

Assessing the human health risks of indoor PM_{2.5} exposure in urban and rural households in two provinces of South Africa

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HIGHLIGHTS

- Low-income urban and rural households in South Africa are at risk of exposure to indoor PM_{2.5} exposure in winter months.
- Indoor PM_{2.5} concentrations exceeded outdoor values at both rural and urban locations.
- Indoor PM_{2.5} peaks are closely aligned with outdoor peaks underscoring the need to mitigate outdoor air pollution.

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ABSTRACT

Background: Exposure to fine particulate matter (PM_{2.5}) is linked to many adverse outcomes, including respiratory and cardiovascular diseases. South Africa's reliance on coal combustion has led to poor air quality. Indoor air pollution exacerbates health risks in low-income households, necessitating thorough assessment. In this study, a human health risk assessment (HHRA) provided an understanding of health risks posed by indoor and outdoor PM_{2.5} concentrations in rural and urban settings.

Methods: During two campaigns, PM_{2.5} concentrations were monitored indoors (low-cost sensors in households) and outdoors (Zephyr sensors). We employed the method of the US Environmental Protection Agency in 22 urban households and 22 rural households.

Results: During a cooler period, indoor PM_{2.5} concentrations in all households exceeded the World Health Organization (WHO) Air Quality Guidelines. In Soweto, the winter 24-h PM_{2.5} concentrations reached as high as 491.4 µg/m³ (Household 19), surpassing all the WHO guideline targets, with the highest at 75 µg/m³. Even with conditions of higher atmospheric dispersion and less solid fuel burning, almost half of rural households had

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Hazard Quotients (HQs) > 1. In both seasons in urban areas and winter in rural areas, HQ values consistently remained >1, signalling greater health risks. Indoor PM_{2.5} concentrations almost consistently exceeded outdoor reference limits in both rural and urban locations throughout the year, underscoring the additional pollution burden due to indoor solid fuel burning and personal smoking habits. One Agincourt household recorded a warm period 24-h peak PM_{2.5} concentration of 1054 µg/m³ indoors, far higher than any corresponding outdoor values. *Conclusions:* There is an urgent need for interventions to mitigate indoor air pollution that presents significant health risks to household occupants. Reducing health risks associated with high PM_{2.5} concentrations require interventions to mitigate outdoor PM_{2.5} levels and solid fuel use indoors. (347 words)

1. Introduction

Air pollution is one of the biggest environmental threats to human health according to the World Health Organization (WHO) (World Health Organization, 2021). Approximately 4.2 million people die annually due to ambient air pollution, with an additional 3.8 million deaths attributed to indoor air pollution mainly from emissions by cookstoves and fuels (Anenberg et al., 2016; Bhat et al., 2021). Since South Africa relies heavily on coal-fired power stations to meet electricity demands, there is a risk of exposure to air pollutants in the broader population (Morosele and Langerman). Specifically, there are three Air Pollution Priority Areas in South Africa (Vaal Triangle Airshed, Highveld, and Waterberg-Bojanala) where the National Ambient Air Quality Standards (NAAQs) are notably more prone to exceedances (DEA. Department of Environmental Affairs, 2012). These areas are known for high air pollutant concentrations from power stations, factories, and mining activities, among others (DEA. Department of Environmental Affairs, 2012). The poor air quality in these areas highlights the pressing need for monitoring and mitigation measures to address the elevated pollutant levels resulting from industrial operations.

Particulate matter (PM), commonly used as an air pollution indicator, is a type of air pollutant that causes significant adverse health consequences (World Health Organization, 2022). PM emissions from anthropogenic sources exceed those from natural sources. Anthropogenic sources include emissions from combustion processes, construction, mining, and others. PM may be directly emitted (primary PM) or formed in the atmosphere through chemical reactions of gases (secondary PM), thus adding to the atmospheric burden. PM emissions equal to or less than 2.5 µm in aerodynamic diameter are known as fine particulate matter (PM_{2.5}) (World Health Organization, 2021). Since finer particles like PM_{2.5} can penetrate deep into the respiratory system and increase the risk of disease, it is important to address air quality issues to safeguard public health.

Exposure to PM_{2.5} is commonly associated with respiratory illness, but recent evidence demonstrates a broader spectrum of health outcomes. Studies show significant associations between PM_{2.5} exposure and gastrointestinal and colorectal cancer (Pritchett et al.), anaemia in children <5 years old (Odo et al., 2023), dementia (Cheng et al., 2022), and changes in the composition of gut microbiota (Li et al., 2023). PM_{2.5} exposure is implicated in reduced life expectancy, surpassing the risks posed by alcohol, tobacco, and infectious diseases combined (Greenstone and Hasenkopf, 2023). Pregnant women exposed to PM_{2.5} face elevated risks of adverse birth outcomes (Li et al., 2019). Additionally, reductions in PM_{2.5} exposure showed a corresponding decline in the risk of pre-eclampsia and the risk of autism in the infant (Molitor et al., 2023; Rahman et al.).

Indoor air pollution arises from cooking and heating using solid fuels, which is particularly prevalent in low-income households. This contributes to the complexity of air quality issues, exacerbating health risks for vulnerable populations (Bohlmann and Inglesi-Lotz, 2018). A significant occurrence of air pollution from second-hand smoke, solid fuels, and kerosene was evident in households with active tuberculosis in Klerksdorp, South Africa (Elf et al., 2017). In 40% of these households, adults reported daily indoor smoking, and air nicotine was detectable in 70% of the households (Elf et al., 2017). The investigation

of indoor air pollution as a health hazard is imperative, given its widespread occurrence among socio-economically disadvantaged and vulnerable populations.

The relationship between indoor and outdoor PM_{2.5} levels is complex and influenced by many *in situ* factors. A study conducted in the Highveld Priority Area in South Africa showed that while daily indoor PM concentrations are usually below outdoor PM levels, they can sporadically exceed regulatory (safe) standards, posing a health risk to residents (Wernecke et al., 2015). By contrast, another study conducted in the same region demonstrated that indoor PM₄ concentrations were significantly higher than outdoor PM₁₀ and PM_{2.5} levels (Language et al., 2016). Another study in the Highveld Priority Area compared PM₄ concentrations in two households, one where coal was the primary source of energy and another that relied on electricity, in summer and winter seasons (Adesina et al., 2020). They found that indoor PM_{2.5} concentrations exceeded outdoor levels in the early morning and evening, whereas the relationship reversed in the mid-afternoon. They found no significant correlation between indoor and outdoor levels in winter, but a significant relationship in summer. Other studies in urban populations show that indoor PM_{2.5} concentrations typically exceed outdoor levels (Martins et al., 2018). Despite numerous attempts to understand the complexities of indoor and outdoor PM dynamics in low-income communities in South Africa, there is a critical data gap, particularly concerning the monitoring and assessing of indoor PM concentrations to study and mitigate health risks.

We present here a human health risk assessment (HHRA) using measured indoor and outdoor PM_{2.5} during two different periods in the largest number of households tested to present (to the best of our knowledge) with the aim of assessing acute (short-term) health risks in rural and urban contexts. Through this process, we gained valuable insights into the relationship between indoor and outdoor PM_{2.5} levels and potential associated health risks.

2. Materials and methods

2.1. Study sites

The study was conducted at two sites located in prominent mining and industrial zones situated in the north-east region of South Africa. One site, Soweto, is a typical urban environment characterised by dense human habitation and associated urban infrastructure. The other site, Agincourt, is in a rural setting characterised by a lower population density and a lower socioeconomic status (Hunter et al., 2021). Each site is situated within an Air Quality Priority Area, with Soweto in the Vaal Air-Shed Priority Area and Agincourt in the Highveld Priority Area. Soweto is a township in the Johannesburg Metropolitan Municipality and has a population of 4.8 million (Stats, 2023). Agincourt is in the Bushbuckridge Municipality, Mpumalanga province. The population of Agincourt is estimated at 120 000 (University of Witwatersrand). Fig. 1 depicts the locations of the two study sites in South Africa.

2.2. Monitoring of outdoor PM_{2.5}

For the Soweto (urban) campaign, we installed an Earthsense Zephyr sensor (Panchal et al., 2022; Peterson et al.) at the outdoor South African

Air Quality Information System (SAAQIS) monitoring stations of Jabavu-NAQI (i.e., National Air Quality Index) (27°52'19.6"E 26°15'09.4"S) and Diepkloof-NAQI (27°57'23.1"E, 26°15'02.6"S) for the February and winter campaigns, respectively. We did not use the data from the SAAQIS stations, given current concerns around data quality and missing data at SAAQIS stations (Wright et al.). The Zephyr sensors are compact air pollution sensors that permit measurement in near real-time using active sampling. For the Agincourt (rural) campaign, we installed Zephyr sensors at a centrally located high school during the winter. However, logistical problems (i.e., We could not install the Zephyrs because it was raining, and the roof was slippery and the metal rod to install the Zephyr was not stable enough to hold the Zephyr) prevented us from installing Zephyr monitors during the summer month.

The calibration of the Zephyr instruments was conducted through collocation with reference instruments situated at the Automatic Urban and Rural Network (AURN) air quality monitoring station located at the University of Leicester in the United Kingdom, operated by the Department for Environment, Food and Rural Affairs (DEFRA). Zephyr calibration methodologies were implemented by Earthsense, with data provided by the researchers, in accordance with procedures outlined in prior studies (Panchal et al., 2022; Peterson et al.). Proprietary quality control procedures are applied to the data during calibration by Earthsense. The Zephyr PM_{2.5} sensor is an optical particle counter characterised by a specified accuracy of $\pm 5 \mu\text{g}/\text{m}^3$.

2.3. Monitoring of indoor PM_{2.5}

Households located nearest to government-run outdoor air quality monitoring stations were recruited among the participants enrolled in the Africa Wits-INDEPTH Partnership for Genomic Research (AWI-Gen) study (Ramsay et al., 2016). Hourly indoor concentrations of PM_{2.5} were taken using low-cost air quality sensors (called Bonolo sensors

manufacturer locally) which were placed inside each household on a flat surface wherever it was convenient for the participants. In Soweto, the Bonolo sensors were placed in 11 households for a 2-week February period (17–31 October 2022) and at 11 different households for a 2-week winter period (16–29 May 2023). Similarly, in Agincourt, Bonolo sensors were placed in 11 households in a summer month (15–28 February 2023) and 11 in a winter month (5–18 July 2023). The sensors were placed where there was space, usually in the kitchen and lounge. However, some dwellings were multi-purpose (one-room) and they were noted down as “bedroom”. The sensors were placed on 25 L buckets, on top of cupboards, on room-dividers, and bedside tables. The installation exclusion criteria were away from heat radiating appliances (i.e. stove, refrigerator, microwave, kettle, etc.), not in direct sunlight, and not on the floor. Low-cost sensor calibration methodology is detailed in the supplementary material (Annex S1). Post-calibration, the sensors demonstrated acceptable accuracy with a mean bias of 14% and root mean squared error of $8 \mu\text{g}/\text{m}^3$.

2.4. Meteorological data

We acquired meteorological data, i.e., temperature, relative humidity and wind direction, from the South African Weather Service for two weather stations (Roodepoort and Machadoodorp weather stations for Soweto and Agincourt, respectively) located within close proximity of our participants' dwellings. We present these data descriptively to illustrate differences in meteorological conditions in the months of measurement at the two study sites.

2.5. Human health risk assessment

The HHRA was conducted for PM_{2.5} exposure using the US-Environmental Protection Agency's (US-EPA) four-step approach (US-

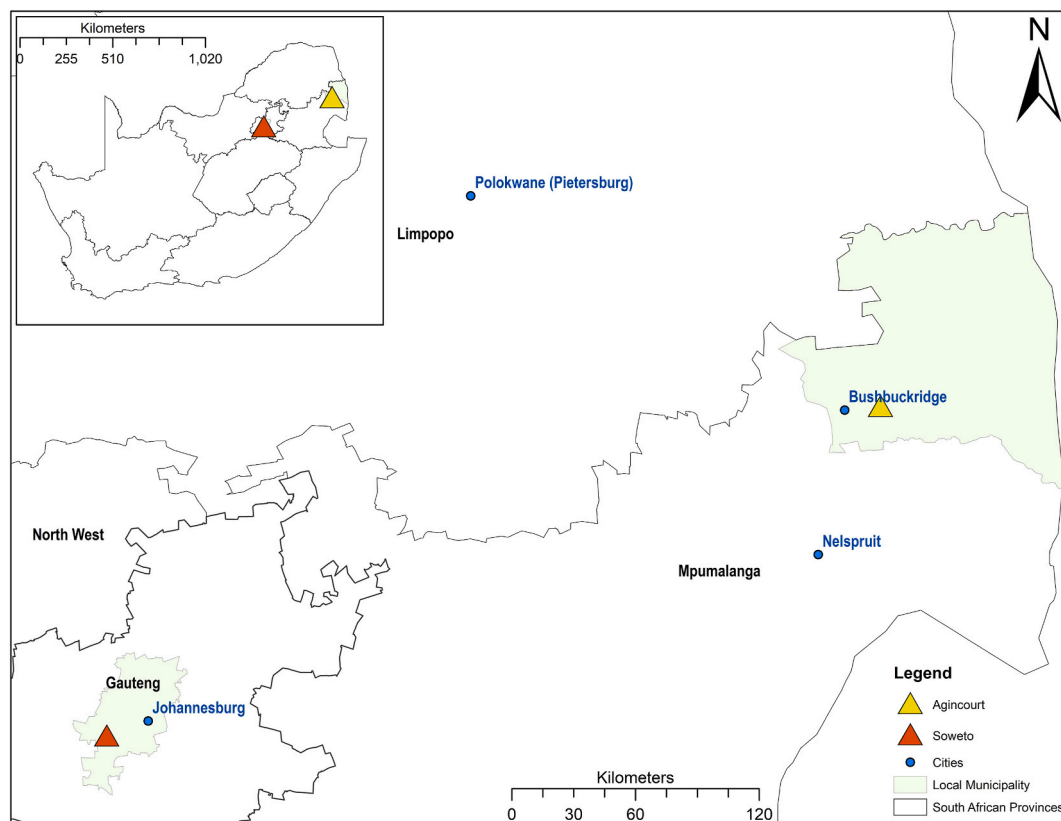


Fig. 1. Map of South Africa indicating the study sites, namely Agincourt and Soweto, with the municipal boundaries shaded in green. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

EPA, 2023) of 1) hazard identification, 2) exposure assessment, 3) dose-response assessment, and 4) risk characterisation. This approach allows for effective interpretation of data collected over a shorter period of time than an epidemiological study.

PM_{2.5} was identified as a hazard as it is a recognized substance that affects health in many populations (Thangavel et al.). Hazard identification is the process of recognising substances that after exposure might be responsible for adverse human health effects. An extensive literature search on health effects of PM_{2.5} was undertaken, and a brief overview is given in the introduction to this article, above.

Exposure assessment involves the determination of concentrations of the hazard, in this case PM_{2.5}, which may be measured or modelled. In this study, we used measured indoor data obtained using Bonolo sensors described above. The exposure of the population of interest to the hazard was assessed based on their typical behaviour and activity patterns. In this study, we assumed that individuals were exposed to the hazard for 24 h per day (noting that this is a worst-case scenario). Exposure can occur through many direct and indirect pathways such as inhalation, ingestion and dermal contact, of which only inhalation was considered in this study. In South Africa, exposure for acute risks is based on the 99th percentile of the short-term (hourly or 24-hourly) measured data (World Health Organization, 2021). In this assessment, the 99th percentile of the 24-h PM_{2.5} indoor concentrations was used for each household for each season.

Dose-response assessment is the estimation of the relationship between exposure or dose and the human body's response to that exposure or dose. Information is derived from many sources such as human epidemiological studies, human exposure studies and even animal exposure studies. In the case of PM_{2.5}, the benchmark or safe level, known as the reference concentration (RfC) is most often used as the standard or guideline of a country, the US-EPA or the WHO. The reference standards (safe levels) of PM_{2.5} used in this study included those from the US-EPA, WHO, and the South African NAAQS (World Health Organization, 2021; South African Government, 2012; Republic of South Africa), as presented in Table 1.

The South African 24-h outdoor air quality standard for PM_{2.5} of 40 µg/m³ should not be exceeded more than four times per year (DEA, Department of Environmental Affairs, 2012). In 2019, the South African Department of Health (DoH) published indoor air quality guidelines to provide guidance for managing domestic indoor air quality (DoH, and Department of Health, 2019). The DoH adopted the WHO 24-h guideline of 25 µg/m³ at the time, with a maximum of three exceedance days per year, as well as the WHO Interim Targets (ITs), which were the same as the current ITs 1 to 3 (DoH, and Department of Health, 2019).

The WHO guideline for 24-h PM_{2.5} which is applicable to outdoor as well as indoor air quality, has ITs (see Table 1) which are concentrations associated with a progressive decrease in health risk and are used as steps in the process of reducing air pollution in areas where air pollution is relatively high (World Health Organization, 2021). The WHO PM_{2.5} guideline is defined as the “99th percentile of the annual distribution of 24-h average concentrations, equivalent to 3–4 exceedance days per year” (World Health Organization, 2021).

There is an approximate 1.2% higher risk of mortality when exposed to the South African 24-h PM_{2.5} standard of 40 µg/m³ than when exposed to the WHO 24-h IT 4 standard of 25 µg/m³ (World Health Organization, 2017). In 2023, the US-EPA designated the annual benchmark for PM_{2.5} as the primary regulatory standard and initiated a

procedural framework aimed at its reduction, keeping the 24-h standard of 35 µg/m³ (US-EPA, 2023). Compliance to the standard is defined as the 98th percentile of 24-h concentrations in one year, averaged over three years, being equal to or below 35 µg/m³. In February 2024, the US-EPA announced their new annual primary (health-based) PM_{2.5} standard of 9 µg/m³ (previously 12 µg/m³) for PM_{2.5} (US-EPA).

Risk characterisation involved the calculation of a Hazard Quotient (HQ) expressed as the risk of developing adverse health effects from PM_{2.5} exposure. The HQ was expressed as a ratio of the PM_{2.5} concentration over a specified period to the reference PM_{2.5} concentration derived from a similar exposure period. An HQ below 1 suggested a low probability of individuals experiencing adverse health effects from indoor PM_{2.5}, while an HQ exceeding 1 indicated the potential for detrimental effects from indoor PM_{2.5}, albeit with the caveat that not all exposed individuals will necessarily manifest such outcomes.

2.6. Uncertainty

In this study, we considered the inherent uncertainty while conducting a HHRA regarding PM_{2.5} exposure. This uncertainty stems from challenges associated with evaluating the probability of adverse health effects. Variable uncertainty may arise from limitations in equipment, spatial or temporal variability in measured quantities, or difficulties in determining individual exposure or health status. Decision-rule uncertainty may emerge from specific choices made by the risk assessor, such as the pollutant selected, reference standards, or identifying significant exposure pathways. We are not aware of any quantitative uncertainty measure to apply in this type of HHRA.

3. Results

3.1. p.m._{2.5} exposure assessment

Forty-four households participated in the study, 22 in Soweto and 22 in Agincourt. The 99th percentiles of the 24-h average PM_{2.5} concentrations for each household for a summer month and a winter month at Agincourt and Soweto are presented in Table 2. Values at Soweto are approximately double those at the rural location of Agincourt in both months. Values in the colder period at both locations were more than double those in the warmer month as expected. For instance, the 99th percentile 24-h average in Soweto during the summer month reached up to 171.5 µg/m³ (Household 7), while in Agincourt, the highest summer month value was 103.7 µg/m³ (Household 11).

PM_{2.5} concentrations were significantly higher in the winter month than in the summer month at both locations. For example, in Agincourt, Household 13 recorded a 99th percentile value of 130.6 µg/m³ in the winter month compared to a summer value of 63.4 µg/m³ in Household 2. In Soweto, winter month values were even more pronounced, with Household 18 recording a 99th percentile value of 313.2 µg/m³, compared to 159.5 µg/m³ in the same household during the summer month.

Soweto households exhibited some exceptionally high maximum 1-h PM_{2.5} values, particularly during the winter month. Household 18 in Soweto recorded a maximum value of 1613.9 µg/m³ during the winter, which is among the highest observed. In comparison, Agincourt's peak values were lower, with the highest recorded in Household 11 during the summer month at 1054 µg/m³.

In addition to indoor PM_{2.5} being generally higher than at Agincourt, the diurnal pattern of the indoor PM_{2.5} values at Soweto was particularly distinct (Fig. 2). There is a marked evening peak (20:00 to 22:00) occurring a few hours later than the evening peak in the rural location, as well as an early morning peak that occurs between 06:00 and 08:00, that is believed to be traffic-related (Han and Naehar, 2005; Feig et al., 2016). An early morning peak is seldom observed at Agincourt.

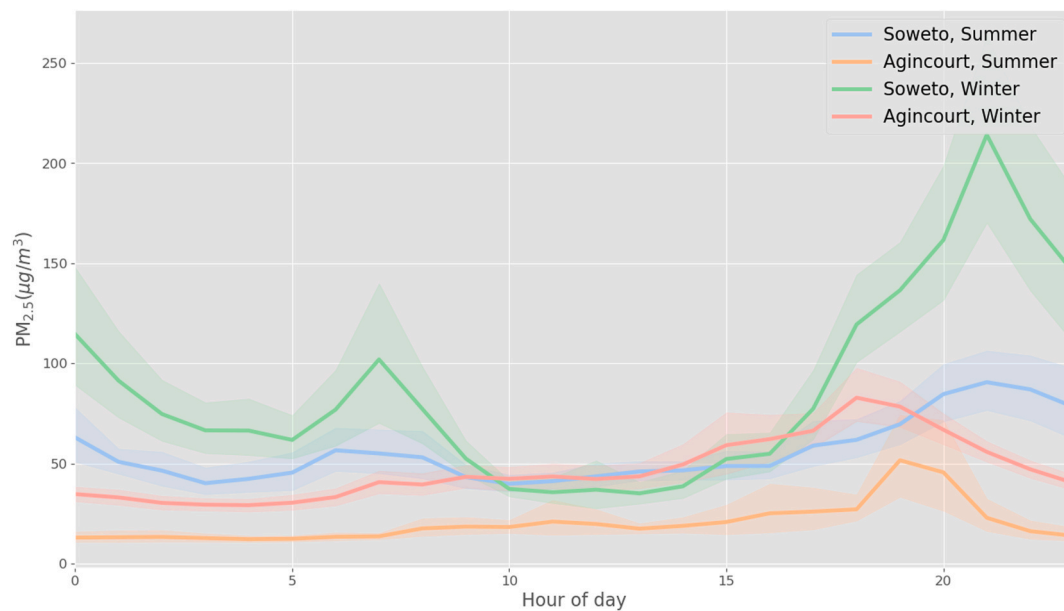
Maximum values recorded at each household, together with the date and time of occurrence, are presented in Table 2 and corroborate the

Table 1
PM_{2.5} 24-h standards and guidelines (µg/m³) used in the HHRA.

SA NAAQS (2012) µg/m ³	WHO guidelines (2021) µg/m ³					US-EPA (2023) µg/m ³
	Target 1	Target 2	Target 3	Target 4	Guideline	
40	75	50	37.5	25	15	35

Table 299th percentile and maximum 24-h $\text{PM}_{2.5}$ ($\mu\text{g}/\text{m}^3$) values at each household at Agincourt and Soweto for summer and winter campaigns.

Household	99th Percentile 24-hr $\text{PM}_{2.5}^a$	Max 1-hr $\text{PM}_{2.5}$	Date	Time	99th Percentile 24-hr $\text{PM}_{2.5}^a$	Max 1-hr $\text{PM}_{2.5}$	Date	Time
Agincourt summer					Soweto summer			
1	30.7	118.6	18/2/23	19:00	69.5	197.7	29/10/22	21:00
2	63.4	516.3	28/2/23	11:00	98.0	591.8	18/10/22	19:00
3	57.7	281.4	20/2/23	19:00	159.5	885.6	27/10/22	23:00
4	*	*	*	*	74.1	150.5	27/10/22	01:00
5	60.5	416.6	19/2/23	17:00	119.4	592.5	25/10/22	21:00
6	22.7	45.3	23/2/23	16:00	157.8	786.7	28/10/22	08:00
7	74.5	551.3	16/2/23	16:00	171.5	546.1	25/10/22	20:00
8	15.2	39.6	20/2/23	20:00	146.6	331.5	22/10/22	20:00
9	26.2	108.8	28/2/23	08:00	85.2	149.2	31/10/22	21:00
10	13.3	34.7	22/2/23	10:00	75.5	161.4	24/10/22	20:00
11	103.7	1054	28/2/23	20:00	84.6	488.4	20/10/2022	21:00
Agincourt winter					Soweto winter			
12	88.6	249.3	9/7/23	**	***	***	***	***
13	130.6	464.2	9/7/23	**	187.2	214.7	22/5/23	23:00
14	85.0	307.6	9/7/23	**	293.0	1220.2	17/5/23	07:00
15	128.3	420.6	9/7/23	**	118.7	1148.0	17/5/23	22:00
16	88.0	259.2	9/7/23	**	115.7	459.9	26/5/23	21:00
17	112.7	460.4	6/7/23	19:00	82.6	259.5	27/5/23	20:00
18	141.0	828.8	15/7/23	18:00	313.2	1613.9	21/5/23	20:00
19	**	**	**	**	491.4	1490.8	20/5/23	07:00
20	127.2	360.3	9/7/23	**	100.5	248.7	24/5/23	19:00
21	**	**	**	**	232.7	1620.1	23/5/23	21:00
22	126.6	410.7	7/7/23	20:00	142.8	662.9	25/5/23	06:00

Note: *household left study; **faulty instrument - data discarded; ***data lost during processing; ^a 99th percentile (i.e. 3–4 exceedance days per year); Avg: average.**Fig. 2.** Diurnal variation in mean $\text{PM}_{2.5}$ across all households for summer and winter at Soweto and Agincourt. Shaded envelopes depict the 95% confidence limits for all households.

mean diurnal pattern observed in Fig. 2. At Agincourt, maxima occur between 16:00 and 20:00, coinciding with the time when residents light fires to cook evening meals. In a few cases, maxima occur between 08:00 and 11:00. Household 11 at Agincourt displays some outlier behaviour, recording a summer month peak of $1054 \mu\text{g}/\text{m}^3$, which exceeds summer month peaks observed at the households in the urban location of Soweto. The second highest peak value at household 11 ($734 \mu\text{g}/\text{m}^3$), recorded on a different day approached peak values recorded at urban households in Soweto.

In accordance with South African NAAQS, a maximum of four exceedances per year is permitted for outdoor $\text{PM}_{2.5}$. During the summer in Agincourt, Households 5, 7, and 11 exceeded this limit, while most

households exceeded the indoor guidelines. Household 11 notably exceeded the limit almost daily. This trend continued into the winter month, with no households' concentrations adhering to the WHO guidelines. In Soweto, all households exceeded both outdoor standards and indoor guidelines during winter monitoring, with some households experiencing daily exceedances.

Household 11 in Agincourt exhibited outlier behaviour, exceeding even urban Soweto peaks during the summer month, indicating unique factors influencing $\text{PM}_{2.5}$ levels. Household 18 recorded exceptionally high values on days not linked to biomass burning, suggesting additional influencing factors. In Soweto, Household 3 had the highest summer month peak ($885.6 \mu\text{g}/\text{m}^3$) which occurred at 23:00 (Table 2).

Analysis of the average $PM_{2.5}$ concentrations across all households showed more apparent seasonal differences in indoor air quality (Fig. 3). In Soweto (urban setting), winter months exhibited significantly higher $PM_{2.5}$ compared to summer. Although Agincourt (rural setting) showed generally lower $PM_{2.5}$ concentrations overall, winter peaks were still higher than those observed during summer.

3.2. Comparison between indoor and outdoor $PM_{2.5}$ levels

Over the 2-week winter period in July 2023, indoor $PM_{2.5}$ concentrations in Agincourt consistently exceeded outdoor $PM_{2.5}$ levels at each of the households (only 0.3% of hourly values across all households showed the reverse). This pattern is depicted in Fig. 4, which shows mean $PM_{2.5}$, across all households, together with 95% confidence limits, compared with outdoor $PM_{2.5}$ concentrations. On average, indoor concentrations exceeded outdoor levels by between 25 and 45 $\mu g/m^3$ (73–131 %) across all households (using average concentrations).

Also evident in the time series (Fig. 4) is a close alignment in peaks and troughs in 1-h outdoor and indoor $PM_{2.5}$ concentrations, with outdoor air pollution providing the baseline or background upon which the indoor burden is superimposed.

Winter month peaks at Agincourt households clustered on a particular day (e.g., July 9, 2023) coinciding with the possible occurrence of a nearby grassland fire. This correlation between indoor and outdoor concentrations highlights the influence of outdoor air quality on indoor levels, particularly in households that are not well insulated in the rural area.

At Soweto, the dominant pattern of indoor $PM_{2.5}$ concentrations exceeding outdoor concentrations was again prevalent, although, compared with Agincourt, there were more occasions (4.6% of hourly values across all households) when the reverse occurred. Fig. 5 shows mean $PM_{2.5}$ levels across all households, together with 95% confidence limits, compared with outdoor $PM_{2.5}$ concentrations at Soweto. Several features stand out – the variability across households as depicted by the magnitude of the confidence interval, the marked diurnal variation shown also in Fig. 2, and again the close alignment in indoor and outdoor maxima. On average, indoor concentrations exceed mean outdoor concentrations by between 26.9 and 117.64 $\mu g/m^3$ (44–246%) across all

households during this period.

3.3. Meteorological conditions

Mean temperatures ranged between around 16 °C–22 °C and 13 °C and 16 °C during the summer and winter month campaigns in Soweto, respectively, while relative humidity was about the same for both measurement periods, i.e., between 40 and 100% (Fig. 6a). In Soweto, during both measurement periods, the wind direction was from the south or south-west except in the summer month when there was some wind from the north (Fig. 6b and c).

Mean temperatures ranged between around 18 °C–23 °C and 4 °C and 14 °C during the summer and winter month campaigns in Agincourt, respectively, while relative humidity was different in both measurement periods, i.e., between 40% and 90% in the summer month, and 19% and 73% in the winter month (Fig. 7a). In Agincourt, during both measurement periods, the wind direction was from the south or south-west except in the summer month when there was some wind from the north (Fig. 7b and c). Conditions for both periods are similar to those experienced annually in these two places.

3.4. Human health risk assessment

Fig. 8 presents the calculated HQs for the four applicable benchmarks (i.e., 1) the South African and 2) US-EPA 24-h standards, the 3) WHO 24-h IT3 guideline, and the 4) WHO 24-h final 2021 guideline) used at the two locations (Agincourt and Soweto) for the winter month and summer month. The findings demonstrate the risk of acute adverse health effects posed by $PM_{2.5}$ exposure in both Agincourt and Soweto households in different months of the year.

3.4.1. Risks of adverse health effects in Agincourt

During the summer month in Agincourt, nearly half of the households (specifically households 2, 3, 5, 7, and 11) exceeded an HQ of 1 when compared against both South African and US-EPA standards, as well as WHO guidelines up to IT 3. Thus, individuals inhabiting these households were at significantly greater risk of experiencing adverse health effects compared to the others. Moreover, when assessed against

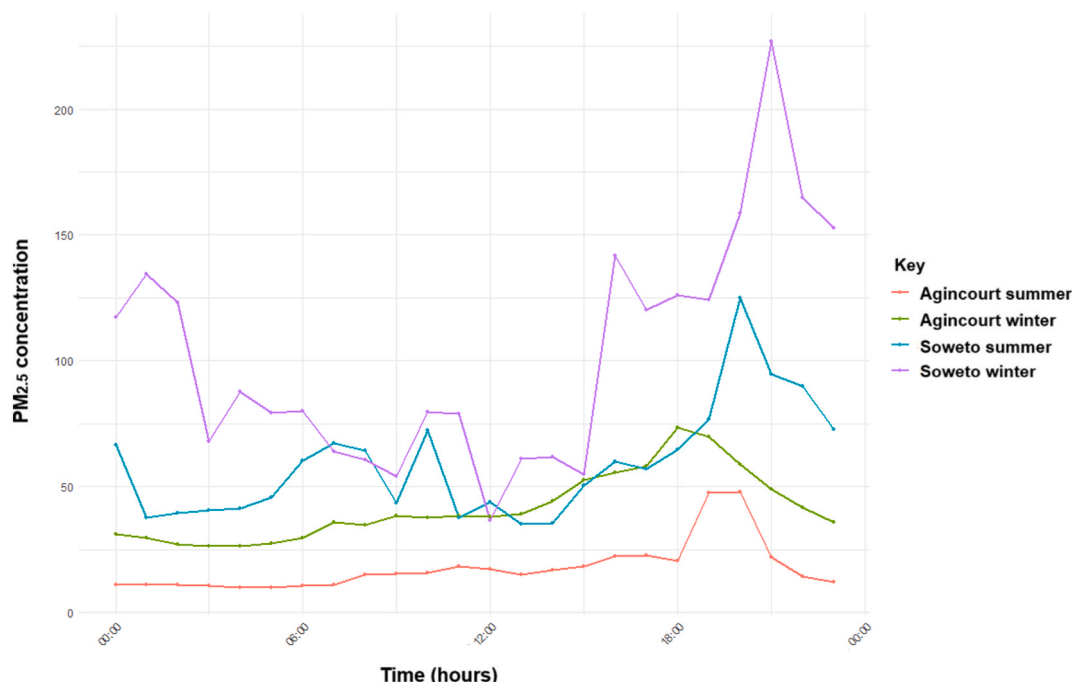


Fig. 3. The average indoor $PM_{2.5}$ concentrations of all households in Soweto (urban) and Agincourt (rural).

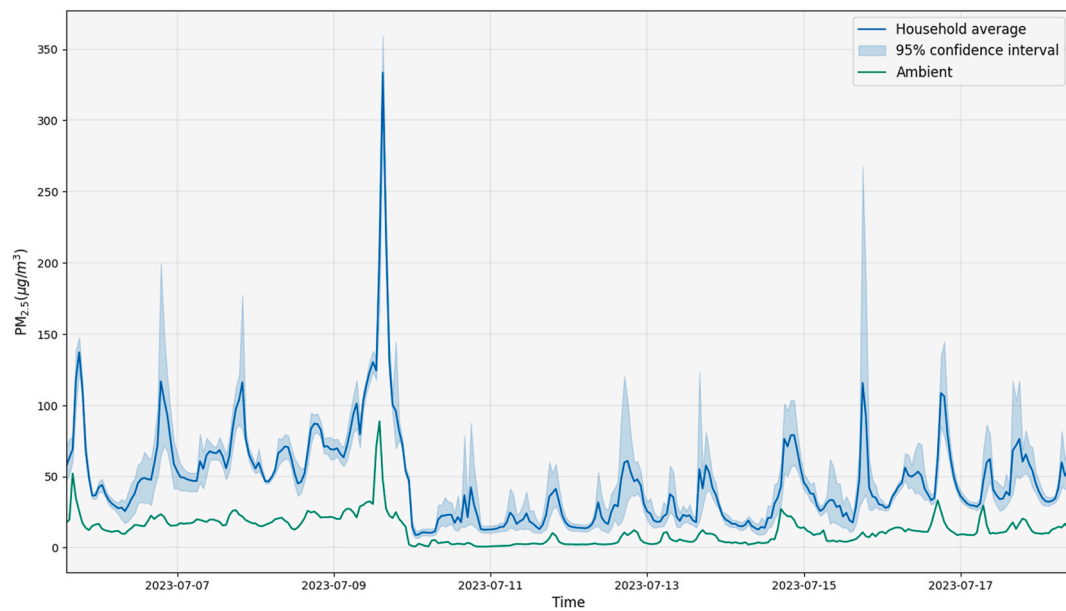


Fig. 4. Comparison of mean household and outdoor PM_{2.5} concentrations at Agincourt for the winter period.

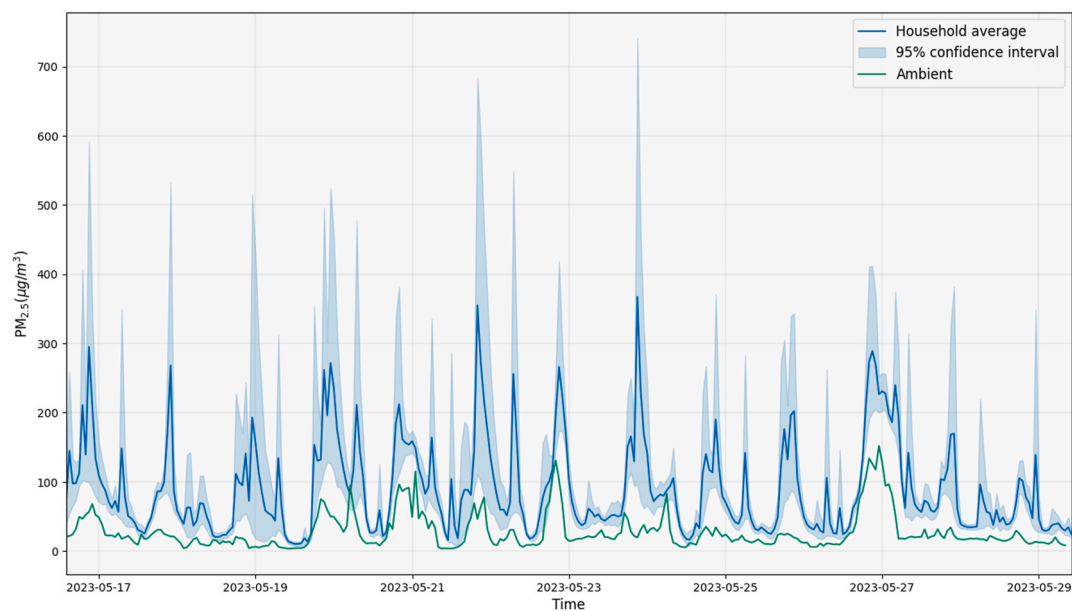


Fig. 5. Comparison of mean household and outdoor PM_{2.5} concentrations at Soweto for the winter period.

the WHO's final guideline of 15 $\mu\text{g}/\text{m}^3$, all households except for Household 10 exhibited HQs greater than 1, indicating an elevated risk of adverse health outcomes. Notably, Household 11 recorded the highest HQs among all the households evaluated.

The assessment of households in Agincourt during the winter month showed that they were all susceptible to experiencing acute adverse health effects, regardless of the PM_{2.5} standard or guideline applied. This is in accordance with the exposure assessment that showed more pronounced PM_{2.5} levels in the winter month than in the summer month. Notably, Household 18 exhibited the highest HQs (Fig. 8).

3.4.2. Risks of adverse health effects in Soweto

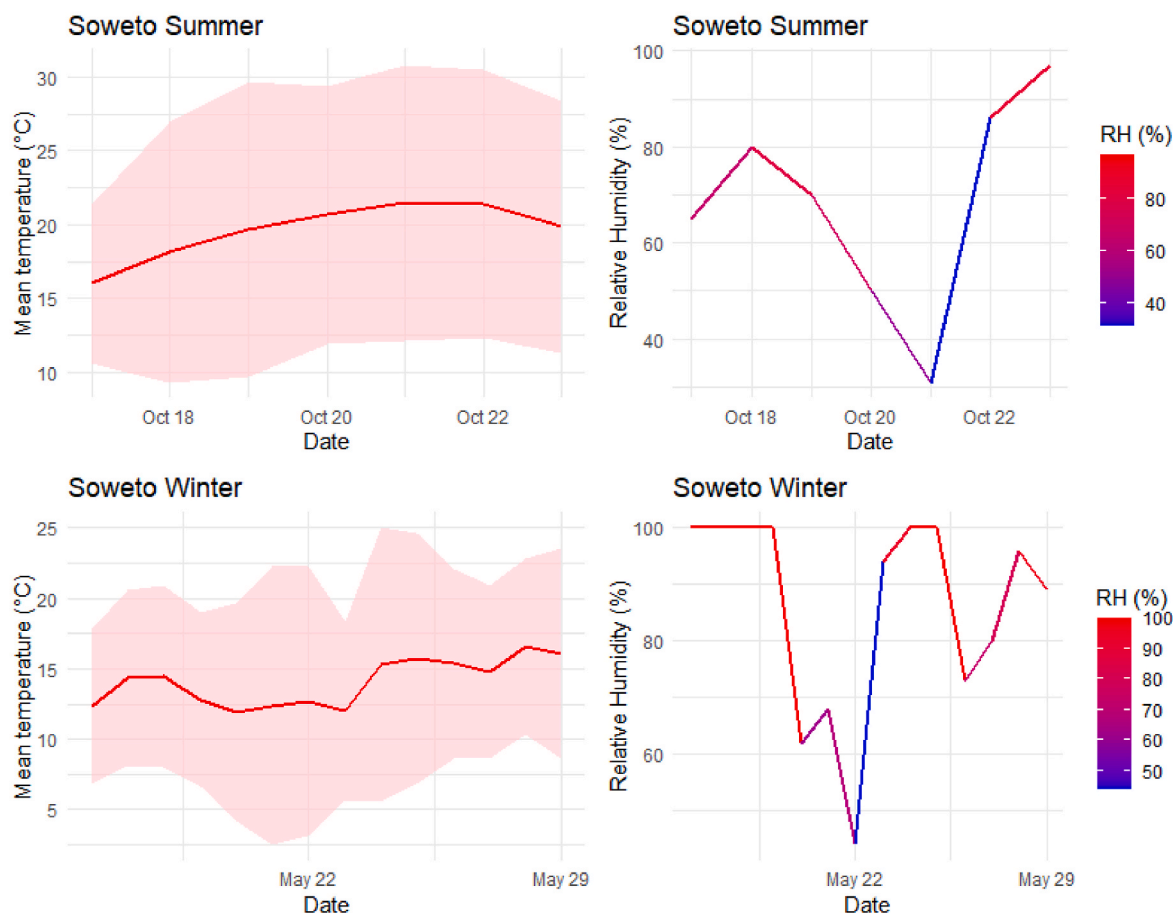
The evaluation of Soweto households during the summer month demonstrated that occupants were at risk of developing acute adverse effects, irrespective of the 24-h PM_{2.5} standard or guideline used. This corresponds to the exposure assessment that showed more elevated

PM_{2.5} concentrations in the urban setting than in the rural setting for both measurement periods that were evaluated. Household 7 recorded the highest HQs in the summer month, ranging between 4.3 and 11.4 depending on the standard or guideline employed. During the winter month, HQs remained well above 1 for all households, with Household 19 showing the highest HQs ranging between 12.3 and 32.8.

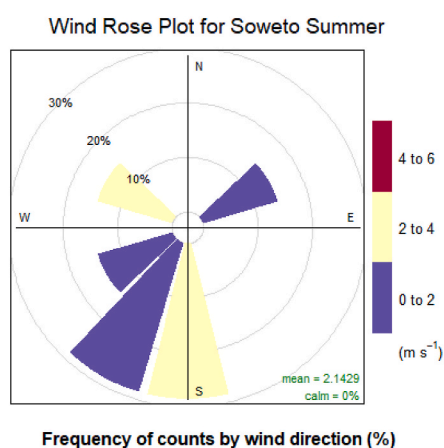
4. Discussion

The United Nations Sustainable Development Goal 7 of universal access to more affordable and cleaner energy sources requires that, by 2030, even the lowest income communities have cleaner fuels for cooking and heating (United Nations, 2023). The present study illustrates the link between indoor air quality and a range of detrimental health effects in the rural and urban South African setting. Health risk evaluation protocols such as those drawn up by the US-EPA (Bhat et al.,

a)



b)



c)

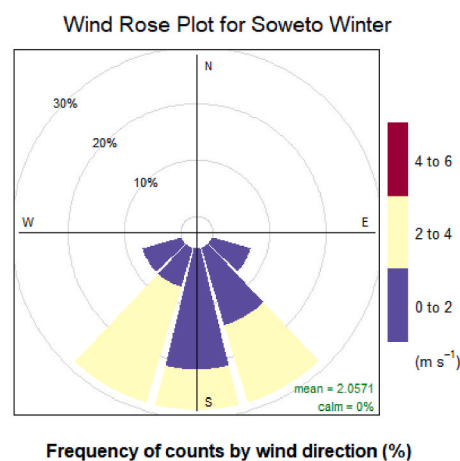


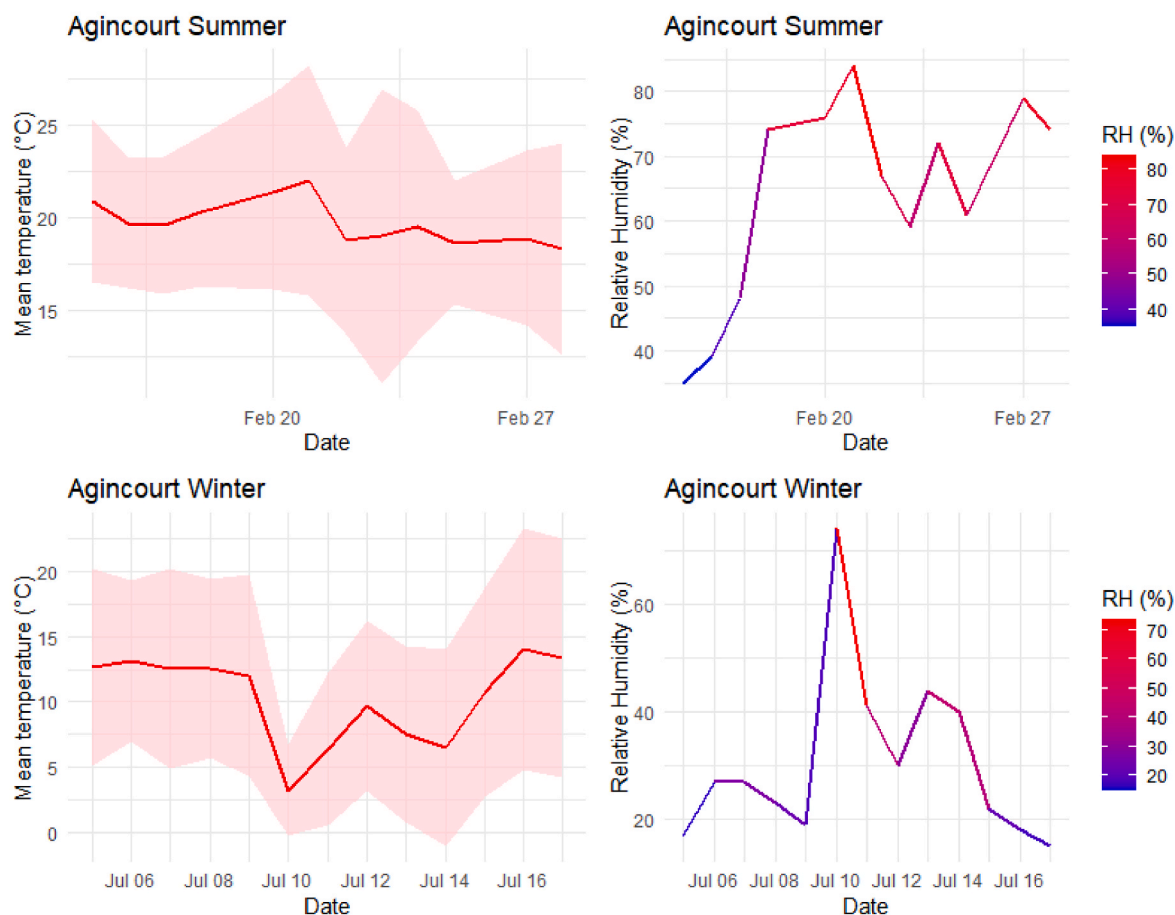
Fig. 6. For Soweto, a) temperature, b) summer wind rose and c) winter wind rose.

2021; US-EPA, 2023) have been applied in numerous settings to characterize the health effects of solid fuels as household/indoor air pollutants (Clark et al., 2013; Zeng et al., 2023), demonstrating the major contribution of air pollutants to the burden of disease in the general population (Chowdhury et al., 2023; Martins et al., 2018).

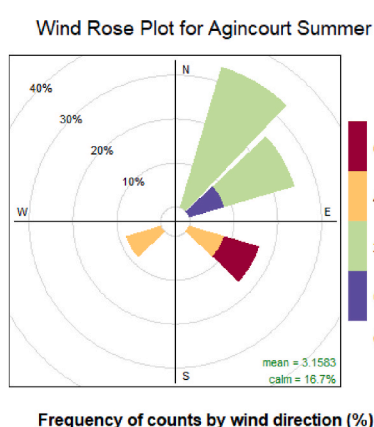
In a global meta-analysis (282 peer reviewed publications) of the effects of dirty fuel emissions in household air pollution, it was concluded that switching to cleaner fuels could lessen $PM_{2.5}$ exposure and lower mortality rates, particularly in rural settings (Mohajeri et al.,

2023). Notably, eastern Sub-Saharan Africa was identified as the region with the highest frequency of traditional stoves and the highest exposure levels to $PM_{2.5}$ ($1075 \mu g/m^3$) while Asia and South America had improved stoves (Mohajeri et al., 2023). North Africa and the Middle East also had high levels of exposure to $PM_{2.5}$ ($674 \mu g/m^3$) (Mohajeri et al., 2023). Another meta-analysis study highlighted that the more vulnerable populations to assess in rural communities are women and children (Balme, 2019). Children with pneumonia and are exposed to biomass smoke are the most frequently associated with early mortality

a)



b)



c)

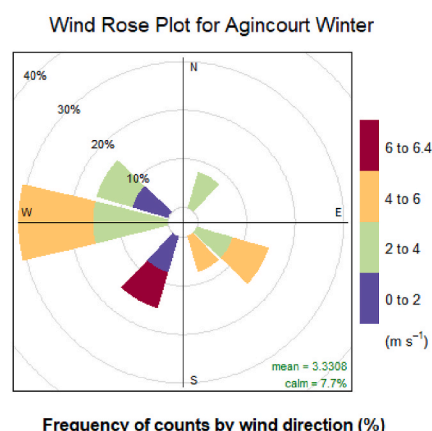


Fig. 7. For Agincourt, a) temperature, b) summer wind rose and c) winter wind rose.

caused by household air pollution. Cardiovascular disease is thought to be the leading cause of mortality and disability among adults and, in low-socioeconomic settings, women who are typically the primary cooks and do not smoke tobacco are particularly vulnerable to lung cancer and chronic obstructive pulmonary disease (Balmes, 2019). The study highlighted that there are gaps in the data and that more studies (such as ours) with direct measurements of indoor pollutant exposure and personal exposure are needed to create opportunities for adaptation and intervention strategies in low- and middle-income countries. The use of solid fuels in rural dwellings and its effects on human health have been

investigated more extensively from improved stoves in countries such as India and China (Shen, 2016), while most of the socioeconomically disadvantaged populations in Africa still use traditional cookstoves and solid fuel biomass for cooking and heating (Mohajeri et al., 2023).

Assessing air quality in different settings is crucial for safeguarding both personal and public health, playing a pivotal role in disease prevention (Bhat et al., 2021). HHRA for assessing air pollution exposure and health risks stand as a vital tool for guiding public policy decision-making, especially in high-risk areas where oftentimes the poorest communities reside. It forecasts the potential health impacts of

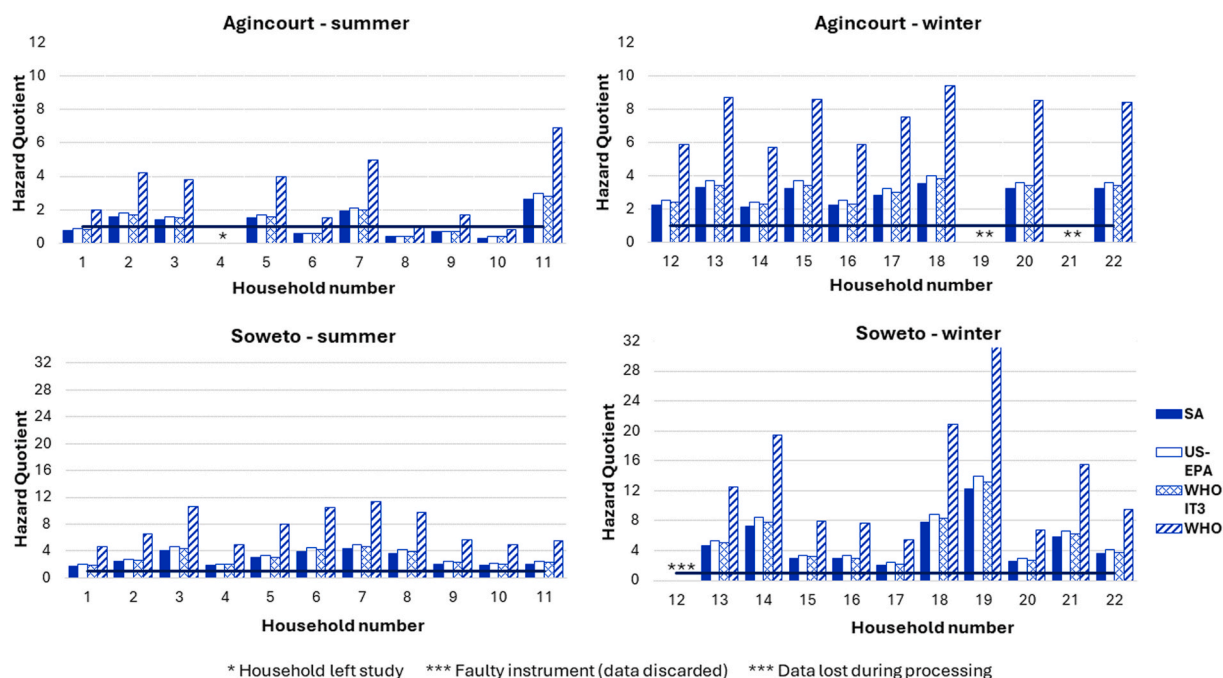


Fig. 8. Hazard Quotients (HQs) calculated for four different benchmarks (SA, EPA and WHO). Note the horizontal line at 1 is the hazard quotient reference.

actions aimed at improving air quality, providing invaluable insights for informed decision-making (Anenberg et al., 2016; Bhat et al., 2021).

In Southwest Ethiopia, a study investigated the effects of household air pollution from solid fuel use on various health outcomes in women (Zewdie et al., 2023). The findings showed that 34.9% of the participants experienced respiratory symptoms (Zewdie et al., 2023). Several factors were significantly associated with these symptoms, including having dusty floors, the presence of black soot on ceilings, using wood as fuel, cooking with a traditional stove, long cooking times, and cooking in a room without a window (Zewdie et al., 2023). These findings underscore the heightened vulnerability of women to respiratory issues in households reliant on solid fuels (Zewdie et al., 2023). In a study conducted in Southern Africa, in Eswatini, cancer and non-cancer risks were assessed for exposure to particulate-bound polycyclic hydrocarbons during cooking events for cooks who were indoors using biomass (Neumann et al., 2024). They found that risk decreased to acceptable levels when households shifted from biomass to LPG stoves. This information is highly relevant for decision-making, for example, when implementing an intervention to reduce household air pollution.

In South Africa, previous HHRAs of $PM_{2.5}$ exposure have shown high HQs in rural and urban sites (Edlund et al.; Howlett et al., 2023), with a greater risk of exposure among informal sector workers in urban areas (Dalasile and Reddy, 2017; Sepadi and Nkosi, 2023). Our study, conducted in different settings from the studies done before, showed higher $PM_{2.5}$ concentrations during a winter month compared to a summer month and characteristic $PM_{2.5}$ peaks were observed during morning and evening hours, most notably at the urban setting. Particularly noteworthy was the significantly higher $PM_{2.5}$ levels in Soweto (urban area) compared to Agincourt (rural setting). These results echo the outcomes of other studies conducted in South Africa, reinforcing their validity and significance (Werneck et al., 2015; Language et al., 2016; Adesina et al., 2020; Edlund et al.). For example, Edlund et al. (Edlund et al.) found that adults were at high risk of both non-cancer and cancer risks due to high $PM_{2.5}$ concentrations, especially during winter months. The most significant recommendation from this study was that the South African NAAQS for $PM_{2.5}$ be made more stringent due to health effects that occurred from exposure to air pollutants even though the area's $PM_{2.5}$ levels met the approved standards.

Our air quality measurement campaigns have yielded strong

evidence of non-compliance to WHO guidelines, South African NAAQS and US-EPS standards in both the rural and urban areas. These findings emphasize the importance of short-duration measurement campaigns (although longer campaigns are referred) to elucidate insights into acute health risks (Blanco et al., 2023). Blanco et al. conducted a simulation study using fixed-site air quality monitors to show how short-term monitoring studies are helpful to inform air pollution interventions (Blanco et al., 2023). This is especially important in locations with power generation, industrial and mining activities that likely exacerbate indoor air pollution. These sources, among others such as traffic, diesel exhaust, crustal dust and domestic wood combustion heaters (Hime et al., 2018).

In South Africa, indoor air pollutant concentrations are at their highest in winter when solid fuel is burned for cooking and heating (Nkosi et al., 2021; Pauw et al.). A previous study found higher levels of PM_{10} attributed to solid fuel burning during the winter months in low income settlements in Jabavu in the South-Western part of Soweto (Matandirotya et al., 2022). Furthermore, weather conditions during wintertime favour increased near-surface stability of pollutants and the development of temperature inversions which trap outdoor pollutants at ground level (Tyson et al., 1976; Wallace and Kanaroglou, 2009). Winters are dry in the eastern regions of South Africa. Thus, there is a significantly reduced removal of $PM_{2.5}$ through wet deposition from sufficient and consistent rainfall. This phenomenon may contribute to explaining higher $PM_{2.5}$ concentrations in winter. In addition, the distinct peaks and the higher $PM_{2.5}$ concentrations in the morning and evening in the urban area may be due to traffic. For example, in Cape Town (South Africa) associations of daily respiratory disease hospital admissions with daily PM_{10} and NO_2 concentrations were found with NO_2 likely originating from traffic pollution (Adebayo et al., 2022).

During the rural summer season, one might expect indoor $PM_{2.5}$ levels from solid fuel burning to decrease, while outdoor concentrations typically diminish due to improved dispersion conditions compared to winter. Surprisingly, nearly half of all households still displayed heightened acute health risks, surpassing the South African 24-h NAAQS, with all households but one exceeding WHO guideline values. This finding is especially problematic since summer is thought to be a season of lower air pollution exposure in homes that burn solid fuels and temperatures are typically warmer. In low-income residential areas that

do not have electricity, households often use solid fuels for cooking, space heating, and boiling water (Nkosi et al., 2021). Clean fuel usage intervention strategies that communities can afford and easily access is essential to enhancing air quality (Nkosi et al., 2021). In an Ugandan study, the transition to solar lighting saw multiple benefits, including improved household health and increased household safety (Sundararajan et al., 2022).

Useful insights into the relationship between indoor and outdoor pollution levels have been found. The consistency of the pattern of indoor excess across multiple households in both rural and urban locations emphasizes the added pollution burden created by indoor solid fuel burning and personal habits such as smoking. It is surprising that the excess in winter is greater at Soweto than Agincourt, suggesting that even in electrified urban households, solid fuel burning still takes place. This finding confirms findings of studies that have noted the prevalence of solid fuel usage for cooking and heating even in electrified houses (Nkosi et al., 2021).

4.1. Study strengths and limitations

This was a feasibility study and so our sample size is small and data are for relatively small time periods therefore these data should not be deemed representative of the season or year when the measurements were made. More instruments are needed to ensure that sampling at different sites can take place concurrently. Longer measurement campaigns are needed for data that represent a full season or year, incorporating both indoor and outdoor monitoring during full summer and winter would offer a more complete picture of PM_{2.5} dynamics. We used Zephyrs that were calibrated by the manufacturer and were not field calibrated. The findings are based on measurements obtained during short-duration summer and winter field campaigns in two contrasting locations. Although the households sampled in the urban and rural campaigns were not the same in both seasons, they were located sufficiently close to each other to avoid the location factor being considered a major contribution to observed seasonal differences in indoor PM_{2.5} levels. The HHRA, of necessity, relied on some assumptions, such as inhalation as the primary pathway and household residents being continuously exposed to indoor pollution for 24-h. The latter is clearly not likely but considered insignificant given that ambient air quality was also a major concern. We also did not include household socioeconomic and behavioural factors that influence indoor air pollution, and this limited our ability to interpret the data. Future studies should do so.

This study's strengths are attributed to the fact that data was gathered from low-income households in High-risk Air Quality Priority areas in South Africa, with Soweto situated in the Vaal Air Shed Priority Area and Agincourt situated in the Highveld Priority Area, demonstrating the health effects of outdoor pollution from coal fired power stations and industry on households that are socioeconomically challenged. In addition, outdoor pollutant comparisons with concomitant measurements of indoor and outdoor pollution in urban and rural settings adds to the data that is available in South Africa.

South Africa's air quality monitoring network is currently limited, with many stations providing minimal data, exacerbated by frequent power interruptions due to load shedding (Wright et al.). These disruptions have led to equipment malfunctions and inconsistent data collection, further diminishing the reliability of existing infrastructure. To ensure continuity in air quality data collection, interim solutions could involve deploying more reliable, climate-resilient monitoring technologies such as passive samplers, battery-powered sensors, and devices powered by renewable energy sources.

Our study underscores the critical role of low-cost air quality sensors, particularly in resource-constrained environments. The deployment of these affordable sensors enables sustained air quality monitoring in low-income contexts, where financial constraints often hinder long-term data collection efforts. This approach not only supports short-term monitoring campaigns but also enhances the potential for air quality

research across the African continent. By adopting this value-based strategy, we can address the current data gaps and encourage more robust, widespread research, contributing to a stronger scientific understanding of air quality in South Africa.

4.2. Future studies

More measurements for a longer duration are required in these study settings to obtain data that may be more representative of the situations. Interestingly, indoor PM_{2.5} levels in Soweto often surpassed those in Agincourt. This was unexpected, as typically, households in rural areas like Agincourt would be assumed to have higher indoor PM_{2.5} levels due to increased reliance on solid fuels rather than electricity in low-income rural households. Studies on housing in Agincourt show that households have become smaller through time (Wittenberg and Collinson, 2020) and there is a need to ensure energy efficiency in household building design, which has been shown in field studies (Lim et al., 2021). It is possible that households in Soweto also made use of solid fuels during electricity outages, known to be common in South Africa (Wright et al.). Understanding household design and pollutant emission patterns is important for linking personal exposure to different types of air pollutants and health outcomes, especially in vulnerable members of the community like children and the elderly, using a HHRA would provide valuable insights. Future studies should include activity diaries to capture more complex exposure patterns as well as additional information about vulnerable groups living in the participating households.

5. Conclusion

This study emphasizes the health risks associated with indoor PM_{2.5} exposure for household residents. Forty-four households were included to assess the potential health implications of indoor and outdoor PM_{2.5} levels in South Africa's rural and urban regions. Distinguishing features of this study over previous research in similar settings were the monitoring of indoor PM_{2.5} levels for a larger number of households (11 in each season and location); and the simultaneous monitoring of indoor and outdoor pollution, which enabled quantification of the indoor pollution burden.

The findings indicated that PM_{2.5} concentrations in both rural and urban areas consistently surpass reference levels set by the WHO guidelines, US-EPA standards, and SA-NAAQS during both winter and summer seasons. The evidence also suggests that addressing household fuel usage alone may not suffice for improved indoor air quality and reduced health risks. Emphasis must be placed on improving outdoor air quality, influenced by traditional urban and industrial sources. The deployment of low-cost sensors provides valuable information in advancing our understanding of indoor air quality and associated health risks, while also guiding interventions.

CRedit authorship contribution statement

Caradee Y. Wright: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Matthew Benyon:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Roseanne D. Diab:** Writing – review & editing. **Natasha Naidoo:** Writing – review & editing. **Ngwako Kwatala:** Writing – original draft, Methodology, Investigation, Formal analysis. **Siyathemba Kunene:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Chiara Batini:** Writing – review & editing. **Lisa K. Micklesfield:** Writing – review & editing. **Samuel Cai:** Writing – review & editing. **Rikesh Panchal:** Writing – review & editing. **Sizwe B. Zondo:** Project administration, Methodology, Investigation. **Brigitte Language:** Writing – review & editing. **Bianca Wernecke:** Writing – review & editing, Methodology. **Scott Hazelhurst:** Writing – review & editing, Methodology, Investigation, Funding acquisition,

Conceptualization. **F. Xavier Gómez-Olivé**: Writing – review & editing. **Joshua Vande Hey**: Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.atmosenv.2024.120996>.

Data availability

Data will be made available on request.

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