Impacts of Outdoor and Indoor Air Pollution on COVID-19 Health Outcomes and Interventions in the Southern African Development Community Region: A Scoping Review

By

Aleya Ramparsad Banwari

BNWALE001

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Supervisors: Prof Hanna-Andrea Rother

Dr Meryl Jagarnath

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Part A: Journal Ready Manuscript

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Authors: **Aleya Ramparsad Banwari[1], Meryl Jagarnath[2], Hanna-Andrea Rother[3]**

Abstract

Purpose of Review: The Southern African Development Community (SADC) faces high poverty and pollution levels, with nearly half of urban residents living in informal settlements. Research on air pollution's impact on COVID-19 in SADC is limited. This review explored how pollutants like fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and household air pollutants (HAP) affect COVID-19 severity. We examined outdoor and indoor exposures, noting that solid fuels and poor ventilation increase respiratory risks in low-income communities. We identified key pollutants, proposed mitigation strategies, highlighted knowledge gaps, and made recommendations for air quality management during and after pandemics.

Recent Findings: Of 331 studies, 19 met eligibility criteria, with 11 from SADC countries like South Africa, Zimbabwe, and Zambia. Findings indicate that prolonged exposure to $PM_{2.5}$ and NO_2 harms lung function, worsens asthma and chronic obstructive pulmonary disease (COPD), and increases COVID-19 hospitalisations and mortality. In many SADC informal settlements, poorly built structures limit ventilation, and burning biomass and paraffin indoors increases pollutant levels. Lockdowns may have reduced outdoor pollution, but indoor pollution increased, particularly harming vulnerable groups. Limited data from rural and low-income areas hinders thorough assessments of pollution-related health risks and the creation of effective, tailored policies.

Summary: The interplay of air pollution, socio-economic inequalities, and constrained healthcare capacity intensifies COVID-19 outcomes in the SADC region. To address these intertwined challenges, urgent cleaner energy transitions, enhanced air quality monitoring, and strategies to reduce household pollution are needed. Stronger local research will support evidence-based policymaking, strengthening public health and pandemic resilience.

Keywords: Air Pollution, COVID-19 Outcomes, Household Air Pollution (HAP), $PM_{2.5}$, SADC Air Pollution Interventions, Environmental Health Disparities

✉ Aleya Ramparsad Banwari
aleyaramparsadbanwari@gmail.com/BNWALE001@myuct.ac.za

[1] Environmental Health Division, School of Public Health, University of Cape Town, Cape Town, WC, RSA, ORCID ID: https://orcid.org/0000-0003-2871-1907
[2] Environmental Health Division, School of Public Health, University of Cape Town, Cape Town, WC, RSA, ORCID ID: https://orcid.org/0000-0003-1668-1675
[3] Environmental Health Division, School of Public Health, University of Cape Town, Cape Town, WC, RSA,ORCID ID: https://orcid.org/0000-0001-5292-8909

Introduction

According to the World Health Organisation (WHO), air pollution, both outdoor and indoor, is a major environmental risk factor responsible for an estimated seven million premature deaths each year globally. It contributes to numerous health conditions, including respiratory and cardiovascular diseases **[1].** Most of the evidence linking air pollution to COVID-19 outcomes comes from Europe, North America and China, where dense monitoring networks and electronic health records enable fine-scale analyses **[7, 8].** In Africa, air pollution accounts for approximately 800,000 premature deaths annually, with two-thirds attributed to particulate matter ($PM_{2.5}$) **[2].**

The Southern African Development Community (SADC) regional body, comprising sixteen member states—Angola, Botswana, Comoros, Democratic Republic of Congo, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Tanzania, Zambia, and Zimbabwe—faces severe air quality challenges driven by fossil fuel dependencies, industrial activities, and the widespread use of traditional fuels for cooking and heating. These factors contribute to both outdoor and indoor air pollution, which, in turn, exacerbate the health impacts of respiratory diseases, including COVID-19 **[3].** These pollution challenges have been further intensified by socio-economic factors, which often determine levels of exposure to harmful pollutants and access to healthcare in the SADC region.

COVID-19 is a critical case study for examining the health impacts of air pollution because the virus primarily affects the respiratory system. Long-term exposure to air pollution, particularly particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2), has been shown to weaken lung function, increase the risk of respiratory infections, and exacerbate pre-existing conditions such as asthma and chronic obstructive pulmonary disease (COPD) **[4].** These vulnerabilities heighten the severity of COVID-19 outcomes, including increased hospitalisations and mortality rates **[5].** This interplay is particularly concerning in the SADC region, where socio-economic disparities, reliance on polluting fuels, and limited healthcare access further amplify the risks **[6].** Understanding how air pollution contributes to COVID-19 severity can inform targeted interventions to reduce exposure and mitigate future health crises. Vulnerable populations, especially those living in low-resource settings, often face uneven exposure to these pollutants, which can result in disproportionate health impacts **[5].**

In the 2024 WHO Ambient Air Quality Database (version 6.1, January 2024), only four of the sixteen SADC member states—Madagascar, Mauritius, South Africa, and the United Republic of Tanzania—report any regulatory-grade $PM_{2.5}$ data for the period 2019-2021, covering just twenty-five monitored urban locations across the region **[9].** Consequently, researchers must rely mainly on satellite retrievals or short-term low-cost sensor campaigns, introducing greater exposure misclassification. Compounding this data gap are region-specific vulnerabilities — widespread solid-fuel use, high HIV/TB co-morbidity and extensive informal housing — that remain under-represented in global syntheses **[5, 33].** Although global studies link air pollution to worsened respiratory conditions **[6]**, reviews focused on the SADC region remain limited, highlighting a critical knowledge gap regarding air pollution's impact on COVID-19 health outcomes within this context.

Environmental injustice plays a critical role in amplifying these challenges. Vulnerable populations, particularly those in informal settlements, where an estimated 43% of the SADC region's urban population resides, as well as rural communities, face disproportionate exposure to air pollution due to systemic inequities, including limited access to clean energy, inadequate governance, and socio-economic vulnerabilities **[10].** The reliance on biomass fuels like wood, paraffin, and coal for cooking and heating among low-income households across the SADC region perpetuates a cycle of exposure to harmful pollutants, disproportionately affecting women and children **[11].** These communities also face exclusion from decision-making processes around energy transitions, highlighting procedural injustices in energy governance. This is because renewable energy transitions in Sub-Saharan Africa often prioritise large-scale infrastructure development over addressing local energy poverty, creating inequalities in resource distribution **[12].** A report by Climate Analytics in 2022 highlighted that a significant portion of international funding for renewable energy in Africa is directed towards large-scale projects intended for export or industrial use, resulting in underserved rural

communities **[11]**. This imbalance underscores the need for an energy transition grounded in distributive justice, where benefits are equitably shared, and procedural justice ensures local participation in policy and project decisions.

Specifically, significant gaps exist regarding how socio-economic disparities and local pollution sources compound the health impacts of air pollution, particularly in relation to infectious diseases such as COVID-19. The role of HAP, a significant issue in SADC countries due to the reliance on solid fuels, has also been underexplored. Studies such as Wright et al. (2022) and Kimemia et al. (2021) highlight that the widespread use of paraffin, wood, and coal for cooking and heating in low-income households contributes to high levels of HAP, exacerbating respiratory vulnerabilities [13, 14]. These findings underscore the pressing need to explore the full impact of HAP on health outcomes in the SADC region.

Although individual studies from low- and middle-income countries (LMICs) link air pollution exposure to worse respiratory outcomes, there is still no systematic synthesis of how outdoor and indoor pollutants have influenced COVID-19 infections and severity in the SADC region. This scoping review, therefore, maps the existing evidence and highlights the remaining research and policy gaps. This review investigated how specific environmental stressors, such as outdoor air pollution (e.g., particulate matter $PM_{2.5}$ and PM_{10}, NO_2) and indoor air pollution, affected COVID-19 outcomes in the SADC region. Prior research, including studies by Katoto et al. (2021) and Manisalidis et al. (2020), demonstrates that exposure to these pollutants exacerbates respiratory conditions, increasing susceptibility to severe COVID-19 outcomes **[5, 6].** This is particularly evident in areas with socio-economic vulnerabilities, where populations are disproportionately exposed to harmful pollutants.

This review synthesises available studies to highlight the role of $PM_{2.5}$, PM_{10}, and HAP in exacerbating respiratory conditions and worsening the severity of COVID-19, especially among vulnerable populations living in the SADC region. In addition to identifying knowledge gaps, we propose recommendations to guide air quality management during and after pandemics based on our findings.

Objectives

The aim of this scoping review was to investigate the relationship between air pollution—both indoor and outdoor—and COVID-19 health outcomes and interventions in the SADC region. Specifically, the study objectives were to:

1. Identify critical pollutants, such as particulate matter ($PM_{2.5}$, PM_{10}), nitrogen dioxide (NO_2), and household air pollutants (HAP), contributing to adverse COVID-19 outcomes.
2. Evaluate the burden of disease linked to these pollutants, focusing on infection rates, morbidity, and mortality, especially among vulnerable populations.
3. Develop evidence-based policy recommendations to mitigate air pollution exposure and its impact on public health during the COVID-19 pandemic and beyond.

Methods

Research Design

This review followed an adapted Arksey and O'Malley's six-stage methodological framework for scoping reviews, as detailed in the study proposal and research protocol (**Appendix A**) **[15]**. This study's protocol was registered as a project on the Open Science Foundation (OSF) with Identifier DOI 10.17605/OSF.IO/C5WU2. The study's data management plan was registered on UCT DMP and is in line with university procedures on data management planning. The six-stage methodological framework included identifying the research question, identifying relevant studies, selecting the study, charting the data, collating, summarising, and reporting the results. Given the focus and scope of

this study on data extraction and analysis, the sixth stage, stakeholder consultation, was excluded **[16]**. Stakeholder consultation, while advised, is an optional step in Arksey & O'Malley's framework and not essential for the primary objective of this desk-based scoping review - namely, mapping and synthesising the published evidence. Since no new data were collected, a formal consultation round would have necessitated separate ethics clearance and multi-country coordination (across SADC states with inconsistent internet access), diverting resources from systematic searching, charting, and analysis. In line with PRISMA-ScR guidance, we therefore limited the review to Stages 1–5 and report this decision transparently. To collect practitioner feedback pragmatically, we will distribute a two-page executive summary to the SADC Secretariat and their relevant network's mailing lists and invite written comments for incorporation into future work.

Identifying Relevant Studies

This scoping review included studies published in English from 2019 to 2024 that explored the relationship between air pollution and COVID-19 outcomes in SADC states. It focused on pollutants like $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3, assessing their effects on COVID-19 infections and mortality. Boolean searches were conducted in PubMed, Scopus, Web of Science Core, Africa-Wide, CINAHL, Google Scholar and the WHO COVID-19 database, combining four key concepts: exposure ("air pollution" OR $PM_{2.5}$ OR NO_2 OR SO_2 OR CO OR O_3), disease ("COVID-19" OR "SARS-CoV-2"), outcome (incidence OR hospitalisation OR mortality OR severity) and geography (all 16 SADC country names); database-specific synonyms and truncation were added as required. The full keyword strings appear in Appendix B. Appendix B contains supplementary tables and figures relevant to search terms and results, while Appendix C presents the Completed Data Charting Form that guided data extraction.

Eligible designs included randomised and non-randomised trials, case-control and cohort studies, correlational and ecological studies, meta-analyses, systematic reviews, case studies, reports, and news articles. Peer-reviewed articles and grey literature (e.g., WHO COVID-19 reports) were included, whereas opinion pieces, letters to editors, duplicates, and non-relevant sources were excluded. Ethics approval documentation can be found in Appendix D, and instructions from the target journal (Current Environmental Health Reports) are outlined in Appendix E.

While systematic reviews do not introduce novel primary observations, scoping reviews can accurately outline them when the objective is to map the concepts, sources, and types of evidence available, regardless of study design **[15]**. Contemporary guidance echoes this flexibility **[17].** Accordingly, two SADC-focused systematic reviews, Katoto et al. 2021 **[5]** and Mwiinde et al. 2022 **[18]**, remain in Table 1 and Table 2. They are explicitly flagged as systematic reviews and discussed narratively rather than treated as independent primary data. Their inclusion signals where evidence has already been synthesised and helps identify residual gaps, thereby helping to comprehensively map existing evidence and delineate the full landscape of available research.

Screening and Data Extraction

The authors developed a pre-defined data-charting form to determine critical variables for extraction, including study design, geographic location, and the burden of disease (see Table 1). This form ensured that the extracted data addressed the research objectives and evaluated the final eligibility of the articles identified. Based on discussions among the authors, the data-charting form was updated iteratively as new insights emerged during the literature review process. In addition to Table 1, Table 2 presents key findings, statistical evidence and policy implications of the included studies.

Data Collation and Analysis

The extracted data were analysed using a qualitative content analysis approach to identify recurring patterns and themes related to air pollution and COVID-19 health outcomes. This process was informed by the framework outlined in Arksey and O'Malley's six-stage scoping review methodology (2005) and further guided by Katoto et al.'s (2021) systematic review of air pollution impacts on respiratory health **[5, 21]**. The themes emerged through systematic

coding of study findings, with an initial inductive phase to identify commonalities, followed by a deductive phase where insights were categorised into pre-defined areas of interest based on the study objectives.

Four primary themes were identified: outdoor and indoor air pollution, socio-economic vulnerabilities and urban-rural disparities, climatic and environmental factors, and the impact of lockdown measures on air quality. These themes were derived through an iterative process that involved reviewing and coding data across included studies, mapping findings to the research objectives, and conducting thematic synthesis to consolidate key insights. The iterative refinement process included regular discussions among the authors to address coding or thematic categorisation discrepancies, ensuring consistency and reliability.

Study Selection Process

In total, 331 studies were identified, of which 19 met the inclusion criteria for analysis. These studies covered primary and secondary data sources. Citation tracking or snowballing was employed to identify new relevant papers using the reference lists of the included documents. Data extraction was conducted independently by the primary author (AB) and co-author (MJ).

This Scoping Review adheres to the PRISMA-ScR guidelines **[16]**, using the PRISMA-ScR checklist to document the search and study identification process, which has been adapted from Page et al. (2021) **[19].** The updated flow diagram (Figure 1) details the number of studies at each selection stage and illustrates database duplicates **[16]**. The flow diagram has been modified to account for studies identified through citation tracking **[20].** A comprehensive overview of included studies is provided in Table 1 and Table 2 (as well as in Appendix B).

This study utilised a backwards and forward citation tracking approach, which required the primary author to look at the reference lists of all included studies. These references were imported into Rayyan, and their abstracts were screened using the previously defined eligibility criteria to exclude irrelevant studies. The forward citation approach required the primary author to follow the same process for identifying any papers cited in the reviewed papers. The inclusion and exclusion criteria were applied to the new papers. This technique included and excluded studies, ensuring that additional papers contributing to the study's objectives were comprehensively assessed. PubMed was searched using the same strategy as Web of Science and Scopus, yielding 320 records. Following both automated and manual de-duplication, all PubMed citations were found to be duplicates already indexed in the other two databases. As a result, no unique studies were identified from PubMed, and these records were excluded to avoid redundancy.

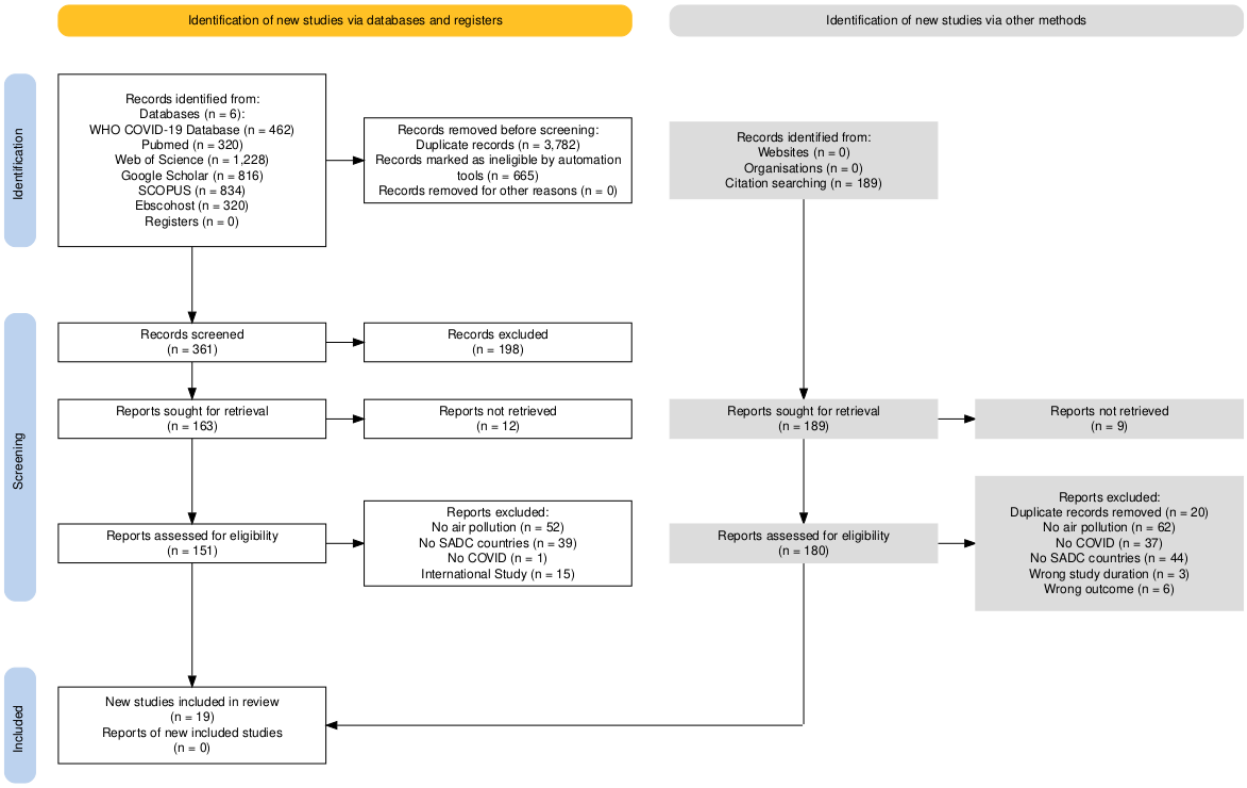

Fig 1. Modified Preferred Reporting Items for Systematic Reviews and Meta-analyses 2020 for Scoping Reviews (PRISMA-ScR)

Adapted from Haddaway, N. R., Page, M. J., Pritchard, C. C., & McGuinness, L. A. (2022). PRISMA2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis Campbell Systematic Reviews, 18, e1230. **[20]**

Results

Characteristics of Included Studies

Nineteen studies were included in this review after screening 331 records (see Table 1). Eleven studies specifically focused specifically on a SADC country, those being Angola **[5, 39],** Mozambique [14, **26, 31, 32]**, South Africa **[**13, 14, **27, 32, 39]** and Zambia **[18, 21]** The remaining eight studies referred to SADC nations as part of broader regional or global analyses without specifying individual countries. South Africa was prominently featured due to its relatively advanced air quality monitoring infrastructure, which provides valuable data on pollution trends, as highlighted by Katoto et al. (2021) and McFarlane et al. (2021) [5, 21]. Visual representations of the included studies are depicted in Figure 2 and Figure 3. Figure 2 maps the geographic coverage of the evidence base: 15 of the 18 studies originate from South Africa, with only scattered investigations elsewhere in the SADC region. Figure 3 summarises exposure coverage, showing that two-thirds of the studies measured $PM_{2.5}$, while other pollutants (PM_{10}, NO_2, SO_2, CO, black-carbon, PAHs) were examined less often.

Eleven studies (58%) emphasised the health impacts of HAP, particularly in low-income communities reliant on paraffin, wood, and coal. Additionally, six studies (32%) explored environmental factors, such as temperature and humidity, influencing COVID-19 transmission and severity. These studies provided critical insights into the interplay between pollution, climate, and health outcomes in the SADC region. Household air pollution (HAP) serves here purely as a broad term for the mixture of emissions from solid-fuel and paraffin usage; in all data-charting tables and

analyses, we refer to the specific constituents measured in each study (e.g., $PM_{2.5}$, CO, black carbon) to ensure pollutant-level precision. Specifically, Cambaza & Viegas (2020) highlighted the correlation between lower temperatures and increased COVID-19 cases in Mozambique **[34]**. Jenkins et al. (2023) demonstrated that seasonal variations in temperature and humidity influenced COVID-19 transmission in both West and Southern Africa **[24]**. Mwiinde et al. (2022) found that regions with higher particulate matter levels experienced compounded vulnerabilities due to climate and pollution interactions **[18].** Ogunjo et al. (2022) identified temperature and humidity as key environmental drivers of COVID-19 transmission in South African cities **[22]**. Yuan et al. (2021a) and Yuan et al. (2021b) reported non-linear relationships between temperature, humidity, and daily COVID-19 cases, noting that colder and drier climates increased transmission risks **[39, 40]**.

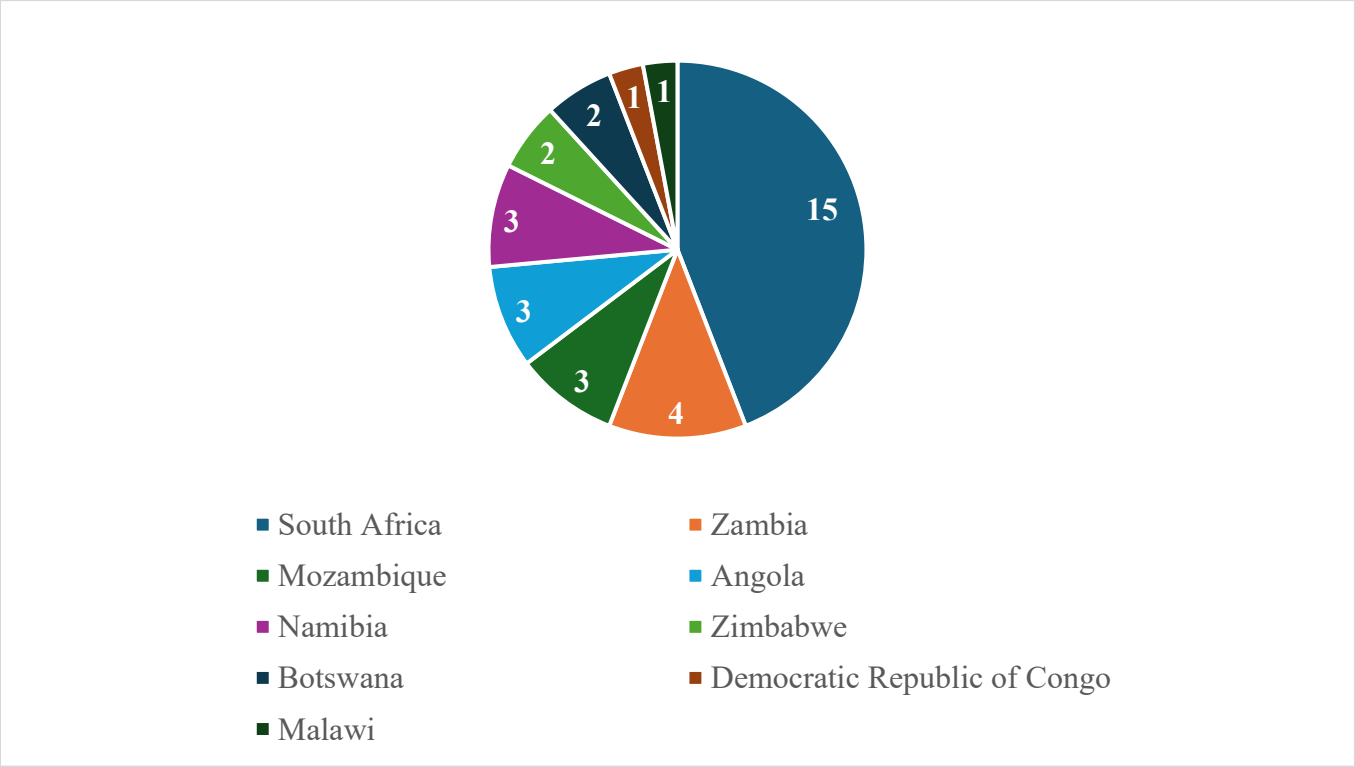

Fig 2. Distribution of Included Studies by Country

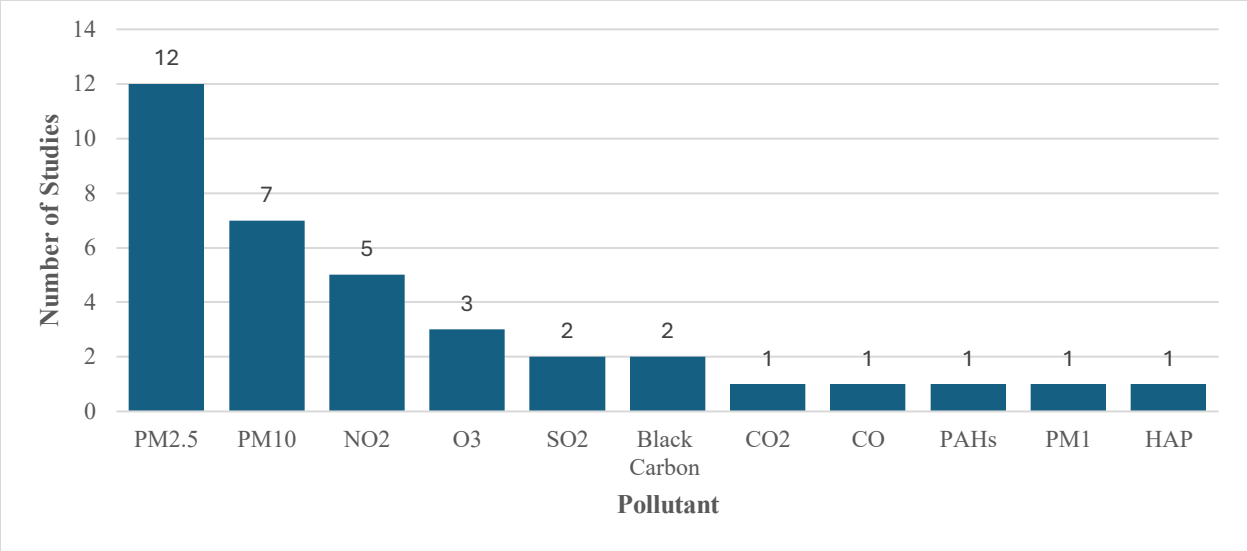

Fig 3. Pollutant Distribution of Studies

Association Between Air Pollution and COVID-19 Outcomes

The reviewed studies revealed significant associations between air pollution and COVID-19 outcomes in the SADC region (notably South Africa, Mozambique, Angola, and Zambia), highlighting the role of both outdoor and indoor pollutants in exacerbating the severity and transmission of COVID-19. However, data were limited or unavailable for the other 12 SADC member states, including Comoros, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Namibia, Seychelles, Tanzania, the Democratic Republic of Congo, Botswana, and Zimbabwe.

Of the 19 included studies, 12 (63%) examined $PM_{2.5}$, 10 (53%) examined NO_2, and 11 (58%) investigated HAP. The remaining studies explored a broader range of environmental factors (e.g., temperature, humidity) or focused on general air quality without specifying individual pollutants. Across the review, these pollutants—commonly stemming from industrial emissions, vehicular traffic, and solid fuel combustion—were consistently identified by the included authors as critical contributors to adverse COVID-19 outcomes, given their well-documented impacts on respiratory health.

For $PM_{2.5}$, Katoto et al. (2021) reported a significant association between chronic exposure to $PM_{2.5}$ and increased severity of COVID-19 outcomes, with a 10 µg/m³ increase in $PM_{2.5}$ linked to a 14% rise in mortality ($p < 0.05$) **[5].** Jenkins et al. (2023) found that elevated $PM_{2.5}$ levels intensified respiratory vulnerabilities in urban areas, correlating with increased hospitalisations and severe COVID-19 outcomes ($p < 0.05$) **[24]**. Lastly, Wright et al. (2022) observed that $PM_{2.5}$-related respiratory risks were exacerbated in low-income South African households during COVID-19 lockdowns, contributing to a significant rise in severe respiratory symptoms ($p < 0.01$) **[13].**

For NO_2, Mwiinde et al. (2022) reported that higher NO_2 levels, particularly in urban areas with dense traffic, were significantly associated with increased COVID-19 infection rates ($p < 0.01$) **[18],** McFarlane et al. (2021) observed a strong correlation between ambient NO_2 concentrations and higher rates of COVID-19 cases and mortality in Kinshasa and Brazzaville (DRC) ($p < 0.01$) **[21].** These findings underscore the importance of mitigating air pollution, particularly $PM_{2.5}$ and NO_2, to reduce the severity of COVID-19 outcomes and improve public health resilience in the SADC region.

Four key themes emerged regarding the relationship between air pollution and COVID-19 outcomes in the SADC region. These are (1) Outdoor and Indoor Air Pollution, (2) Socio-Economic Vulnerabilities and Urban-Rural Disparities, (3) Climatic and Environmental Factors, (4) Impact of Lockdown Measures.

Theme 1: Outdoor and Indoor Air Pollution

Outdoor Air Pollution

Eleven studies examined the effects of outdoor pollutants $PM_{2.5}$, PM_{10}, and NO_2 on COVID-19 outcomes. Urban areas such as Johannesburg (South Africa), Lusaka (Zambia), and Maputo (Mozambique) reported elevated levels of these pollutants, driven by dense traffic and extensive industrial activity. $PM_{2.5}$ was the most frequently studied pollutant. The findings also showed that NO_2 exacerbates airway inflammation, impairs lung function, and worsens COVID-19 symptoms [**5, 23**].

Katoto et al. (2021) found that long-term exposure to $PM_{2.5}$ exacerbated respiratory conditions and significantly increased vulnerability to severe COVID-19 outcomes **[5]**. In comparison, Jenkins et al. (2023) demonstrated how high $PM_{2.5}$ levels intensified respiratory symptoms in Southern African urban areas **[24]**. Similarly, Sang et al. (2022) conducted a global analysis showing that $PM_{2.5}$ exposure significantly increased respiratory vulnerability, particularly in LMICs like those in the SADC region **[23]**. McFarlane et al. (2021) identified a significant correlation between ambient $PM_{2.5}$ levels and increased COVID-19 infection rates in Kinshasa and Brazzaville (DRC). Thus highlighting the role of air pollution in exacerbating the spread of the virus **[21]**. Onafeso et al. (2021) analysed spatial and temporal trends of COVID-19 in Africa. They found a strong link between air pollution and increased case numbers in urban areas, particularly where $PM_{2.5}$ and other pollutants were prevalent **[33]**. While Yuan et al. (2021a) highlighted how long-term exposure to $PM_{2.5}$ significantly contributed to respiratory complications in Southern Africa **[40].**

Additional studies, such as World Bank (2022), emphasised the health burden of $PM_{2.5}$ in the SADC region, and Sumbana et al. (2020) found that $PM_{2.5}$ was a major contributor to respiratory illnesses. Sumbana et al. (2020) noted that mean urban $PM_{2.5}$ levels in Mozambique (~21 µg m³, double the WHO guideline) coexist with high prevalences of hypertension (14–33%) and obesity (18–31%). The authors argue that this combination of chronic pollutant exposure and comorbidities is likely to exacerbate the severity of COVID-19, even though clinical outcome data were not yet available at the time of their review [38, 26]. Cambaza & Viegas (2020) also highlighted the effects of particulate matter on respiratory health in Mozambique, particularly during COVID-19 [34]. Kimemia et al. (2021) demonstrated "worsened health" in informal-settlement households that rely on paraffin by documenting that more than 5 000 paraffin-related shack fires and almost 100 000 burn injuries recorded nationally each year, and toxicological evidence that paraffin combustion products impair lung function and increase the risk of tuberculosis and asthma exacerbations - clear indicators of both acute trauma and chronic respiratory harm [14]. Collectively, the epidemiological evidence demonstrates a clear dose-response association: higher ambient $PM_{2.5}$ levels correlate with increased COVID-19 infection, hospitalisation, and mortality rates. [5, 23]

In the SADC region, informal settlements that fringe busy roads and industrial zones, ambient $PM_{2.5}$ often reaches 45–65 µg m³ and roadside NO_2 approaches 50 µg m³, four to five times the WHO limits [21, 36]. Meta-analysis indicates that every 10 µg m³ rise in $PM_{2.5}$ is associated with a 14% increase in COVID-19 mortality [5]. These pollution-related risks are magnified by limited healthcare access: a recent narrative review reports that about 40% of people in Southern Africa—and one-third across Central, Eastern and Western Africa—live more than 30 minutes from a hospital able to deliver basic emergency surgery, with public facilities averaging only 0.5 per 100 000 population [37]. Thus, targeted interventions—such as cleaner energy options, enhanced ventilation, and robust air quality monitoring—are crucial for reducing the severity of COVID-19 among the most vulnerable urban populations in the SADC region.

Indoor Air Pollution

Indoor air pollution, particularly from paraffin, wood, coal, and other solid fuels, emerged as a dominant theme in 11 studies (58%). In urban informal settlements, paraffin and coal are frequently used for cooking and heating, whereas wood and biomass fuels are more prevalent in rural households [23]. Poor ventilation and reliance on these fuels consistently appeared as key risk factors. Wright et al. (2022) reported that $PM_{2.5}$-related respiratory risks were intensified in low-income South African households during COVID-19 lockdowns. They also demonstrated that HAP during lockdowns worsened respiratory symptoms in low-income households across four South African provinces [13]. Similarly, Sumbana et al. (2020) identified household fuel use as a significant contributor to severe respiratory outcomes in Mozambique [26].

Women, children, and the elderly—especially those living in informal settlements and impoverished rural areas—were most vulnerable to HAP, since they spend extended periods indoors in poorly ventilated dwellings. Wright et al. (2022) found a robust association between household air pollution exposure and acute respiratory morbidity: the 95% confidence intervals for dry cough (1.69–3.06), wet cough (1.30–2.68), and wheeze (1.25–2.55) all lie entirely above 1.0, with $p < 0.001$ for each symptom, indicating a significantly higher prevalence of these symptoms in paraffin or wood-using, smoke-exposed homes compared to electrified, smoke-free homes) [20]. Complementing these primary data, Mbandi (2020) cites Global Burden of Disease estimates of approximately 404,000 premature deaths per year in Africa attributable to household air pollution and models a 15% increase in COVID-19 mortality for every 1 µg m^3 rise in long-term $PM_{2.5}$, underscoring the severity pathway relevant to SADC informal settlement residents [32].

Although Deol et al. (2021) assessed ventilation in primary healthcare settings rather than residential buildings, their findings remain relevant, as the study focused on naturally ventilated, single-room structures similar to informal dwellings. The authors reported baseline ventilation rates of approximately 3–5 air changes per hour, which increased more than twofold after enlarging window openings, resulting in a modelled reduction in airborne infection risk exceeding 50%. These results highlight a practical, low-cost intervention potentially applicable to improving ventilation in informal housing within the SADC region. It also reinforces the broader point that inadequate ventilation significantly heightens airborne transmission risk, especially in high-density indoor environments [27]. This finding is relevant not only to clinics and hospitals but also to residential spaces, particularly informal homes, where overcrowding and limited air circulation can facilitate the spread of COVID-19.

In this study, the authors recommend improving ventilation standards in both healthcare facilities and households, including the introduction of basic structural modifications (e.g., larger windows and improved airflow design) that reduce indoor pollutant concentrations. Jenkins et al. (2023) further underscored how reliance on polluting fuels like paraffin and coal in poorly ventilated homes significantly exacerbated respiratory issues during the pandemic in West and Southern Africa [24]. Collectively, these studies show that substandard housing (e.g., cramped layouts, few or small windows, and reliance on polluting fuels) intensifies the risk of respiratory diseases; therefore, upgrading dwelling structures to ensure cross-ventilation, larger window areas, and cleaner domestic energy sources is essential for reducing adverse health outcomes in the SADC region.

Theme 2: Socio-Economic Vulnerabilities and Urban-Rural Disparities

Socio-economic Vulnerabilities

In informal settlements, where people often contend with poor ventilation, overcrowding, and reliance on polluting fuels, the infiltration of $PM_{2.5}$ poses disproportionate risks. Limited access to healthcare compounds these challenges. Socioeconomic factors, such as poverty, reliance on polluting fuels, limited access to healthcare, overcrowded living conditions, and lack of infrastructure for clean energy, were critical areas identified in exacerbating air pollution's health impacts during the COVID-19 pandemic. Eleven studies [5, 13, 14, 23, 24, 26, 27, **31, 32, 36, 39**] emphasised the heightened vulnerability of low-income populations in both urban informal settlements and rural communities.

While these groups share similar challenges—such as depending on paraffin, wood, and coal for cooking or heating—there are context-specific differences.

In urban informal settlements, overcrowding and inadequate ventilation compound the effects of HAP. Many dwellings are structurally substandard, making it difficult to introduce cleaner energy solutions even if they are affordable. Conversely, rural households often lack grid electricity and have limited economic opportunities, which leads to a heavy reliance on biomass fuels. In both settings, poverty restricts access to safer energy alternatives, amplifying respiratory health risks. This underscores that economic constraints and infrastructural deficits—whether in dense urban areas or sparsely populated rural regions—play a pivotal role in driving severe COVID-19 outcomes related to air pollution.

For instance, Katoto et al. (2021) highlighted that prolonged exposure to air pollutants like $PM_{2.5}$ disproportionately affects marginalised communities, increasing their susceptibility to severe COVID-19 outcomes **[5]**. Kimemia et al. (2021) and Wright et al. (2022) examined the socio-economic challenges faced by households relying on paraffin and biomass fuels, noting that these fuels not only exacerbate indoor air pollution but also pose risks of burns and carbon monoxide poisoning **[13, 14].** Jenkins et al. (2023) pointed to the lack of affordable alternatives to polluting fuels as a key barrier to reducing household air pollution, while Deol et al. (2021) highlighted the compounding effects of overcrowded living conditions and inadequate ventilation in informal settlements [**24**, **27**]. Cambaza & Viegas (2020) and Sumbana et al. (2020) stressed the role of limited access to healthcare in delaying treatment for respiratory conditions worsened by air pollution **[34, 26]**. Onafeso et al. (2021), Sang et al. (2022), and Yuan et al. (2021a) examined broader socio-economic inequalities, such as income disparities and regional disparities in air quality management, which leave low-income populations disproportionately exposed to harmful pollutants [**23, 36, 39].** Mbandi (2020) emphasised the disproportionate impact of both outdoor and indoor air pollution on vulnerable populations in Africa, especially in urban informal settlements, which led to worsened COVID-19 outcomes [**32].** Lastly, Kimemia et al. (2021) discussed the health consequences of paraffin use in South African informal settlements, emphasising the urgent need for policy interventions to mitigate the risks of HAP, which intensified COVID-19 risks **[14].**

Urban-Rural Disparity

Eight out of the nineteen included studies explicitly examined the disparities between urban and rural areas, identifying distinct pollution sources and socio-economic challenges. While formal urban centres generally experience higher levels of ambient air pollution from industrial activities and vehicular traffic (particularly Johannesburg and Harare), large informal settlements within these cities also face pronounced HAP due to overcrowded living conditions and insufficient infrastructure. This exacerbates health disparities and affects access to healthcare services **[18, 26, 36, 38]**. The World Bank (2022) reported that $PM_{2.5}$ pollution significantly contributed to the global disease burden, with over 400,000 premature deaths attributed to pollution annually in Africa. The report emphasised that air pollution worsened health outcomes during the COVID-19 pandemic, particularly in urban areas, and called for international cooperation to invest in cleaner energy alternatives [38]. Mwiinde et al. (2022) analysed country-level temperature, humidity, and satellite-derived $PM_{2.5}$ data for Zambia, Botswana, and South Africa, linking cooler, particle-rich conditions to higher COVID-19 growth rates. However, since the environmental and case datasets were available only as national aggregates—sourced mainly from urban monitoring stations—the study did not distinguish urban from rural transmission patterns; therefore, its findings should be interpreted at the country level rather than the settlement scale [18].

Long-term exposure to ambient pollution further worsened health disparities in urban areas such as Johannesburg and Harare. In Johannesburg, Onafeso et al. (2021) highlighted high $PM_{2.5}$ levels due to industrial emissions and vehicular traffic associated with increased COVID-19 morbidity and mortality rates **[36]**. Similarly, Katoto et al. (2021) found that Harare's elevated NO_2 levels, primarily from urban traffic congestion and fossil fuel combustion, significantly

contributed to respiratory vulnerabilities and severe COVID-19 outcomes **[5]**. While facing lower ambient pollution levels, rural areas struggled with inadequate healthcare access and continued reliance on HAP from solid fuels such as paraffin, wood, and coal. Jenkins et al. (2023) found that the use of these fuels in poorly ventilated homes exacerbated respiratory conditions in both urban informal settlements and rural communities across SADC countries **[24]**.

Theme 3: Climatic and Environmental Factors

Six studies explored the influence of environmental factors, such as temperature and humidity, on COVID-19 transmission and severity. Cambaza & Viegas (2020) highlighted the link between lower temperatures and higher COVID-19 cases in Mozambique **[34]**. Yuan et al. (2021a) and Yuan et al. (2021b) examined non-linear relationships between temperature, humidity, and COVID-19 outcomes, finding that colder, drier climates increased transmission risks in SADC countries like South Africa and Botswana **[39, 40]**. Ogunjo et al. (2022) found similar associations in South Africa and Nigeria, emphasising the combined impact of climatic stressors and pollution exposure **[22]**. Mwiinde et al. (2022) provided a broader African perspective, noting that regions with higher particulate matter levels experienced compounded vulnerabilities due to climate and pollution interactions **[18].** These studies, including Katoto et al. (2021) and Jenkins et al. (2023), emphasised the importance of stricter emissions regulations, investments in clean energy solutions, and enhanced air quality monitoring infrastructure as necessary climate-adaptive public health measures **[5, 24]**.

Theme 4: Impact of Lockdown Measures on Air Quality

Lockdown measures during COVID-19 demonstrated the potential for pollution reduction through decreased industrial and vehicular activity. The temporary reduction in outdoor air pollution during lockdowns, noted, for example, Fu et al. (2020) and Cárcel-Carrasco et al. (2022) observed significant reductions in $PM_{2.5}$, NO_2, and SO_2 levels in urban centres (such as Johannesburg) during lockdowns, correlating with improved respiratory health outcomes **[35, 25].** Yet, these improvements were short-lived, rebounding after restrictions were lifted. Jenkins et al. (2023) highlighted the temporary nature of these gains, noting that pollution levels rebounded once restrictions were lifted, reinforcing the need for sustainable long-term interventions **[24]**. They found that reduced movement led to lower pollution levels in urban centres, correlating with reduced COVID-19 severity **[18].** Lastly, Sumbana et al. (2020) explored the complex interactions between air pollution, poverty, and healthcare access in Mozambique, concluding that air pollution, compounded by non-communicable diseases, significantly worsened COVID-19 outcomes [**26**]

Table 1: Characteristics of the Included Studies, Reported Air Quality Variables, and Associated COVID-19 Health Outcomes

Author	Study Design	Study Period	Location	Air-quality variables (Pollutants + Quantitative Measurements Reported)	Burden of Disease
Cambaza & Viegas (2020) [34]	Observational	March-May 2020	Mozambique	None, the paper only looks at temperature and atmospheric pressure as meteorological drivers of COVID-19, with no air-pollutant data.	COVID-19 cases were higher during cooler temperatures in central Mozambique.
Cárcel-Carrasco et al. (2022) [25]	An observational and analytical study using data from multiple cities	January - September 2020 (Data from during and post-COVID-19 lockdowns), compared to historical air pollution data from 2014 - 2019 during the same months	Global analysis, including Johannesburg, South Africa, as the only SADC city studied. Other cities included Hong Kong, Los Angeles, London, São Paulo, Bangalore, and Sydney.	Pollutants: NO_2, PM_{10} Johannesburg's mean fell from approximately 20 µg m³ (2014-19 average) to below 2 µg m³ during the Level 5 lockdown. PM_{10} in Johannesburg decreased from 26 µg m³ to 21 µg m³. No $PM_{2.5}$ data is reported.	Global data analysis shows that restricted mobility during COVID-19 lockdowns temporarily lowered air pollution levels but revealed chronic exposure in some cities.
Deol et al. (2021) [27]	Comparative study of two different methods for estimating room ventilation rates	Not specified	Clinics situated in high TB and HIV prevalence settings in the Western Cape and KwaZulu-Natal, South Africa	Pollutants: CO_2 used as an indoor proxy gas to estimate ventilation. No other pollutants are measured. Mean indoor CO_2 levels range from 397 to 505 ppm across the two ventilation set-ups, with corresponding air change rates of 3 to 11 h^{1} and a total flow of 2,407 to 2,743 L s^{1}.	Improper ventilation contributes to the spread of airborne diseases like COVID-19, particularly in confined indoor spaces.
Fu et al. (2021) [35]	Observational and analytical	January – April 2020	20 cities globally, including Johannesburg, South Africa, as the only SADC city studied	Pollutants: $PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3 For Johannesburg (Jan–Apr 2020 compared to the 2016-19 baseline): $PM_{2.5}$ decreased by 31.3 %; PM_{10} decreased by 27.6 %; NO_2 decreased by 28.9 %; SO_2 decreased by 18.9 %; O_3 increased by 11 %	Reduced respiratory burden during lockdown due to improved air quality.

Jenkins et al. (2023) [24]	Observational study using satellite data and sensor measurements.	January 2020 – March 2021	Southern and West African countries, including Angola and Namibia.	Pollutants: $PM_{2.5}$ Satellite and low-cost ground sensors were used across South and West Africa to measure pollution. These are some of their mean $PM_{2.5}$ concentrations: Praia 13.3 µg m³; Dakar 22.5 µg m³; Ibadan 70.9 µg m³; Luanda 23.6 µg m³; Windhoek 10.5 µg m³; Johannesburg 27.1 µg m³; Cape Town 15.0 µg m³; Lusaka 22.7 µg m³; Harare 14.1 µg m³; Gaborone 8.7 µg m³.	Despite temporary improvements in air quality, the underlying burden of disease from chronic air pollution exposure remains high.
Katoto et al. (2021) [5]	Systematic Review and Meta-Analysis	December 2019 – September 2020	Analysis of global data with a focus on African regions, including South Africa and urban areas within the SADC region, such as Johannesburg and Lusaka	Pollutants: $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2 The review pooled 25 primary studies and harmonised risk estimates to a 10 µg m³ increment. A rise of that magnitude in $PM_{2.5}$ was associated with a 5% increase in short-term COVID-19 incidence (RR 1.05, 95%) and an 11% rise in long-term mortality (RR 1.11). Comparable increments resulted in a 3% higher incidence for PM_{10} (RR 1.03), 6% for NO_2 (acute RR 1.06; chronic RR 1.06), and 2% for O_3 (RR 1.02). Evidence for SO_2 was sparse, and the authors did not meta-pool it due to inconsistent findings.	Populations in African regions with high air pollution levels face a higher burden of respiratory diseases.
Kimemia et al. (2021) [14]	Literature Review and Policy Analysis	Not specified, cross-sectional in nature	South Africa, focusing on urban informal settlements	Pollutants: $PM_{2.5}$, PM_{10}, black-carbon/soot, carbon monoxide (CO) and polycyclic aromatic hydrocarbons (PAHs) emitted by household paraffin stoves. The article presents a policy viewpoint rather than a field study, summarising earlier monitoring instead of new data. It notes that indoor $PM_{2.5}$ often reaches 100 to 150 µg m³ in paraffin-using informal dwellings—about four to six times the WHO guideline—and highlights cooking-time CO spikes exceeding 35 ppm in poorly ventilated rooms. These figures demonstrate the significant household air pollution burden for paraffin users. No additional numeric concentrations for pollutants are provided in the paper.	Respiratory illnesses associated with paraffin use increase the burden on healthcare systems during the COVID-19 pandemic.

Mbandi (2020) [32]	Literature Review	March – June 2020	Southern Africa, including South Africa, Zimbabwe, and Zambia	Pollutants: $PM_{2.5}$, PM_{10}, NO_2, O_3 and household-fuel smoke/black-carbon aerosols from biomass and kerosene use. This three-page commentary does not provide new concentration data on polluatnts. It notes that: ambient $PM_{2.5}$ in many African capitals routinely exceeds the WHO 10 µg m³ guideline by five to eight times; indoor cooking with solid fuels or paraffin can drive 24-h $PM_{2.5}$ exposures of about 100-150 µg m³; episodic biomass-burning and traffic emissions contribute to chronic particulate and NO_2 burdens. While high-ozone episodes are increasingly observed in the Global South. No additional numeric values beyond these ranges are provided.	Worsening COVID-19 outcomes linked to air pollution, especially in low-income settings.
McFarlane et al. (2021) [21]	Observational study using low-cost sensors for $PM_{2.5}$ measurement	January 2018 - August 2020	Kinshasa (Democratic Republic of Congo) and Brazzaville (Republic of Congo). Model site: Kampala (Uganda)	Pollutants: $PM_{2.5}$ Kinshasa's annual mean for 2019 was 43.5 µg m³; the network-wide mean from 2018 to 20 was 46.1 µg m³; the median daily level was 42.1 µg m³; during the lockdown period, $PM_{2.5}$ levels were 14.7 µg m³, approximately 40 % lower; peaks exceeded 180 µg m³ on biomass-burning days.	Highlights that $PM_{2.5}$ levels in African cities like Kinshasa (43.5 µg/m³ in 2019) significantly exceed the WHO guideline of 10 µg/m³. This indicates a disproportionately higher regional air pollution burden than global standards.
Mwiinde et al. (2022) [18]	Systematic Review and Meta-Analysis	13 February 2020 – 11 November 2022	Focused on Zambia, Botswana, and South Africa	Pollutants: $PM_{2.5}$ This review is mainly meteorological, but cites $PM_{2.5}$ burden statistics. It does not include any pollutant metrics.	The review highlights that Africa may experience higher COVID-19 morbidity due to environmental factors.

Ogunjo et al. (2022) [22]	An observational study was conducted using linear and quantile regression analyses and the Granger causality test.	7 March 2020 – 30 June 2021	Pretoria and Cape Town (South Africa)	Pollutants: PM_1, $PM_{2.5}$, PM_{10} This paper examined air pollution alongside the meteorological drivers of SARS-CoV-2. The daily means for each South African city during the study period are as follows: Cape Town – $PM_{2.5}$ 7.89 µg m^3, PM_{10} 9.45 µg m^3, PM_1 4.37 µg m^3; Pretoria – $PM_{2.5}$ 30.02, PM_{10} 34.21, PM_1 22.43 µg m^3. The Level-1 lockdown reduced $PM_{2.5}$ by 43.7% in Pretoria and 26.7% in Cape Town.	Identifies temperature and humidity as potential environmental drivers of COVID-19 transmission.
Onafeso et al. (2021) [36]	Geographical Trend Analysis	February – August 2020	Africa-wide, with emphasis on urban centres in South Africa, Mozambique, and Zimbabwe	Pollutants: $PM_{2.5}$ This geographic trend analysis indicated higher urban cases where $PM_{2.5}$ levels are elevated. However, no numerical values for pollutants were noted.	Increased COVID-19 mortality in highly polluted urban areas.
Sumbana et al. (2020) [26]	Observational and analytical review of epidemiological data and risk factors related to COVID-19 severity	22 March – 24 April 2020	Mozambique, focusing on provinces like Maputo and Cabo Delgado	Pollutants: $PM_{2.5}$, PM_{10} This narrative review for Mozambique cites pollution as a risk factor for contracting SARS-Cov-2, especially exposure to $PM_{2.5}$ and PM_{10} from biomass and kerosene in areas with poor ventilation. However, no quantitative pollutant levels are provided.	The study identified a high burden of respiratory infections due to air pollution, increasing the risk of severe COVID-19 symptoms.
Sang et al. (2022) [23]	Systematic analysis using Global Burden of Disease Study 2019 data	Longitudinal data from 1990 - 2019	Global study including SADC countries such as South Africa, Angola, and Namibia	Pollutants: $PM_{2.5}$ The Global Burden of Disease estimate for 2019 found that ambient $PM_{2.5}$ levels exceeded 25 µg m^3 in every SADC country studied.	The study finds a significant disease burden attributable to air pollution in low- and middle-income countries.
Wright et al. (2022) [13]	Cross-sectional survey	29 October 2020 – 2 December 2020	Four provinces in South Africa (Gauteng, Western Cape, KwaZulu-Natal, and Eastern Cape)	Pollutants: Household-air-pollution (biomass smoke) This survey focusing on households attributes respiratory risk to household air pollution from solid fuel and paraffin smoke, as well as environmental tobacco smoke. Since this is a survey paper, there are no numerical pollutant values.	High levels of household air pollution correlate with worsened respiratory health, leading to more severe COVID-19 outcomes in South Africa.

World Bank (2022) [38]	Global Health Analysis	2021	Africa-wide analysis with SADC-specific references to South Africa, Zambia, and Malawi	Pollutants: $PM_{2.5}$ (ambient & household) The population-weighted ambient $PM_{2.5}$ in Sub-Saharan Africa is approximately 43 µg m³ (2019). Typical household exposure to solid fuels is around 140 µg m³, and 81% of the population in SSA relies on solid fuels.	Air pollution significantly worsened health outcomes during COVID-19, especially in urban areas.
Yuan et al. (2021) [39]	Time series analysis using generalised additive models (GAM)	January – December 2020	138 countries globally, including South Africa, Botswana, and Namibia	Pollutants: None Core variables include meteorological factors such as temperature, humidity, and wind; air pollution is only mentioned in the background – no pollutant dataset has been analysed.	Higher COVID-19 case counts linked to meteorological factors.
Yuan et al. (2021) [40]	Non-linear analysis	January – August 2020	127 countries globally, including South Africa and Angola.	Pollutants: None Similar to the study above: assesses temperature, relative humidity, and wind speed; no air pollutant measurements.	Higher COVID-19 transmission rates correlated with low temperature and humidity levels.

Table 2: Statistical Evidence and Key Findings on Air Quality and COVID-19 Links

Author	Main Findings & Health Outcomes	Criteria Pollutant Exposure & COVID-19	Statistical Test Used	Confidence Intervals (Cis)	Key Conclusions & Policy Implications
Cambaza & Viegas (2020) [34]	Association between temperature, atmospheric pressure, and COVID-19 cases. Lower temperatures correlated with higher COVID-19 cases in certain regions of Mozambique	Temperature and atmospheric pressure are the main environmental drivers of COVID-19 transmission	Spearman and Pearson correlations; simple linear regression	*None.* The results table gives Spearman ρ values and p-values only.	Emphasises localised research on meteorological factors in disease transmission. Recommends upgrading health infrastructure and real-time weather monitoring for early intervention.
Cárcel-Carrasco et al. (2022) [25]	The impact of mobility restrictions during the COVID-19 pandemic on air pollution levels in various cities, including South Africa.	COVID-19 lockdowns caused a short-term reduction in air pollution levels, although long-term pollution remained an issue.	Descriptive statistics; paired **t**-test / Wilcoxon signed-rank for pre- vs. post-lockdown means.	*None.* Lock-down vs. baseline pollutant means presented as percentage change; no CIs	Calls for evaluating long-term health impacts of lockdown measures on air pollution and respiratory outcomes, including whether restrictions effectively reduce pollution.

Deol et al. (2021) [27]	Compared different ventilation techniques for reducing airborne transmission risks, especially for viruses like COVID-19, in indoor settings.	Ventilation rates affect indoor air quality and reduce airborne transmission risks, particularly for viruses like COVID-19.	Tracer-gas decay method; paired *t*-tests; bootstrap resampling to derive the 95 % CI.	Ventilation rates shown with 95 % CIs around mean air-changes-per-hour (ACH), e.g. 0.8 ACH (0.6 – 1.0) for naturally ventilated rooms.	Advocates for improved ventilation standards in high-risk areas by updating building codes and implementing cost-effective solutions to reduce airborne transmission.
Fu et al. (2021) [35]	Significant reductions in $PM_{2.5}$, NO_2, and SO_2 during lockdowns in Johannesburg led to better air quality and fewer respiratory complaints.	$PM_{2.5}$ and NO_2 levels dropped significantly in urban areas during the lockdown.	Mann–Whitney U; Kruskal–Wallis ANOVA on pollutant medians.	*None.* Figures show median and inter-quartile range; tables quote %-reductions without CIs.	Recommends sustainable post-lockdown strategies—cleaner transport, stricter industrial standards, and expanded renewable energy—to maintain respiratory gains from lockdown.
Jenkins et al. (2023) [24]	Air quality improved during the pandemic-related lockdowns, but the long-term effects of air pollution on respiratory health remain concerning.	Criteria Pollutants: $PM_{2.5}$, NO_2; COVID-19: Decrease in pollution levels during lockdowns correlated with reduced COVID-19 hospitalisations.	Season-stratified multiple linear regression; generalised least squares; Kendall τ trend tests.	*None.* City means given without intervals; regression slopes reported with p-values only.	Emphasises the insufficiency of temporary lockdown improvements, urging sustained emission reductions and expanded air quality monitoring for evidence-based policymaking.
Katoto et al. (2021) [5]	A correlation between chronic exposure to air pollution and heightened vulnerability to respiratory infections, including COVID-19, was reported.	Criteria Pollutants: $PM_{2.5}$, O_3; COVID-19: Strong correlation between air pollution and susceptibility to severe COVID-19 outcomes.	Random-effects meta-analysis (DerSimonian-Laird); Higgins I^2; Begg & Egger bias tests.	Pooled random-effects meta-analytic 95 %CIs, e.g.: $PM_{2.5}$—RR 1.05 (1.02-1.07) short-term; RR 1.11 (1.02-1.21) long-term (per 10 µg m^3).	Supports stricter urban emissions standards, clean air policies targeting $PM_{2.5}$ and O_3, and regional collaboration to tackle shared pollution challenges across Africa.
Kimemia et al. (2021) [14]	Review of the dangers of paraffin used for cooking and its socio-economic and health effects, particularly respiratory diseases in South African households, which may worsen COVID-19 outcomes.	Criteria Pollutants Present: Paraffin use for cooking contributes to indoor air pollution, exacerbating respiratory illnesses and COVID-19 symptoms.	Narrative synthesis only	*None.* Commentary only; cites earlier monitoring work but no new estimates.	Urges cleaner household energy transitions and stricter paraffin regulations. Highlights affordable LPG/electricity solutions for protecting vulnerable populations.

Mbandi (2020) [32]	Both outdoor and indoor pollution are linked to worsened COVID-19 outcomes, especially in informal settlements. Indoor pollution from solid fuel use contributed to an increased risk of severe respiratory outcomes.	$PM_{2.5}$, NO_2, and HAP all contributed to increased respiratory infections and COVID-19 severity.	Narrative review only	None. Commentary only.	Calls for cleaner cooking fuels, stricter emissions standards, and improved air quality monitoring in low-income areas to mitigate disproportionate air pollution burdens.
McFarlane et al. (2021) [21]	Detected high $PM_{2.5}$ levels in Kinshasa and Brazzaville, exceeding WHO guidelines. · Observed significant reductions in $PM_{2.5}$ during COVID-19 lockdowns. Focused on the impact of lockdowns on $PM_{2.5}$ levels but does not directly measure COVID-19 infections	Criteria Pollutants Present: $PM_{2.5}$ COVID-19: The study discusses the impact of COVID-19 lockdowns on $PM_{2.5}$ levels but does not measure COVID-19 infections directly.	Descriptive time-series; LOESS smoothing; no hypothesis tests.	*None.* Daily means ± SD; no CIs.	Stresses urgent expansion of urban air monitoring in Kinshasa/Brazzaville. Encourages reducing household fuel usage and adopting clean energy solutions to mitigate $PM_{2.5}$ pollution.
Mwiinde et al. (2022) [18]	Climatic and environmental factors, particularly temperature, are associated with COVID-19 transmission and severity.	COVID-19: The review finds that temperature may influence COVID-19 severity but does not directly connect air pollution to the disease.	Systematic-review methods (PRISMA); no meta-analysis.	The review reproduces 95% CIs from individual studies (e.g. OR 1.19 [1.05–1.35]) but does not pool them.	Encourages further research on pollution–climate–health linkages. Recommends integrating environmental and public health policies in temperature-sensitive regions.
Ogunjo et al. (2022) [22]	Association between weather parameters and SARS-CoV-2 transmission in multiple regions with significant regional variation. The highest correlation was observed with temperature and humidity.	Criteria Pollutants: None explicitly mentioned. COVID-19: The study identifies weather patterns that contribute to COVID-19 transmission.	Linear and quantile regression; Granger-causality tests; Pearson r.	Regression β for temperature on cases is 0.018 (95 % CI 0.006–0.030); humidity β is –0.012 (–0.019 to –0.004). The PM models list coefficients with p values only.	Recommends incorporating weather factors into public health strategies and gathering region-specific data for more targeted COVID-19 interventions.

Onafeso et al. (2021) [36]	Found spatial and temporal variations in COVID-19 case trends across African countries. Higher temperatures were associated with fewer cases, whereas air pollution was associated with higher case numbers in urban areas.	$PM_{2.5}$ and other pollutants were correlated with higher COVID-19 case counts in cities.	Geographically weighted regression; Getis–Ord Gi* hot-spot analysis.	*None.* Spatial regression βs given without CIs; significance at $p < 0.05$.	Underscores urban air pollution's link to higher COVID-19 mortality. Suggests cleaner energy solutions and robust urban air quality management to address disparities.
Sumbana et al. (2020) [26]	Reviewed the correlation between air pollution and risk factors, suggesting a possible buffer effect against the severity of COVID-19 in certain regions.	COVID-19 lockdowns caused a short-term reduction in air pollution levels, although long-term pollution remained an issue.	Qualitative synthesis.	*None.* Narrative risk-factor overview, no CIs	Highlights household air pollution's impact on respiratory risks. Calls for cleaner energy transitions and expanded monitoring in Mozambique.
Sang et al. (2022) [23]	This global burden of disease analysis links air pollution to increased mortality from respiratory infections, including COVID-19.	Criteria Pollutants: $PM_{2.5}$, NO_2; COVID-19: Clear evidence of heightened mortality due to air pollution in individuals with COVID-19.	Bayesian hierarchical Global Burden of Disease (GBD) framework with CODEm ensemble; Monte-Carlo posterior sampling	The total deaths attributed to ambient $PM_{2.5}$ in 2019 totalled 4.14 million (95% UI 3.71 – 4.58 million).	Advocates for global action—including renewable energy and emissions standards—to reduce pollution-driven respiratory mortality in LMICs, including COVID-19 cases.
Wright et al. (2022) [13]	Cross-sectional analysis linking household air pollution to increased respiratory infections and worsened COVID-19 symptoms in South African populations**.**	Criteria Pollutants Present: Household air pollution (HAP). COVID-19: Increased severity of respiratory infections from air pollution worsened COVID-19 outcomes in South Africa.	Multivariable logistic regression; Rao-Scott χ^2 for survey data.	Adjusted odds ratio for wheeze with HAP aOR 1.42 (95 % CI 1.11–1.82).	Promotes cleaner cooking technologies and sustainable household energy to curb indoor air pollution, with an emphasis on public awareness in vulnerable communities.

World Bank (2022) [38]	Found that $PM_{2.5}$ pollution contributes significantly to the global disease burden, with over 400,000 premature deaths attributed to pollution annually in Africa.	$PM_{2.5}$ exposure is linked to higher mortality from respiratory diseases, including COVID-19.	Comparative risk-assessment model with Latin-Hypercube Monte-Carlo simulation	The total number of deaths attributed to $PM_{2.5}$ in Sub-Saharan Africa in 2019 is 389,000 (334,000 – 440,000) – a 95% uncertainty interval.	Recommends stricter emissions standards, renewable energy investments, and international collaboration to mitigate $PM_{2.5}$ related disease burdens in LMICs.
Yuan et al. (2021) [39]	Lower temperatures and relative humidity were negatively correlated with COVID-19 case counts, while wind speed was positively correlated. High diurnal temperature variation increased COVID-19 cases.	Air pollution was indirectly considered as part of environmental stressors affecting respiratory health.	Generalised additive model (quasi-Poisson) with distributed-lag non-linear component	Slope for T < 10 °C: 0.42% increase in daily cases per 1 °C (95% CI 0.18 – 0.66%)	Calls for integrated environmental and public health approaches, plus further meteorological research to strengthen disease resilience in African contexts.
Yuan et al. (2021) [40]	Non-linear relationships between temperature, humidity, and wind speed were found in daily new COVID-19 cases. Lower temperatures increased the risk of COVID-19 transmission.	Environmental factors, including temperature, wind speed, and humidity, affected COVID-19 transmission.	Country fixed-effects multivariate non-linear regression; 1 000-run sensitivity analysis	Low-temperature RR 1.33 (95% CI 1.08 – 1.64); large diurnal temperature range RR 1.31 (1.12 – 1.57)	Suggests integrating meteorological monitoring into public health planning and aligning climate/air quality policies to safeguard respiratory health in vulnerable regions.

Discussion

This scoping review highlights how outdoor and indoor air pollution significantly intensify COVID-19 risks in the SADC region, aligning with global research yet underscoring critical regional distinctions. In urban hubs like Johannesburg and Lusaka, pollutants such as $PM_{2.5}$ and NO_2 correlate strongly with higher infection rates and worse respiratory outcomes **[5, 18, 19]**. Although these patterns resemble those in high-income countries (HICs), the lack of local data in many SADC countries forces reliance on extrapolations from HIC contexts **[18].** Addressing these gaps necessitates local research initiatives that accurately reflect the region's disparities in resources, health systems, and environmental conditions.

A significant insight is the disproportionate impact of air pollution in informal settlements, where an estimated 40–50% of urban residents in some SADC countries live in substandard housing [**32**]. Prolonged lockdowns amplified these risks: reliance on biomass and paraffin fuels in poorly ventilated structures exacerbated HAP, heightening COVID-19 severity **[13, 14].** While alternatives like LPG or grid-based electricity can mitigate HAP, high costs and inadequate infrastructure frequently hinder widespread adoption **[22, 41].** Additionally, inadequate monitoring capacity—evident in cities such as Lusaka and Harare—undermines rigorous air quality oversight and data-driven policy interventions **[21].**

Notably, NO_2 emerged as another critical pollutant. Studies underscore significant associations between NO_2 concentrations and heightened COVID-19 morbidity and mortality, particularly in traffic-congested urban areas **[21, 19]**. NO_2, primarily from vehicular emissions and industrial activities, can impair lung function and exacerbate chronic conditions like asthma. This underscores why vehicular emissions reduction is crucial for improving population-level health resilience in SADC cities. Moreover, NO_2 exposure can compromise immune responses, making individuals more susceptible to viral infections and increasing the likelihood of severe COVID-19 outcomes.

In addition, gaps in monitoring SO_2 and O_3 restrict comprehensive analysis of air pollution's health impacts **[18, 31]**. Reduced industrial and vehicular activity led to significant reductions in $PM_{2.5}$, NO_2, and SO_2 levels. **[21, 35]**. However, these gains were short-lived, with pollution levels rebounding after restrictions eased. For example, transitioning industrial sectors to cleaner energy sources, as trialled in Johannesburg during the lockdown, could reduce pollution while supporting economic growth **[5].** Investments in public transit systems must complement these efforts to reduce urban vehicular emissions sustainably. Adopting low-cost sensor networks or satellite-based tools (e.g., Sentinel-5P, NASA's MODIS, AQICN) offers a pathway for real-time data collection in under-resourced settings, as demonstrated in Kinshasa and Brazzaville **[21, 21, 42].**

Findings from other LMIC regions, such as Southeast Asia and South America, highlight comparable challenges in addressing indoor air pollution and vehicular emissions. For example, Akrofi et al. (2024) emphasise that procedural and distributive injustices in both Sub-Saharan Africa and Southeast Asia undermine the effectiveness of renewable energy transitions, as marginalised communities often lack access to clean energy technologies **[12].** Similarly, renewable energy transitions in South America, such as Brazil's large-scale hydropower projects, have exacerbated energy inequities by prioritising export markets over local access **[11]**. Contrasting South Africa in the SADC region with Kenya in the East African Community (EAC) illustrates regional differences in addressing air pollution and advancing sustainability goals. Despite its relatively advanced industrial base and air quality monitoring infrastructure, South Africa remains heavily reliant on coal for electricity generation, contributing to substantial greenhouse gas emissions.

Conversely, Kenya derives over 75% of its electricity from geothermal, wind, and hydropower, backed by the ability to attract international climate finance and implement decentralised energy projects, such as solar mini-grids in rural areas **[43, 44].** Although comprehensive health-outcome data linked directly to Kenya's renewable energy growth are not extensively documented, preliminary reports from community-based interventions suggest reduced household air pollution and lower incidences of respiratory ailments, particularly among children, in areas adopting cleaner fuels and solar-powered solutions. In contrast, South Africa's energy transition has been more gradual, shaped by its

historical reliance on coal and challenges in mobilising large-scale funding for renewable infrastructure **[11]**. These examples illustrate how policy, financing, and technology all influence the pace of decarbonisation and its downstream impact on public health.

Another critical distinction lies in household energy use and policy outcomes. While informal settlements in both regions face high levels of HAP, Kenya's urban areas have seen increased adoption of cleaner cooking technologies like LPG, facilitated by targeted subsidy programs and public awareness campaigns. In South Africa, the reliance on biomass and paraffin remains persistent, particularly in low-income and rural areas **[43, 45]** Kenya demonstrates stronger inclusive energy policies, yet both regions face challenges in involving marginalised communities in energy transition planning to combat injustices **[46].** This indicates that the SADC region needs equitable frameworks for addressing energy poverty and environmental health during renewable energy transition disparities. Environmental factors like temperature and humidity also exacerbate the health impacts of air pollution **[47].**

Lower temperatures and reduced humidity levels have been associated with increased COVID-19 transmission and worsened respiratory outcomes **[31, 18].** Integrated strategies, such as urban greening initiatives, could reduce urban heat islands while improving air quality. Climate-resilient infrastructure investments can mitigate the combined effects of pollution and climatic stressors, reducing respiratory vulnerabilities in high-risk communities. Urban greening initiatives have shown great promise in addressing environmental and social challenges. Shammi et al. (2023) analysed urban forestry programs in Dhaka, Bangladesh. They found that increasing vegetation coverage significantly reduced the impacts of urban heat islands and enhanced air quality by promoting carbon sequestration. The study also highlighted the co-benefits of biodiversity conservation and improved urban resilience, which are particularly beneficial for vulnerable communities **[48].** These successes provide a blueprint for scaling urban greening interventions in SADC cities like Lusaka and Johannesburg, where similar urbanisation pressures exist.

Policy interventions—including subsidies for cleaner fuels and public awareness campaigns—have shown demonstrable success in pilot projects within South Africa and other low-income regions, leading to reductions in indoor air pollution regions **[8, 13].** Scaling these initiatives across the SADC region could alleviate heavy reliance on paraffin and biomass fuels, particularly in informal settlements and remote rural communities. Parallel investments in renewable energy infrastructure, such as solar mini-grids, offer a dual advantage: they diversify energy sources and make clean electricity more accessible to populations currently off-grid.

Additionally, transportation policies aimed at clean energy transitions present transformative opportunities for reducing vehicular emissions. For instance, Wang et al. (2021) documented a 45% reduction in NO_2 levels—and a notable decline in $PM_{2.5}$—after Shenzhen (China) adopted electric buses, resulting in improved respiratory health outcomes **[49].** This success underscores the potential for SADC cities to electrify public transport, cut traffic-related pollution, and bolster health resilience. This initiative demonstrates how public transportation systems in SADC countries could adopt electrification to mitigate vehicular emissions. These findings highlight the critical need for more localised research and enhanced air quality monitoring infrastructure to address the region's unique challenges and improve public health resilience against future pandemics.

Expanding monitoring systems in underserved areas is vital for assessing pollution's health impacts and informing policy decisions **[28, 34, 50]**. By applying lessons from successful global interventions, SADC countries can adopt evidence-based methods to reduce air pollution's health effects and boost public health resilience. Key recommendations include establishing low-cost air quality monitoring systems and promoting cleaner energy solutions. These strategies fill crucial data gaps and address the health burden from HAP. Both approaches are feasible within the region's limited resources, providing scalable solutions to enhance air quality and public health resilience **[28]**.

Finally, major research gaps exist in countries like Eswatini, Lesotho, and Comoros, where resource constraints limit comprehensive environmental health data collection **[5, 28, 29, 30, 36]**. These gaps impede evidence-based policymaking and limit the ability to address overlapping health burdens such as human immunodeficiency virus (HIV) and tuberculosis (TB). Collaborative, cross-border frameworks—exemplified by West Africa's pollution

control programs and the revived Malé Declaration in South Asia—highlight the potential of coordinated strategies, data-sharing, and harmonised policies **[18, 33, 50].** In 2022, the Malé Declaration was reactivated by member countries of the South Asia Co-operative Environment Programme (SACEP), demonstrating renewed commitment to tackling transboundary air pollution through joint monitoring and policy alignment **[51].** Notably, only 26% of included studies utilised direct regional air monitoring data, underscoring the urgency of expanded surveillance networks for robust analysis of COVID-19 and pollution linkages. Notably, subsidies for cleaner fuels have proven promising in small-scale pilots in South Africa, reducing HAP-related respiratory symptoms **[11, 13].** However, large-scale adoption demands robust governance, sustained financing, and culturally sensitive outreach to ensure communities can transition to safer technologies.

In summary, governments in the SADC region must prioritise advanced monitoring infrastructure, invest in equitable renewable energy policies, and enact community-driven interventions—from NO_2 reduction strategies in congested cities to improved ventilation in informal settlements. Integrating these environmental and social measures, guided by local data, can reduce the disproportionate burden of respiratory illness and strengthen overall pandemic resilience in the SADC region.

Policy Recommendations

Several studies (42%) highlighted key recommendations to mitigate air pollution's health impacts in the SADC region, particularly during pandemics like COVID-19. These recommendations are presented below in order of frequency, along with discussions of their feasibility and relevance to the SADC context.

Establishing Comprehensive Air Quality Monitoring Systems: Approximately 42% of studies emphasised the need for comprehensive air quality monitoring systems to address the scarcity of real-time data **[5, 13, 22, 23, 24, 26, 39, 40].** McFarlane et al. (2021) and Katoto et al. (2021) highlighted low-cost sensors and satellite systems as practical solutions for monitoring $PM_{2.5}$ and NO_2, particularly in urban centres and informal settlements **[21, 5].** These technologies are practical for the SADC region due to their scalability and cost-effectiveness, addressing infrastructure limitations while providing reliable data for air quality management. While these approaches are feasible due to their relatively modest infrastructure requirements, funding constraints, lack of technical expertise, and inconsistent political support can hinder widespread implementation.

Promoting Cleaner Energy Alternatives: Roughly 37% of studies advocated transitioning households to cleaner fuels like LPG or electricity, supplemented by public health campaigns and subsidies, to reduce reliance on solid fuels **[13, 14, 31].** However, limited affordability and distribution networks pose significant barriers in low-income areas. Even when subsidies exist, safety concerns (e.g., LPG handling) must be addressed through awareness campaigns and training. Despite these challenges, prioritising cleaner energy remains an impactful and cost-effective strategy to reduce household air pollution over the long term.

Implementing Stricter Emissions Regulations: Over 30% of studies recommended enforcing stringent industrial and vehicular emissions standards—particularly targeting $PM_{2.5}$ and NO_2—to reduce ambient pollution in heavily industrialised SADC regions **[5, 23].** While technically feasible, sustained political will and strong regulatory frameworks are essential. Barriers include insufficient enforcement capacity, limited monitoring infrastructure, and potential economic pushback from industries reliant on fossil fuels. Overcoming these obstacles requires multisectoral collaboration and possibly incentives (e.g., tax breaks, low-interest green loans) that encourage cleaner production methods.

Fostering Regional Collaboration on Pollution Control: About 26% of studies stressed cross-border cooperation to address transboundary pollution and shared environmental challenges **[5, 13, 21, 23].** Jenkins et al. (2023) underscored the importance of data sharing and joint monitoring **[19]**. Although feasible in principle, regional collaboration can be hampered by political differences, varying legal frameworks, and unequal resource levels among

member states. Successful models require coordinated policies, dedicated regional funding mechanisms, and harmonised air quality guidelines—factors that demand high-level commitment and strong institutional structures within the SADC region.

Enhancing Ventilation in Indoor Spaces: Approximately 21% of the studies identified improving ventilation in homes, workplaces, and public buildings as critical for reducing indoor air pollution and airborne disease transmission **[5, 13, 18, 27]**. Deol et al. (2021) recommended updating building codes and implementing low-cost ventilation solutions, such as promoting natural ventilation and retrofitting buildings **[27].** While these interventions are technically straightforward and relatively low-cost, they remain underutilised due to a lack of awareness, limited financial resources, and slow policy adoption of improved building standards. In many low-income communities, the high cost of renovations and the informal nature of housing complicate implementation, perpetuating inadequate ventilation conditions despite the approach's demonstrated efficacy in lowering health risks.

These recommendations focus on promoting clean energy alternatives, improving air quality monitoring, and implementing stricter emissions regulations to protect public health and mitigate the long-term effects of air pollution. Taken together, these policies represent significant steps towards reducing both outdoor and indoor pollution in the SADC region. However, they are often introduced in a fragmented manner or on a limited scale. Challenges, such as weak enforcement mechanisms, limited local capacity, and uneven funding, highlight the need for coordinated, long-term approaches that align with local economic and social realities. Building on these recommendations through stronger governance, focused community engagement, and reliable financing can enhance their effectiveness. Ultimately, integrating these strategies into more comprehensive public health, economic development, and environmental protection plans will ensure that SADC nations can address air pollution more thoroughly and sustainably.

Limitations and Strengths

A notable limitation of this review is its exclusion of non-English studies. Due to time and language constraints, the review was restricted to English-language publications, which may have led to the omission of relevant research published in other languages. This language limitation could potentially bias the findings by overlooking studies offering different perspectives or data, particularly from non-English-speaking countries within the SADC region. Despite this limitation, the review's strengths include a robust methodological framework and a specific focus on the SADC region. By concentrating on this region, the study provides valuable insights into the local context, often underrepresented in global research. The methodological rigour ensures that the findings are reliable and can serve as a foundation for future research.

Countries such as Eswatini, Lesotho, and Comoros were not represented in the studies included in this review, highlighting significant regional disparities in environmental health research. This lack of representation may stem from resource constraints, limited research capacity, or the absence of region-specific studies addressing air pollution and COVID-19 outcomes **[31, 38].** These gaps underscore the urgent need for expanded monitoring systems and targeted research efforts to ensure that public health interventions are inclusive and responsive to the needs of all SADC member states. Bridging these gaps will be critical for developing comprehensive strategies to mitigate air pollution and its regional health impacts.

Implications for Future Research

Region-specific studies are urgently needed in the SADC region to address the current lack of local data on air pollution and disease outcomes. Although findings from HICs are been informative, extrapolating them to SADC contexts may overlook unique socio-economic and infrastructural constraints, gaps in air quality monitoring and limited research capacity undermine accurate assessments of both pollution exposure and associated health burdens, as highlighted by Katoto et al. (2021) and McFarlane et al. (2021) **[5, 21].** To overcome these gaps, improved

monitoring systems—particularly low-cost sensors and community-based data collection—could provide robust, real-time evidence for tailoring interventions. Collaboration among national governments, local researchers, and international partners is equally vital. Joint research initiatives led by governments and monitored by independent agencies can better capture the region's diverse settings, strengthening our understanding of how air pollution exacerbates infectious diseases like COVID-19 **[22]**. Finally, investing in local capacity to generate data on pollutant levels and disease outcomes will help shape context-specific interventions and guide effective public health policies.

Conclusion

This scoping review highlights how air pollution—particularly $PM_{2.5}$, NO_2, and HAP—contributes to severe COVID-19 outcomes in the SADC region, disproportionately affecting low-income and vulnerable populations in informal settlements and rural areas. While cities grapple with industrial and vehicular emissions that elevate ambient pollution, rural communities remain heavily reliant on biomass fuels, exacerbating indoor air quality issues and respiratory risks.

Although data gaps persist for many SADC countries, the evidence underscores the urgent need for enhanced air quality monitoring and the broad implementation of cleaner energy alternatives. Integrating these measures into existing national development plans, climate strategies, and public health initiatives can ensure that air pollution control becomes a cross-cutting priority rather than an isolated intervention. Moving beyond a narrow pandemic focus, these findings call for sustained regional collaboration to tackle both air pollution and the socio-economic disparities that underpin it.

By prioritising vulnerable populations, embedding air quality management into public health policies, and investing in robust surveillance across rural and urban contexts, SADC countries can strengthen their resilience against both current and future public health threats. Lastly, this review contributes to the growing body of evidence linking air pollution to the severity of COVID-19. It provides a foundation for evidence-based policymaking that addresses the intertwined challenges of air pollution, infectious diseases, and socio-economic inequality in the post-pandemic landscape in the SADC region.

Finally, addressing the twin challenges of pollution and socio-economic vulnerability necessitates coordinated efforts across public health, environmental management, and policy spheres. Specifically, cross-ministerial collaboration, sustained governance, and community-level engagement are pivotal for scaling cleaner energy transitions, enforcing stricter emissions standards, and promoting equitable access to healthier environments. By implementing these integrated strategies, SADC governments can make meaningful strides in reducing pollution's health impacts and fostering long-term environmental and public health resilience.

Author Contributions

The authors would like to extend their gratitude to all contributors who played an integral role in the completion of this review. The following outlines the contributions of each individual to this work:

- **Aleya Ramparsad Banwari (First Author):** Aleya conceptualised the research question, developed the methodology, conducted the literature search, screened and analysed the studies, and drafted the manuscript. This work forms part of their Master of Public Health dissertation, and all contributions were completed during their registration and under the supervision of the co-authors. Aleya also led the data extraction, synthesis, and the development of recommendations presented in this review.

- **Dr. Meryl Jagarnath (Co-Author):** Dr. Jagarnath provided critical oversight during the conceptualisation and design of the study. She also guided the data analysis process and offered detailed feedback on the draft manuscripts. Her expertise in environmental health and public health policy informed the interpretation of findings and the framing of the review's conclusions.

- **Hanna-Andrea Rother (Senior author):** Professor Rother provided supervisory guidance throughout the review process, offering critical insights into the methodology and ensuring the rigor and relevance of the review. She also contributed to refining the discussion and conclusion sections, ensuring alignment with the journal's expectations and the research's broader public health implications.

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- Ethical Considerations: This review did not involve primary data collection and relied solely on publicly available information.

- Data Availability: All data supporting the findings of this study are included within the article and its supplementary materials. The online version contains supplementary material available at https://doi.org/10.17605/OSF.IO/G4FU5

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Acronyms and Abbreviations

Acronyms and Abbreviations	Abbreviations
EAC	East African Community
GAM	Generalised Additive Models
COPD	Chronic Obstructive Pulmonary Disease
COVID-19	Coronavirus Disease (2019 / SARS-CoV-2
DRC	Democratic Republic of Congo
HAP	Household Air Pollution
HIV	Human Immunodeficiency Virus
HIC(s)	High-income country(ies)
LPG	Liquid Petroleum Gas
LMICs	Low- and Middle-Income Countries
NO_2	Nitrogen Dioxide
$PM_{2.5}$ / PM_{10}	Particulate Matter of 2.5 micrometres and smaller / Particulate Matter of 10 micrometres and smaller
SACEP	South Asia Co-operative Environment Programme
SADC	Southern African Development Community
TB	Tuberculosis

Part B: Appendices

Appendix A: Research Protocol

The Effect of Outdoor and Indoor Air Pollution on COVID-19 Infections and Mortality Rates in the Southern African Development Community: A Scoping Review

By

Aleya Ramparsad Banwari

BNWALE001

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specialising in Environmental Health

Supervisors: Prof Hanna-Andrea Rother and Dr Meryl Jagarnath

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1. Introduction and Rationale

Air pollution is a primary environmental cause of early loss of life and illness (Landrigan et al., 2018). In 2021, the World Health Organisation (WHO) estimated that roughly seven million people die prematurely each year as a result of air pollution (World Health Organisation, 2021a). Air pollution is an important risk factor for increasing the risk of getting respiratory infections, heart disease, and lung cancer, amongst others. Additionally, air pollution aggravates existing chronic health conditions and diseases such as asthma, stroke, hypertension, chronic pulmonary disease (COPD), and diabetes, to name a few (Ritchie, Spooner & Roser, 2019). Understanding the severity of air pollution as a risk factor for respiratory diseases, especially in the context of COVID-19, highlights the urgent need for further investigation into effective preventative measures.

The Coronavirus Disease 2019 (COVID-19) pandemic is an illustration of the co-existence of the double burden of disease in contemporary times (World Health Organisation, 2021b). The double burden of disease refers to "the co-existence of communicable and non-communicable or chronic diseases" (Hussein, 2014: 3). Exposure to air pollution can cause increased vulnerability and susceptibility to COVID-19 because the polluted air damages the lungs and causes respiratory diseases such as asthma, lung cancer, and obstructive pulmonary diseases (Maheswari, Pethannan & Sabarimurugan, 2020).

This virus and resulting respiratory infection have come at a time when the health effects of air pollution are gaining acknowledgement as a climate change issue and a threat to public health (Saadat, Rawtani & Hussain, 2020). Air pollution and climate change are inextricably linked. Air pollution and climate change are both worsened by anthropogenic activities (including the burning of fossil fuels). This directly and indirectly affects the environment, including global warming and reduced air quality. The double burden of disease is also heavily affected by context, such as the population demographics and the time period in which it occurs.

Low- and middle-income countries (LMICs) bear a disproportionately large share of the disease burden associated with environmental pollution (World Health Organisation, 2017). This is particularly pertinent for areas such as the Southern African Development (SADC) region. The reason for this is that many LMICs, such as most countries in the SADC region, have overstretched healthcare systems which carry a disproportionate burden of non-communicable and communicable diseases (Mbandi, 2020). Many low-income communities in SADC member states lack access to electricity and resort to burning charcoal, wood, and kerosene for cooking, heating, and lighting their homes (Francioli, 2020). The burning of these traditional fuels is a major cause of air pollution, both indoor and outdoor.

Air pollution in the SADC region is acknowledged by several organisations, such as SADC, the African Union, and the United Nations. With the challenges of climate change and the rise of emerging infectious diseases (EIDs) like COVID-19, it is essential to understand air pollution's impact. This knowledge will shape our strategies and insights regarding these diseases in the SADC area. Additionally, SADC itself notes that healthcare is a huge challenge in the region, particularly in terms of poor health infrastructure. Compounding the issue is the fact that SADC citizens also suffer from poor nutrition and that rates of both communicable and non-communicable diseases are high (Southern African Development

Community, 2022b). This is due to several factors, including poor legislation (or poor enforcement mechanisms) governing air emissions, the prevalence of industrial processes in the economy (such as mining or smelting), and activities like the burning of wood for warmth or cooking (Southern African Development Community, 2022a).

Data on the effects of air pollution on COVID-19 morbidity and mortality in LMICs is limited, and therefore, calculations and estimations carried out for most of the globe are based on the data collected from high-income countries (HICs). The SADC region also tends to have less access and ability to implement health technologies like vaccines, which makes understanding and mitigating risk factors one of the most important and high-impact strategies that can be undertaken in this area. As an emerging research area, data and research on this topic within the SADC region is scarce.

Due to this limited amount of data, this proposal is to conduct a scoping review. A scoping review will allow for an overview of the available research on this topic to be assessed for knowledge gaps to be identified, concepts to be clarified, and the body of literature to be scoped out. These findings can guide further research questions and reviews such as systematic reviews (Sucharew & Macaluso, 2019; Munn, Stern et al., 2018). The expected outcome of this scoping review is that findings will help to pinpoint interventions to reduce the mortality from COVID-19 infections exacerbated by air pollution in the SADC region.

Given the fact that the COVID-19 pandemic has encompassed multiple waves, it is vital to understand the factors that influence COVID-19's transmission patterns. This will aid in finding ways to prevent or slow its spread (as new variants emerge) and empower health policy through socio-economic, political, and environmental interventions (Okello et al., 2022). This is particularly relevant within a SADC context. SADC countries are unable to rely on medical and pharmaceutical interventions to the same extent that other regions of the world can due to unequal access to resources (Ogunleye et al., 2020). Limited access to healthcare facilities and resources is a reality in the SADC region (Ranchod et al., 2016). Environmental pollutants that may exacerbate COVID-19 outcomes are also a concern. Therefore, in order to effectively combat the COVID-19 pandemic within this region, interventions must be socio-economic, political, and environmental in nature to address the root causes. These root causes include a lack of access to healthcare facilities, which will, in turn, support medical and pharmaceutical interventions. For this reason, this research aims to analyse the impacts of air pollution on COVID-19 infection and mortality rates across the globe and use those findings to make recommendations for the SADC region.

2. Literature Review

2.1. Air Pollution

Air pollution is one of the greatest threats to human health across the globe. Air pollution refers to the contamination of the air (both indoor and outdoor) by pollutants caused by natural events such as volcanic eruptions as well as anthropogenic activities such as the burning of biofuels, transport, and industry emissions (Munsif et al., 2021). Globally, approximately seven million people die prematurely due to indoor and outdoor air pollution annually (World Health Organisation, 2021). Air pollution in Africa causes around 800,000 premature deaths each year, two-thirds of which are caused by particulate matter ($PM_{2.5}$) (Bauer et al., 2019).

In Africa, air pollution is the second leading cause of mortality, surpassing tobacco, alcohol, road accidents, and drug abuse, with only HIV/AIDS claiming more lives (Fisher et al., 2021). Air pollution is generated from natural sources, man-made sources, and a mixture of natural and man-made aerosols released by biomass burning (Bauer et al., 2019). Exposure to air pollution, as well as smoking, increases the risk of developing respiratory and pulmonary diseases, including asthma and pulmonary tuberculosis (World Health Organisation, 2021a).

Within Africa, SADC is a regional economic community (REC) formed in 1992 with the objective of promoting development, peace, security, and economic growth among member states as well as alleviating poverty and enhancing the standard and quality of life for citizens of these countries through regional integration (Southern African Development Community, 2012). SADC includes sixteen member states: Angola, Botswana, Comoros, Democratic Republic of Congo, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Tanzania, Zambia, and Zimbabwe.

2.1.1. Indoor and Outdoor Air Pollution

The surge in global economies and populations has intensified exposure to air pollution, necessitating the understanding of its effects in various settings like indoor and outdoor. This growth, fuelled by extensive resource usage, has escalated pollution due to reliance on fossil fuels for electricity, transportation, and heating, which then impacts human health (Leung, 2015; Manisalidis et al., 2020). Outdoor air pollution has been widely studied (Bourdrel et al., 2021; Fisher et al., 2021; Bagula et al., 2021; Leung, 2015). However, research on indoor air pollution gained traction since the mid-2000s, focusing on air quality in confined areas, such as vehicles, houses, and schools, that are not used in industrial processing.

High-income countries (HICs) have conducted more research on the impact of poor indoor air quality on human health than LMICs, which disproportionately affects women, children, and the elderly (Sundell, 2004; Mannan & Al-Ghamdi, 2021). With individuals spending 80-90% of their time indoors, it is a significant global public health issue (Tran, Park & Lee, 2020). Factors like poor ventilation in confined spaces can worsen indoor pollution, with primary pollution sources including tobacco smoke, cleaning products, and Volatile Organic Compounds (VOCs) from various household items (World Health

Organisation, 2010). Further research, particularly in LMICs, is required to develop effective pollution reduction measures.

2.1.2. Major Air Pollutants

There are many air pollutants that have an adverse effect on human health, but much of the impact generally attributed to air pollution is caused by a few specific pollutants that have a very high impact. This paper focuses on seven of these major outdoor and indoor air pollutants, volatile organic compounds, and toxic metals which adversely affect COVID-19 outcomes (Comunian et al., 2020).

Two main indoor and outdoor sources of air pollutants are the burning of fossil fuels, such as diesel, and industrial processes. Exposure to air pollution, including particulate matter, sulphur dioxide, nitrogen dioxide, carbon monoxide, ozone, and benzene, can cause respiratory illness and impaired respiratory function in vulnerable populations such as children. This can have an impact on brain development and cognitive function in early childhood (Fisher et al., 2021).

The pollutants will be discussed in relation to their impact on human health and the environment, as well as how exposure to these pollutants occurs globally, with a specific focus on the SADC region. Table 1 will provide a breakdown of each pollutant's indoor and outdoor sources as well as health impacts.

Table 1: Examples of Global Air Pollutants, Indoor and Outdoor Sources, and their Health Impacts

Air Pollutant	Indoor Sources	Outdoor Sources	Health Impacts	References
Particulate Matter (PM)	Cooking stoves, fireplaces, smoking	Diesel exhaust fume emissions	Respiratory and cardiovascular illnesses	(Ali, Khan & Ilahi, 2019), (Briffa, Sinagra & Blundell, 2020), (Comunian et al., 2020), (Kim, Kabir & Kabir, 2015), (Naidja, Ali-Khodja & Khardi, 2018)
Sulphur Dioxide (SO_2)	Cooking stoves, fireplaces	Large-scale production, including creation of electricity, production of metals, and manufacturing of oil	Impairment of respiratory function	(Adebayo-Ojo et al., 2022; Martins, 2009), (Badenhorst, 2007), (Bagula et al., 2021), (Canadian Centre for Occupational Health & Safety, 2017), (Marais et al., 2019), (Munawer,

				2018), (World Health Organisation, 2014)
Lead (Pb)	Paints	Mining effluence in rivers and streams, dumping sites	Digestion issues and impairment of the nervous system	(Jaishankar et al., 2014), (Kim et al., 2015), (Wani, Ara & Usmani, 2015), (World Health Organisation: Regional Office for Africa, 2015), (World Health Organisation, 2021c)
Nitrogen Dioxide (NO_2)	Cooking stoves, fireplaces, tobacco smoke, coal-burning	Vehicle emissions, electricity power plants, industrial boilers and other industrial processes such as petroleum refining, and metal processing	Irritation of the lungs and decreased resistance to respiratory infections	(Centres for Disease Control and Prevention, 2014), (Meth, 2018), (Oluwoye et al., 2017), (United States Environmental Protection Agency, 2022a)
Carbon Monoxide (CO)	Tobacco smoke, incorrectly installed/ poorly maintained/poorly ventilated cooking or heating appliances that burn fossil fuels	Vehicle emissions from burning fossil fuels	Reduces function of the heart, brain, and other organs by affecting the blood's capability to move oxygen	(Gharbia & Hassanien, 2021), (Ng, Long & Koyfman, 2018), (Theodore & Theodore, 2010)
Ozone (O_3)	Certain electrical devices like air purifiers, disinfecting devices, facial steamers, photocopiers, laser printers	Pollution emissions from vehicles, electricity power plants, industrial boilers and other industries like chemical plants and refineries chemically react in the presence of sunlight	Asthma and allergic triggers	(Laakso et al., 2013), (Manisalidis et al., 2020), (Theodore & Theodore, 2010), (United States Environmental Protection Agency, 2021), (Zhang, Wei & Fang, 2019)
Benzene (C_6H_6)	Fireplaces, tobacco smoke	Emissions from motor vehicle exhausts (poor quality gasoline), petrochemical spills	In the long-term, cancer and reproductive disorders. In the short-term, physical weakness, head pain, sleepiness, and skin irritation.	(Alewu & Nosiri, 2011), (Haq & Schwela, 2012), (Tshehla & Wright, 2019), (World Health Organisation, 2014)

2.1.3. Air Pollution within the Southern African Development Community (SADC)

Mining and industrial activities in SADC countries, such as South Africa, Zambia, and Zimbabwe, have made significant contributions to air pollution emissions in the region (Fayiga, Ipinmoroti & Chirenje, 2018). However, out of the SADC member states, South Africa is the most industrialised and is the

leading contributor of air pollution emissions (Bauer et al., 2019). The SADC region is often considered extremely vulnerable to climate change. As a result, due to both the region's own emissions and global emissions, the region is already disproportionately experiencing the impacts related to a changing climate.

According to a 2019 UNICEF report, there has been roughly a 60% increase in deaths caused by outdoor air pollution on the African continent from 1990 to 2017 (Rees, Wickham & Choi, 2019). This is expected to be exacerbated as Africa has one of the fastest-growing populations in the world. It is estimated that by 2025, there will be at least a 25% increase in urban population in Africa (Amegah & Agyei-Mensah, 2017). With the development of megacities in Africa, there is a rise in fossil fuel use through increased industrial activity and vehicle emissions due to increased urbanisation, which ultimately leads to a degradation in ambient air quality (Opiyo & Nzuve, 2021). Ambient air pollution and its associated diseases are beginning to increase across Africa, whereas household air pollution and its diseases are in decline (Mbandi, 2020). However, it must still be noted that household air pollution still accounts for 60% of all air pollution-related deaths across Africa, and polluting fuels such as charcoal and kerosene are still prevalent in cooking and for use in heating and lighting (Fisher et al., 2021). However, it is also important to understand air pollution in relation to climate change.

Air pollution is a significant contributor to climate change, and climate change worsens air pollution both directly and indirectly (Chen et al., 2017). Direct effects include increasing ozone and particulate matter levels at ground level, which can have longer-lasting impacts on human health. Indirect effects include increasing the frequency of extreme weather events that increase air pollution, such as fires (Orru, Ebi & Forsberg, 2017). Climate change also affects indoor air quality, as it increases the likelihood of storms and flooding that result in increased mould growth (Vardoulakis et al., 2015).

Climate change's effects on air pollution disproportionately affect those in hot climates with poor mitigation strategies, such as Asia, South America, and Africa (Hoegh-Guldberg et al., 2019; Hanna & Oliva, 2016). The SADC region is expected to experience the most devastating effects of climate change due to its geographical location, low income, limited institutional and technological capacity, and reliance on climate-sensitive natural resources (Urama & Ozor, 2010). Climate disasters such as floods and droughts impact people socially, economically, and physically, leading to increased migration to susceptible areas (Matthew et al., 2022).

The SADC region, along with other African states, has committed to addressing environmental threats (e.g., air pollution) through the Libreville Declaration. The Declaration includes eleven health-related actions to investigate the effects of pollution on health, build capacity to reduce environmental exposures, and monitor the effects of measures taken to reduce these exposures (Bagayoko et al., 2018). Through this research, this paper aims to support the Libreville Declaration's efforts by gathering evidence on the impact of air pollution on COVID-19 outcomes. This data will provide the SADC region with scientific evidence that air pollution worsens the effects of COVID-19, aligning with the Declaration's focus on pollution's health impacts. This research will also identify indoor and outdoor air pollutants associated with adverse COVID-19 outcomes. We plan to use the findings from this scoping review to provide policy recommendations to mitigate pollutant exposures that may aggravate COVID-19 effects. These recommendations will be particularly valuable to SADC member states as they work to align their strategies with the Libreville Declaration's goals, especially in building capacity to reduce environmental exposures.

Unfortunately, implementation of the Libreville Declaration has been slow, and the impacts of climate change may not be felt uniformly across SADC member states due to different socio-economic levels and climate forces. While SADC member states need to work on their adaptation measures independently, SADC itself can also implement adaptation measures and support members. Adaption and mitigation measures are needed in sectors such as agriculture to maintain socio-economic stability and promote public health in the region (The South African Department of Environmental Affairs, The South African National Biodiversity Institute, (SANBI) & Gesellschaft für Internationale Zusammenarbeit, 2014). Policies that promote integration within SADC, such as information sharing and technology transfer, are necessary to build regional climate change resilience.

Attempts to shift towards responsible emission standards, as defined by bodies like the WHO, have been uneven. Only seven out of fifty-four African countries have reliable real-time air pollution monitors (Rees, Wickham & Choi, 2019). However, efforts are being made to transition to sustainable technologies and reduce emissions (Okello et al., 2022). For example, South Africa's Carbon Tax Act came into effect in June 2019. The purpose of this legislation is to impose specific taxes on greenhouse gases from fuel burning and industrial processes and emissions (Okonjo-Iweala, 2020). Legislative measures, such as the South African Air Quality Act of 2005, have also been introduced, albeit with limitations in their effectiveness. It puts in place measures like mandatory atmospheric emission licenses for companies or individuals reaching a certain level of emissions and mandates that companies or individuals working with substances deemed *priority pollutants* may be required to create pollution prevention plans. Unfortunately, both measures are fairly easy for major polluters to comply with without changing their practices. For instance, certain industries in South Africa, like the national electricity provider, Eskom, continue to exceed the emission limits and apply for the postponement of the minimum emission standards for several years (Tshehla & Wright, 2019).

The COVID-19 pandemic has highlighted the impact of anthropogenic emissions on the environment. Given the global response to the pandemic, which have often included “lockdowns” that involved large-scale cessation of normal economic activities, the pandemic has presented a unique opportunity for the detection and comprehension of the effects of anthropogenic emissions on the Earth's atmosphere (Wahaj, Alam, & Al-Amin, 2022; Mohommad & Pugacheva, 2022; Gkatzelis et al., 2021; Gupta, Rouse, & Sarangi, 2021; Zang et al., 2021). The pandemic has also drawn attention to the links between globalisation, human population growth, and the emergence of infectious diseases (McNeely, 2021). This protocol aims to analyse the impacts of air pollution on COVID-19 infection and mortality rates across the globe and use those findings to make recommendations for the SADC region. An important aspect to consider is that this situation presents an opportunity for humanity, as efforts to reduce air pollution can simultaneously lead to a reduction in greenhouse gases (GHGs), which can lessen the impact of climate change on our environment and on human health (Gavurova, Rigelsky, & Ivankova, 2021).

2.1.4. Vulnerable and at-risk populations

Social inequalities may increase susceptibility to air pollution and to EIDS (Bambra, 2022). Air pollution may worsen health issues such as asthma, respiratory infections, stroke, chronic obstructive pulmonary

disease, hypertension, and lung cancer (Manisalidis et al., 2020). This is true for all populations. However, socio-economically disadvantaged communities and children are most at risk as both a result of their higher exposure and as a direct or indirect result of their social class (O'Neill et al., 2003). Lack of access to water, nutrition, healthcare, and heightened psychosocial stress in impoverished communities has been identified as a mechanism for increased susceptibility in these populations.

2.2. COVID-19

2.2.1. COVID-19 in the SADC Region

In response to the COVID-19 pandemic, as declared by the WHO on 11 March 2020, SADC member states implemented public health measures such as movement restrictions, closures of schools and businesses, as well as geographical area quarantine and international travel restrictions to prevent the spread of infection (SADC Secretariat, 2020).

Figure 1 provides a visual of the spread of COVID-19 within the SADC region as of July 2021. It should be noted that this is based on reported data, which may not be accurate in many of the listed SADC countries. While Figure 2 illustrates the level of exposure to $PM_{2.5}$ (micrograms per cubic metre) for each SADC member state in 2019.

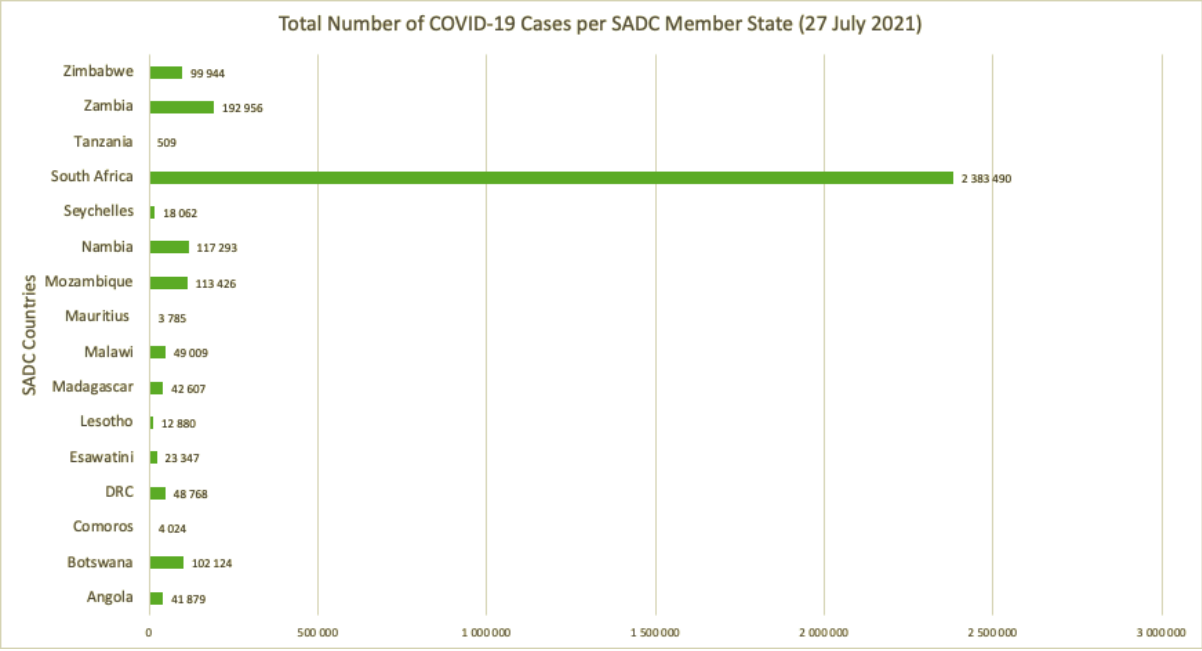


Figure 1: Total Number of COVID-19 Cases per SADC Member State (27 July 2021)

Source: (Worldometer, 2021)

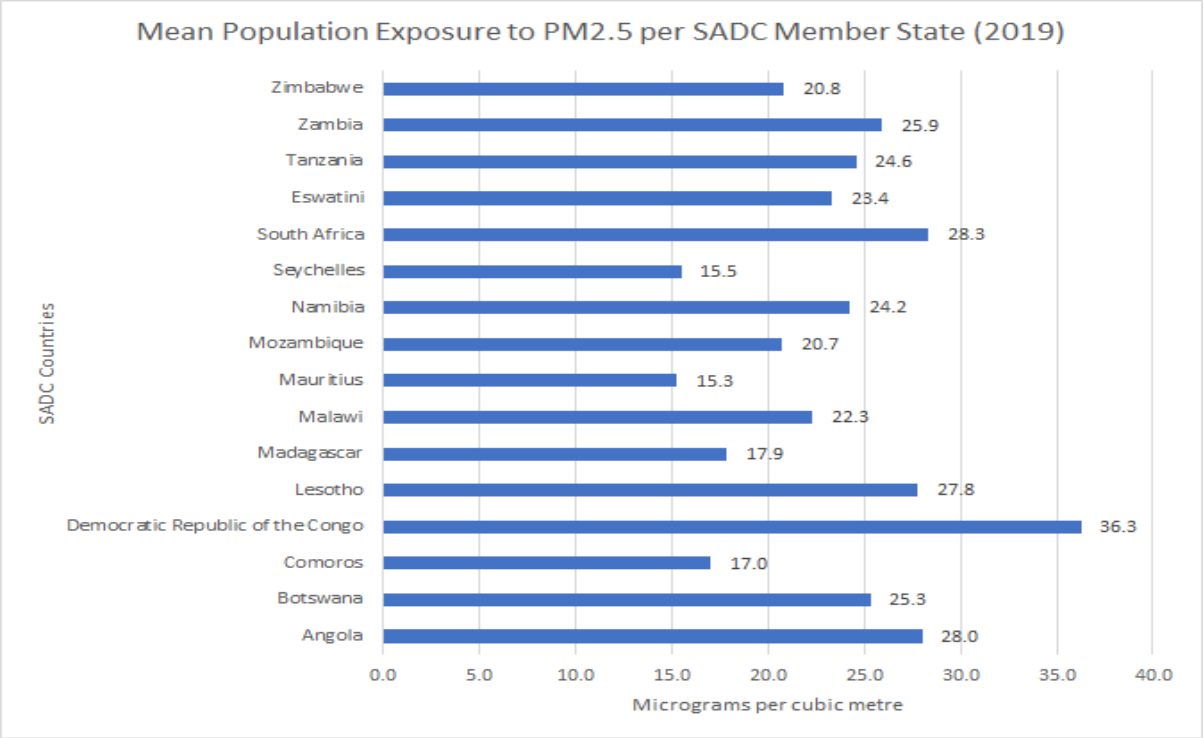


Figure 2: Mean Population Exposure to MP2.5 per SADC Member States (2019)

Source: (Organisation for Economic Co-operation and Development, 2022)

2.2.2. Vulnerable and at-risk populations

COVID-19's mortality was directly affected by comorbidities, such as cardiovascular conditions like arterial hypertension, diabetes, obesity, and heart disease, as well as respiratory conditions like asthma and chronic obstructive pulmonary disease (COPD), which are similar to those influenced by air pollution (Sanyaolu et al., 2020). Rates of mortality also appeared to be particularly high in geriatric patients, men, socio-economically disadvantaged populations and some ethnic populations (Bambra et al., 2020). When analysing connections between risk factors and outcomes, these confounding conditions must be considered, including hospital admission, increased susceptibility to disease, and death (Ejaz et al., 2020). The size of populations living in poverty, the capacity of the healthcare services, and the size of the elderly population could all act as risk factors for poor outcomes of COVID-19.

2.3. Links between Air Pollution and COVID-19

There has been a clear causal relationship established between air pollution and cardiovascular and respiratory diseases (Andrews et al., 2023; Wong et al., 2023; Estol, 2020; Newby et al., 2015). Air pollution reduces the body's ability to defend itself against pathogens and, therefore, leads to the body being more susceptible to respiratory infections such as COVID-19 (Manisalidis et al., 2020). Those who are ailed by respiratory diseases and infections, therefore, have an increased risk of mortality from COVID-19 when compared to those who do not have these diseases (Johns Hopkins Medicine, 2021).

Existing research confirms that there is a positive correlation between the spread of the virus and air pollution (Bhaskar et al., 2023; Carballo, Bakola, & Stuckler., 2022; Petroni et al., 2020). This is understood through the infection rates. An infection rate refers to the rate at which a disease or infection is spread amongst a population (Zeb et al., 2020). However, further research is needed to determine whether long-term exposure to hazardous air pollutants (HAPs) is also associated with an increased risk of COVID-19-related mortality. Mortality rates refer to the proportion of a population that dies in a specific geographic region during a defined time period due to a specific cause, in this case, COVID-19 (Lim et al., 2021).

HAPs are a unique group of pollutants that include both volatile organic compounds and metals and have been linked to a higher risk of respiratory and immune conditions (Pansini & Fornacca, 2021). Air pollutants which are hazardous are those that are suspected to cause serious health effects such as cancer, congenital abnormalities and reproductive diseases, as well as causing severe environmental damage (United States Environmental Protection Agency, 2022b).

It is pertinent to look at the impact of air pollution on transmission and the impact of the virus because COVID-19 is a disease that has airborne transmission, with people contracting the virus through the inhalation of droplets. Though COVID-19 can also be spread through the faecal-oral route and pregnancy (Comunian et al., 2020), the infectiousness is primarily driven by airborne transmission. Particulate matter (PM) acts as a transport vector for the virus, which increases its spread as the PM creates a microenvironment suitable for the virus to survive (Tung et al., 2021). Findings have found statistically significant positive correlations between high levels of air pollution and COVID-19 infections in China, Iran, Italy, Spain, France, Germany, the United Kingdom, and the United States, using several annual satellite and ground air quality indexes in these countries (Pansini & Fornacca, 2021). The link between poor air quality, COVID-19 infections, and COVID-19-induced mortality was strongest in Italy (Ali & Islam, 2020). In the United States, a 2020 study indicated that long-term exposure to air pollution increased vulnerability to the incidence of more severe COVID-19 outcomes (Liang et al., 2020). These findings suggest the well-established link between $PM_{2.5}$ exposure and several cardiovascular and respiratory comorbidities that enhance the risk of death in COVID-19 patients (Wu et al., 2020).

It is important to understand that SARS-CoV-2 is similar to the first severe acute respiratory syndrome coronavirus, SARS-CoV-1 (both are classified as Beta coronaviruses). Similarly, to COVID-19, SARS was a zoonotic virus whose origin has been traced to a bat (Sallard et al., 2021). SARS-CoV-1 and SARS-CoV-2 have other similarities, such as close RNA genome relation and the same entry point into the body. These strong similarities allow us to apply insights from SARS-CoV-1 to SARS-CoV-2. Beta coronaviruses, one of seven coronavirus subtypes that can infect humans, can cause severe illness and

rates of mortality, whereas alpha coronaviruses produce asymptomatic or mild clinical presentations of disease (Velavan & Meyer, 2020). Some areas of the world have experienced greater infection and fatality rates than other areas. These variations are believed to be partially attributable to the impact of air pollution.

This idea was reinforced by a 2003 study that found that the likelihood of death from SARS was more than 80% higher in areas with moderate air pollution, and double that in areas that were heavily polluted (Pozzer et al., 2020). Evidence indicates that long-term exposure to air pollution results in increased rates of respiratory morbidity and mortality. Recent research (Bourdrel et al., 2021; Li et al., 2020) has indicated that there is a link between the transmission of infectious diseases and air pollution. For example, poor air quality has been linked to higher mortality for SARS and increased influenza infection. Furthermore, under clinical conditions, SARS-CoV-2 remained stable in ambient aerosols - suggesting that this could be a significant source of COVID-19 transmission (Domingo & Rovira, 2020).

Emerging research from the Harvard T.H. Chan School of Public Health has found that for every one microgram/cubic meter increase in air pollution, there is an eleven percent increase in mortality from COVID-19 infection (Wu et al., 2020). In comparison, most adults from the United States breathe air with eight micrograms/cubic meters of particulate matter (Wu et al., 2020). However, individual-level COVID data is not publicly available for this study at the Harvard T.H. Chan School of Public Health (Ali & Islam, 2020; Wu et al., 2020). Lastly, preliminary research shows that SARS-CoV-2 ribonucleic acid (RNA) can be detected in outdoor particulate matter (PM) under specific circumstances of atmospheric stability and high PM_{10} levels (Ali & Islam, 2020; Setti et al., 2020).

COVID-19 is a challenging endpoint to assess because the virus is passed from individual to individual, and the spread of the disease is, therefore, dynamic in both time and location. When researching an emerging topic such as the relationship between air pollution and COVID-19, methods that work well to explore connections between long-term exposure to air pollution and chronic illness development are limited (Brunekreef et al., 2021). A recent study made up of five thousand seven hundred (5 700) people hospitalised because of COVID-19 in New York hospitals found that they all had higher $PM_{2.5}$ levels and that 57% had hypertension, 42% had obesity, and 34% had diabetes, suggesting the possibility of a link between exposure to $PM_{2.5}$ and the cardiovascular system in relation to COVID-19 (Richardson et al., 2020).

Preliminary studies addressed the impact of air pollution on COVID-19 in different regions. In China, the incidence of COVID-19 and exposure to elevated levels of $PM_{2.5}$ was found to significantly enhance the risk of hospitalisation, while a correlation between ambient $PM_{2.5}$ and the mortality rate was also established (Pozzer et al., 2020). During the first two weeks of the global lockdown in 2020, a decrease in outdoor air pollution was observed in 27 countries globally. Specifically, fine particulate matter decreased by 9%, ozone decreased by 11%, and nitrogen dioxide decreased by 29% (Venter et al., 2020). These emissions have been attributed to reduced industry and transport-related activities (McElroy & Vaidyanathan., 2022; Venter et al., 2020). However, such studies must be compared against others to account for seasonal meteorological variation.

Closer to home, a 2022 cross-sectional study was conducted to investigate changes in fuel-use patterns in relation to household air pollution (HAP) across four provinces in South Africa with the highest rates of

COVID-19 (Wright et al., 2022). The study surveyed over two thousand five hundred people. The study found that during South African Lockdown Levels Four and Five, most participants spent more time indoors and with increased cooking and cleaning reported. This could explain exposure to HAP. However, the most relevant aspect of the article by Wright et al. (2022) to this paper was the fact that the study found 83% of participants found it difficult to make financial ends meet during the lockdown. Many began switching from electricity to alternative or "dirty" fuels such as coal, wood, and paraffin, which are associated with greater HAP should there be insufficient ventilation indoors. Therefore, it is important to consider how the impact of COVID-19 affects air pollution beyond simply the virus itself and how the measures put in place to curb the virus (Lockdown) might increase air pollution.

2.4. Gaps in the Literature

Research suggests that both indoor and outdoor air pollution can cause a variety of health issues, including exacerbating COVID-19 mortality rates (Sharma et al., 2020). However, it is essential to note that more research is needed in LMICs, where exposure rates are highest, but data availability is limited (Vilcassim & Thurston, 2023). Unfortunately, the bulk of this literature comes from HICs with sophisticated technology dedicated to monitoring the health of their populations and environments. This has led to a gap in the literature in terms of data from LMICs, which normally have the highest exposure rate but relatively less data available (Vilcassim & Thurston, 2023). Though some LMICs like India and China have published studies based on their data, the lack of data from Africa specifically is a major concern.

The lack of data from Africa is an issue that carries through to the SADC region, one of the focal points of this data. There is a significant lack of data specific to SADC that deals with air pollution and its effects, which hampers the development of interventions and policy responses. As a result, many conclusions drawn on the link between air pollution and COVID-19 are ultimately derived from data in HICs, and not from the SADC region.

To address these limitations, the scoping review will attempt to match existing SADC data to conclusions drawn by studies that are not based on SADC. While many of these papers and their conclusions are based on HICs, it is often possible to use existing SADC data to attempt to support their conclusions in an SADC context. In addition to this, higher weight and consideration will be given to literature based on SADC data in the review. In this way, the scoping review will attempt to bridge the current gap in the literature.

3. Aim and Objectives

3.1. Aim

This study aims to illustrate an association between air pollution and COVID-19 health outcomes both globally and, more specifically, within SADC countries to assist SADC country policymakers in improving air quality management both during and post-pandemic.

3.2. Objectives

The aim of the study will be met through the following objectives:

1. To identify key indoor and outdoor air pollutants that are linked to negative health outcomes for COVID-19 infections and mortality with relevance for the SADC member states.
2. To provide evidence on the burden of disease of the interlinkage between air pollution and COVID outcomes in general and for the SADC region specifically.
3. To provide policy recommendations for SADC member states for reducing indoor and outdoor air pollution exposure that may exacerbate COVID-19-type infections and mortality rates.

3.3. Hypothesis

SADC countries with high levels of ambient air pollution experience severe COVID-19 outcomes, including higher mortality rates from COVID-19.

4. Methodology

4.1. Background: Focusing on the SADC Region

The SADC region was chosen as the area of focus for this research because it represents a unique combination of high exposure to air pollution, poor healthcare infrastructure, and the presence of populations that are especially vulnerable to infectious diseases. Similarly to the Economic Community of Central African States (ECCAS), SADC's economic recovery is said to be low compared to other regional economic communities (RECs). However, the reporting of both COVID-19 and air pollution is better within the SADC region – another part of why the region was chosen. This poor economic recovery contributes to rising inequality in the form of reduced incomes, rising food price inflation, and reduced health services, including access to vaccines (United Nations Human Settlements Programme (UN-Habitat) & United Nations World Food Programme, (WFP), 2021). Bearing in mind that the region has much lower vaccination rates and smaller fiscal resources than other African regions that have attempted to refloat their economies, it is an unfortunate fact that the SADC region was not able to access or rely on costly interventions to combat COVID-19 challenges. This, combined with the fact that air pollution in the SADC region is relatively high and it has a large section of the population that is vulnerable, makes it a relatively unique area of study (Renzaho, 2020). Most of these member states fall within the category of LMICs, with the exception of the Seychelles, which is currently listed as an HIC (The World Bank, 2022).

4.2. Research Design

A systematic review is unsuitable for this study as its purpose is to identify knowledge gaps, survey literature, refine concepts, or examine research conduct (Grant & Booth, 2009). Therefore, a scoping review is best suited for this research topic. While scoping reviews are used to methodically map fundamental concepts underpinning a study topic, as well as mapping the forms and primary sources of evidence rapidly, despite lacking an exact definition or procedure (Arksey & O'Malley, 2005). Scoping reviews are particularly effective in addressing research areas that are broad, emerging, not yet thoroughly assessed, or are wide or changeable, especially in situations where it is unclear whether there is a substantial body of literature to support a literature review or systematic review (Levac, Colquhoun & O'Brien, 2010; Grant & Booth, 2009; Munn et al., 2018; Munn, Peters et al. 2018).

This review will be guided by Arksey and O'Malley's six-stage methodological framework, which are: (1) identifying the research question, (2) identifying relevant studies, (3) study selection, (4) charting the data, (5) collating, summarising and reporting the results, and lastly (6) consulting with stakeholders to inform or validate study findings (Arksey & O'Malley, 2005). The 6th stage is often skipped. It is critical if the review is being conducted to inform health or economic policies (Khalil et al., 2016). However, they do note that this step is optional. Keeping in mind the narrow scope of this mini-dissertation, this stage will be skipped.

4.2.1. Stage 1: Identifying the Research Question

Considering the SADC region's unique context outlined in Section 5.1, the review aims to address several specific questions to guide the review of existing research evidence. Questions will be formulated using the Population, Concept and Context (PPC) mnemonic to help define the inclusion criteria.

Review Questions:

1. What are the air pollutants and their sources associated with COVID-19 infections and mortality globally and in SADC countries?

Population: All individuals infected with COVID-19, including specific populations (e.g., elderly, healthcare workers, and people with pre-existing conditions) within both global and SADC contexts.

Concept: The types of air pollutants (e.g., $PM_{2.5}$, PM_{10}, Pb, CO, O_3, SO^2, NO^2, C_6H_6) that have been studied or reported to be associated with COVID-19 infections and mortality.

Context: Global and SADC-specific literature, to include epidemiological studies, reviews, or policy reports that offer insights into the relationship between air pollutants and COVID-19.

2. What are the sources of these air pollutants (such as indoor vs. outdoor air pollutants)?

Population: Populations exposed to air pollutants within SADC countries

Concept: Sources of air pollution, broken down by indoor and outdoor factors like vehicular emissions, industrial processes, tobacco smoke, and household cooking.

Context: Studies, reports, or articles that examine the sources of air pollutants, focused on global context with a focus on SADC countries

3. Are there any strategies or recommendations to reduce air pollution that are relevant for SADC countries?

Population: Vulnerable populations in LMICs

Concept: Strategies, interventions, and recommendations aimed at reducing air pollution to mitigate COVID-19 infections and mortality.

Context: Published literature, including policy papers, intervention studies, and review articles, that provide strategies for air pollution reduction relevant to SADC countries.

4. How has air pollution been managed during the COVID-19 pandemic in the SADC region?

Population: SADC countries, their governments, and organisations involved in air quality management during the COVID-19 pandemic.

Concept: Measures, policies, and practices that were employed to manage air pollution during the pandemic. This could include monitoring, regulations, and public awareness campaigns.

Context: Documents, reports, and studies that focus on air pollution management in SADC countries during the COVID-19 pandemic, including government reports, scholarly articles, and NGO publications.

5. To what extent have studies from LMICs explored the impact of air pollution on COVID-19 infections? What has been the primary focus of these investigations?

Population: All individuals, with a highlight on specific demographics like the elderly, healthcare workers, and those with pre-existing conditions, who have been infected with COVID-19 within LMICs

Concept: Examination of existing literature concerning the types and sources of air pollutants (e.g., $PM_{2.5}$, PM_{10}, Pb, CO, O_3, NO^2, SO^2, C_6H_6) in correlation with COVID-19 infections and mortality within LMICs. Analysis of the primary focus and findings of these studies in delineating the relationship between air pollution and COVID-19 outcomes.

Context: The body of literature emerging from LMICs, encompassing epidemiological studies, reviews, or policy reports that shed light on the interplay between air pollutants and COVID-19 infections.

4.2.2. Stage 2: Identifying Relevant Studies

The primary objective of this stage is to gather all pertinent information, both published and in preprint, that could be of relevance. Since scoping reviews can include a broad scope of information ranging from books and peer-reviewed articles to theses, not all information may easily be obtained through a database search (Pollock et al., 2021).

A search for relevant articles will be conducted by using keywords, Boolean operators and truncated terms. When using a database or search engine, Boolean operators can be used to widen or reduce one's search criteria. Boolean operators refer to words like AND, OR, and NOT and symbols like quotation marks ", parentheses (), and asterisks *. These words and symbols can help narrow one's search to locate the most applicable sources and results by combining terms. This search is referred to as a "Boolean search" (Aromataris & Riitano, 2014).

The search will be restricted to articles published from 2019 to 2023. This particular time period was chosen to ensure that this research incorporates the latest studies that have emerged since the emergence

of the COVID-19 pandemic in 2019. This approach guarantees that the data included in this review is comprehensive and contains up-to-date data.

The following electronic databases will be searched:

1. PubMed/Medline
2. Google Scholar
3. WHO COVID-19 Database (as grey literature)
4. Scopus
5. EbscoHost (6, 7, 8 and 9 are a part of this)
6. AfricaWide
7. CINAHL
8. Greenfile
9. Biological and Agricultural Index
10. Web of Science (11, 12, 13 and 14 fall under this)
11. Biological Abstracts
12. Web of Science Core Collection
13. SciELO Citation Index
14. Preprint Citation Index

The search terms in Table 2 will be used and are adapted from (Katoto et al., 2021)

Table 2: Search Strategy for Scoping Review

#1	"air pollution" OR "outdoor air pollution" OR "ambient air pollution" OR "particulate matter" OR "coarse particulate matter" OR "fine particulate matter" OR "ultra-fine particulate matter" OR "fine particles" OR "ultra-fine particles" OR "coarse particles" OR lead OR "sulphur dioxide" OR "nitrogen dioxide" OR "carbon monoxide" OR ozone OR "benzene" OR "O3" OR "SO2" OR "Sox" OR "NO2" OR "NOx" OR "PM" OR "PM1" OR "PM2.5" OR "PM10" OR "volatile organic compound*"
#2	"air pollution" OR "indoor air pollution" OR "particulate matter" OR "coarse particulate matter" OR "fine particulate matter" OR "ultra-fine particulate matter" OR "fine particles" OR "ultra-fine particles" OR "coarse particles" OR lead OR "sulphur dioxide" OR "nitrogen dioxide" OR "carbon monoxide" OR ozone OR "benzene" OR "O3" OR "SO2" OR "Sox" OR "NO2" OR "NOx" OR "PM" OR "PM1" OR "PM2.5" OR "PM10" OR "volatile organic compound"
#3	"COVID-19" OR "novel coronavirus" OR "coronavirus disease" OR "coronavirus" OR "SARS-CoV-2″ OR "SARS-2″ OR "severe acute respiratory syndrome coronavirus 2"

#4	outcome OR prevalence OR incidence OR mortality OR asymptomatic mild OR asymptomatic moderate OR asymptomatic severe
#5	South Africa OR Angola OR Botswana OR Comoros OR Democratic Republic of Congo OR Eswatini OR Lesotho OR Madagascar OR Malawi OR Mauritius OR Mozambique OR Namibia OR Seychelles OR Tanzania OR Zambia OR Zimbabwe
#6	"lockdown" OR "social distancing" OR isolation OR quarantine
#7	"public health intervention" OR "policy intervention" OR "regulatory intervention" OR "health education" OR "risk communication" OR "air quality monitoring" OR "pollution control" OR "emission control" OR "source reduction" OR "ventilation" OR "clean energy" OR "air purifier" OR "face masks" OR "filtration system" OR "scrubber" OR "carbon capture" OR "public transportation" OR "vehicle emission standard"
#8	"vaccination" OR "vaccine" OR "antiviral" OR "treatment" OR "medical intervention" OR "hospital care" OR "clinical management" OR "contact tracing" OR "hand hygiene" OR "sanitisation" OR "disinfection" OR "PPE" OR "personal protective equipment" OR "therapeutics" OR "early detection" OR "telemedicine" OR "remote consultation" OR "contact tracking" OR "exposure notification" OR "exposure alert"
#9	#7 OR #8
#10	#2 AND #3 AND #4 AND #5 AND #6
#11	#1 AND #3 AND #4 AND #5 AND #6
#12	#1 AND #3 AND #4 AND #5
#13	#2 AND #3 AND #4 AND #5
#14	#2 AND #3 AND #4 AND #5 AND #6 AND #9
#15	#1 AND #3 AND #4 AND #5 AND #6 AND #9

This search strategy was defined in consultation with a specialist librarian at UCT. Due to the rapidly changing nature of the COVID-19 pandemic, efforts will be made to include news articles, government reports, and literature in preprint by searching Google and Google Scholar. Relevant articles will be selected based on an abstract screening process. The reference lists of literature included will be manually searched for additional references which meet the inclusion criteria (Schoeman, 2019).

4.2.2.1. Eligibility Criteria

Table 3: Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Publication Date	Articles published from 2019 to the present.	Articles published before 2019.
Geographic Location	Research conducted in a SADC (Southern African Development Community) member state or Research that includes information on SADC member states	Research conducted outside of a SADC member state. Or Research that does not include information on SADC member states
Language	Publications written in English	Articles published in language other than English.
Topic	Studies focusing on the relationship between air pollution and COVID-19 health outcomes in a SADC country.	Studies that do not focus on the relationship between air pollution and COVID-19 health outcomes in a SADC country.
Study Types	Randomised trials, non-randomised trials, case-control studies, cohort studies, qualitative meta-analysis, case studies, correlational studies, ecological studies, ethnography, discourse analysis, reports, and news articles.	Opinion Articles, Letters to the Editor, and duplicate articles of an already selected article.
Criteria Air Pollutants	Studies addressing one or more of the seven most common air pollutants: Particulate Matter, Sulphur Dioxide, Lead, Nitrogen Dioxide, Carbon Monoxide, Ozone, and Benzene.	Studies not focusing on the seven mentioned air pollutants.
Air Pollution Definition & Focus	Studies that provide research findings on the contamination of the air (both indoor and outdoor) by pollutants due to natural events and anthropogenic activities in SADC countries.	Articles that do not fit this definition or that focus on air pollution outside of SADC countries.
COVID-19 Definition & Focus	Studies addressing COVID-19 caused by the SARS-CoV-2 virus, emphasising its health outcomes in relation to air pollution in SADC countries. It should note the range of symptoms and its status as a global pandemic.	Studies that do not fit this criterion regarding the focus and definition of COVID-19 or those not focusing on SADC countries.

4.2.3. Stage 3: Study Selection

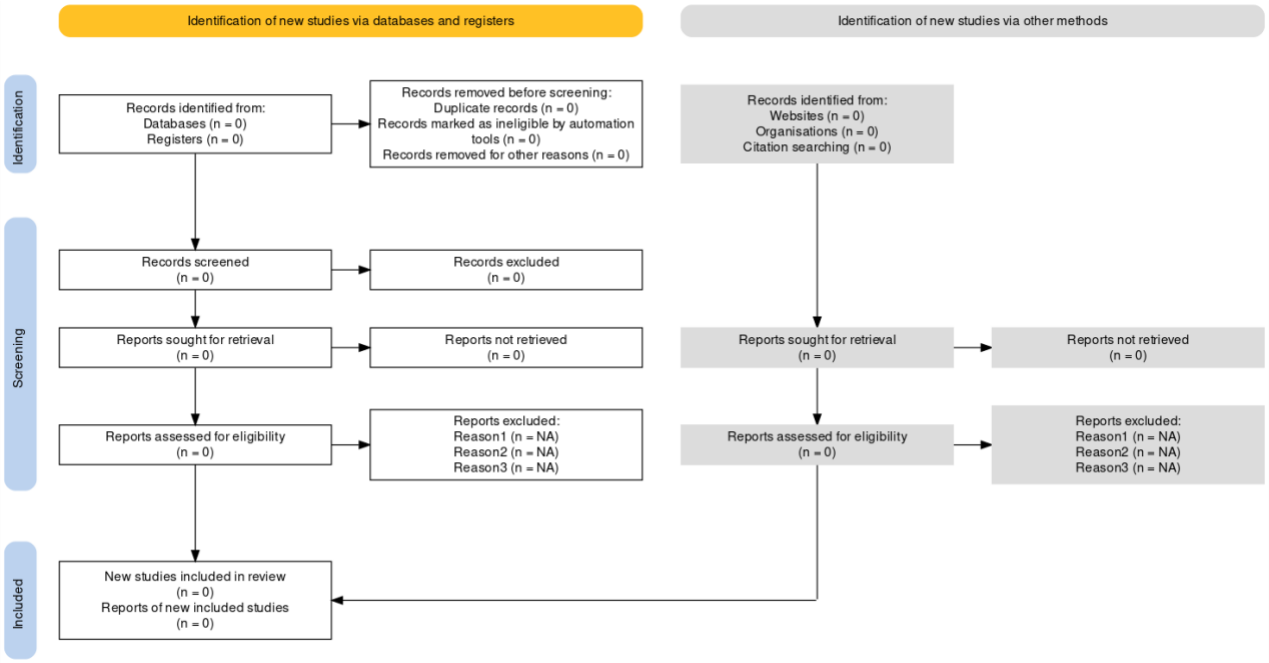
To ensure a thorough evaluation of all possible relevant sources, the student will conduct a systematic search on various academic databases such as PubMed, Scopus, Web of Science, and Google Scholar. Additionally, they will also search for grey literature sources like repositories, organisational websites, and conference proceedings. The search strategy will involve using a combination of MeSH terms, keywords, and Boolean operators that are tailored to each specific database. (Taylor & Pagliari, 2018)

Once the database searches have been completed, relevant documents will be imported into Rayyan, a systematic and scoping review management software. The screening process will involve the student (Aleya Banwari) and their co-supervisor (Meryl Jagarnath), who will independently screen titles and

abstracts using electronic searchers and the "snowballing" technique for relevance based on the established inclusion criteria (Taylor & Pagliari, 2018). The snowballing approach is a technique to identify important literature relevant to the relevant research topic by tracking citations in key texts on the relevant topic(s) (Sayers, 2007). If there is a disagreement or consensus cannot be reached about what to include/not include in the following screening or final analysis, the third reviewer (Andrea Rother) will determine if a study is to be included and resolve the disagreement (Hassan, 2018).

This study protocol follows the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR). The PRISMA-ScR checklist will be used to document the search and the identification of studies (Tricco et al., 2018). The number of studies determined at each step of the study selection process will be recorded to visually represent the process. The diagram will help to report duplicates found between databases (Peters et al., 2020a).

Table 4: Prisma-ScR 2020 Flow Diagram Draft



Source: (Haddaway et al., 2022)

4.2.4. Stage 4: Charting the Data

Annex 1 is the data-charting form developed between the student and their supervisors to determine which variables to extract. This will address the research questions and will be used to assess the final

eligibility of the articles found through the scoping review search. The student will discuss the results with their supervisors and continuously update the data-charting form in an iterative process.

The student (AB) and a supervisor (MJ) will independently extract data from the first ten included studies using the data-charting form (see Annex 1). A data extraction table will be used to extract the data. During the extraction process, the extraction tables will be updated as appropriate, as requirements can be added or omitted after the literature has been reviewed. The aim of data extraction is to eliminate any possible bias and ensure that findings are accurate and true. They will meet in person or via an online Microsoft Teams meeting to determine whether their approach to the data extraction is consistent with the research questions and focus of the study. The data will then be analysed using a qualitative content analysis approach.

4.2.4.1. Critical Appraisal of Individual Sources of Evidence

Guided by the recommendations of Levac et al. (2010), this scoping study will rely on a qualitative content analysis approach to critically appraise the literature. A descriptive synthesis of the main findings of the included studies will be shared to review the data currently available from different surveillance systems. COVID-19 infections and mortality rates for SADC will be calculated based on available data.

4.2.5. Stage 5: Collating, Summarising and Reporting the Results

4.2.5.1. Analysis (including Descriptive Numerical Summary Analysis and Narrative Synthesis)

To ensure a comprehensive analysis, a mixed approach that incorporates a Descriptive Numerical Summary Analysis and Narrative Synthesis will be used. The Descriptive Numerical Summary Analysis

will include the following: a frequency analysis, cross-tabulation, and trend analysis. The frequency analysis will provide a numerical summary of key variables, such as study designs, years of publication, and intervention types, while cross-tabulation helps identify relationships or patterns between different categorical variables, such as geographic location and study outcomes. Trend analysis will analyse trends over time, such as the publication year of studies against key findings, to identify any evolving patterns (Peters et al., 2020b). Statistical software like R can be used to perform frequency analysis, cross-tabulations, and trend analysis.

On the other hand, Narrative Synthesis will be used to interpret the findings and understand the relationships within and across the studies. The findings from the above analyses will be initially synthesised to map the data and understand the relationships between the findings (Popay et al., 2006). To

perform the narrative synthesis, the software tool NVivo will be used for its well-suitedness to manage, analyse and visualise qualitative data.

The narrative synthesis will be interpreted considering the research questions, and reflections on the implications of the findings will be discussed. This structured approach, incorporating both a numerical summary and a narrative synthesis analysis, will provide a robust and comprehensive understanding of the data. The utilisation of appropriate software tools for analysis will ensure accuracy and efficiency in managing and analysing the large volume of data. This approach will aid in extracting meaningful insights from the data, significantly contributing to the understanding of the relationship between air pollution and COVID-19 health outcomes in the SADC region, and offering clear, actionable insights for policymakers, practitioners, and other stakeholders.

4.2.5.2. Reporting the Results and Producing the Outcome that Refers to the Overall Purpose or Research Question

The student will meet with their supervisors to resolve any conflicts and to help ensure consistency between reviewers and with the research question and purpose (Levac, Colquhoun, & O'Brien, 2010). All included studies will be grouped according to all possible and anticipated themes during full-text screening, with room left over for unforeseen themes if they occur. The studies will be grouped by theme using a logic map to illustrate how themes are similar or dissimilar to one another. Each theme will be compared to the research questions to review whether the themes (and selected studies) are relevant to the overall purpose/research questions.

4.2.5.3. Consider the meaning of the findings as they relate to the overall study purpose; discuss implications for future research, practice and policy.

The report will feature a section dedicated to the findings concerning the study's aim. This will provide an overall summary, assess the feasibility of a systematic review based on the analysed studies, and offer policy recommendations for the SADC regions based on the analysis.

This final thesis (including a journal-ready article) will be submitted in partial fulfilment of the requirements for a UCT Master's degree in Public Health (MPH). It will be published in the format of a dissertation on the University of Cape Town's institutional web-based depository, OpenUCT. In order to disseminate the results, a publishable manuscript will be submitted to relevant journals, as required by MPH. The author will also upload their completed dissertation to their profiles on social academic networks such as ResearchGate and Academia.edu to aid dissemination efforts.

4.3. Ethical Considerations

A scoping review does not involve primary research and uses published literature available through publicly accessible data; therefore, no ethical review or approval is needed. This is in accordance with

Section 1.1.8 of the Department of Health's Ethics in Health: Principles, Processes and Structures (South African Department of Health, 2015), which states, "Research that relies exclusively on publicly available information or accessible through legislation or regulation usually need not undergo formal ethics review. This does not mean that ethical considerations are irrelevant to the research." However, this protocol will need to be reviewed and approved by the departmental research committee (DRC) in the School of Public Health at the University of Cape Town to evaluate the protocol's scientific merit and potential risk. The protocol will be registered with the Open Science Foundation (OSF).

4.4. Risk of Bias

To mitigate the risk of bias within this scoping review, a structured approach will be adopted to avoid selection bias, information bias, and confounding bias. Initially, utilising two reviewers to independently screen all articles using a pre-defined set of eligibility criteria (see Table 5.4.1 for Inclusion and Exclusion Criteria) to ensure that there is a consistent selection process, thus minimising the risk of selection bias. This will prevent relevant studies from being omitted or including irrelevant studies based on subjective judgment.

In order to address information bias which may arise from inaccurate or inconsistent data collection and interpretation, a standardised data extraction form will be used to cross-verify the data to rectify any discrepancies. A third reviewer (Rother) will assist in reaching a consensus should the initial two reviewers be unable to meet an agreement.

Lastly, to address confounding bias, there will be meticulous documentation and analysis of all identified potential confounders during the data extraction process. Furthermore, this review will also include a diverse range of studies with varying methodologies and settings to ensure a broader understanding and identification of potential confounders. Thus, enhancing the validity and generalisability of our findings. This multi-faceted approach aims to substantially reduce the risk of bias, ensuring a rigorous, transparent, and reliable scoping review.

5. Conclusion

The quest for appropriate and efficient strategies to minimise anthropogenic emissions, which cause both air pollution and climate change, needs to be expedited, according to the newfound environmental understanding that has been developed during the COVID-19 pandemic. Unlike the COVID-19 pandemic, there is no vaccine that can help against climate change and poor air quality. The only solution to tackle climate change and air pollution is to reduce emissions. At the local level, efforts can be made to improve air quality, which will then help to prevent climate change on the global level. Therefore, the move to a sustainable economy with green, renewable energy sources will benefit both environmental and public health (Pozzer et al., 2020).

Many African countries are still in their infancy in terms of development. As a result, they could use other non-polluting economic paths rather than becoming imprisoned in fossil-fuel-based economies. African governments need to invest in air quality monitoring to address the significant data gap in this field. They should also train health professionals to detect diseases related to air pollution, provide funding for environmental protection agencies to set air quality standards and ensure adherence, and lobby international funding organisations to set up funding initiatives specifically for African researchers to adequately address the disease burden caused by air pollution (Fuller & Amegah, 2022). In conclusion, Africa's countries can prevent ambient air pollution, generate human capital, and drive development by making prudent and forward-thinking investments in renewable energy and clean technologies (Fisher et al., 2021).

6. Study Timeline

	April 2021 – November 2023	November 2023	December 2023	January 2024	February 2024	March 2024	April 2024
Protocol Development and Literature Review							
Ethics Approval							
Data Collection							
Data Analysis							
Journal Ready Manuscript							
First Full Draft to Supervisors							
Submission of Letter of Intent (LoI)							
Submission of Turnitin Report to Supervisors							
Thesis Submission							

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Appendix B: Tables and Figures

Appendix C: Completed Data Charting Form

Study Characteristics	Category	Description
General Information	1. Authors	Names and Institution
	2. Title	As per the Database
	3. Year of Publication	Month and Year
	4. Origin of Study	Country or Countries that the study took place in
	5. Source	URL Address of publication/Journal
	6. Type of Data	Primary data collected from study, Secondary data from an existing source
	7. Study design	Systematic Review, Scoping Review, Cross-sectional, Cohort, etc.
	8. Study duration	Time period over which the study took place or observed
	9. Publication Type	Journal article, Report, Grey literature
Population	10. Sample size	Size of sample in the study
	11. Location	Area where the study was based
	12. Gender	Male, Female, Gender Non-Conforming, Trans
	13. Type of living dwelling	Urban or rural
Health Outcomes	14. Asthma	Yes or No
	15. COPD	Yes or No
	16. Lung Cancer	Yes or No
	17. Stroke	Yes or No
Criteria Pollutant Exposure and COVID-19	18. Criteria pollutants present	Discussion of criteria pollutants (particulate matter, nitrogen dioxide, sulphur monoxide, lead, ozone, benzene) in relation to COVID-19 infections and mortality
	19. COVID-19 Infections	
	20. COVID-19 Mortality	
Air Pollution	21. Indoor/Household Air Pollution	Is it present? Yes or No
	22. Outdoor Air Pollution	Is it present? Yes or No
	23. Both Indoor and Outdoor Air Pollution	Is it present? Yes or No
Recommendations and Conclusions	24. Recommendations	Recommendations that are relevant or applicable to SADC countries' contexts
	25. Conclusions and Findings.	Findings will be discussed, and conclusions drawn from the study

SADC Interventions and Effectiveness	26. SADC Intervention	Description of the intervention implemented by SADC
	27. Was the intervention effective?	Yes, No, or Partially
	28. Reason for Effectiveness/Ineffectiveness	Explanation based on study
	29. Mapping of Interventions	Geographic regions or countries where the intervention was applied

Appendix D: Ethics Approval Documentation

UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee

Room 45, E-52 Old Main Building
Groote Schuur Hospital
Observatory 7925
Telephone [021] 406 6492
Email: hrec-enquiries@uct.ac.za
Website: https://health.uct.ac.za/home/human-research-ethics

19 December 2023

HREC/REF: 969/2023

Prof H-A Rother
Environmental Health Division
Falmouth Building-FHS
Email: andrea.rother@uct.ac.za
Student: BNWALE001@myuct.ac.za

Dear Prof Rother

PROJECT TITLE: THE EFFECT OF OUTDOOR AND INDOOR AIR POLLUTION ON COVID-19 INFECTIONS AND MORTALITY RATES IN THE SOUTHERN AFRICAN DEVELOPMENT COMMUNITY: A SCOPING REVIEW
(MATER IN PUBLIC HEALTH – MS ALEYA BANWERI)

Thank you for submitting your request to the Faculty of Health Sciences Human Research Ethics Committee.

The HREC note that the proposed study is a scoping review.

As the scoping review involves published literature available through publicly accessible electronic databases, research ethics review and approval is not required.

This is in accordance with Section 1.1.8 of the Department of Health's Ethics in Health Research: Principles, Processes and Structures (South African Department of Health, 2015), which states: *"Research that relies exclusively on publicly available information or accessible through legislation or regulation usually need not undergo formal ethics review. This does not mean that ethical considerations are irrelevant to the research."*

The HREC acknowledges that the student- Mr Aleya Banwari is also involved in this project.

Yours sincerely

PROFESSOR MARC BLOCKMAN
CHAIRPERSON, FACULTY OF HEALTH SCIENCES HUMAN RESEARCH ETHICS COMMITTEE

Appendix E: Instructions for Authors for the Target Journal – Current Environmental Health Reports

Submission Guidelines

Current Environmental Health Reports

Link: https://link.springer.com/journal/40572/submission-guidelines

Instructions for Authors

Types of Papers

Review Articles and Invited Commentaries

Additional information

Please supply author biographies and photographs with submitted papers.

Manuscript Submission

Manuscript Submission

Submission of a manuscript implies: that the work described has not been published before; that it is not under consideration for publication anywhere else; that its publication has been approved by all co-authors, if any, as well as by the responsible authorities – tacitly or explicitly – at the institute where the work has been carried out. The publisher will not be held legally responsible should there be any claims for compensation.

Permissions

Authors wishing to include figures, tables, or text passages that have already been published elsewhere are required to obtain permission from the copyright owner(s) and to include evidence that such permission has been granted when submitting their papers. Any material received without such evidence will be assumed to originate from the authors.

How to Submit

Manuscripts should preferably be submitted in the original file format and in PDF format.

Please ensure you provide all relevant editable source files. Failing to submit these source files might cause unnecessary delays in the review and production process.

Title Page

Please make sure your title page contains the following information.

Title

The title should be concise and informative.

Author information

- The name(s) of the author(s)
- The affiliation(s) of the author(s), i.e. institution, (department), city, (state), country
- A clear indication and an active e-mail address of the corresponding author
- If available, the 16-digit ORCID of the author(s)

If address information is provided with the affiliation(s) it will also be published.

For authors that are (temporarily) unaffiliated we will only capture their city and country of residence, not their e-mail address unless specifically requested.

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Abstract

Please provide an abstract of 150 to 250 words. The abstract should not contain any undefined abbreviations or unspecified references.

For life science journals only (when applicable)

- Trial registration number and date of registration for prospectively registered trials
- Trial registration number and date of registration, followed by “retrospectively registered”, for retrospectively registered trials

Keywords

Please provide 4 to 6 keywords which can be used for indexing purposes.

Statements and Declarations

The following statements should be included under the heading "Statements and Declarations" for inclusion in the published paper. Please note that submissions that do not include relevant declarations will be returned as incomplete.

- **Competing Interests:** Authors are required to disclose financial or non-financial interests that are directly or indirectly related to the work submitted for publication. Please refer to “Competing Interests and Funding” below for more information on how to complete this section.

Please see the relevant sections in the submission guidelines for further information as well as various examples of wording. Please revise/customize the sample statements according to your own needs.

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Text

Text Formatting

Manuscripts should be submitted in Word.

- Use a normal, plain font (e.g., 10-point Times Roman) for text.
- Use italics for emphasis.
- Use the automatic page numbering function to number the pages.
- Do not use field functions.
- Use tab stops or other commands for indents, not the space bar.
- Use the table function, not spreadsheets, to make tables.
- Use the equation editor or MathType for equations.
- Save your file in docx format (Word 2007 or higher) or doc format (older Word versions).

Manuscripts with mathematical content can also be submitted in LaTeX. We recommend using Springer Nature’s LaTeX template.

Headings

Please use no more than three levels of displayed headings.

Abbreviations

Abbreviations should be defined at first mention and used consistently thereafter.

Footnotes

Footnotes can be used to give additional information, which may include the citation of a reference included in the reference list. They should not consist solely of a reference citation, and they should never include the bibliographic details of a reference. They should also not contain any figures or tables.

Footnotes to the text are numbered consecutively; those to tables should be indicated by superscript lower-case letters (or asterisks for significance values and other statistical data). Footnotes to the title or the authors of the article are not given reference symbols.

Always use footnotes instead of endnotes.

Acknowledgments

Acknowledgments of people, grants, funds, etc. should be placed in a separate section on the title page. The names of funding organizations should be written in full.

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References

Citation

Reference citations in the text should be identified by numbers in square brackets. Some examples:

1. Negotiation research spans many disciplines [3].

2. This result was later contradicted by Becker and Seligman [5].

3. This effect has been widely studied [1-3, 7].

Reference list

The list of references should only include works that are cited in the text and that have been published or accepted for publication. Personal communications and unpublished works should only be mentioned in the text.

The entries in the list should be numbered consecutively.

If available, please always include DOIs as full DOI links in your reference list (e.g. “https://doi.org/abc”).

- Journal article

Smith JJ. The world of science. Am J Sci. 1999;36:234–5.

- Article by DOI

Slifka MK, Whitton JL. Clinical implications of dysregulated cytokine production. J Mol Med. 2000; https://doi.org/10.1007/s001090000086

- Book

Blenkinsopp A, Paxton P. Symptoms in the pharmacy: a guide to the management of common illness. 3rd ed. Oxford: Blackwell Science; 1998.

- Book chapter

Wyllie AH, Kerr JFR, Currie AR. Cell death: the significance of apoptosis. In: Bourne GH, Danielli JF, Jeon KW, editors. International review of cytology. London: Academic; 1980. pp. 251–306.

- Online document

Doe J. Title of subordinate document. In: The dictionary of substances and their effects. Royal Society of Chemistry. 1999. http://www.rsc.org/dose/title of subordinate document. Accessed 15 Jan 1999.

Always use the standard abbreviation of a journal's name according to the ISSN List of Title Word Abbreviations, see

ISSN.org LTWA

If you are unsure, please use the full journal title.

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Tables

- All tables are to be numbered using Arabic numerals.
- Tables should always be cited in text in consecutive numerical order.
- For each table, please supply a table caption (title) explaining the components of the table.
- Identify any previously published material by giving the original source in the form of a reference at the end of the table caption.
- Footnotes to tables should be indicated by superscript lower-case letters (or asterisks for significance values and other statistical data) and included beneath the table body.

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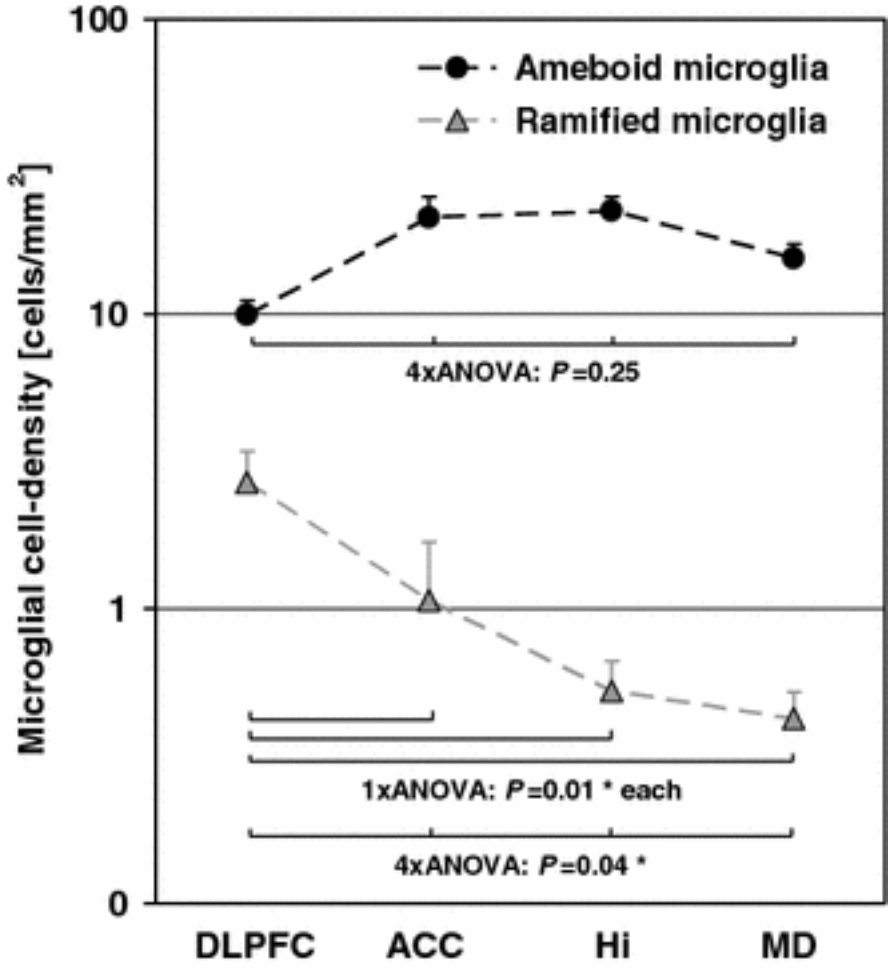
Artwork and Illustrations Guidelines

Electronic Figure Submission

- Supply all figures electronically.
- Indicate what graphics program was used to create the artwork.

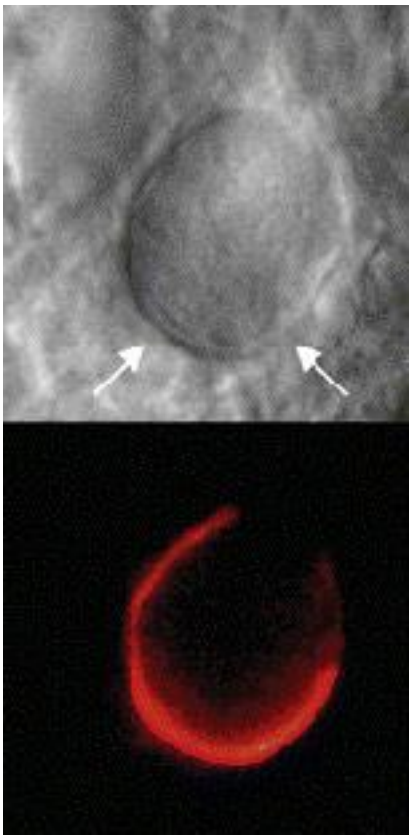
- For vector graphics, the preferred format is EPS; for halftones, please use TIFF format. MSOffice files are also acceptable.
- Vector graphics containing fonts must have the fonts embedded in the files.
- Name your figure files with "Fig" and the figure number, e.g., Fig1.eps.

Line Art



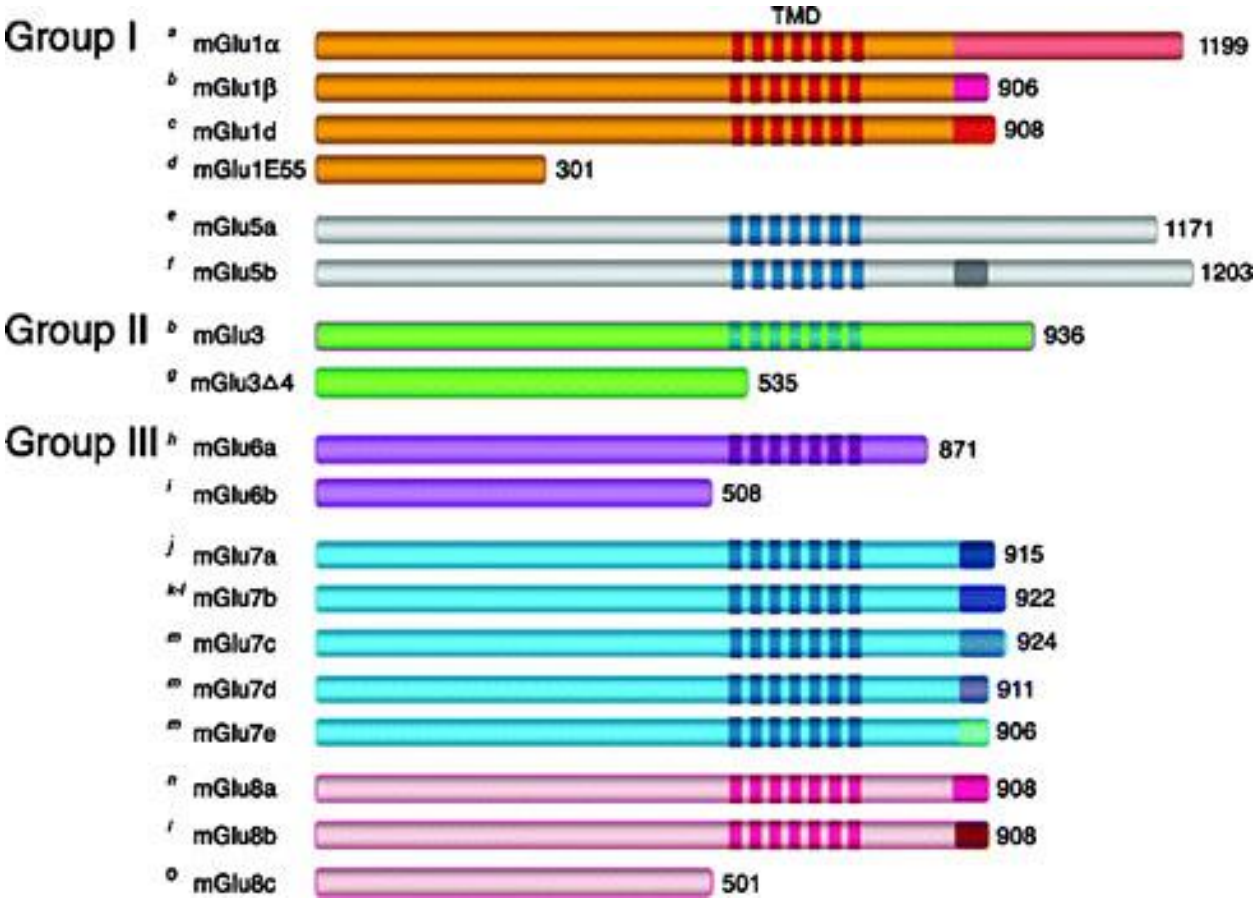
- Definition: Black and white graphic with no shading.
- Do not use faint lines and/or lettering and check that all lines and lettering within the figures are legible at final size.
- All lines should be at least 0.1 mm (0.3 pt) wide.
- Scanned line drawings and line drawings in bitmap format should have a minimum resolution of 1200 dpi.
- Vector graphics containing fonts must have the fonts embedded in the files.

Halftone Art



- Definition: Photographs, drawings, or paintings with fine shading, etc.
- If any magnification is used in the photographs, indicate this by using scale bars within the figures themselves.
- Halftones should have a minimum resolution of 300 dpi.

Combination Art



- Definition: a combination of halftone and line art, e.g., halftones containing line drawing, extensive lettering, color diagrams, etc.
- Combination artwork should have a minimum resolution of 600 dpi.

Color Art

- Color art is free of charge for online publication.
- If black and white will be shown in the print version, make sure that the main information will still be visible. Many colors are not distinguishable from one another when converted to black and white. A simple way to check this is to make a xerographic copy to see if the necessary distinctions between the different colors are still apparent.
- If the figures will be printed in black and white, do not refer to color in the captions.
- Color illustrations should be submitted as RGB (8 bits per channel).

Figure Lettering

- To add lettering, it is best to use Helvetica or Arial (sans serif fonts).

- Keep lettering consistently sized throughout your final-sized artwork, usually about 2–3 mm (8–12 pt).
- Variance of type size within an illustration should be minimal, e.g., do not use 8-pt type on an axis and 20-pt type for the axis label.
- Avoid effects such as shading, outline letters, etc.
- Do not include titles or captions within your illustrations.

Figure Numbering

- All figures are to be numbered using Arabic numerals.
- Figures should always be cited in text in consecutive numerical order.
- Figure parts should be denoted by lowercase letters (a, b, c, etc.).
- If an appendix appears in your article and it contains one or more figures, continue the consecutive numbering of the main text. Do not number the appendix figures,"A1, A2, A3, etc." Figures in online appendices [Supplementary Information (SI)] should, however, be numbered separately.

Figure Captions

- Each figure should have a concise caption describing accurately what the figure depicts. Include the captions in the text file of the manuscript, not in the figure file.
- Figure captions begin with the term Fig. in bold type, followed by the figure number, also in bold type.
- No punctuation is to be included after the number, nor is any punctuation to be placed at the end of the caption.
- Identify all elements found in the figure in the figure caption; and use boxes, circles, etc., as coordinate points in graphs.
- Identify previously published material by giving the original source in the form of a reference citation at the end of the figure caption.

Figure Placement and Size

- Figures should be submitted within the body of the text. Only if the file size of the manuscript causes problems in uploading it, the large figures should be submitted separately from the text.
- When preparing your figures, size figures to fit in the column width.

- For large-sized journals the figures should be 84 mm (for double-column text areas), or 174 mm (for single-column text areas) wide and not higher than 234 mm.
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Springer accepts electronic multimedia files (animations, movies, audio, etc.) and other supplementary files to be published online along with an article or a book chapter. This feature can add dimension to the author's article, as certain information cannot be printed or is more convenient in electronic form.

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Submission

- Supply all supplementary material in standard file formats.

- Please include in each file the following information: article title, journal name, author names; affiliation and e-mail address of the corresponding author.
- To accommodate user downloads, please keep in mind that larger-sized files may require very long download times and that some users may experience other problems during downloading.
- High resolution (streamable quality) videos can be submitted up to a maximum of 25GB; low resolution videos should not be larger than 5GB.

Audio, Video, and Animations

- Aspect ratio: 16:9 or 4:3
- Maximum file size: 25 GB for high resolution files; 5 GB for low resolution files
- Minimum video duration: 1 sec
- Supported file formats: avi, wmv, mp4, mov, m2p, mp2, mpg, mpeg, flv, mxf, mts, m4v, 3gp

Text and Presentations

- Submit your material in PDF format; .doc or .ppt files are not suitable for long-term viability.
- A collection of figures may also be combined in a PDF file.

Spreadsheets

- Spreadsheets should be submitted as .csv or .xlsx files (MS Excel).

Specialized Formats

- Specialized format such as .pdb (chemical), .wrl (VRML), .nb (Mathematica notebook), and .tex can also be supplied.

Collecting Multiple Files

- It is possible to collect multiple files in a .zip or .gz file.

Numbering

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- Refer to the supplementary files as “Online Resource”, e.g., "... as shown in the animation (Online Resource 3)", “... additional data are given in Online Resource 4”.
- Name the files consecutively, e.g. “ESM_3.mpg”, “ESM_4.pdf”.

Captions

- For each supplementary material, please supply a concise caption describing the content of the file.

Processing of supplementary files

- Supplementary Information (SI) will be published as received from the author without any conversion, editing, or reformatting.

Accessibility

In order to give people of all abilities and disabilities access to the content of your supplementary files, please make sure that

- The manuscript contains a descriptive caption for each supplementary material
- Video files do not contain anything that flashes more than three times per second (so that users prone to seizures caused by such effects are not put at risk)

Generative AI Images

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- Research that may be misapplied to pose a threat to public health or national security should be clearly identified in the manuscript (e.g. dual use of research). Examples include creation of harmful consequences of biological agents or toxins, disruption of immunity of vaccines, unusual hazards in the use of chemicals, weaponization of research/technology (amongst others).
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Upon request authors should be prepared to send relevant documentation or data in order to verify the validity of the results presented. This could be in the form of raw data, samples, records, etc. Sensitive information in the form of confidential or proprietary data is excluded.

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These guidelines describe authorship principles and good authorship practices to which prospective authors should adhere to.

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All authors whose names appear on the submission

1) made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; or the creation of new software used in the work;

2) drafted the work or revised it critically for important intellectual content;

3) approved the version to be published; and

4) agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

* Based on/adapted from:

ICMJE, Defining the Role of Authors and Contributors,

Transparency in authors' contributions and responsibilities to promote integrity in scientific publication, McNutt at all, PNAS February 27, 2018

Disclosures and declarations

All authors are requested to include information regarding sources of funding, financial or non-financial interests, study-specific approval by the appropriate ethics committee for research involving humans and/or animals, informed consent if the research involved human participants, and a statement on welfare of animals if the research involved animals (as appropriate).

The decision whether such information should be included is not only dependent on the scope of the journal, but also the scope of the article. Work submitted for publication may have implications for public health or general welfare and in those cases it is the responsibility of all authors to include the appropriate disclosures and declarations.

Data transparency

All authors are requested to make sure that all data and materials as well as software application or custom code support their published claims and comply with field standards. Please note that journals may have individual policies on (sharing) research data in concordance with disciplinary norms and expectations.

Role of the Corresponding Author

One author is assigned as Corresponding Author and acts on behalf of all co-authors and ensures that questions related to the accuracy or integrity of any part of the work are appropriately addressed.

The Corresponding Author is responsible for the following requirements:

- ensuring that all listed authors have approved the manuscript before submission, including the names and order of authors;
- managing all communication between the Journal and all co-authors, before and after publication;*
- providing transparency on re-use of material and mention any unpublished material (for example manuscripts in press) included in the manuscript in a cover letter to the Editor;
- making sure disclosures, declarations and transparency on data statements from all authors are included in the manuscript as appropriate (see above).

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In absence of specific instructions and in research fields where it is possible to describe discrete efforts, the Publisher recommends authors to include contribution statements in the work that specifies the contribution of every author in order to promote transparency. These contributions should be listed at the separate title page.

Examples of such statement(s) are shown below:

• Free text:

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [full name], [full name] and [full name]. The first draft of the manuscript was written by [full name] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Example: CRediT taxonomy:

• Conceptualization: [full name], …; Methodology: [full name], …; Formal analysis and investigation: [full name], …; Writing - original draft preparation: [full name, …]; Writing - review and editing: [full name], …; Funding acquisition: [full name], …; Resources: [full name], …; Supervision: [full name],….

For **review articles** where discrete statements are less applicable a statement should be included who had the idea for the article, who performed the literature search and data analysis, and who drafted and/or critically revised the work.

For articles that are based primarily on the **student's dissertation or thesis**, it is recommended that the student is usually listed as principal author:

A Graduate Student's Guide to Determining Authorship Credit and Authorship Order, APA Science Student Council 2006

Affiliation

The primary affiliation for each author should be the institution where the majority of their work was done. If an author has subsequently moved, the current address may additionally be stated. Addresses will not be updated or changed after publication of the article.

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Authors are strongly advised to ensure the correct author group, the Corresponding Author, and the order of authors at submission. Changes of authorship by adding or deleting authors, and/or changes in Corresponding Author, and/or changes in the sequence of authors are **not** accepted **after acceptance** of a manuscript.

- **Please note that author names will be published exactly as they appear on the accepted submission!**

Please make sure that the names of all authors are present and correctly spelled, and that addresses and affiliations are current.

Adding and/or deleting authors at revision stage are generally not permitted, but in some cases it may be warranted. Reasons for these changes in authorship should be explained. Approval of the

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For cases in which a co-author dies or is incapacitated during the writing, submission, or peer-review process, and the co-authors feel it is appropriate to include the author, co-authors should obtain approval from a (legal) representative which could be a direct relative.

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In the case of an authorship dispute during peer review or after acceptance and publication, the Journal will not be in a position to investigate or adjudicate. Authors will be asked to resolve the dispute themselves. If they are unable the Journal reserves the right to withdraw a manuscript from the editorial process or in case of a published paper raise the issue with the authors' institution(s) and abide by its guidelines.

Confidentiality

Authors should treat all communication with the Journal as confidential which includes correspondence with direct representatives from the Journal such as Editors-in-Chief and/or Handling Editors and reviewers' reports unless explicit consent has been received to share information.

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Compliance with Ethical Standards

To ensure objectivity and transparency in research and to ensure that accepted principles of ethical and professional conduct have been followed, authors should include information regarding sources of funding, potential conflicts of interest (financial or non-financial), informed consent if the research involved human participants, and a statement on welfare of animals if the research involved animals.

Authors should include the following statements (if applicable) in a separate section entitled "Compliance with Ethical Standards" when submitting a paper:

- Disclosure of potential conflicts of interest
- Research involving Human Participants and/or Animals
- Informed consent

Please note that standards could vary slightly per journal dependent on their peer review policies (i.e. single or double blind peer review) as well as per journal subject discipline. Before submitting your article check the instructions following this section carefully.

The corresponding author should be prepared to collect documentation of compliance with ethical standards and send if requested during peer review or after publication.

The Editors reserve the right to reject manuscripts that do not comply with the above-mentioned guidelines. The author will be held responsible for false statements or failure to fulfill the above-mentioned guidelines.

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