions on ecology and the environment,* 227–36. Billerica, MA: WIT Press. https://doi.org/10.2495/AIR160211

Leiman, A., Standish, B., Boting, A. & Van Zyl, H. 2007. Reducing the healthcare costs of urban air pollution: The South African experience. *Journal of Environmental Management,* 84(1), 27–37. https://doi.org/10.1016/j.jenvman.2006.05.010

Li, T., Zhang, Y., Wang, J., Xu, D., Yin, Z., Chen, H., Lv, Y., Luo, J., Zeng, Y., Liu, Y., Kinney, P.L. & Shi, X. 2018. All-cause mortality risk associated with long-term exposure to ambient $PM_{2.5}$ in China: A cohort study. *The Lancet Public Health,* 3(10), e470–e477. https://doi.org/10.1016/s2468-2667(18)30144-0

Lindeque, L.F., Burger, R.P. & Piketh, S.J. 2021. The health and economic benefits of reduced residential solid fuel burning on the South African highveld. *Atmosphere,* 12(11), 1405. https://doi.org/10.3390/atmos12111405

Matandirotya, N.R., Moletsane, S.D., Matandirotya, E. & Burger, R.P. 2022. State of ambient air quality in a low-income urban settlement of South Africa. *Scientific African,* 16(2022), e01201. https://doi.org/10.1016/j.sciaf.2022.e01201

Mathuthu, M., Dudu, V.P. & Manjoro, M. 2019. Source apportionment of air particulates in South Africa: A review. *Atmospheric and Climate Sciences,* 9(1), 100–113. https://doi.org/10.4236/acs.2019.91007

Moletsane, S., Lindeque, L.F., Language, B., Nkosi, N.C., Adesina, J., Burger, R.P., Mkhatshwa, G. & Piketh, S.J. 2021. Intra-urban variability of PM2.5 in a dense, low-income settlement on the South African highveld. *Clean Air Journal,* 31(1), 1–9. https://doi.org/10.17159/caj/2020/31/1.9413

Murray, M., Pauw, C.J. & Smith, H.J. 2023. *Evaluation of a Household Intervention Implementation in the Sasol Secunda Air Quality Offset Programme*. Proceedings of the 2023 NACA National Conference. Polokwane, Limpopo.

Mutahi, A.W., Borgese, L., Marchesi, C., Gatari, M.J. & Depero, L.P. 2021. Indoor and outdoor air quality for sustainable life: A case study of rural and urban settlements in poor neighbourhoods in Kenya. *Sustainability,* 13(4), 2417. https://doi.org/10.3390/su13042417

Muyemeki, L., Burger, R.P., Piketh, S.J., Language, B., Beukes, J.P. & Van Zyl, P.G. 2021. Source apportionment of ambient PM10-2.5 and PM2.5 for the Vaal Triangle, South Africa. *South African Journal of Science,* 117(5/6), 1–11. https://doi.org/10.17159/sajs.2021/8617

Naidoo, S., Piketh, S.J. & Curtis, C. 2015. *Domestic Fuel Combustion in Un-Electrified Low-Income Settlements in South Africa*. Proceedings of the International Emission Inventory Conference 2015 in San Diego. United States Environmental Protection Agency.

Nel, C.L. 2023. *Thermal Performance and Comfort in Subsidy Housing in South Africa.* Master's dissertation, Stellenbosch: Stellenbosch University. Available at: https://scholar.sun.ac.za/bitstream/handle/10019.1/127317/nel_thermal_2023.pdf

Nkosi, N.C., Burger, R.P., Pauw, C.J., Ayob, N. & Piketh, S.J. 2023. The impact of vehicle parameters on road PM10 vehicle resuspended emissions: A case in South African low-income settlement. *Clean Air Journal,* 33(2), 1–10. https://doi.org/10.17159/caj/2023/33/2.15497

Nkosi, C.N., Piketh, S.J., Burger, R.P. & Annergan, J.H. 2017. *Variability of domestic burning habits in the South African highveld: A case study in the KwaDela Township*. Proceedings of the 2017 International Conference on the Domestic Use of Energy (DUE), 23–29. Cape Town, South Africa: IEEE. https://doi.org/10.23919/DUE.2017.7931820

NWU (North-West University) 2024. *Coal Stove Project*. NWU Engineering. [Online]. Available at: https://engineering.nwu.ac.za/engineering/coalstove-project [Accessed: 12/09/2025].

Olaniyan, T., Dalvie, M.A., Röösli, M., Naidoo, R., Künzli, N., De Hoogh, K., Parker, B., Leaner, J. & Jeebhay, M. 2019. Asthma-related outcomes associated with indoor air pollutants among schoolchildren from four informal settlements in two municipalities in the Western Cape province of South Africa. *Indoor Air*, 29(1), 89–100. https://doi.org/10.1111/ina.12511

Ozil, F., Tschamber, V., Haas, F. & Trouvé, G. 2009. Efficiency of catalytic processes for the reduction of CO and VOC emissions from wood combustion in domestic fireplaces. *Fuel Processing Technology,* 90(9), 1053–61. https://doi.org/10.1016/j.fuproc.2009.03.019

Pant, P. & Harrison, R.M. 2012. Critical review of receptor modelling for particulate matter: A case study of India. *Atmospheric Environment,* 49(2012), 1–12. https://doi.org/10.1016/j.atmosenv.2011.11.060

Pauw, C.J., Murray, H.M. & Howard, M.A. 2022. The use of dirty fuels by low-income households on the South African highveld. *Clean Air Journal,* 32(1), 1–17. https://doi.org/10.17159/caj/2022/32/1.12508

Qhekwana, M.M. 2019. *Characterising Indoor and Ambient Particulate Matter in Kwazamokuhle, Mpumalanga.* PhD Thesis, North-West University (South Africa).

Rodseth, C., Notten, P. & Von Blottniz, H. 2020. A revised approach for estimating informally disposed domestic waste in rural versus urban South Africa and implications for waste management. *South African Journal of Science,* 116(1/2), 1–6. https://doi.org/10.17159/sajs.2020/5635

RSA (Republic of South Africa). 1965. *Atmospheric Pollution Prevention Act No. 45 of 1965*. [Online]. Available at: https://www.up.ac.za/media/shared/600/LAS%20Legislation/air-pollution-prevention-act_17-april-1965.zp53523.pdf

RSA (Republic of South Africa). 1998. National Environmental Management Act No. 107 of 1998 (NEMA). *Government Gazette, No. 19519*. [Online]. Available at: https://www.gov.za/sites/default/files/gcis_document/201409/a107-98.pdf

RSA (Republic of South Africa). 2004. National Environment Management: Air Quality Act No. 39 of 2004. *Government Gazette, No. 27318*. [Online]. Available at: https://www.gov.za/sites/default/files/gcis_document/201409/a39-04.pdf

Sasol. 2023a. *Sasol Submits Appeal to Minister of Forestry, Fisheries and Environment on National Air Quality Office Decision on Alternative Load-Based Emission Limit Application*. Sasol. [Online]. Available at: https://www.sasol.com/media-centre/media-releases/sasol-submits-appeal-minister-forestry-fisheries-and-environment-national-air-quality-office

Sasol. 2023b. *Sustainability Report for the year ended 30 June 2023*. Sasol. [Online]. Available at: https://www.sasol.com/sites/default/files/2023-09/SASOL%20Sustainability%20Report%20 2023%2020-09_0.pdf

Segakweng, C.K., Van Zyl, P.G., Liousse, C., Beukes, J.P., Swartz, J.S., Gardrat, E., Dias-Alves, M., Language, B., Burger, R.P. & Piketh, S.J. 2022. Measurement report: Size-resolved chemical characterisation of aerosols in low-income urban settlements in South Africa. *Atmospheric Chemistry and Physics,* 22(15), 10291–317. https://doi.org/10.5194/acp-22-10291-2022

Sepadi, M.M. & Nkosi, V. 2023. Health risk assessment of informal food vendors: A comparative study in Johannesburg, South Africa. *International Journal of Environmental Research and Public Health,* 20(3), 2736. https://doi.org/10.3390/ijerph20032736

Sorgnit, H.T. 1968a. *A Preliminary Study of Heating and Cooking Requirements of Urban Bantu.* Report at Fuel Research Institute of South Africa. CSIR. Available at: http://hdl.handle.net/10204/12876

Sorgnit, H.T. 1968b. *Testing of a Magazine Equipped Prototype of a Domestic Cooking and Heating Stove for the Smokeless Combustion of Bituminous Coals as Mined in South Africa*. Fuel Research Institute of South Africa. Technical Memorandum No. 3 of 1968. CSIR. Available at: http://hdl.handle.net/10204/12829

StatsSA (Statistics South Africa). 2022. *General Household Survey, 2021. Statistical Release P0318*. Statistics South Africa. https://www.statssa.gov.za/publications/P0318/P03182021.pdf.

Steyn, M., Claassen, N. & Forbes, P.B.C. 2023. Studies into the reduction of domestic fuel burning emissions by means of facile catalytic abatement technology. *Clean Air Journal,* 33(1), 1–8. https://doi.org/10.17159/caj/2023/33/1.14951

Tshehla, C. & Djolov, G. 2018. Source profiling, source apportionment and cluster transport analysis to identify the sources of PM and the origin of air masses to an industrialised rural area in Limpopo. *Clean Air Journal,* 28(2). https://doi.org/10.17159/2410-972x/2018/v28n2a18

Tshehla, C. & Wright, C.Y. 2019. 15 years after the National Environmental Management Air Quality Act: Is legislation failing to reduce air pollution in South Africa? *South African Journal of Science,* 115(9/10), 1–4. https://doi.org/10.17159/sajs.2019/6100

US-EPA (United States Environmental Protection Agency). 2023. *Exposure Assessment Tools by Media - Air.* EPA. [Online]. Available at: https://www.epa.gov/expobox/exposure-assessment-tools-media-air [Accessed: 11/09/2025].

Van den Berg, B. 2015. *Source Apportionment of Ambient Particulate Matter in Kwadela, Mpumalanga.* Master of Science Thesis, Potchefstroom: North-West University.

Van der Westhuizen, D., Howlett-Downing, C., Molnár, P., Boman, P., Wichmann, J. & Von Eschwege, K.G. 2024. Source apportionment of fine atmospheric particles in Bloemfontein, South Africa, using positive matrix factorization. *Environmental Monitoring and Assessment,* 196(2), 188. https://doi.org/10.1007/s10661-023-12293-4

Van Doornum, G.A.W. 1965. *Smokeless Combustion of Bituminous Coal Small Appliances. Fuel Research Institute of South Africa.* Technical Memorandum No. 17 of 1965. CSIR. Available at: https://researchspace.csir.co.za/dspace/bitstream/handle/10204/12865/Smokeless%20combusion%20of%20bituminous%20coal%20small%20appliances.pdf?sequence=1

Van Loggenberg, E. 2020. *Applicability of Analytical Techniques to Quantify Trace Metals in Particulate Matter for Source Apportionment in South Africa.* Dissertation submitted in partial fulfilment of the requirements for the degree Master of Science. North-West University.

Wagner, N.J., Schoonraad, P., Swanepoel, P., Van Niekerk, A.S, Scholtz, C., Kornelius, G., Julies, A., Pretorius, O., Wasserman, J. & Muller, A. 2005. *Results of Domestic Smoke Reduction Programmes at eMbalenhle (Mpumalanga) and Zamdela (Free State)*. Proceedings of the NACA Conference (Cape Town, 27-30 September 2005) [Conference Proceedings on CD-ROM], 1-16. Johannesburg: NACA. https://doi.org/10.13140/2.1.2485.4725

Walton, N. 2021. *Aerosol Source Apportionment in Southern Africa*. Master of Science Thesis, Potchefstroom: North-West University.

Walton, N.M., Piketh, S.J., Van Zyl, P.G., Maenhau, W., Burger, R.P., Language, B. & Formenti, P. 2021. Source apportionment of ambient fine and coarse aerosols in Embalenhle and Kinross, South Africa. *Clean Air Journal,* 31(2), 1–13. https://doi.org/10.17159/caj/2020/31/2.11980

Wang, Q. & Liu, S. 2023. The effects and pathogenesis of PM2.5 and its components on chronic obstructive pulmonary disease. *International Journal of Chronic Obstructive Pulmonary Disease,* 18(2023), 493–506. https://doi.org/10.2147/copd.s402122

Wang, X., Firouzkouhi, H., Chow, J.C., Watson, J.G., Carter, W. & De Vos, A.S.M. 2023. Characterization of gas and particle emissions from open burning of household solid waste from South Africa. *Atmospheric Chemistry and Physics,* 23(15), 8921–8937. https://doi.org/10.5194/acp-23-8921-2023

Wen, C.P. & Gao, W. 2018. PM☒.☒: An important cause for chronic obstructive pulmonary disease? *The Lancet Planetary Health,* 2(3), e105–e106. https://doi.org/10.1016/s2542-5196(18)30025-1

Wernecke, B., Burger, R.P., Language, B., Wright, C.Y. & Piketh, S.J. 2021. Quantifying potential particulate matter intake dose in a low-income community in South Africa. *Clean Air Journal,* 31(2). https://doi.org/10.17159/caj/2021/31/2.9426

Wernecke, B., Language, B., Piketh, S.J. & Burger, R.P. 2015. Indoor and outdoor particulate matter concentrations on the Mpumalanga highveld – A case study. *Clean Air Journal,* 25(2), 12–16. https://doi.org/10.17159/2410-972X/2015/v25n2a1

Xue, T., Wang, R., Tong, M., Kelly, F.J., Liu, H., Li, J., Li, P., Qiu, X., Gong, J., Shang, J. & Zhu, T. 2023. Estimating the exposure-response function between long-term ozone exposure and under-5 mortality in 55 low-income and middle-income countries: A retrospective, multicentre, epidemiological study. *The Lancet Planetary Health,* 7(9), e736–e746. https://doi.org/10.1016/s2542-5196(23)00165-1

Yadav, H., Kumar, P. & Singh, V.P. 2019. *Hazards from the Municipal Solid Waste Dumpsites: A Review*. Proceedings of the 1st International Conference on Sustainable Waste Management through Design, edited by Harvinder Singh, Prashant Garg, and Inderpreet Kaur, 21, 336–42. Lecture Notes in Civil Engineering. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-02707-0_39.

Yazdi, M.D., Wang, Y., Di, Q., Requia, W., Wei, Y., Shi, L., Benjamin Sabath, M., Dominici, F., Coull, B., Evans, J.S., Koutrakis, P. & Schwartz, J.D. 2021. Long-term effect of exposure to lower concentrations of air pollution on mortality among US Medicare participants and vulnerable subgroups: A doubly-robust [sic] approach. *The Lancet Planetary Health*, 10(2021), e689-e697. https://doi.org/10.1016/s2542-5196(21)00204-7