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ORIGINAL ARTICLE

Using mixed methods and community participation to explore household and ambient air pollution practices in a rural community in Malawi

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Abstract

Aim Globally, household and ambient air pollution (HAAP) accounts for almost 7 million premature deaths each year. Over half of these are from incomplete biomass fuel combustion in open fires and inefficient cookstoves. Solutions to the problem remain challenging due to cost, people's perception of pollution and unsuitability to meet user needs.

Subject and methods We used mixed methods and participatory approaches to measure and understand practices and beliefs relating to HAAP in a low-resource community in Malawi. Eighty-six households were randomly sampled for the survey, fine particulate matter ($PM_{2.5}$) levels were measured in 46 kitchens and four ambient locations, and 38 households were engaged during participatory transect walks. We analysed the data using descriptive and thematic analysis.

Results Kitchen $PM_{2.5}$ levels far exceeded the World Health Organization's recommended safe levels. Open-burning practices further contributed to ambient air pollution in the community. While there was high awareness of smoke in cooking areas, participants did not associate it with adverse health outcomes. Availability and affordability of cleaner alternatives influenced household energy choices. Integrating participatory methods alongside quantitative data allowed an in-depth understanding of the community's practices and relationship with HAAP.

Conclusion The findings demonstrate that energy poverty is a key factor in access to clean energy sources and highlight the importance of engaging communities to design HAAP interventions that meet their physical, socioeconomic and cultural needs.

Keywords Indoor air pollution · Ambient air pollution · CBPR · Energy poverty · Health intervention · Participatory transect walk

Background and rationale

Exposure to household and ambient air pollution (HAAP) causes millions of premature deaths globally from pollutants every year, including fine particulate matter ($PM_{2.5}$), carbon monoxide (CO), nitrogen oxides (NOx), black carbon and methane (CH_4) (World Health Organization 2021, World Health Organization 2022). Exposure has been linked to several diseases, including heart disease, stroke, lung cancer and adverse pregnancy outcomes (Amegah et al. 2012). Communities in rural and low-resource areas, especially in sub-Saharan Africa (sSA), are at the greatest disadvantage from practices such as open burning of household and agricultural waste and use of polluting fuels such as firewood, dung and charcoal, typically with open fires or inefficient, traditional cookstoves. This issue is compounded by a lack of efficient waste disposal options and limited access (availability and affordability) to cleaner energy sources and efficient cooking technologies in poor rural communities (Hoornweg and Bhada-Tata 2012, World Health Organization 2021).

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Malawi is a landlocked country in south-eastern Africa, with a population of 19.1 million; of which 80% live in rural areas, and 73% live in poverty earning ≤ $1.90/day. Less than 7% are connected to the national electric grid and rely on charcoal and firewood for household needs. This high reliance contributes to household air pollution (HAP) as the leading risk factor for respiratory illness and the leading cause of pneumonia-related deaths in children under five years (Lazzerini et al. 2016, Government of Malawi 2018). In addition, Malawi's shared death (11.49%) from any cause attributed to HAP (from burning solid fuels) is higher than the average rate for the World Health Organization (WHO) African region (8.91%) and the rest of the world (4.10%) (Institute for Health Metrics and Evaluation 2019). These figures reflect the magnitude of air pollution-related health impacts and the need for sustained health and environmental interventions.

The Malawi National Charcoal Strategy (2017–2027) seeks to reduce reliance on firewood and charcoal consumption and promote affordable, safe, reliable and fuel-efficient technologies such as improved cookstoves (ICS) (Republic of Malawi 2018). However, these improved stoves often produce pollution levels that are significantly higher than WHO safe indoor air quality interim targets (World Health Organization 2023), albeit lower than levels produced by the existing three-stone fire (3SF) used in most rural and low-socio-economic households (Pope et al. 2017, Kumar et al. 2021). Similarly, the widespread adoption of cleaner fuel and efficient cooking technologies continues to be hampered by various barriers (Stanistreet et al. 2014, Puzzolo et al. 2016, Agbokey et al. 2019, Pye et al. 2020), including the tendency for project-led, top-down interventions that are not situated in the social fabric of the community (Sovacool et al. 2015, Adane et al. 2020) and lack the users' voices in the design of the intervention (Phillip et al. 2023). Sesan (Sesan 2014) articulates this as a 'movement without attention to the lived experiences and the engagement of local communities with technologies and interventions, designed and driven by the constant shifting of the global north agenda'. Arnstein's ladder of citizen participation (Arnstein 1969), depicts this as 'informing' – a degree of 'tokenism' where expert knowledge is shared with the community without enabling them to engage in genuine participation. On the other hand, enabling communities allows them to engage actively and co-create knowledge of health issues and feasible solutions (Panter-Brick et al. 2006).

Therefore, using a mixed-methods, participatory approach, this study measures and explores households' beliefs, attitudes and interactions with energy and air pollution in a rural village in Malawi. We aimed to understand existing practices to inform potential HAAP solutions that could be co-created and designed with the community to promote behaviour change and reduce air pollution levels in the community.

Methods

This study was part of The Smokeless Village Project (TSVP), which sought to co-identify and implement a suite of feasible, affordable, efficient and sustainable interventions to reduce emissions and exposure to household and outdoor pollution. This paper reports the project's baseline data using three data sources: a household survey, kitchen and ambient $PM_{2.5}$ monitoring, and participatory transect walks (PTWs) to understand the practices and beliefs around household and ambient air pollution.

Study location and population

The study site was selected through an engaged-consultative process with members of the Chiradzulu district assembly using the following pre-determined criteria established by the project team.

- Close to Chiradzulu Boma and easily accessible by car all year round.
- Geographically bounded by physical features such as mountains and rivers for ease of identification.
- Community should have a minimum of 100 households.
- Households should predominantly use biomass (firewood) for cooking with limited or no access to electricity or other clean energy sources.

The engaged process involved the district health officer, district environmental officer, assistant district environmental health officer, village gatekeepers, and a non-resident community health surveillance assistant. The goal was to discuss the project's objectives and jointly decide with community leaders if they suited the community's needs. We complemented this with an online introduction to the Ireland-based research team via Microsoft Teams and a presentation of the project's aims to the community and the district policymakers to begin a process of familiarity and trust-building. Malawi researcher, VJ, facilitated the gatekeepers' activities.

Nsungwi village is in Chiradzulu district, about 38 km outside Blantyre city in southern Malawi. The community is accessible all year by road. However, the last 3 km of clay-soil road to the village is slippery and requires caution during the rainy season. The village is governed under the traditional leadership of a chief and his six advisors (five men and one woman). At first contact with the community and without current official population statistics, the health surveillance assistant estimated the population at about 515 people (male = 221; female = 294) in 120 households. Our first transect walk took a defined path across the village with the community leaders to explore and map the structures, resources and other project-related issues (Keller 2020). The village is bounded by hills, and two intersecting roads divide it into four quadrants (Q1, Q2, Q3, Q4) that are used as geographical references throughout the project (Fig. 1). The community is a dispersed subsistence farming settlement with self-built houses constructed with locally produced fired earth bricks. Most roofs are thatched with grass, with a layer of polythene underneath; only a few are made of aluminium. Most compounds have fruit trees, such as mango, avocado pear, sugar plum (Masuku) and blue gum woodlots. The depiction of fire smoke from most of the houses and farmlands in Fig. 1 attest to the possible high level of HAAP in the community. Farmlands are often divided and gifted by parents to the children at marriage. The community is not connected to the national electricity grid and relies on solid biomass fuel for daily energy needs.

Household listing

A household census was carried out in September 2021 by two researchers (EP, VJ) and two trained data collectors with the support and guidance of three village members and the community health surveillance assistant. A total of 179 households (sampling frame) were identified. Census data included geographical location (GPS, sequential numbering), separate kitchens, presence of children under five years old and pregnant women in the households.

Ethical considerations, informed consent and cultural appropriateness

The study was reviewed and approved by the College of Medicine Research Ethics Committee (COMREC) in Malawi (P.03/21/3279) and the Research Ethics Committee, Royal College of Surgeons in Ireland, University of Medicine and Health Sciences (212558360). The village chief and leaders assented to us engaging with the community. This was followed by a total village meeting where we explained and discussed the project's aim, participatory approach, data collection methods and tools, including photography, video and audio recordings. We emphasised that individuals could opt out by informing the research team and/or community leaders. Signed or thumbprint consent was obtained from participants after reading the information leaflet aloud in the Chichewa language to the respondents. Interactions were all with adults (18+). Where children were involved in sightings of HAAP activities during our transect walks, the household heads or adults (mainly mothers) were engaged in the conversations.

In the rare instances where a participant appeared confused or unsettled, we halted the process and asked the guide to determine the cause (Biros 2018) and address any issues as they arose. These instances were due to unclear questioning (lost in translation) and expression difficulties and were resolved by rephrasing the questions. We engaged community guides chosen daily by the community leaders as translators and for fieldwork support.

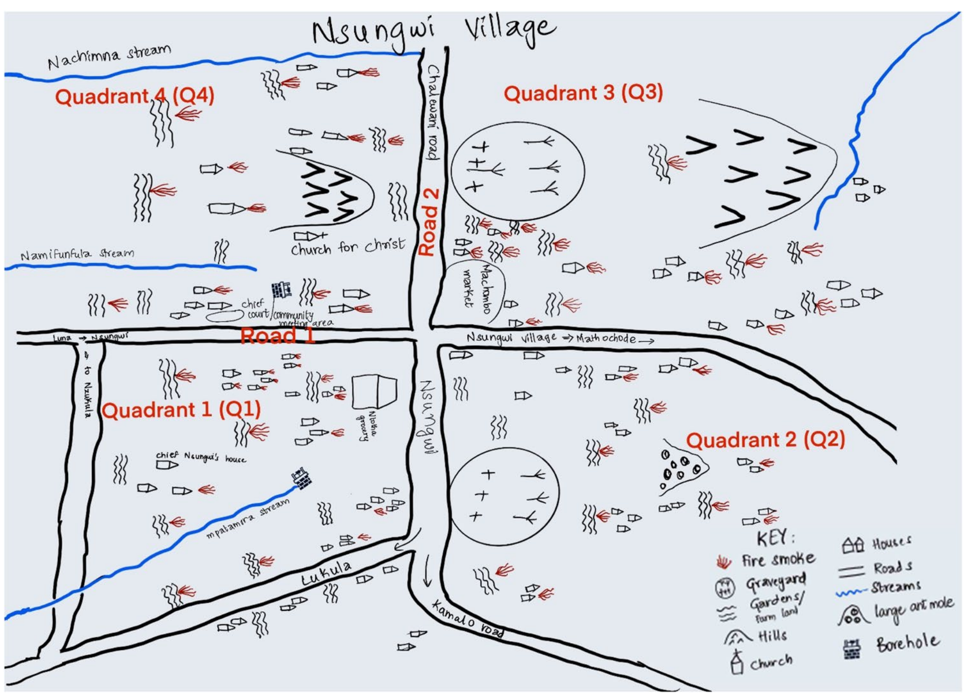

Fig. 1 Community mapping of Nsungwi village layout: Jointly drawn by community leaders and the research team during the first transect walk. It shows the two major intersecting roads which divide the community into four quadrants used for geographical sampling. **Description of Map key**: Fire_Smoke: Presence of smoke where drawn on houses, or active fire or smoke from farm lands and household gardens; Graveyards: Community burial sites with trees; Hills: These are very steep hills; Borehole: Community access to portable drinkable water source; Streams: another source of water mostly during the rainy season and limited water access during dry seasons

Personal data were excluded from analysis and kept confidential, with access only by core team members.

Household survey

The baseline survey was adapted from a previous survey of a field-based cross-sectional study in South-West Cameroon (Pope et al. 2018). The adapted survey included questions from the Malawi 2016 Demographic Health Survey (National Statistical Office 2017) on household waste management and ventilation and free-text to record kitchen observations (Online Resource 1).

The team held several meetings with social research experts to modify and review the questionnaire to suit the Malawi setting, including tailoring cooking questions to staple foods, cooking practices and seasonal-related issues. The updated version was translated verbatim into the Chichewa language by VJ. The English and Chichewa versions were piloted in four households in a similar village about 3 km from the study site to ensure face and content validity (Srinivasan and Lohith 2017). Questions deemed challenging and/or unclear by the team and respondents were discussed and revised by the research team. The agreed final version was re-uploaded onto computer-assisted personal interviewing technology (CAPI) (Baker 1992) on the KOBO open data kit platform – a free, open-source tool for primary field data collection which synchronises and safeguards against data loss (Kobotoolbox 2022).

Sample size was calculated using the Stata - power 'pairedmeans' - command. A sample size of 84 paired observations gives a 95% power to detect a difference of 0.4 standard deviations between baseline and follow up. Such a difference would mean, in the case of normally distributed data, that roughly two-thirds of households had reduced values and a third had increased. Given the far-from-normal distribution of the actual data, this is best thought of as a practical illustration of the size of the effect detectable by the study. The actual sample size was somewhat higher to allow for data loss.

Ninety-one households were randomly selected using the statistical software R (R Core Team 2021) with probability proportion sampling to balance the sample across the four quadrants (Online Resource 2). Only the selected households were invited to participate in the survey. The rationale was communicated to the entire community to facilitate trust and openness. Three data collectors carried out the interviewer-administered questionnaire in Chichewa language from October to November 2021. This is the dry season when farmlands are cleared and farm waste burned, in preparation for the next planting season. Respondents were either the primary cook or the head of the household. Information was sought on economic and demographic data of the household, fuel use, cooking practices and self-reported health outcomes related to air quality.

Kitchen and ambient $PM_{2.5}$ measurements

The selection of households for $PM_{2.5}$ monitoring was informed by the answers to the survey question 'Do you have a separate kitchen?'. Houses with such structures were deemed eligible for inclusion in kitchen $PM_{2.5}$ measurements and stratified random sampling was used to identify the 50% of households selected for monitoring. EP and one trained community member measured $PM_{2.5}$ levels in 41 kitchen structures from October to November 2021 (Online Resource 3). A repeat measurement was done in a subset (n = 20) in March 2022 (rainy season). We recorded 24-h kitchen $PM_{2.5}$ levels at one-minute intervals, with the University of California Berkeley Particle and Temperature Sensor (PATS+) monitors (Pillarisetti et al. 2017) have been successfully deployed in several field studies. Monitors were placed at least one metre away from the three-stone fire to keep moisture away and prevent accidental knocking down, and about 1.2 m above the ground, the breathing height of a standing woman.

We interviewed the primary cooks after each monitoring period on cooking-related activities in the past 24 h. This included the type of food cooked, number of people cooked for, when, type of fuel used and fuel collection time. Observed kitchen characteristics such as holes in the wall, roof gaps, lack of a roof, and the presence of a physical door were captured to inform data interpretation.

Ambient $PM_{2.5}$ quality was monitored for 48 h in the four village quadrants. The PATS+ monitors were placed at a height of approximately 3-4 m off the ground in areas of contrasting population density. They were protected from rain and elements in a box co-designed by a community carpenter and a community leader.

Participatory transect walks

Accompanied by village guides and leaders, EP, a doctoral scholar of Nigerian background with an Irish institution and RC, an experienced social researcher of Irish background conducted PTWs throughout the village for two weeks in November 2021 (dry season) and three weeks in March 2022 (wet season). The aim was to understand HAAP-related attitudes, practices, and the underlying seasonal variations of measured household $PM_{2.5}$ patterns in the community. PTWs have been found effective in health intervention projects such as water sanitation, and hygiene to provide opportunities to observe the community's interactions with health issues and highlight how context and surroundings influenced their views and accounts (Mulopo et al. 2020).

The walks were structured to provide opportunities to observe cooking and other HAAP-related activities and behaviours across the length and breadth of the village. We used conversational prompts to informally ask questions to members of the community we came across during the walks (Online Resource 4). The walks took place during both mealtimes and non-mealtimes to enhance our chances of observing cooking and non-cooking HAAP-related activities such as open-burning and roasting corn for snacks. Participants' accounts were captured using fieldnotes and audio-visual recordings.

We spent considerable time engaging in the community's non-research-related activities to enhance familiarity with the community, build rapport and foster trust. This included alphabet recitals with children, traditional dancing, active listening, support of health-related matters, and economic support by buying some of our food supplies at the community market. In some of the observations of cooking 'nsima', a community and Malawi staple dish of stiff white maize porridge which requires continuous stirring in close proximity to the fire, EP participated in stirring the food to ascertain the heat/fire intensity and risk of burns.

Data analysis

The household survey and $PM_{2.5}$ data were analysed using Stata/SE version 17 software (StataCorp TX, USA). Descriptive statistics are presented with associated confidence intervals. Regression models use ordered logistic regression with robust standard errors. The $PM_{2.5}$ trace and spikes were mapped against the community mealtimes to support existing knowledge of higher levels of exposure at meal preparation time and its related health impact on primary cooks (Smith et al. 2014). The comprehensive baseline household survey and air monitoring data will be published separately with the post-intervention data. PTWs data were transcribed and analysed in Office 365 Excel® using a thematic analysis approach (Braun and Clarke 2006). Participants' data was inductively coded and assigned to categories that explore and describe the observed HAAP-related activities.

Results

This study reports on the household survey, $PM_{2.5}$ monitoring and participatory transect walk data.

Household survey

Survey responses are presented in Table 1.

Table 1 Demographic characteristics of respondents and households surveyed (N = 86)

Characteristics of respondent	n	%
Age (mean/SD) (years)	37.5 (13)	
Sex		
Women	77	90%
Men	9	10%
Marital status		
Married	52	61%
Separated	19	22%
Widowed	8	9%
Divorced	4	5%
Single mother	2	2%
Cohabiting	1	1%
Education		
None	8	9%
Primary	54	63%
Secondary	24	28%
Household composition		
Number of rooms (Mean/SD)	3.0	(1.2)
Number living in household		
0-2	14	16%
3-5	56	65%
6-8	16	19%
Children under 5 years old		
Yes	42	49%
No	44	51%
Household Income Kwacha (USD)/month		
≤25,000 (24.5)	74	86%
26,000–50,000 (25.5–48.6)	10	12%
>51,000 (49.6)	2	2%
Home Ownership		
Homeowner	71	83%
Lives with relation(s)	14	16%
Renting	1	1%
Cook only in a separate kitchen		
Yes	20	23%
No	66	77%
Cooking cookstove		
Traditional three-stone fire	66	77%
Manufactured stove	20	23%
Type: • Chitetezo Mbaula	2	10%
• Charcoal burner	18	90%
Heating cookstove		
Traditional three-stone fire Charcoal	36	67%
Manufactured stove	18	33%
Type: ▪Chitetezo Mbaula	1	6%
▪Charcoal burner	15	88%
▪Other	1	6%
Cooking fuel (primary wet season) (N = 85)		
Wood	66	78%
Charcoal	17	20%
Crop residue	1	1%
Garbage/plastic	1	1%

Table 1 (continued)

Characteristics of respondent	n	%
Cooking fuel (primary dry season) (N = 85)		
Wood	39	46%
Charcoal	31	37%
Crop residue	9	11%
Garbage/plastic	5	6%

Demographics

The participation rate was 94.5% in the 91 households sampled. There were no participation refusals; however, we excluded one household because of health status (Biros 2018) and four households were classified as 'not contactable' after three visit attempts. The mean age of the respondents was 38 years (SD = 13). Most respondents were women (77, 90%), and almost half of the households had at least one child under five years old. Inter-generational sharing of housing and/or kitchens is also common in this community, with the majority of respondents living in a house they owned (71, 83%), with all but one of the remainders living in a house belonging to their family or a relative. Only four of the 39 respondents who moved into a house less than two years before the survey were from outside the community.

Typically, most (85%) houses have two to four rooms, excluding any room or space used as a kitchen. However, two of the two-roomed households reported seven to eight people residing in them. Excluding the kitchen, built as a separate outbuilding, there were eight single-room houses (9%). A quarter of the houses sampled had no separate kitchen structure, and all but one of these households cooked outdoors.

In most households, the head of the house, generally the husband, had several sources of livelihood, but most household heads either farmed their land, worked as farm labourers, or both. Eight households were headed by people who were not farmers, of which six were employed or self-employed. Despite multiple sources of livelihood, monthly income remained below the international poverty line (1.90 USD/day) in over 97% of the households, and only six households had monthly income ≥35,000 Kwacha ~34.2 USD per month – the Malawi minimum wage.

Women had lower educational attainment than men, with a median of 6 years of education, compared to 9 years. The difference is not only statistically significant (P = 0.014, Wilcoxon Mann–Whitney test) but also influences the learning of the English language (the official language in Malawi), since teaching of English only begins in 'standard five' in Malawi's education system. We related our result to the higher dropout rate in girls compared to boys between standard five and eight due to poverty and early pregnancy (Gondwe 2016) .

Fuel used for Household heating and lighting

Heating fuel was not used in 95% (82) of households. Where households were heated, charcoal was the fuel of choice. Only a slight variation with season was noted, with five households heating their homes during the wet season, compared to one household during the dry season. Sixty-six of the 86 households used a battery-powered flashlight, torch or lantern. Among other lighting sources, biomass was relied upon in only one home and candles in seven others.

Household cookstove

The primary cookstove used was a three-stone fire (3SF) in 75% of the houses. However, of the 20 that had manufactured stoves, i.e. chitetezo mbaula (2) and charcoal burners (18), they were used in addition to the 3SF. Similarly, of the 54 households using cookstoves for heating, 67% used a three-stone fire instead of manufactured cookstoves.

Household cooking fuel use

Wood was cited as the primary fuel for cooking in 80 of 86 houses. The remainder of the houses cited charcoal (5) and crop residue (1). Wood was also the most used fuel in 66 and 79 households during the wet and dry seasons, respectively. The use of charcoal as the primary cooking fuel increased from three households in the dry season to 17 houses in the wet season. Other fuel sources, including crop residues, garbage and plastic, were used less during the wet season (Table 1). Fifty-eight households (67.4%) did not pay for fuel and relied solely on fuel gathering. The fuel-gathering task mainly fell to girls and women in 53 of these households. The purchasing of fuel in households (n = 28, 32.56%) saw a mean expenditure at the last purchase of 2.08 USD (SD 4.88; min 0.1, max 26.34) over 7–14 days.

Household cooking

Women are usually the main cooks in the household (88%). Nsima was cooked in all households and daily by almost 90% of households. Fish was less often cooked, but 44% of households had fish on one or two days a week, and a further 30% had it three days a week. While fish are an important dietary constituent, the dried fish are of two small varieties, one about 10 cm and the other sprat sized (10–13cm). On the other hand, meat was not eaten at all by 45% of households and eaten only once a week by a further 45%. Rice was similar, with 45% of households not eating it and a further 40% eating it only once a week; 70% of households ate cassava one, two or three days a week, but only four households ate it more often. Half of the households had beans once a week, with a further quarter having them twice. The percentage of households eating a given food at least three days a week is highlighted in Fig. 2.

Estimates of cooking times varied widely, with improbably low cooking times for foods such as beans, cassava, rice and nsima reported (Fig. 3). Post kitchen $PM_{2.5}$ household interview data was more consistent; typically, it takes half an hour to cook nsima and rice, with cassava cooking quicker. Beans take considerably longer, a median of two and a half hours. However, beans were eaten in fewer households per week compared to nsima, fish and cassava, as in Fig. 2.

Household waste management

Fifty-three of the 64 households who burned household waste also said they buried some of it outside. Only three of the 70 households who reported burying their waste used compost as manure. Throwing out to the street was only reported in 5.8% (n = 86) households.

Burns injury

Forty-two respondents reported incidence of burns or scalds in the household in the past 12 months. In most cases, this was from an open flame (69%) and scalds from pots tilting (19%). Other sources included accidental touching of a hot surface and scalding from porridge.

Ambient and kitchen $PM_{2.5}$ monitoring

The ambient $PM_{2.5}$ average level in the four measured quadrants ranged from 1.2 to 44.5 mg/m^3. The lowest level was consistent with the expectation of a sparsely populated area. The highest mean level of 44.5 mg/m^3 in Q3 was in a less densely populated area compared to Q1 (9.5 mg/m^3) and Q2 (11.1. mg/m^3).

Of the 45 kitchens monitored for $PM_{2.5}$, 44.4% (20) were completed in households with children ≤ 5 years old, and three had no physical roof. All recorded $PM_{2.5}$ levels were many times higher than the WHO's 24-h safe indoor levels for $PM_{2.5}$ (World Health Organization 2023) The $PM_{2.5}$ 24-h moving log and the corresponding stove use spikes in two houses are shown in Fig. 4a and b. The spikes in household 32 (Fig. 4a), reflect periods of stove lighting and meal preparation in the morning and midday. It shows the stove being kept lit until it was time to cook the evening meal, after which it was allowed to go out.

Conversely, household 124 shows 'round-the-clock' $PM_{2.5}$ levels of at least 50 mg/m^3 (Fig. 4b). Although the spike in both houses corresponds to meal cooking time in Malawi, there were vast differences in diurnal variation in $PM_{2.5}$ levels among households in the community. The cooking-related activities of these households were explored during transect walks to understand these variations.

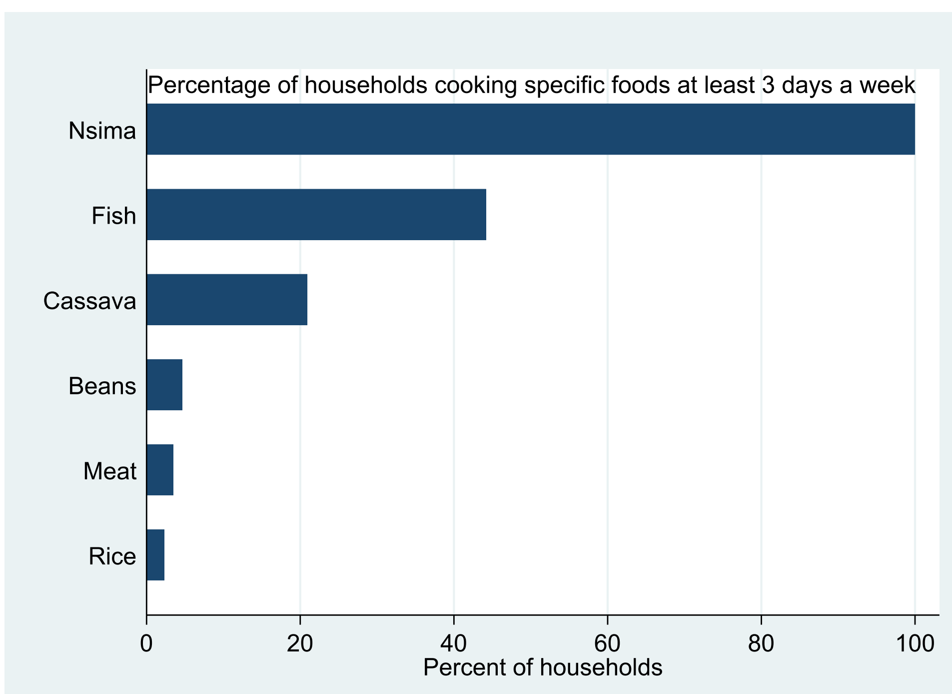

Fig. 2 Food cooked – the percentage households cooking these specific foods at least three days a week

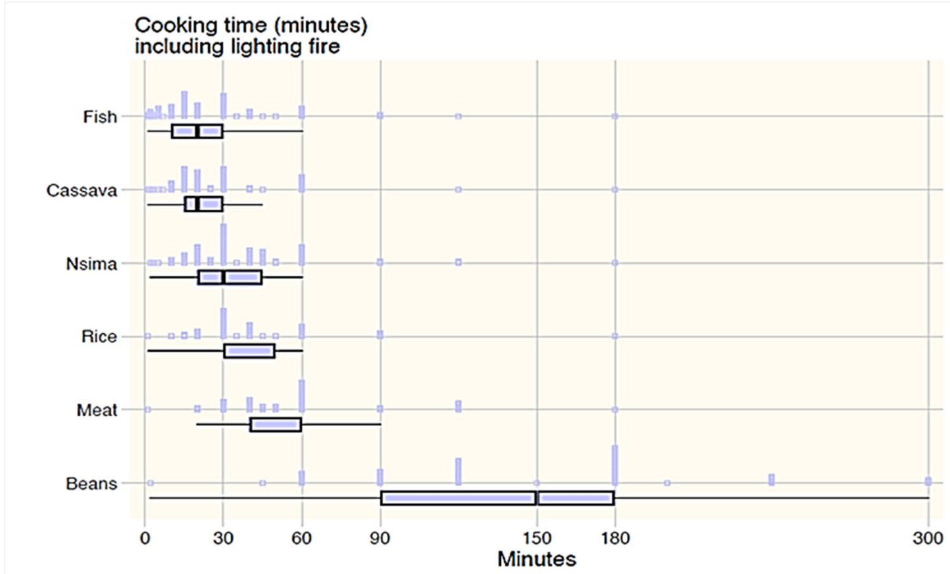

Fig. 3 Estimates of cooking time (minutes), including lighting fire, by food cooked in households

Participatory transect walks

Thirty-four households were engaged in conversation during the PTWs. Rather than having a centre, the houses are widely scattered; therefore, in most cases, smoke from one house is likely to dissipate before reaching neighbouring houses (Fig. 5a).

Kitchens in many houses are in small buildings separate from the dwelling house with an open doorway, wall ventilation holes and roof ventilation made by omitting bricks at the top of the gable wall on one or both ends (Fig. 5a). This construction protects the fire from strong winds, but smoke builds up quickly, especially if the wind is blowing from the door side, in which case the only exit for the smoke is at roof level. In all the kitchens observed, there was no window for ventilation, with most citing no means to make one, a concern that household livestock might turn over the stove, and the potential for theft of gathered firewood and goods from kitchens.

Around half of the observed households cooked exclusively inside the kitchen, and a further quarter had a kitchen but also cooked outdoors, most of them daily. The only light source into the kitchen was the doorway and the omitted bricks. Where cooking is done often varies seasonally, with owners of open-roofed kitchens (Fig. 5b) moving their cooking to the veranda or inside the main household during the rainy season. In one observation, a black plastic bag was a makeshift roof cover from the rain. It is noteworthy to mention that fieldwork later in the year saw some loss of kitchen structures to heavy rainfall resulting in an increased number of households cooking outside and some within their living spaces.

Increased levels of observed smoke from kitchens in the community correlated with breakfast, lunch and dinner cooking times at 5:30 AM, 12:30 PM and 6 PM, respectively, as demonstrated in the HAP kitchen level measurements. We observed on a number of occasions that the smoke levels were high enough to force the cook to leave the kitchen (Fig. 5a). All observed households cooked primarily on a 3SF.

Cooking-related practices

Time spent preparing food, a proxy for pollution-exposure time, was dependent on the type of dish and varied among participants even with the same dish. The lowest cooking (10–15) minutes was reported for ‘relish’, a side dish, often of green vegetables such as cabbage and pumpkin leaves in fresh tomatoes. The time to cook beans was longer, at about two hours for fresh beans and three for dried ones. Generally, dried beans are not soaked before cooking. During one of the community meetings, a female community member mentioned that pre-soaking beans ‘removes the taste and the goodness’ (EP fieldnote). Others were not aware of the cooking-time benefit. All participants, however, said they did not spend the whole cooking time in the presence of the fire but only attended as needed to rekindle the flame, add more water or stir the beans.

The limited use of potlids observed throughout the community also affected cooking duration. Reasons for not using pot lids included not having one and not being able to afford one. Most participants mentioned the potlid’s nuance when preparing certain dishes, such as nsima, a staple maize meal cooked daily in most households. Nsima requires stirring with a wooden spatula intermittently initially and

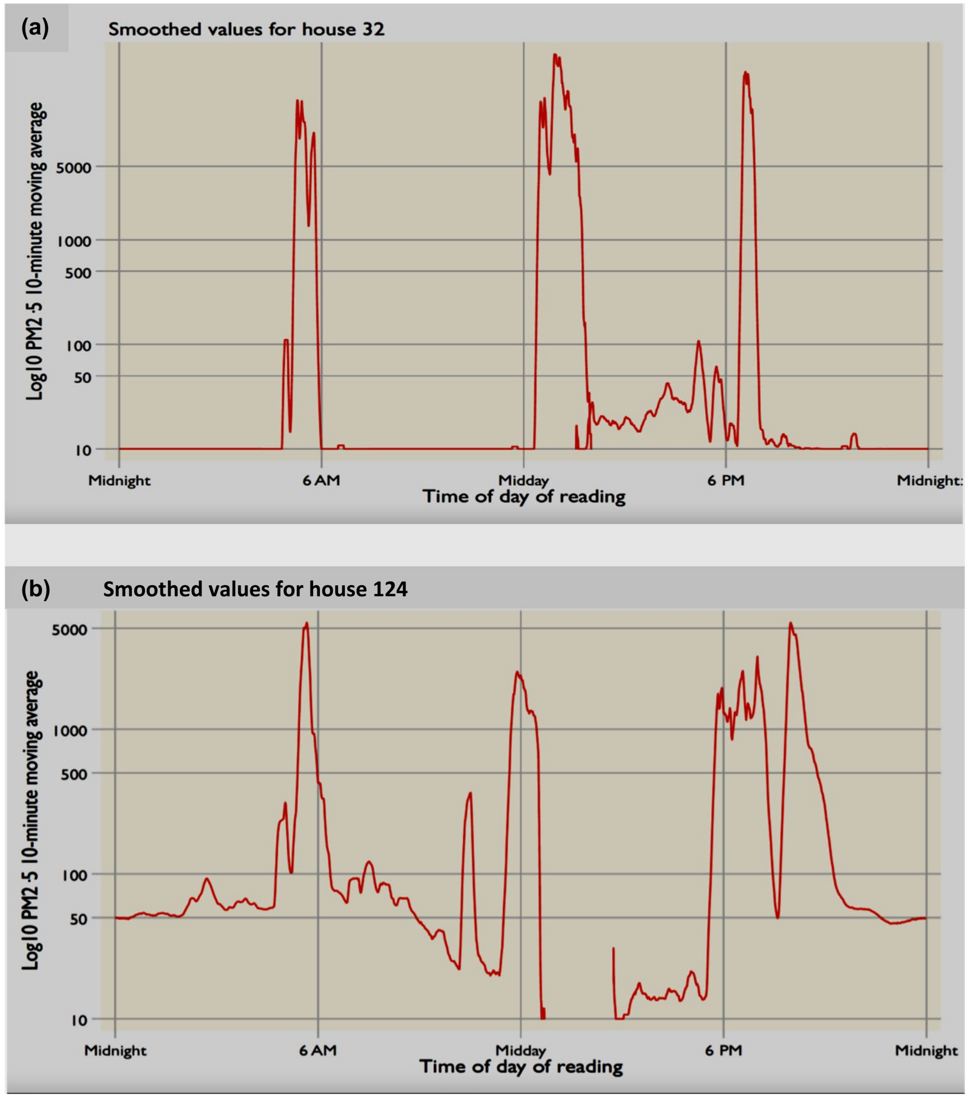

Fig. 4 This is the 24-h smooth $PM_{2.5}$ kitchen levels showing spikes correlating to meal cooking times in two households: (**a**) An indication of extended three-stone fire use between lunch and dinner time; (**b**) An indication of extended three-stone fire use and $PM_{2.5}$ level in the kitchen throughout the night

Fig. 5 Sample of kitchen structures in the village: (**a**) Smoke from a cooking fire started in a separate kitchen. Note the firewood drying on the roof and the smoke vents below the top on the gable wall; (**b**) The kitchen structure shows an open doorway, roofless and omitted bricks

continuously for the final ten minutes as extra maize flour is added to thicken it (Fig. 6) and the risk of food boiling over and dousing the fire when left unattended.

> *I don't have a cover for the pots. You have to buy it… if I have, it would be hard to leave the food alone because you have to make sure that it will not pour out and kill the fire when put on the cover.*
> *(Female participant HH97)*

In household 124, we observed the fermentation process of 'Kachaso', a locally brewed alcohol for sale. According to the participants, the process requires a steady and constant low heat (fire) to keep the kitchen warm to aid fermentation (Fig. 7). This gave credence to the recorded continuous kitchen $PM_{2.5}$ spikes throughout the 24—h measurement in Fig. 4b.

Fig. 6 This shows a woman cooking nsima on a three-stone fire in an enclosed kitchen with minimal light source and shows the unsuitability of potlids with the continuous need to stir in more maize flour

Household heating practices

The use of the 3SF for heating was mentioned by most participants as a practice in the wet season when people gather early in the morning to warm up from the remaining heat following cooking and boiling water. The 3SF is not lit specifically for heating purposes.

Only two households were actively using charcoal stoves, both in living areas. Subsequent discussions revealed the assumption that charcoal use was safer indoors than wood because it produces little smoke and does not have a strong 'smell' compared to firewood. After cooking on the veranda, the lighted charcoal stove was often moved inside as a heating source. In the other instance, heated 'char' (small charcoal pieces) from the 3SF is gathered on aluminium plates for home heating.

> *[we] take small charcoal pieces from the fire we used to cook dinner in this [shows flat aluminium plate], and we take it inside to make it warm for the small children.*
> *(Female participant HH67).*

In all instances, we explained the characteristics and risk of carbon monoxide poisoning from burning charcoal inside, which was accepted after some discussions, despite some participants initially being sceptical.

Household lighting practices

One household reported using a solar home system in the survey to generate electricity, but we found none during our field observations. In contrast, solar panels (A5 notebook size) were seen charging outside a handful of houses, headed

Fig. 7 Continuous slow-lit fire in the fermentation and distilling of 'Kachaso' – a local alcohol brew. This clarifies the overnight kitchen $PM_{2.5}$ levels observed in Fig. 5b (household 124)

mostly by young people or bachelors to power radios or, in some cases, to charge mobile phones.

Of great significance to health is the grass bundle residues used for lighting inside two households with children under five years of age. Conversations with both mothers suggested replacing the batteries in lamps or buying candles that 'melt so fast' was too expensive.

We priced three AA-size batteries at the village store at 60 cents. These last about three to seven days, depending on family size and frequency of use. According to participants, used batteries are often disposed of in the field, with household waste, in latrine holes, or used as toys by children. Although we did not observe children playing with alkaline batteries, the danger of exposure to toxic heavy metals such as mercury cannot be overlooked and further supports the associated health risk of limited access to clean energy.

Access to fuel

Crop residues, mostly 'nandolo' (Pigeon peas) stalk, maize cobs and blue-gum stalk, gathered from farm clearing and produce, were seen being burned as fuel with the 3SF. Other biomass fuel use included branches from fruit trees within the compound, wood from the 'community forest' and felled trees in the community. Although the survey reported 28 (33%) households paying for fuel, no participants reported paying for firewood during the observation period.

Gathering fuel for drying before use was rarely observed in the community. Most households gathered wood daily due to scarcity and control of firewood gathering in the forest, which the community leaders reported as a forest conservation and climate impact measure. When gathered, excess fuel is sometimes stored in the kitchen for safe keeping, on rooftops, and in a makeshift drying shed in one household. Drying fuel for household use was further limited during the rainy season (March), resulting in increased use of wet wood. While participants were aware of the associated smoke increase, alternatives were limited due to the (i) risk of theft when drying outside, (ii) arduous task of bringing them in when it rains and (iii) inability to gather more at a time due to old age.

> *We can only carry little when we go and gather. You know we are old now (laughs). We use whatever we have.*
> *(Male participant HH 62).*

Fuel-stacking, the concurrent use of more than one fuel type (Pye et al. 2020), was not observed but most participants mentioned using more than one fuel type when cooking.

Waste disposal and ambient air pollution

Compared to household waste, open burning of farm/crop waste contributed more to ambient air pollution (Fig. 8a). It was more common during the dry season when farmlands were cleared for the next planting season. Farmers saw this as a more efficient practice than clearing a large volume of crop waste, rationalising the wind effect in dispersing the smoke.

Other notable contributions to ambient air pollution were practices related to the firing of bricks needed to build houses and charcoal production for sale or household use (Fig. 8b). Higher levels of brick firing and charcoal making observed in quadrant 3 would explain why this area had the highest mean $PM_{2.5}$ of all ambient levels measured in the village.

Burns injury

In relation to exposure to pollution and proximity to the fire, we observed only two episodes of children under five being in the vicinity of active cooking. With a newborn cradled on one arm, one of the mothers attending to cooking pigeon peas outside, explained the practice as a one-off occurrence because the child needed attention with no one around to assist. The other mother (not the cook) did not consider it an issue, sitting with her newborn twins in the direct path of smoke from the kitchen.

There were, however, more occurrences of older children roasting corn on the 3SF and burning household waste without supervision. In one instance, where an adult was within a short distance, he explained that it was common for children in the village to roast leftover corn for snacks and suggested it was an enjoyable and not an unusual activity in the community.

Throughout the PTWs, an 8-year-old boy with a recent burn to the lower torso from playing with melting plastic constituted our only observed burn case.

Other safety-related practices and burn risks included crouching and blowing air by mouth into the fire at close proximity, to ignite or rekindle the flame. Most participants saw this practice as the norm. In cases where participants accommodated us by fanning the smoke with a plate, it was accompanied by laughter. It is also fair to say the fanning with the plate was less effective than the blowing, which could explain the laughter as what participants likely 'considered a ludicrous idea to suggest fanning with a plate' (EP-reflective note).

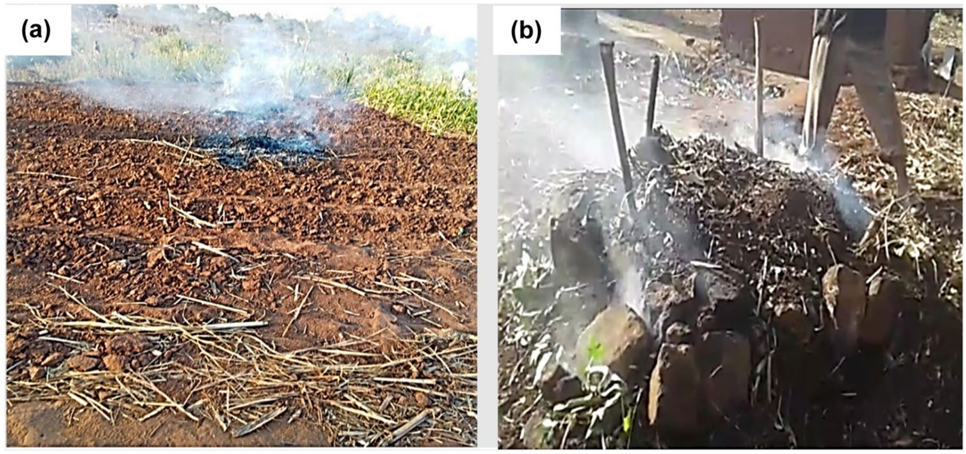

Fig. 8 Display of sources of ambient air pollution: (**a**) Burning of crop waste on farmland; (**b**) process of incomplete combustion of firewood to make charcoal

Discussion

This study proposed using a mixed-methods participatory approach, to measure and explore households' beliefs, attitudes and interactions with air pollution and identify potential solutions that could be co-created to reduce air pollution in a rural village in Malawi. The following section outlines what was learned in relation to the level of smoke, household design, cooking practices and fuel choices.

Levels of household air pollution and community awareness of health implications

Household air pollution levels in the community were far higher than WHO air quality guidelines (International Energy Agency 2017), in line with the findings of similar previous studies (Jary et al. 2014, Wathore et al. 2017). However, while the community was aware of the air pollution problem (often called 'utsi'(smoke)), it was primarily associated with teary eyes and coughing. It was not linked to serious ill health, such as high blood pressure, stroke and pregnancy-related outcomes. This is similar to the participants' perceptions described by Tamire et al.'s (Tamire et al. 2018) of the awareness of only minor discomfort of smoke and further support enhanced knowledge of health impact as a facilitator to behaviour change and adoption of air pollution interventions (Rehfuess et al. 2014).

Kitchen structure

Community members prefer to build a separate brick kitchen to protect the stove from high winds and reduce spark and associated risk of burns. Small, poorly-ventilated kitchens increase smoke exposure, particularly as most cooks' face away from the doorway, the primary source of air exchange. A significant barrier to improving ventilation was limited household economic resources to add structures such as windows. The expressed concern about livestock eating the limited food supply, and the increased chance of gathered wood and limited food supplies being stolen, highlighted other underlying factors at play with improving ventilation. These concerns are broadly consistent with earlier study findings in rural Ethiopia (Tamire et al. 2018) and add to Saleh et al.'s report of households' preference to cook in an enclosed kitchen because it provides privacy when cooking, as women preferred that their scarcity of food supplies were not on display to other households (Saleh et al. 2021).

Cooking practices and exposure levels

Our findings showed variations in the cooking time (used as a proxy for personal exposure) from the household survey compared to the participant observation reports. For example, the cooking time for beans is 200% longer than for nsima, the daily staple food in the community. However, the length of exposure differs between these two dishes, irrespective of kitchen $PM_{2.5}$ levels, which are generally higher when cooking beans due to prolonged use of the 3SF in a confined space. Concerning personal exposure (the length of time spent near the smoke), exposure levels are likely much lower when cooking beans that do not require constant attention, compared to cooking nsima, which must be stirred intermittently initially, and then continuously for the final ten minutes. This view reflects the findings of Smith and Pillarisetti (Smith and Pillarisetti 2017), who also found that different food preparations requiring constant or intermittent attention, influenced personal exposure levels. In this present study, this relationship between type of food and cooking practice, such as making nsima, are likely to stay the same; therefore, it is vital to engage communities to find feasible ways to reduce daily exposure to pollutants and improve health.

Household energy choices and poverty

Stanistreet et al. (Stanistreet et al. 2019) describe the experience of energy choice as households needing to negotiate between their limited funds for household needs and clean fuel adoption. In addition to high costs, the uneven distribution of cleaner energy first to the urban areas before trickling down to the rural communities (Smith and Pillarisetti 2017) limits available choices to maize and 'nandolo' (beans) stalks, grass, plastic, and other high-polluting fuel sources to meet their daily energy needs.

Further, we found that households' inability to afford 60 cents to replace solar-lamp batteries made lighting the home with grass bundles a necessary but undesirable option. Saleh and colleagues describe these practices as deeply rooted in global inequities that shape communities' experiences with air pollution (Saleh et al. 2021). The interrelated factors of accessibility and affordability situate air pollution practices in economic scarcity and further support Sesan's call to respond to the socio-economic realities of households living on less than $1.90/day when planning clean energy solutions (Sesan 2012).

Behaviour change

It is common in this community for a mother to tie a child to her back while cooking, often for convenience, to multitask and keep the child safe from wandering while the mother is occupied. In this study, though the mothers recognised the need to prevent burns, they had no explicit concerns about reducing smoke exposure to the children. This is consistent with previous studies suggesting a need for more awareness of smoke exposure to facilitate the adoption of cleaner cooking practices (Puzzolo et al. 2016, Pye et al. 2020, Saleh et al. 2021). Raising awareness allows for sharing ideas and co-creating alternatives with the community, enhancing behaviour change (Goodwin et al. 2015). Other opportunities for knowledge exchange around cooking practices include views that pre-soaking beans might reduce their nutrients and 'goodness', using charcoal as a better option because it has less smell than firewood, and using alkaline batteries as toys for children. While sharing these health and behavioural messages, Akintan, Jewitt and Clifford (Akintan et al. 2018) suggest that they should be positioned in the broader context of social beliefs to address the issue and support behaviour change.

These related factors highlight the value of a community's voice in understanding why people do what they do and recognising the different factors at play before planning an intervention project could allow the negotiation of a suite of interventions to meet user needs rather than focusing only on one intervention.

The study's added value to intervention projects

Most studies (Hankey et al. 2015, Coffey et al. 2017, Dickinson et al. 2019) only report quantitative air pollution data with few qualitative insights into extrinsic factors influencing household and ambient air pollution. While quantitative data in our study clarified the extent of air pollution in the community, the participatory transect walks helped to explore air pollution practices and attitudes. It allowed and enhanced the voices of the community members to co-construct the knowledge of air pollution in the community rather than community members as research subjects (Given 2008). Integrating both approaches gave the study a more robust understanding of community perspectives on HAAP previously unknown to the research team. This fed into research team discussions about potential interventions to initiate a participatory decision-making process with the community. For example, PTWs raised the possibility of potlids, and alerted the research team to the concurrent use of more than one three-stone fire in large membered households, suggesting likelihood of stove stacking in these households. Inadequate sizing and design of the improved cookstove could also imply barriers to adoption in households where income is supplemented through brewing alcohol. Equally, the importance of ventilation and kitchen structure in relation to air pollution levels is constrained by cost and community concerns for the safety of belongings. In Table 2, we compiled possible interventions based on our findings that could guide household and ambient air interventions discussions with the community.

Table 2 Potential interventions identified from the study for discussion with the community

Intervention	HAP/health source target.
Kitchen windows	Dissipate smoke from the immediate kitchen environment, lighting the dark kitchen (solutions to theft issues to be discussed)
Improved cookstove	Emission levels, burns/open fire, fuel efficiency, and timesaving (type, cost)
Pot lids	Fuel efficiency, time saving, burns/scalds
Solar lamps	Reduce emission levels, burns/open flame, money saving, reduced the availability and use of batteries as toys
Composting	Reduce open burning and reduce expenditure on fertiliser

Study limitations

Owing to limited time and resources, we did not monitor personal $PM_{2.5}$, which could provide more information on exposure levels based on activity and time spent actively with HAP-related activities. Also, we relied on participants' recall of activities and practices when retrieving the air monitoring equipment. Therefore, we cannot rule out recall bias. Further, with the transect walks, the Hawthorn effect (modification of behaviour in response to being observed) from participants may have impacted community behaviour and increased awareness of the study's objectives. We minimised this by creating rapport with the community and carried out observations over longer and varied periods during the project.

Conclusion

The use of fire for cooking and heating is central to human culture. The cultural values and social roles associated with preparing and consuming food are of value and fundamental importance to a community.

Therefore, we stress the critical role of mixed methods and participatory approaches to contextualising the quantitative survey and air monitoring data in air pollution studies to explore feasible interventions for the community's socio-economic, cultural, energy and health needs. The persistent economic poverty influences community choices and interactions with air pollution, especially in rural areas and supports the importance of interdisciplinary intervention designs which focus on human-energy interactions (Sovacool et al. 2015).

Future research should plan the design, type, accessibility and cost of any proposed air pollution-reducing intervention alongside the community's self-identified needs and priorities. The added advantage to this approach is the opportunity to share knowledge of feasible and effective solutions with the community so that their decision-making process is informed by evidence. This will also require time to be built into project planning and funding to support the implementation of different interventions to reduce household air pollution.

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Availability of data and material Quantitative data analysed during the current study are readily available from the corresponding author. Due to potentially identifiable data, even where deanonymized, qualitative data are available only upon approved individual request. Data collection materials are provided and are available in this manuscript.

Code availability Not applicable.

Declarations

Ethics approval The study was conducted in accordance with the Declaration of Helsinki and approved by the College of Medicine Research Ethics Committee (COMREC) in Malawi (P.03/21/3279) and the Research Ethics Committee, Royal College of Surgeons in Ireland (212558360).

Consent to participate Informed consent was obtained from all participants.

Consent for publication Informed consent for dissemination was obtained from all participants.

Conflict of interest The authors declare no conflict of interest. The funder had no role in the design, collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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