



RESEARCH ARTICLE

REVISED **Personal exposures to fine particulate matter and carbon monoxide in relation to cooking activities in rural Malawi [version 2; peer review: 2 approved]**

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Abstract

Background: Air pollution is a major environmental risk factor for cardiorespiratory disease. Exposures to household air pollution from cooking and other activities, are particularly high in Southern Africa. Following an extended period of participant observation in a village in Malawi, we aimed to assess individuals' exposures to fine particulate matter (PM_{2.5}) and carbon monoxide (CO) and to investigate the different sources of exposure, including different cooking methods.

Methods: Adult residents of a village in Malawi wore personal PM_{2.5} and CO monitors for 24-48 hours, sampling every 1 (CO) or 2 minutes (PM_{2.5}). Subsequent in-person interviews recorded potential exposure details over the time periods. We present means and interquartile ranges for overall exposures and summaries stratified by time and activity (exposure). We employed multivariate regression to further explore these characteristics, and Spearman rank correlation to examine the relationship between paired PM_{2.5} and CO exposures.

Results: Twenty participants (17 female; median age 40 years, IQR: 37-56) provided 831 hours of paired PM_{2.5} and CO data.

Concentrations of PM_{2.5} during combustion activity, usually cooking, far exceeded background levels (no combustion activity): 97.9µg/m³ (IQR: 22.9-482.0), vs 7.6µg/m³, IQR: 2.5-20.6 respectively. Background PM_{2.5} concentrations were higher during daytime hours (11.7µg/m³ [IQR: 5.2-30.0] vs 3.3µg/m³ at night [IQR: 0.7-8.2]). Highest exposures were influenced by cooking location but associated with charcoal use (for CO) and firewood on a three-stone fire (for PM_{2.5}). Cooking-related exposures were higher in more ventilated places, such as outside the household or on a walled veranda, than during indoor

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cooking.

Conclusions: The study demonstrates the value of combining personal PM_{2.5} exposure data with detailed contextual information for providing deeper insights into pollution sources and influences. The finding of similar/lower exposures during cooking in seemingly less-ventilated places should prompt a re-evaluation of proposed clean air interventions in these settings.

Keywords

air pollution; particulate matter; carbon monoxide; exposure; monitoring; cooking

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REVISED Amendments from Version 1

The paper has been edited in response to comments by the two reviewers. Key edits include:

- Clarification of the main language spoken in the village
- Additional information on the air pollution sources in the village other than cooking, and signposting to further details of this in a separate publication
- Clarification of stove types used in the village
- Discussion and citation of the use of CO monitoring as a proxy for PM_{2.5} and Explanation of the role of the current study in the air pollution monitoring discourse

Any further responses from the reviewers can be found at the end of the article

Background

Air pollution is the fourth leading risk factor for premature mortality worldwide¹. It is estimated to have contributed to 6.67 million deaths in 2019, largely through respiratory and cardiovascular pathology, with the highest risks occurring in low- and middle-income countries (LMICs)^{1,2}. Across sub-Saharan Africa particularly, poor air quality is a persisting issue, with little of the improvements sometimes seen in more affluent regions^{2,3}. Household air pollution, from cooking, heating, and lighting, accounts for a large proportion of the deaths attributable to air pollution, particularly in low-income countries in sub-Saharan Africa¹; it also contributes to ambient air pollution. In Malawi, where air pollution remains a leading risk factor for morbidity and mortality⁴, exposure to fine particulate matter (PM_{2.5}), defined as particles of diameter <2.5 µm, from household sources, was responsible for an estimated 12,400 deaths in 2019⁵. Other common air pollution sources in Malawi include pollution from vehicles and burning of farmland and brick ovens^{6–8}.

In Malawi and similar settings, PM_{2.5} and carbon monoxide (CO) exposures relate strongly to cooking^{9–11} and far exceed internationally agreed cut-offs¹². This suggests that cleaner cooking devices might be beneficial^{13–17}, although provision of these in intervention trials have not significantly improved health endpoints^{18,19}. Data on additional non-cooking-related sources of air pollution are available, but specific source apportionment in the context of overall daily exposures is uncommon^{14,20,21}.

In a recent report from Malawi, we drew insights from in-depth participant observation to inform the design of a monitoring study, providing contextual observational data of cooking behaviour⁸. Participants' mobility around the household area, even during cooking episodes, means that stationary monitoring inaccurately reflects personal exposure¹⁷. Importantly, individuals within a household use varying sites for cooking, and different fuels and stoves, even within a 24-hour period. More detailed data on cooking-related and additional exposure sources are required to better understand where and to what extent exposures are happening and, therefore, the potential effects of exposure-reduction interventions²². We set out to fill this evidence gap through concurrent personal PM_{2.5} and

CO exposure monitoring, coupled with detailed time-activity data to explore the influence of cooking and of individual cooking characteristics, such place, fuel, and device use. This allows us to develop a more granular model of air pollution exposures. We also examined the relationship between paired PM_{2.5} and CO exposures, adding to the existing evidence on correlates of air quality in this context.

Methods

Ethical considerations

The study was approved and sponsored by the LSTM Research Ethics Committee (19-007). In-country ethical approval was granted by the College of Medicine Research Ethics Committee (COMREC) in Blantyre (P.06/19/2600). Written informed consent processes were completed for all participants involved in air quality monitoring. Further information around ethical aspects of the study has been published separately²³.

Study design

This study was nested within a larger ethnographic study which incorporated extended participant observation concurrent personal PM_{2.5} and CO exposure measurement in a Malawian village⁸. Household-based participant observations in and around the village took place between July 2019 and January 2020 (during the hot season and part of the cooler rainy season in Malawi), with observations and preliminary quantitative data collected from researchers through proxy exposure sampling informing the sampling design.

Summary measures from the preliminary phase have been reported separately⁸. Definitive exposure data reported in this paper reflect results of 48-hour personal monitoring in a cohort of village participants between January and March 2020 (Figure 1) ('extended' dataset).

Study setting

Participants lived in a rural village of approximately 840, comprising 722 adults: 380 men and 342 women (population data from local health surveillance assistant, personal communication, 30 September 2021). The main language spoken was Chichewa. During daylight hours, the adult population present in the village was largely female, as many men travelled to neighbouring areas seeking employment. The village was 12 km from Blantyre, the commercial capital of Malawi, and approximately 2 km from nearest tarmac single-carriageway road. Much of the area was not accessible by any type of road. Village life focussed around subsistence farming, reflecting the lifestyle seen across most rural communities in the country²⁴. Whilst there were multiple air pollution exposure sources in and around the village environment preliminary ethnographic work in this setting, incorporating personal exposure monitoring, demonstrated that cooking was consistently the most important source of airborne particulate exposure, both in terms of frequency and magnitude⁸. Fires were infrequently lit solely for lighting or warming, although cooking fires were also used for these purposes at times (meaning exposures were captured in our monitoring data). In terms of cooking, three-stone fires were habitually used in almost all households, with some individuals also using charcoal stoves and, less frequently, firewood stoves (chitetezo

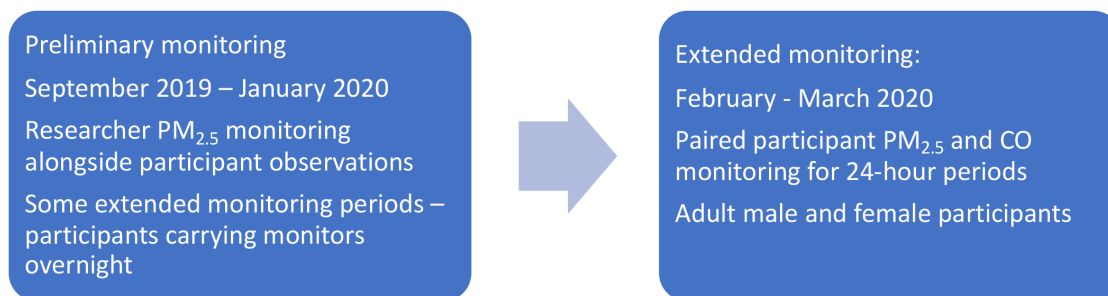


Figure 1. Phases of air quality monitoring.

mbaula). Individuals' stove and fuel use and place of cooking often varied by weather, food cooked (or other stove activity, such as bathwater warming), and occasion. Further details of the setting, including common cooking modalities, have been published separately⁸.

Participants

Adult male and female residents (>18 years of age) spending at least 6 days of the week in and around the village were invited to participate. Details of recruitment and related study approaches are discussed separately²³. Only participants giving written informed consent were included. People aged 18 or under, or unable to provide informed consent, were excluded.

Data collection

PM_{2.5} and CO measurement. Participants each spent 48 hours carrying two personal air quality monitors in waist bags specifically designed for this study. PurpleAir PA-II-SD laser particle counting devices (PurpleAir, Draper, UT, USA) with 20-Ah portable power banks (Anker Innovations, Changsha, China), previously employed in a number of African settings^{25,26}, logged PM_{2.5} concentrations at 2-minute intervals. LASCAR EL-USB-CO devices (Lascar Electronics, Erie, PA, USA) logged CO concentrations every minute. Each PurpleAir monitor was positioned on a large hole in the base of the bag, and the CO data logger protruded from a zip pocket.

Activity data. At the end of each 24-hour monitoring period, potential exposures were identified through an in-person review of PM_{2.5} traces created from PurpleAir data using a line graph in Excel, Version 16.63 (Microsoft, Redmond, WA, USA)²⁷, viewed on a laptop screen by the participant and a researcher together. Information on potential exposures were gathered at this point, guided by participant recall (around cooking periods each day, for instance), together with visible peaks on traces. Data on potential exposures covered the following key areas, informed by observations during the preceding fieldwork period and preliminary monitoring:

1 Combustion source, including:

- Cooking/bathwater warming/other household fires
- Farming-related exposures
- Traffic exposure
- Other

2 For cooking-related exposures, additional data were gathered on:

a) Place of cooking:

- 'Indoors' – either inside the household or in an enclosed kitchen
- Kitchen with no roof
- Walled *khonde* (veranda)
- *Khonde* with no walls
- Outdoors (in yard area)

b) Device used for cooking:

- Three-stone fire
- Charcoal cookstove
- Firewood cookstove

c) Fuel used for cooking:

- Firewood
- Charcoal
- Other

Data management and statistical analysis

For PM_{2.5}, 'CF=1' values were selected, on expert advice, in view of key environmental features. The PurpleAir PM_{2.5} monitors each have two separate sensors. Data from these was managed by checking, for each trace, that readings from both sensors were in agreement throughout, before using an average of the two values for the analysis. Times for these devices were set through connection to the internet, with regular reconnection ensuring no significant drift. Each 2-minute PM_{2.5} concentration was paired with CO concentration, and with activity data, and these data used for subsequent analyses.

Matching time-activity data generated through interviews were used to indicate which periods on each trace represented 'activity' (when there was an identified exposure source present), with the remainder of the time points constituting 'background' exposures (no identified source of combustion present). More detailed activity data also allowed analysis by cooking details (device, fuel, and place of cooking).

Medians and interquartile ranges (IQRs) for $PM_{2.5}$ and CO during ‘activity’ periods were calculated and compared with the remainder, identified as ‘background’ exposures, across the full dataset. Medians and IQRs were also calculated for daytime background exposures (05:00 h to 22:00 h) and compared with background exposures through the night (22:00 h to 05:00 h). Selection of these time categories was informed by the previous ethnographic work in the village. Medians and IQRs were preferred over means throughout the analysis in view of the skewed nature of the exposure data and in line with other work in the area^{11,21,28}.

The medians and IQRs of all datapoints across the dataset during cooking were compared with those associated with ‘no activity’, and summary measures were similarly used to compare various cooking characteristics (cooking device, fuel, and place of cooking). For boxplots, CO +1 values were used before log transformation to allow for transformation of zero values.

Multivariate regression models were employed to explore the effects of these cooking characteristics in greater detail, while

also acknowledging autocorrelation between datapoints from the same participant over time (hence the use of mixed models).

Correlation between paired $PM_{2.5}$ and CO exposures was analysed both visually using a scatter plot and through the calculation of a Spearman rank correlation coefficient. All data were analysed using R (R Foundation for Statistical Computing, 2020, Vienna, Austria) (RRID:SCR_001905)²⁹, and figures were created using the package ggplot2 (RRID:SCR_014601)³⁰. Linear regression was done using the lme4 package (RRID:SCR_015654)³¹ and outputs created using the Stargazer package³².

Results

The extended dataset included a total of 831 hours of paired $PM_{2.5}$ and CO exposure data from 20 participants, all of which was included in the analysis (Figure 2). 11 of these 20 participants had two full contiguous 24-hour traces amounting to more than 48 hours of monitoring. Shorter samples were due to battery faults, but there were no individual or sporadic missing values within the existing data traces.

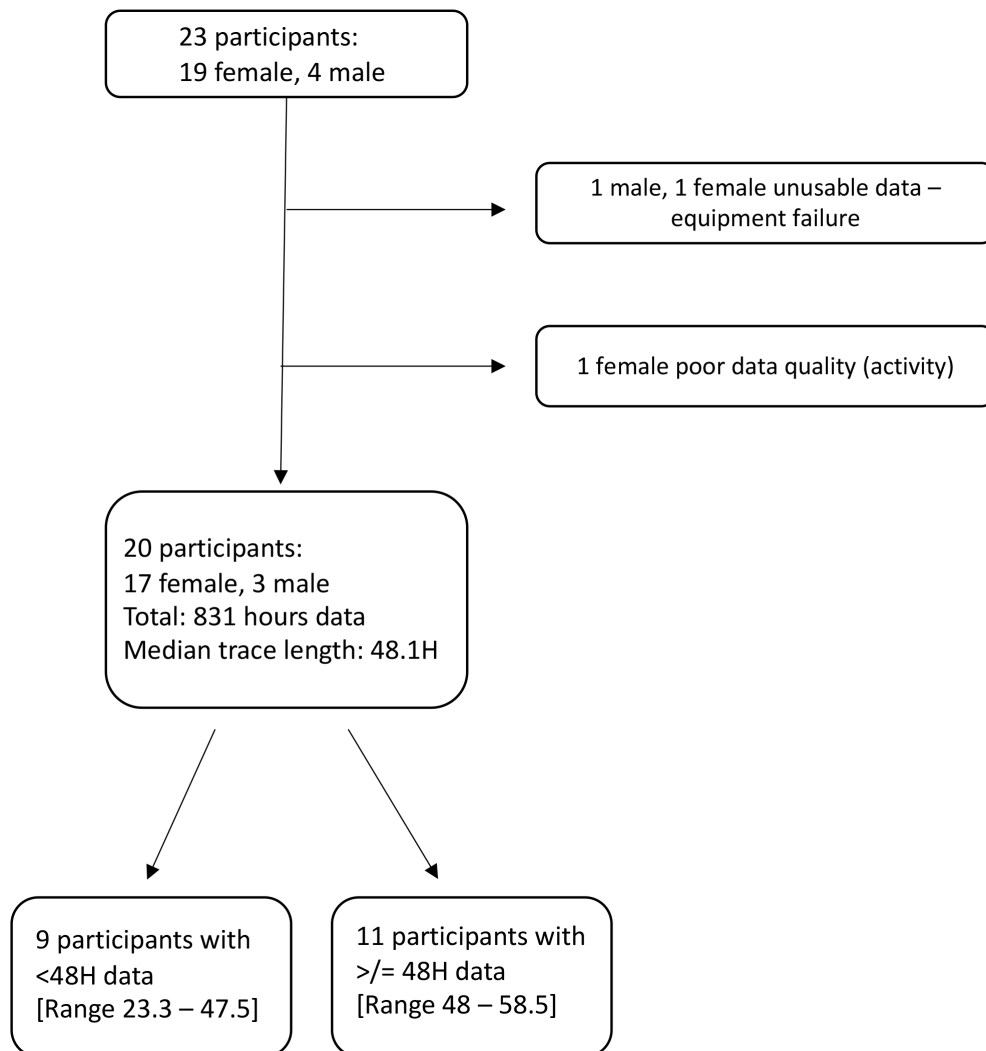


Figure 2. Flow chart depicting participants included and excluded, with data on duration of monitoring.

Both $PM_{2.5}$ and CO traces showed a ‘baseline + peak’ pattern, with echoing patterns in paired traces (Figure 3).

Testing for normality using the Shapiro–Wilk test revealed the data to be highly skewed, with a left skew representing lower $PM_{2.5}$ concentrations (in the absence of combustion activity), and a long tail representing $PM_{2.5}$ concentrations reaching $>1,000 \mu\text{g}/\text{m}^3$ during cooking activity.

Activity-related and background exposures

‘Peaks’, or periods of ‘activity’ (where there was an identified source of combustion) represented 23% of the overall recording period. Median $PM_{2.5}$ exposure during these activity periods was $97.9 \mu\text{g}/\text{m}^3$ (IQR: 22.9–482.0), whereas median $PM_{2.5}$ background exposure concentrations (at times of no identified combustion sources) were $7.6 \mu\text{g}/\text{m}^3$ (IQR: 2.5–20.6). This comparison is shown in the box plots (Figure 4a), which also depict the wide dispersal of values, which often reached above $1,000 \mu\text{g}/\text{m}^3$ during periods of ‘activity’. Median carbon monoxide exposure during periods of identified activity was 4 ppm (IQR: 1–12), compared with median background exposures of 0 ppm (Figure 4b).

Of the total ‘activity’ time period, 86% represented cooking or a related activity in the household (including starting a cooking fire and use of this fire—or cookstove—for warming bathwater and warming oneself). Other exposure sources captured in the dataset included burning grass at the farm, proximity to a minibus, soldering of a radio, and an identified cooking fire in a neighbouring household.

When ‘no activity’ periods were stratified by diurnal period, there were 399 hours of ‘no activity’ data during the day, compared with 237 hours at night. Median ambient $PM_{2.5}$ exposures were higher in the day than the night (Figure 4c): $11.7 \mu\text{g}/\text{m}^3$ [IQR: 5.2–30.0] and $3.3 \mu\text{g}/\text{m}^3$ [IQR: 0.7–8.2] respectively.

Male and female exposures were not compared because of the small number of male participants involved in this study.

Cooking characteristics

Of all identified cooking time, 80% involved the use of a three-stone fire. The remainder of the cooking time involved either charcoal or firewood cookstoves (10% and 9%, respectively). Indoor cooking was most common (60% of total cooking time, of which 82% was in a closed kitchen, and the remainder in a house). Less commonly, cooking was done on walled verandas (24% of all cooking time), outside (11%), or on open verandas (no walls). Only one participant cooked in a kitchen with no roof (2% of total cooking time).

Univariate analysis suggested that use of firewood was associated with higher $PM_{2.5}$ exposures than charcoal (median $115.0 \mu\text{g}/\text{m}^3$ [IQR: 26.7–506.0] *versus* median $25.7 \mu\text{g}/\text{m}^3$ [IQR: 11.0–65.0] for charcoal). In contrast, CO exposures were slightly lower during cooking periods using firewood compared with charcoal (median 3.5 ppm [IQR: 1.0–10.0] *versus* median 5.0 ppm [IQR: 1.5–14.0]). These differences are shown in Figures 5a & b.

Use of three-stone fires was associated with higher $PM_{2.5}$ exposures than either firewood or charcoal cookstoves (median $127.0 \mu\text{g}/\text{m}^3$ [IQR: 30.7–535.0]; median $39.5 \mu\text{g}/\text{m}^3$ [IQR: 9.8–221.0]; median $26.7 \mu\text{g}/\text{m}^3$ [IQR: 11.3–68.0], respectively). This again contrasted with CO concentrations, which were lower during cooking episodes using firewood stoves than with either three-stone fires or charcoal stoves (median 1.0 ppm [IQR: 0.0–3.0]; median 4.0 ppm [IQR: 1.5–11.5]; median 5.0 ppm [IQR: 1.5–14.0], respectively).

All cooking episodes could be represented by one of three combinations:

- 1 Firewood on a three-stone fire
- 2 Firewood on a firewood cookstove
- 3 Charcoal on a charcoal cookstove

Fuel and stove were, therefore, combined into a single ‘fuel_stove’ categorical variable for the purposes of the regression

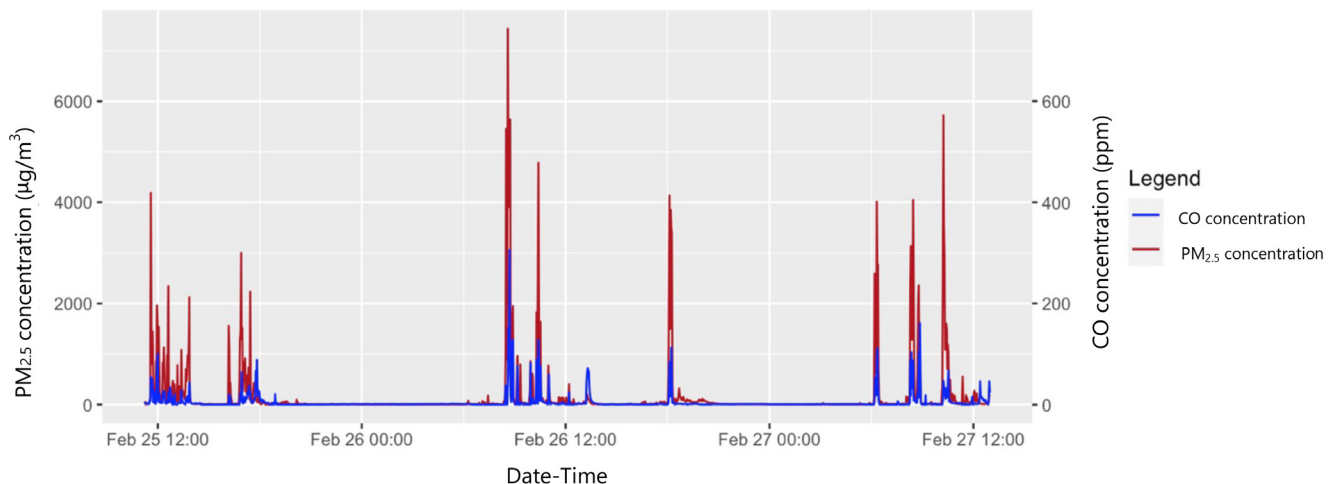
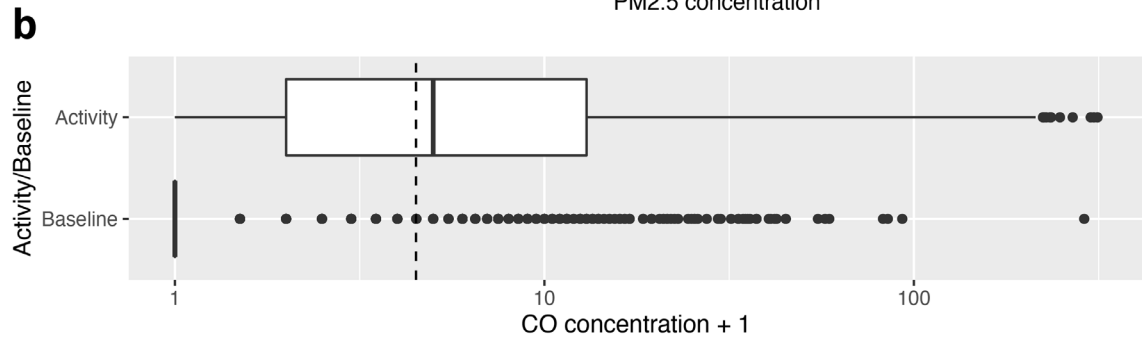
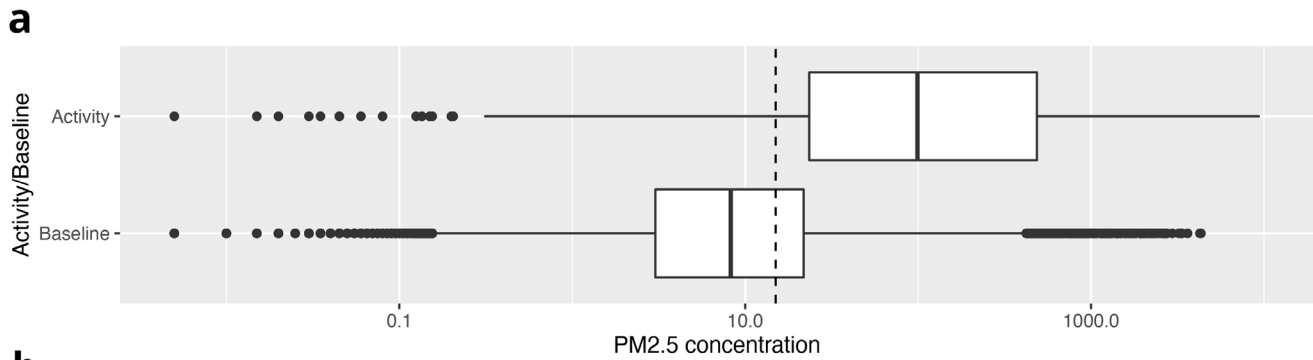
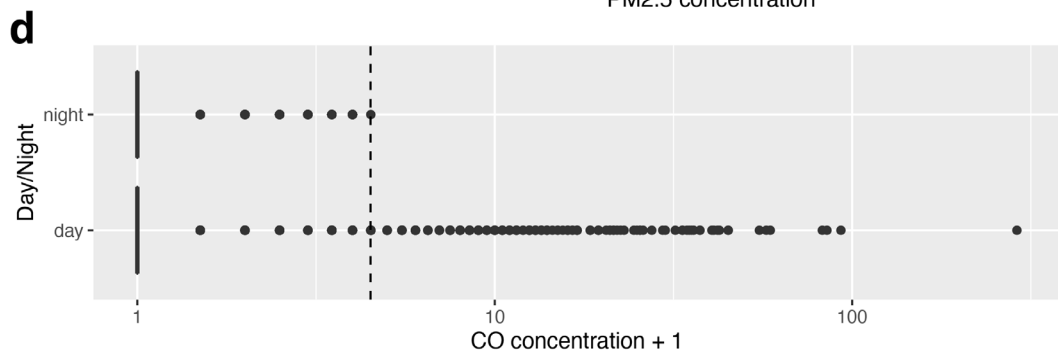
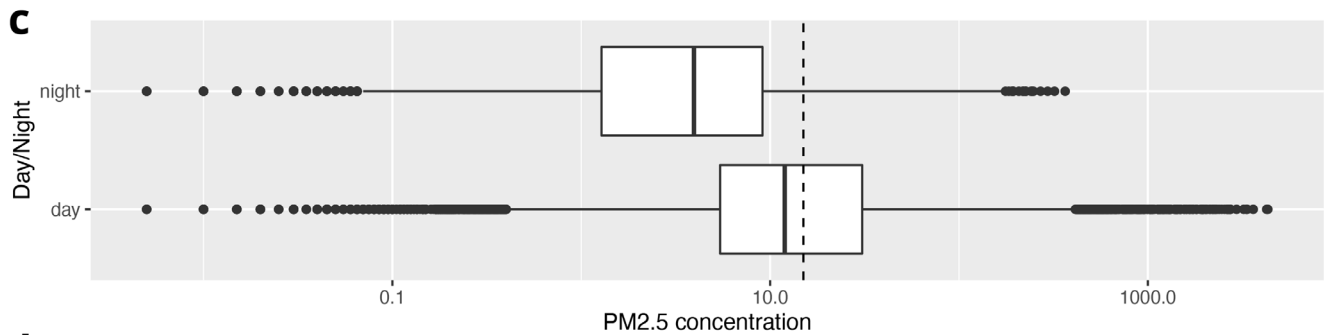


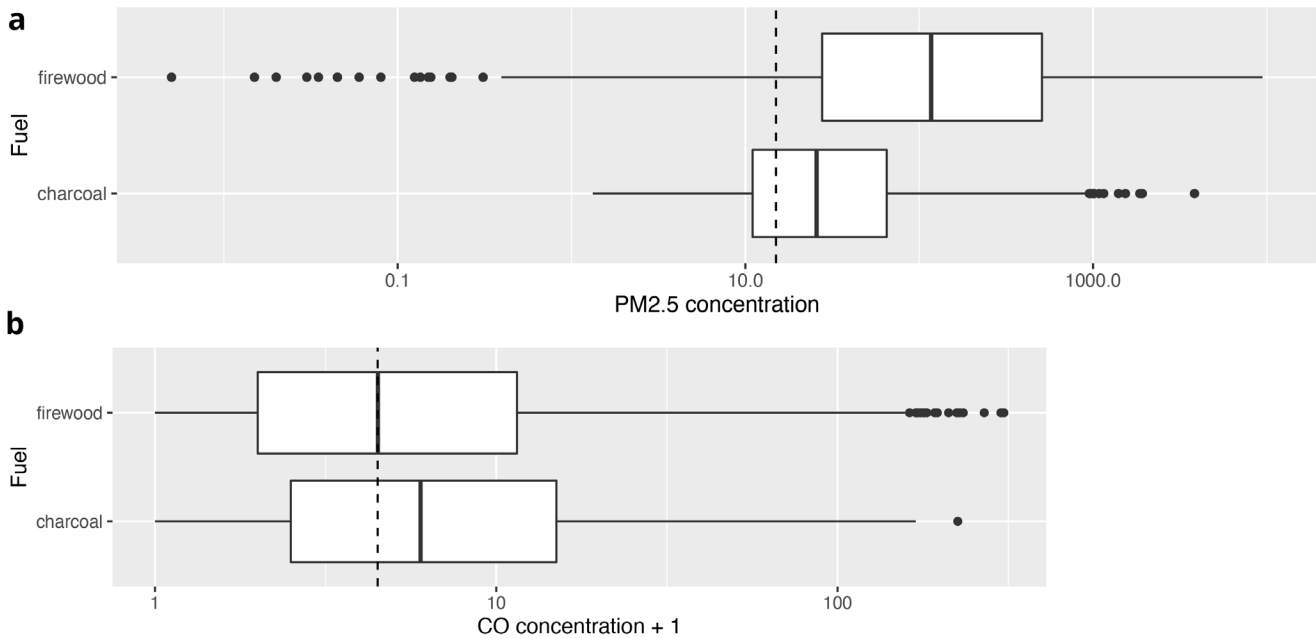
Figure 3. Variation in $PM_{2.5}$ and CO concentrations over a 48-hour time-period in a sample participant.



Figures 4a & b. Box plots depicting median $PM_{2.5}$ and CO exposures during periods of combustion activity and at baseline (background exposures) across the dataset, with $PM_{2.5}$ /CO concentrations plotted on a log scale. Dotted lines indicate WHO-recommended 24-hour upper limits ($PM_{2.5}$ concentration $15 \mu g/m^3$; CO concentration $4 \text{ mg}/m^3 = 3.492 \text{ ppm}$)¹².



Figures 4c & d. Box plot depicting background median $PM_{2.5}$ and CO exposures (where no identified combustion activity), during daytime and night-time hours, with $PM_{2.5}$ /CO concentrations plotted on a log scale. Dotted lines indicate WHO-recommended 24-hour upper limits ($PM_{2.5}$ concentration $15 \mu g/m^3$; CO concentration $4 \text{ mg}/m^3 = 3.492 \text{ ppm}$)¹².



Figures 5a & b. Box plot depicting median cooking related PM_{2.5} and CO exposures during cooking episodes using firewood compared with those using charcoal, with PM_{2.5}/CO concentrations plotted on a log scale. Dotted lines indicate WHO-recommended 24-hour upper limits (PM_{2.5} concentration 15 µg/m³; CO concentration 4 mg/m³ = 3.492 ppm)¹².

model. The full model thus includes ‘fuel_stove’ and ‘place of cooking’ as fixed effects and participant number as a random effect (in recognition of the likely individual/household-level determinants involved). The dependent variable was log normalised using $(\log_{10}(1+[PM_{2.5}]))$ to allow treatment of zero values. Results of regression analyses presented here only relate to the PM_{2.5} outcome. Results of the regression model using CO as a dependent variable have been included in the supplementary materials.

$$(\log_{10}(1+[PM_{2.5}])) \sim \text{‘place’} + \text{‘fuel_stove’} + (1|\text{‘participant’})$$

An initial mixed model examining fuel_stove alone (with ‘participant’ as a random effect) indicated that use of firewood—either on a three-stone fire, or on a firewood cookstove—predicted higher PM_{2.5} exposure compared with use of charcoal on a charcoal stove. The increase in exposure was greater for firewood on a three-stone fire (estimate = 1.25, error = 0.095, $P < 0.01$) than for firewood on a firewood cookstove (estimate = 0.25, error = 0.14, $P < 0.1$).

A similar mixed model using ‘place of cooking’ alone indicated that—compared with cooking indoors—cooking in a kitchen with no roof, walled veranda, or outside the household were all significantly associated with higher exposures ($P < 0.01$ in all three cases). Cooking in an unwalled veranda in this model appeared to be associated with higher exposures ($P < 0.01$). Both models indicated that inter-participant variation was less than variation due to other factors.

Compared with the fuel_stove-only model, adding place of cooking (to give the full model) significantly improved the prediction of PM_{2.5} exposures ($\chi^2(4) = 23.7$, ANOVA $P = 0.001$). This model affirmed the significance of fuel_stove in shaping exposures, with wood on a three-stone fire significantly associated with higher exposures than charcoal used on a charcoal stove (estimate = 1.12, error = 0.11, $P < 0.01$); firewood on a firewood stove was, in this model, not associated with significantly different exposures than charcoal. In the full model, compared with cooking indoors, cooking in a walled veranda or outside the household were associated with significantly higher personal exposures (Extended data, Table S1). Cooking taking place in a kitchen with no roof and in an unwalled veranda were not associated with any significant differences.

Correlation between PM_{2.5} and CO concentrations

On visual inspection of a contour plot with an overlaid line of best fit (Figure 6a), there appeared to be a correlation between PM_{2.5} and CO concentrations across the whole dataset. The Spearman rank correlation coefficient (r_s) was 0.50 ($P < 0.001$), indicating a moderate correlation between PM_{2.5} and CO concentrations overall.

The apparent clustering in this graphic was explored using separate plots for ‘cooking’ and ‘background’ periods (Figures 6b & c). Analysis of correlation in these subgroups found a stronger relationship during cooking activity ($r^2 = 0.42$) compared with background periods ($r^2 = 0.22$).

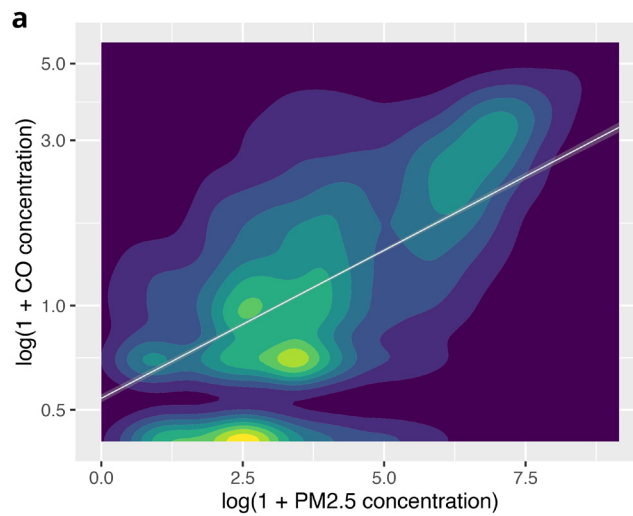
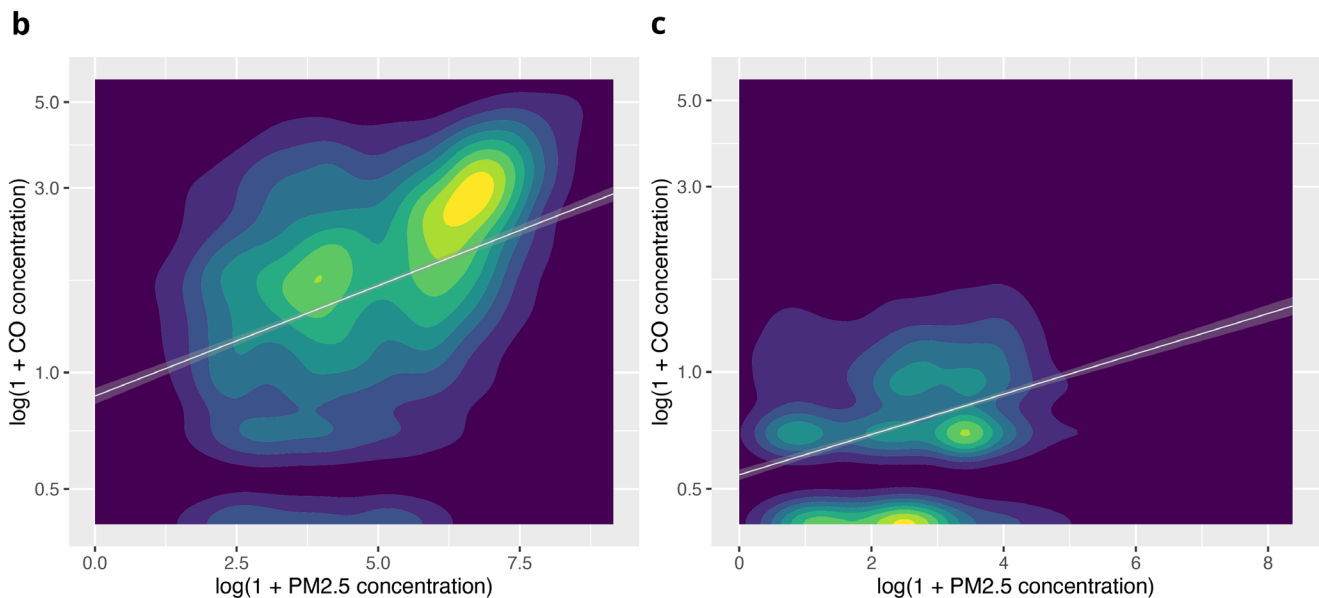


Figure 6a. Contour plot illustrating the relationship between $PM_{2.5}$ and CO across the complete dataset, using $\log(1+CO)$ and $\log(1+PM_{2.5})$.



Figures 6b & c. Contour plots illustrating the relationship between $PM_{2.5}$ and CO during cooking activity, and background periods (no identified combustion activity), using $\log(1+CO)$ and $\log(1+PM_{2.5})$.

Discussion

Our personal monitoring results, coupled with in-depth data around daily exposures, demonstrated the primacy of cooking in individuals' exposure landscapes in Malawi. Median $PM_{2.5}$ and CO exposures were significantly higher during activity (usually representing cooking) than background exposures, in the absence of identified combustion activity. Analysis of paired cooking data revealed the use of wood on a three-stone fire to be significantly associated with higher

exposures than cooking using charcoal or firewood stoves, and cooking in a walled veranda or outside the household were associated with significantly higher personal exposures than cooking outdoors.

The data indicated that median background $PM_{2.5}$ and CO concentrations— $7.6 \mu\text{g}/\text{m}^3$ and 0 ppm for $PM_{2.5}$ and CO, respectively—were below World Health Organization (WHO)-recommended 24-hour levels¹² but that cooking episodes

frequently exposed participants to extremely high pollutant concentrations ($PM_{2.5}$ often $>1,000 \mu\text{g}/\text{m}^3$). High pollutant concentrations have been previously reported in this setting^{9,33}, but using personal monitoring with paired activity data, we were able to separately analyse background and peak $PM_{2.5}$ concentrations, framing cooking as a key exposure source. This echoes findings from Uganda, Ethiopia, and Ghana^{14,17}, with further analysis exploring specific factors which shape cooking-related exposures.

The diurnal difference in background $PM_{2.5}$ concentrations reveals the contribution of daily activity across the village to ambient levels. This contrasts with data from more urban LMIC settings, which describe higher pollutant concentrations at night, likely driven by atmospheric changes related to cooling³⁴. While our observations in and around the village revealed a variety of potential contributors to air pollution (*e.g.*, burning farmland, environmental dust), cooking clearly constituted the primary source of exposure for participants in the village environment⁸. The shared nature of air pollution here demands interventions which can be near-universally adopted in a given geographical area^{35,36}.

Following an initial period of ethnographic observation for better understanding of the context, personal monitoring paired with fine-grain data on individual cooking episodes, collected after each monitoring period, allowed for analysis of personal cooking exposures by fuel, device, and place of cooking. The association of lower $PM_{2.5}$ concentrations with charcoal cooking reflected community members' own understandings and echoed findings in the literature³⁷. Small reductions in $PM_{2.5}$ concentrations with use of firewood cookstoves compared with three-stone fires supports the use of these low-cost local stoves, although the health impacts of such modest reductions are unclear^{38,39}.

Personal $PM_{2.5}$ exposures associated with cooking indoors were found to be lower than exposures associated with cooking outdoors or on walled verandas and no different from exposures encountered while cooking in other structures. While the idea that cooking in apparently better-ventilated places might be associated with similar or higher exposures than cooking in more enclosed spaces initially seems counterintuitive—and counter to the mainstream discourse^{40–43}—cooking patterns regularly witnessed in the village help explain these effects. We frequently noted that women cooking in smoky kitchens spent time sitting outside or away from the kitchen between visits to tend the fire or the pot, whereas cooking done in a more 'social' space, such as a veranda, involved the cook, as well as family and friends, spending extended periods by the fire. In view of the high $PM_{2.5}$ concentrations produced during any cooking activity, periods of physical distancing from the site may plausibly produce similar or more marked reductions in personal exposures than continuous cooking in spaces with a degree of ventilation. Awareness-raising interventions around the harms of 'smoke' and support for women to spend less time close to cooking devices could constitute a first step to reducing exposures in the village setting, although

structural changes to overcome contextual limitations will be required to achieve sustainable improvements⁴⁴.

Concurrent measurements revealed a strong association between individual $PM_{2.5}$ and CO exposures at peak concentrations but an absence of this association during background periods. This builds on review-level evidence from a range of global settings indicating inconsistencies in the correlation^{45,46}. In view of the clinical significance of background concentrations of pollutants, even where peak concentrations are reduced^{12,47,48}, our findings indicate weaknesses in the application of CO measurement as a proxy for $PM_{2.5}$ exposure, as has been used in the past^{49–51}. We successfully demonstrated the utility of small, soundless, portable $PM_{2.5}$ monitors in personal exposure monitoring. In view of the similarities in costs of the two monitors, we would favour their use for direct $PM_{2.5}$ monitoring, superseding the use of proxies.

The current study involved a relatively small number of participants, preventing detailed regression analyses and more precise models. Residual variation in cooking exposures, possibly related to firewood type or moisture content, type of food cooked, or daily weather conditions, was unexplained by the current models. Observations in the village suggested a role for these factors in influencing cooking related $PM_{2.5}$ concentrations, in keeping with evidence from other studies^{52–54}, but difficulties in quantification and sample size limitations precluded their incorporation in the analysis.

The retrospective reviewing, with participants, of traces on laptop screens to determine exposure periods could potentially have introduced recall bias in exposure categorisation. Combustion activities tended to create clear exposure peaks (Figure 3), but timing inaccuracies could lead to misclassification of datapoints around the start and end of activities. This system was used because while village residents tended to split their days broadly into 'morning'/'afternoon'/'evening' (with lunch usually consumed at around 12 o'clock), they were otherwise generally unaware of the time and did not use watches or clocks at all. Together with the predominance of spoken (over written) communication, this precluded the use of self-completed activity diaries, for example.

The use of medians rather than means in this study—in keeping with other similar studies^{11,21,55}—reduced the effects of potential exposure misclassification, and whilst still constituting an inherent risk in the study design, this is unlikely to have significantly impacted the key study findings around diurnal variation or cooking characteristics for example.

Further study limitations include a relatively short study period (excluding certain seasonal variations, such as changes in fuel use) and the occurrence of very high $PM_{2.5}$ values ($>250 \mu\text{g}/\text{m}^3$) during cooking-related peaks, lying outwith the calibration range of the instruments²⁵. This highlights the need for gravimetric calibration of the monitors in rural sub-Saharan African settings but does not change the direction of inference of the current results.

Conclusions

High cooking-related PM_{2.5} and CO concentrations in this study and a raised background level during the day compared with night signal the need for accessible, population-wide approaches to achieve clinically meaningful exposure reductions. The study demonstrated the feasibility of direct PM_{2.5} monitoring using personal devices, which is important, given our finding of poor PM_{2.5}–CO correlation during background (non-activity) periods. The finding of lower or similar exposures during cooking in less-ventilated places outlines the value of our personal, activity-matched monitoring approach, together with detailed participant observations in the setting. This gives added value to exposure assessment and consequent decisions surrounding interventions and their evaluation.

Data availability

Underlying data

Harvard Dataverse: Underlying data and code for “Personal exposures to fine particulate matter and carbon monoxide in

relation to cooking activities in rural Malawi”. <https://doi.org/10.7910/DVN/7A0XIS>⁵⁶

The project contains the following underlying data:

- Original data - anonymised
- R code for analysis

Extended data

Harvard Dataverse: Extended data for “Personal exposures to fine particulate matter and carbon monoxide in relation to cooking activities in rural Malawi”. <https://doi.org/10.7910/DVN/7A0XIS>⁵⁶

This project contains the following extended data:

- Extended data - ‘Personal exposures to fine particulate matter and carbon monoxide in relation to cooking activities in rural Malawi’

Data are available under the terms of the [Creative Commons Zero “No rights reserved” data waiver](#) (CC0 1.0 Public domain dedication).

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Open Peer Review

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Reviewer Report 14 December 2022

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Suzanne E. Bartington

Institute of Applied Health Research, University of Birmingham, Birmingham, UK

This is a well conducted study, investigating cooking-related exposure to PM_{2.5} and CO among a sample of adult residents living in biomass fuel households in rural Malawi. Importantly, this study links contextual information and time-activity behaviour with primary paired measurements of PM_{2.5} and CO thereby demonstrating the value of combining this information to understand personal exposure profiles; of relevance for epidemiological and health impact assessment studies.

Although the study was conducted using a small convenience sample (20 participants) it includes 831 hours of data collection for the respective individuals. The data gaps experienced are typical for primary data collection in this context, with just 11 or 20 participants providing full 24-hour traces. This learning is important for future logistical considerations for personal exposure assessment studies in LMIC settings, where reliance upon battery/powerbank powered devices is typical. Further methodological detail would be welcome for the approaches used to calibrate sensors, both pre-and post- field deployment.

Clear differences were observed for PM_{2.5} and CO concentrations during peak periods of activity, compared to background concentrations, consistent with previous literature in domestic biomass combustion contexts (e.g. Bartington *et al.* (2017)¹). Similarly, the finding of higher exposures associated with cooking using three-stone fires when compared to wood or charcoal stoves is consistent with previous investigations. However, some further detail regarding the fuel used for the three-stone fires would be beneficial - including if this is a mix of sources (e.g. straw/dung) and also information as to which fuel is used to light the stove. The findings also suggest an important contribution of daily activities in this context to ambient pollutant levels - of relevant to future research in rural LMIC settings.

A key limitation of the study was reliance upon recall for activity data and it is unclear how this was validated against objective measures. However, given the ethnographic study context, the involvement of participants is also relevant providing an opportunity for them to explore potential exposures together with a researcher. This approach may also yield a greater depth of understanding than could be achieved by alternative methods for recording time-activity data,

which may omit relevant information. Further limitations are discussed in detail by the authors, including a relative short study period and concentrations which exceed the calibration range of instrumentation. Reproducibility is also unclear given study findings are based upon single monitoring campaign. However, overall this study demonstrates utility of this approach for personal exposure assessment in this rural context, of value to inform future studies.

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Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Yes

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Environmental epidemiology, public health

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 06 Feb 2023

Sepeedeh Saleh, Liverpool School of Tropical Medicine, LIVERPOOL, UK

We thank the reviewer for this thoughtful review which raises some useful points for consideration. The following are responses to individual points in the review and we are submitting an edited version of the paper with relevant changes in response to reviewer considerations.

Regarding calibration of the devices, this has been done by others - as cited in the paper - in settings including African environments similar to that in which the current work is set. Our

own planned calibration was prevented, however, by problems relating to the gravimetric monitors we planned to use. This is, as mentioned, a limitation of the current study and we highlight our recommendation that further, more extensive monitoring work in this setting should incorporate formal, site-specific calibration as a first step.

In response to the queries surrounding fuels used, three stone fires used in the village were great majority of the time, used with collected firewood. Acknowledging this, we devised the three categories of 'fuel_stove' (Firewood on a three-stone fire; Firewood on a firewood cookstove; Charcoal on a charcoal cookstove) for the analytic regression model, which considered fuel and device in simple combined categories. We agree that there were in reality subtleties in cooking fuel which were not fully captured in this model (for example when additional substances were added to the fire or used for the initial lighting process, or when firewood was damp) but this categorisation was broadly characteristic of the main cooking practices and represented a clear and measurable model. The use of maize cobs and stalks was seen during the extended participant observation, but only during specific periods (around harvesting time), which were outside of the observation period for this study. This is indicated in the discussion around 'seasonal variations'. Dung was not generally used as a fuel in this setting.

We agree fully with the reviewer's points around daily activities and contributions in the village and refer the reviewer to related comments of the first reviewer around these questions, and to our responses.

Finally, we appreciate the reviewer's point around limitations associated with the element of recall in identification of exposures, but highlight the fact that this was carried out on a background of an extended period of in-person participant observation in the village with concurrent personal exposure monitoring (which showed a characteristic baseline + peak pattern). Findings around context and exposure sources – formally reported elsewhere – paved the way for the use of participant recall in combination with reviewing of traces in the current study. We would not advise the use of these methods in isolation without the prior investigations and understanding of the setting.

Competing Interests: None.

Reviewer Report 31 October 2022

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Deborah Stanistreet

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Dublin, Ireland

This paper is well constructed and organised and explores an extremely important issue; that of household air pollution, a major health burden in many low income countries. Around 40% of the global population still do not have access to clean fuels for cooking and the issue is only likely to be compounded by the current energy crisis.

Using ethnographic observations alongside survey data is a methodology which is underused in the HAP field. This paper makes a powerful case that adding context to survey data aids greatly in data interpretation. In fact, I would argue that mixed methods including observations, should be a standardised methodology in understanding household air pollution in relation to cooking practices. The author makes a good case for this in a previous paper¹, (which could also be referenced in relation to this).

The paper has used standard methods of personal exposure measurement, but as the authors state, personal exposure is a more valid measurement of the impact of exposure on health than those studies that measure levels of pollution close to the stove. In terms of methods, the matching of time activity to the HAP measurements is also a useful demonstration of the importance of context. I think it would be useful to explore other additional activities that may be related to the measurements produced.? (See later comments).

Results

The authors distinguish between a three stone fire, cookstove and also charcoal stove. Could you identify which cookstove(s) was / were being used? This may be significant in that not all 'improved' cookstoves have shown demonstrated reductions in PM2.5 under lap conditions, but there is some evidence that the chitetetzo mbaula does reduce HAP and this is the most commonly available 'improved' stove in Malawi. e.g. Jagger *et al.* (2017)²

I would personally be keen to ensure that improved cookstoves are all identified by name so that the reader can assess whether there is any independent evidence that it is more fuel efficient and / or reduces HAP.

"Median PM2.5 exposure during these activity periods was 97.9 µg/m3 (IQR: 22.9–482.0) demonstrating a wide range in terms of level of PM2.5."

Were you able to explore any of the reasons for this? For example, it would be useful to know which cooking practices resulted in exposure to the highest levels of PM2.5. Can you provide any further information about the houses? Any windows / ventilation?

How homogenous were the cooking practices? In Malawi, Nsima, the staple dish, requires stirring , especially the last ten minutes or so, so the cook is required to stay close to the pot. Conversely, beans require less watching or stirring, but potentially may lead to greater exposure as they require much longer to cook. These factors can also increase exposure.

Were there any other behavioural practices that could have contributed to greater exposure? E.g. Did you observe any Crouching and blowing air by mouth on burning of wet wood (did anyone dry wood prior to use for instance) . Were there any other behavioural differences such as burning of

maize cobs, stalks or burning of plastic on the fire, or use of pot lids which would reduce cooking times? Did some participants maintain the stove for warmth overnight.

Was lighting a further source of pollution or was it mostly battery lighting?

If the authors have any information on these factors, which could potentially explain differences in exposure, these would be useful to include, even within the discussion.

The finding that cooking on a veranda led to greater exposure is a very interesting one!

The authors discuss the validity of using CO as a proxy for PM2.5. How common is this? Could you provide a brief discussion? I only found a handful or recent publications on a quick scan and wonder whether 67a, 6b and 6c are of real value to the main message on this study, but I am open to be corrected!

Finally other issues that might be touched on during the discussion include:

- If / whether cooking practices vary with season?

- Any language issues. Was the spoken language of the community, Chichewa

Overall, an excellent paper, which has huge value in promoting the use of ethnography to provide context when interpreting HAP data.

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Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and is the work technically sound?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Yes

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Epidemiology, mixed methods, household air pollution

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 06 Feb 2023

Sepeedeh Saleh, Liverpool School of Tropical Medicine, LIVERPOOL, UK

We thank the reviewer for this detailed and insightful review. The following are responses to individual points in the review and we are submitting an edited version of the paper with relevant changes in response to reviewer considerations.

We are grateful for the observations on our use of mixed methods in exploring air pollution exposures.

We agree that our experiences and findings support the use ethnographic and survey methodologies in parallel, and we hope to see other researchers follow our lead in this.

In terms of additional activities which might have contributed to air pollution in and around the village environment, our preliminary ethnographic work (reported separately) revealed that other smoke-producing activities resulted in much lower exposures, and took place more infrequently, than cooking. This statement has now been added to the paper for clarity.

We would welcome larger, more formalised studies of this, and research involving individuals spending more time away from the village environment, to extend these findings.

In response to the query about stove types, wood burning cookstoves were, in all cases, basic chitetezo mbaula, as mentioned by the reviewer. This has now been made clear in the paper. These stoves, present in a few households, were later distributed to all households in the village as part of our study, generating further evidence around their impacts on personal exposures.

We thank the reviewer for the important questions about the statement "*Median PM2.5 exposure during these activity periods was 97.9 µg/m3 (IQR: 22.9–482.0) demonstrating a wide range in terms of level of PM2.5*". Whilst these data were exposures for overall cooking periods, our regression work - presented under the subheading, 'Cooking Characteristics' - allowed further exploration of the role of place of cooking (reflecting ventilation factors) and stove and fuel use. We found that cooking in a kitchen with no roof, walled veranda, or outside the household were all significantly associated with higher exposures than cooking indoors. Potential reasons for this - informed also by our extended participant observations - are proposed in the Discussion section.

We agree with the observations around homogeneity of cooking activities. Although most meals in the village involved nsima (taking between 30 and 45 minutes to cook) and accompanying ndiwo (vegetables, etc, cooked for a shorter period), beans were also cooked at times. We initially attempted to record type of cooking (food cooked) as an additional variable in this study but found it impossible due to complexity involving frequent concurrent cooking of different foods. Our use of individual observations (every 2 minutes) throughout cooking periods, with regression by measurable cooking characteristics, was our attempt at a 'best estimate'.

The reviewer also makes interesting observations on the subject of behavioural practices relating to cooking/fuel burning. We selected – on the basis of preliminary observations in the village – the most measurable and likely important characteristics for inclusion in the regression analysis, as mentioned in the discussion. Sadly, individual small-scale actions such as blowing the fire could not be captured in this way, although these were likely to increase individual exposures. Maize cobs and stalks were not burned during the period of observation (this tends to happen mainly during a time-bound period after the harvest) and plastic and other substances were occasionally added to a fire, sometimes to help with lighting, or for disposal, but usually not as a main fuel source. Although there was little active drying of wood fuel, we would have ideally measured the dampness of wood as this can be an important factor. This measurement was outside the scope of our study, however. Factors such as extended cooking times and continuation of stove burning for heat after cooking were implicitly included in our measurements as we categorised all 2-minute observations as 'cooking' or 'non-cooking' (with cooking periods extending to the point at which the fire was extinguished). In relation to the use of lighting, fires were rarely – if ever – used solely for lighting in this setting (although undoubtedly the evening cooking fire also provided light). This has now been clarified in the 'settings' section.

Regarding the use of CO as a proxy for PM2.5, this was seen more commonly in the past, but is reducing in frequency due to the increasing scientific consensus critiquing its validity for use in this capacity, as well as the rise of smaller, more convenient PM2.5 monitors, such as those employed in our study. Thus our findings both added to the literature on the relationship between these two outcomes (in particular finding differences in the strength of correlation by the presence of absence of specific cooking activity in the near vicinity) and provided early evidence of the feasibility of use of these newer portable PM2.5 monitors for conducting personal monitoring. This has been clarified in the text, with references as appropriate.

We thank the reviewer for noting the issue of seasonal variation in cooking and other practices. Our extended ethnographic work revealed that, whilst diet and main cooking practices in the village varied little throughout the year, there were small differences such as the use of maize cobs/stalks as fuel around harvest time and roasting of a little maize on charcoal for eating around this time also. There was also likely to be seasonal variation in the dampness of wood fuel, depending on the season. These are all elements of 'seasonal differences' noted briefly but not discussed in detail in the discussion, due to limitations in space. Further work on these factors would be valuable.

Finally, we have added the main language used, correctly identified by the reviewer as

Chichewa, into the text. Related issues of language are discussed in more detail in the main ethnographic paper.

Competing Interests: None.