INFORMING EFFECTIVE PUBLIC HEALTH INTERVENTIONS TO REDUCE EXPOSURE HOUSEHOLD AIR POLLUTION IN URBAN RWANDA

by

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Abstract

Cooking with solid biomass fuel is a global public health concern, presenting significant morbidity and mortality due to exposure to household air pollution (HAP). The HAP burden in urban Rwanda is high because of ongoing reliance upon solid biomass usage and rapid population growth.

This thesis aims to inform the future development of effective public health interventions to address HAP in urban Rwanda, using a convergent mixed-methods approach. A systematic review, secondary data analyses of a population-based dataset and primary quantitative (semi-structured survey) and qualitative (in-depth interviews) data collection and analysis have been undertaken. Results of these activities have been interpreted and integrated using the development phase of the Medical Research Council's (MRC) complex intervention framework.

Health risk assessments showed reduced risks of acute respiratory infections for children under five years associated with outdoor compared to indoor biomass fuel cooking, which may inform development of a health behaviour focussed intervention. In addition, biomass fuel use was not protective against risk of malaria infection, of relevance for a health educational intervention. Transition from charcoal to wood fuel (as observed during the COVID-19 pandemic) may be associated with increased risks of acute respiratory infection; of importance for future unintended consequences arising from fuel restriction policies, including a proposed charcoal ban in Rwanda. Qualitative investigation identified that cleaner fuels were the desired cooking fuel of choice, but structural and cultural barriers remain to access, uptake and concerns persist regarding outdoor cooking practices.

The evidence from this thesis has enabled identification of potential health behavioural change interventions to mitigate HAP harms in urban Rwanda. Findings highlight the importance of early user involvement and co-production to ensure cultural suitability and sustained uptake.

Interventions may be supported by appropriate policy initiatives, which must identify and mitigate potential unintended consequences at a policy formulation stage.

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Dedication – To Grandad

Acknowledgments

Thought out my PhD journey my supervisors, Professor Neil Thomas, Dr Suzanne Bartington, Professor Sheila Greenfield and Professor Francis Pope have been an enormous support to guide me on the right path in devising and shaping the thesis, sourcing funding, offering development opportunities and providing valuable comments and suggestions on completed work; for which I am eternally grateful.

I am also very appreciative for the support and dedication of Dr Telesphore Kabera for helping facilitate the research within Rwanda. In addition, I would like to thank the undergraduate students at University of Rwanda College of Science and Technology Aldo Muhizi, Claude Mugabe and Omar Ahishakiye for aiding with data collection during a very challenging time. I am also grateful to Dr Catherine Campbell for her fieldwork advice and collaboration on and allowing use of data she collected in Rwanda prior to the start of my PhD.

The PhD would not have been possible without receiving a University of Birmingham Global Challenges Studentship, funding from All Systems Approach to air pollution (ASAP), and The Institute of Global Innovation (IGI).

Finally, to Conor and my family for always being there, having unwavering support and faith in my ability when I did not.

PREVIOUSLY PUBLISHED AND DISSEMINATED WORK INCLUDED WITHIN THIS THESIS

CHAPTER 3 Methods: Systematic review protocol

The content of this chapter has been published in BMC *Systematic Reviews.*

Woolley, K.E., Dickinson-Craig, E., Bartington, S.E., Oludotun, T., Kirenga, B., Mariga, S.T., Kabera, T., Coombe, A., Pope, F.D., Singh, A. and Avis, W.R., Day, R., Warburton, D., Manaseki-Holland, S., Moore, D.J., Thomas, G.N. (2021). Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low-and middle-income countries: a systematic review protocol. Systematic Reviews, 10(1), pp.1-7. doi: 10.1186/s13643-021-01590-z.

The systematic review protocol was initially initiated by KEW, with subsequent protocol refinement being undertaken by KEW and EDC. Methodological advice was gained from DJM, with a manuscript review from SEB and search strategy support from AC. EDC was in charge of the PROSPERO protocol and KW in charge of manuscript preparation. GNT and SEB provided additional methodological and writing support; with all other authors on the protocol editing and approving the manuscript for publication.

CHAPTER 4 Results: Systematic review: Are interventions effective? Current state of evidence

The result from this chapter have previously been published in *Indoor Air*.

Woolley, K.E., Dickinson-Craig, E., Lawson, H.L., Sheikh, J., Day, R., Pope, F.D., Greenfield, G.M., Bartington, S.E., Warburton, D., Manaseki-Holland, S., Price, M.J., Moore, D.J., Thomas, G.N. (2022). Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low- and middle-income countries: A systematic review and meta-analysis, Indoor Air, 00, pp. 1–32. doi: 10.1111/INA.12958.

The systematic review was initiated and devised by KEW and EJC, with methodological support being provided by DJM and MJP. KEW organised and led the process of searching, screening and data extraction. Screening and data extraction were undertaken by KEW, EJC, JS and HL (UoB Intercalating

Medical students). The analysis and manuscript preparation were undertaken by KEW. Initial review and editing was completed by EJC, with subsequent review and editing being undertaken by all other authors.

CHAPTER 6 Results: Health risk assessment: Biomass fuel type

The results from this chapter have previously been published in *International Journal of Environmental Research and Public Health*.

Woolley, K.E., Bartington, S.E., Kabera, T., Loa, X-Q., Pope., F.D., Greenfield, S.M., Price, M.J., Thomas, G.N. (2021) Comparison of respiratory health impacts associated with wood and charcoal biomass fuels: A population-based analysis of 475,000 children from 30 low- and middle-income countries. International Journal Environmental Research and Public Health. 18(17), pp.9305. doi: 10.3390/ijerph18179305

These results have been disseminated at the following events:

Poster presentation (virtual) at the 2020 *Universitas 21 Health Sciences Group Doctoral Student Forum*, University College Dublin

Oral presentation (virtual) at the *33rd Annual Conference of the International Society for Environmental Epidemiology / ISEE 2021*, New York City, with a theme of Promoting Environmental Health and Equity in a Shifting Climate.

The research was directed by KEW under the supervision from the lead supervisor (GNT) and co-supervisors (SEB, FDP, SMG). KEW was responsible for data management, analysis and manuscript preparation, with supervisors providing project curation support, methodological support and manuscript editors. Additional statistical support was sort from MJP. Contextual information was sought from KT and QL.

CHAPTER 7 Results: Harm mitigation: Cooking location

The results of this chapter have been accepted for publication in *Atmospheric Environment*.

Woolley, K.E., Thomas, G.N., Kirenga, B., Okello, G., Kabera, T., Lao, X.-Q., Pope, F.D., Greenfield, S.M., Price, M.J., Bartington, S.E., on behalf of Global - CLEAR, Association of household cooking location behaviour with acute respiratory infections among children aged under five years; a cross sectional analysis of 30 Sub-Saharan African Demographic and Health Surveys, Atmospheric Environment (2022), doi: https://doi.org/10.1016/j.atmosenv.2022.119055

These results have been disseminated at the following events:

Oral presentation (virtual) at the *14th UK & Ireland Occupational and Environmental Epidemiology Society Annual Meeting*, Leicester

The research was directed by KEW under the supervision from the lead supervisor (GNT) and co-supervisors (SEB, FDP, SG). KEW was responsible for data management, analysis and manuscript preparation, with supervisors providing project curation support, methodological support and manuscript editors. Additional statistical support was sort from MJP. Contextual information was sought from KT, QL, BK and GO.

CHAPTER 8 Results: Unintended consequences: Malaria

The chapter has been published at *BMC Malaria Journal*.

Woolley, K.E., Bartington, S.E., Pope, F.D., Greenfield, S.M., Tusting, L.S., Price, M.J. and Thomas, G.N. (2022) Cooking outdoors or with cleaner fuels does not increase malarial risk in children under 5 years: a cross-sectional study of 17 sub-Saharan African countries. Malaria Journal 21(133) https://doi.org/10.1186/s12936-022-04152-3

The results in this chapter have been disseminated at the following events:

Oral presentation (virtual) at the 2021 *Universitas 21 Health Sciences Group Doctoral Student Forum*, The School of Medicine and Health Sciences at Tecnologico de Monterrey

The research was directed by KEW under the supervision from the lead supervisor (GNT) and co-supervisors (SEB, FDP, SMG). KEW was responsible for data management, analysis and manuscript preparation, with supervisors providing project curation support, methodological support and manuscript editors. Additional statistical support was sought from MJP. Contextual and malaria methodological support was sought from LT.

CHAPTER 9 Results: Fuel switching with economic uncertainty

The chapter is under-peer review at *Energy for Sustainable Development*.

This piece of work was directed by KEW with support advice and direction received from the lead supervisor (GNT) and co-supervisors (SEB, FDP, SMG). Contextual and in country support was provided by TK. Methodological support for the willingness to pay questions was provided by SJ. KEW was responsible for fieldworker training, data collection, analysis and manuscript preparation. In country data collection was undertaken by AM, CM, OA, under the supervision of KEW and TK. All authors read and approved the manuscript for publication.

CHAPTER 10 Methods: Complexities of cross-cultural research and devising appropriate qualitative methodology

A section of this chapter uses data from a previously collected survey undertaken in Kigali, Rwanda, which has previously been published in the *International Journal of Environmental Research and Public Health*.

Campbell, C.A., Bartington, S.E., Woolley, K.E., Pope, F.D., Neil Thomas, G., Singh, A., Avis, W.R., Tumwizere, P.R., Uwanyirigira, C., Abimana, P., Kabera, T., 2021. Investigating cooking activity patterns and perceptions of air quality interventions among women in urban Rwanda. International Journal Environmental Research and Public Health. 18. doi: 10.3390/ijerph18115984

CHAPTER 11 Results: Qualitative: opinions and barriers of behaviour change interventions

The chapter has been published in *Sustainability* and is presented in this style for this journal.

Woolley, K.E., Bartington, S.E., Thomas, G.N., Pope, F.D., Muhizi, A., Mugabe, C., Ahishakiye, O., Kabera, T., Greenfield, S.M., (2022) Women's perceptions and attitudes to household air pollution exposure and capability to change cooking behaviours in urban Rwanda. Sustainability; 14. pp.1608. doi: 10.3390/su14031608

KEW directed this piece of work with support advice and direction received from the lead supervisor (GNT) and co-supervisors (SEB, FDP, SMG). Qualitative methodological support was given by SMG and in country support was received from TK. fieldworker training, data collection, analysis and manuscript preparation were undertaken by KEW. AM, CM, AO under the supervision of KEW and TK. All authors read and approved the manuscript for publication.

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ABBREVIATIONS

A	ALRI	Acute lower respiratory infection
	ARI	Acute respiratory infection
	ASAP	All systems approach to air pollution
B	BMC	BioMed Central
C	CAPS	The cooking and pneumonia study
	CENTRAL	The Cochrane central register of controlled trials
	CH4	Methane
	CIA	Central Intelligence Agency
	CMHS IRB	College of Medicine and Health Sciences Institutional Review Board
	CO	Carbon monoxide
	CO_2	Carbon dioxide
	COPD	Chronic obstructive pulmonary disease
	COREQ	COnsolidated criteria for REporting Qualitative research
D	DALYs	Disability adjusted life years
	DfID	United Kingdom Department for International Development
	DHS	Demographic and Health Survey
E	EA	Enumeration area
	EPHPP	Effective public health practice project
	ERS	European respiratory society
G	GDP	Gross domestic product
	GIM	Global index medicus
	GNI	Gross national income
	GPS	Global positing system
	GRAPHS	Ghana randomised air pollution and health study
H	HAP	Household air pollution
	HAPIN	Household air pollution intervention network
	HIV	Human immunodeficiency virus
I	IAQ	Indoor air quality
	ICS	Improved cookstove
	ICTRP	International clinical trials registry platform
	IQR	Interquartile range
	ISSF	Institutional strategic support fund
	ISCO	International standard classification of occupations
	ITN	Insecticide treated bed nets
	IUGR	Intrauterine growth retardation
L	LBW	Low birth weight
	LMIC	Low- and middle-income country

	LPG	Liquefied petroleum gas
M	MAR	Missing at random
	MCAR	Missing completely at random
	MICE	Multiple Imputation by Chained Equations
	MIS	Malaria indicators survey
	MRC	Medical Research Council
N	NDBP	National domestic biogas program
	NGO	Non-governmental organisation
	NMAR	Missing not at random
O	OPC	Optical particle counter
P	PAYGO	Pay as you go
	PCA	Principle component analysis
	PICOS	Population–Intervention–Comparator–Outcome–Study design
	PM	Particulate matter
	PRISMA	Preferred reporting items for systematic reviews and meta-analyses
	PRISMA-P	Preferred reporting items for systematic reviews and meta-analyses protocol
	PROSPERO	International prospective register of systematic reviews
	PSU	Primary sampling unit
	PTB	Pre-term birth
	RCT	Randomised control trial
	RDT	Rapid diagnostic test
R	RESPIRE	Randomised exposure study of pollution indoors and respiratory effects
S	SARI	Severe acute respiratory infections
	SDG	Sustainable development goal
	SGA	Small for gestational age
	SSA	Sub-Saharan Africa
T	TB	Tuberculosis
U	UN	United nations
	UNICEF	United nations children’s fund
	UoB	University of Birmingham
	UoR	University of Rwanda
	UR-CST	University of Rwanda College of Science and Technology
	USAID	United States Agency for International Development
	USD	United States dollar
V	VAT	Value added tax
W	WASH	Water, sanitation and hygiene
	WHO	World Health Organization

CHAPTER 1 INTRODUCTION

This thesis came about from a collaboration between Dr Suzanne Bartington at the University of Birmingham (UoB) and Dr Telesphore Kabera at the University of Rwanda (UoR), who received a Wellcome Trust institutional strategic support fund (ISSF) global mobility award to document preliminary indoor pollutant levels and determinants of cooking practices. From this initial research, the Global Challenges Research Fund PhD Studentship was obtained to explore further the potential and role of household air pollution (HAP) interventions in Kigali, Rwanda, as a self-directed project.

1.1 Thesis aims and objectives

Using a mixed-method convergent approach[1], this thesis aims to inform interventions that reduce the health harms of HAP. The assessment of the evidence base, deployment of theory and assessing potential behavioural and legislative intervention feasibility aims to be evaluated through understanding current interventions, quantitative analysis of beneficial and unintended health events and fuel switching behaviour. Complemented with a qualitative assessment of the community opinions and barriers to behavioural change interventions, to inform future initiatives.

The thesis has the following objectives:

- Systematically review the existing evidence base for the health benefit of currently researched HAP interventions to identify the research gaps and methodical complexities of evaluating HAP interventions.
- Explore the feasibility and challenges of undertaking cross-cultural qualitative research, to inform the qualitative methodology for the thesis.
- Assessment of the relative health risks and benefits of different cooking practices (cooking fuel type, cooking location) in low- and middle-income countries (LMICs) and sub-Saharan Africa using the Demographic and Health Survey (DHS) data.

- Explore cooking fuel choices in Kigali, under different economic and market forces and the instabilities caused by the COVID-19 pandemic. This objective will help inform a proposed legislative charcoal ban.
- A qualitative assessment of the community's perception of air pollution and women's views of a behavioural intervention in Kigali, Rwanda. The findings will identify facilitators and barriers to potential HAP interventions.

The results gained will provide strong evidence for an efficient HAP intervention to be implemented and evaluated as future research within the urban setting of Kigali, in addition to informing and driving policy change for both short and long-term solutions, which may be generalisable to other settings.

1.2 Thesis structure

The thesis will follow the following structure, which links into the Medical Research Council (MRC) Framework for Complex Interventions (detailed in section 2.6) and is split into the systematic review, quantitative and qualitative research.

- **Introduction** (CHAPTER 2)
- **Systematic review:** Systematic assessment of secondary data sources of published, un-published and grey literature to determine the effectiveness of previous interventions aimed at reducing negative pregnancy, infancy and child health outcomes. The systematic review also includes details of implementation and adoption of interventions. Methods are detailed in CHAPTER 3 followed by the results in CHAPTER 4.
- **Quantitative methods:** Detailed documentation of the quantitative methods used from all three sets of secondary data analysis using the DHS. In addition, to documentation of the methods for primary data collection using a semi-structured survey.

- **Quantitative: Fuel switching and health risks:** Quantitative cross-sectional analysis of the DHS data from 30 countries, assessing the association of wood and charcoal cooking with respiratory health outcomes within children under five (CHAPTER 6); providing evidence of the potential health impacts of restricting charcoal sales. The primary data collection from a semi-structured survey in an informal settlement in Kigali, Rwanda, will complement the secondary data analysis, exploring the impact of economic changes on cooking fuel choice, including questions on the charcoal cooking fuel ban and willingness to pay for alternative cooking fuels (CHAPTER 9).
- **Quantitative: Community driven behaviour change intervention:** An analysis of 30 sub-Saharan countries using the DHS data, assessing (i) the contextual and household determinants of cooking location and (ii) the risk of acute respiratory infection in children under five with cooking location (CHAPTER 7). This is complemented with further analysis investigating the risk of malaria with differing household cooking practices (CHAPTER 8). The analysis is to investigate whether cooking practices to reduce cooking smoke would increase the risk of malaria within children under five, as biomass fuel users have previously reported that cooking smoke keeps mosquitos away.
- **Evaluating and informing qualitative methods:** An appraisal of undertaking cross-cultural research, with a preliminary analysis of previously collected data, which together inform the qualitative methodology for the thesis, is documented within this chapter.
- **Qualitative: Opinions and Barriers:** Qualitative primary data collection in Kigali, Rwanda, using photovoice and interviews (CHAPTER 11); providing rich data of community perception of air pollution and opinions and barriers to behavioural change interventions, to inform intervention development at a community level.

- **Discussion:** A summary of the preceding chapters, presenting the overall evaluation of the thesis and discussion of potential HAP interventions in urban Rwanda, including implications for policy and future research (CHAPTER 12).

CHAPTER 2 HOUSEHOLD AIR POLLUTION, RWANDA AND INTERVENTION OPTIONS

2.1 Household air pollution (HAP)

Approximately 2.4 billion people worldwide rely solid biomass fuels (wood, dung, charcoal, crop residue and coal)[2,3] for domestic energy[2] in low- and middle-income countries (LMICs).[4,5] The percentage of solid biomass users globally is slowly declining over time from 1990, with the greatest change in Asia,[6] yet the actually number of solid biomass users globally has remained relatively stable.[7] HAP is produced from the combustion of these solid biomass fuels for cooking, heating and lighting.[8] The energy ladder concept (Figure 2.1) shows the difference between cost and level of HAP emission with the cleanest fuels (electricity, solar, liquid petroleum gas [LPG]) at the top of the energy ladder being most energy efficient and cleanest but also the mostly costly. Conversely, the cheapest fuels are at the bottom of the fuel ladder and are typically the most readily available, freely collectable and the most polluting. The main pollutants produced from biomass burning include particulate matter (PM) and carbon monoxide (CO),[9] which often exceed the World Health Organization (WHO) guideline levels during cooking periods (Table 2.1). Although domestic burning of solid fuel is the main source of HAP other sources of air pollution are common in LMICs, including smoking[10,11] and the transfer of outdoor pollutants[12] from outside to inside. Outdoor pollutants include those derived from vehicle emissions, industry, windblown dust and biogenic sources.[13] In addition, HAP also influences ambient air pollution concentrations.

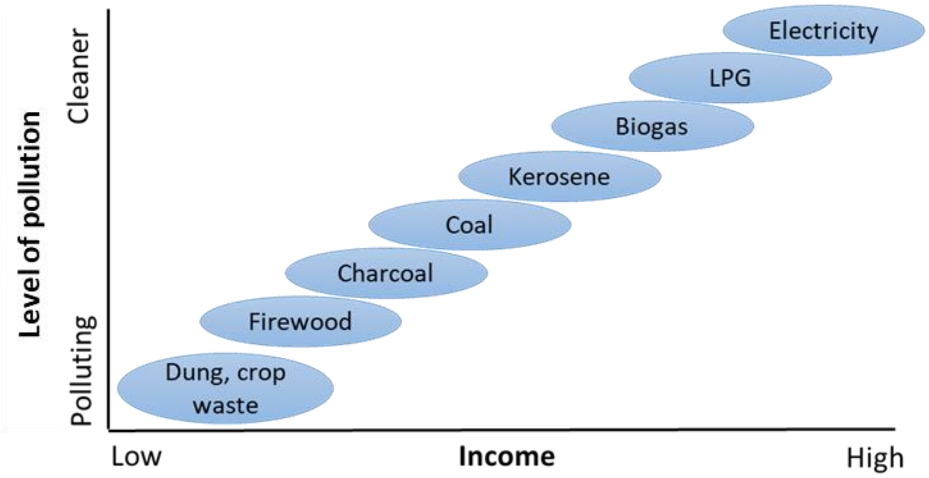

Figure 2.1 Energy ladder adapted from Smith 1994[14]

Table 2.1 WHO annual and 24-hour air quality guidelines

	$PM_{2.5}$ (μg/m^3)	PM_{10} (μg/m^3)	CO (μg/m^3)
Ambient and Household guidelines[15–17]			
Annual	10	20	-
24-hour	25	50	7
Interim target 1 - Annual	35	70	-
Interim target 2 - Annual	25	50	-
Interim target 3 - Annual	15	30	-
Interim target 1 - 24-hour	75	150	-
Interim target 2 - 24-hour	50	100	-
Interim target 3 - 24-hour	37.5	75	-
Ambient guidelines[18]			
Annual	5	15	-
24-hour	15	45	4
Interim target 1 - Annual	35	70	-
Interim target 2 - Annual	25	50	-
Interim target 3 - Annual	15	30	-
Interim target 4 - Annual	10	20	-
Interim target 1 - 24-hour	75	150	7
Interim target 2 - 24-hour	50	100	-
Interim target 3 - 24-hour	37.5	75	-
Interim target 4 - 24-hour	25	50	-

Household guidelines updated in 2005 (PM) and 2010 (CO). Ambient guidelines updated in 2021.
The 2005 PM guidelines were calculated for ambient air pollution, however, can be applied to the household setting.[15,17]

HAP represents the largest population level exposure of air pollution worldwide, even though ambient pollution sources have the largest emissions.[19] Women, especially those of reproductive age,[20] foetuses and children are disproportionately affected by HAP (discussed in section 2.1.1.1),[3] as a result of increased exposure[21] due to being within the house when cooking is taking place;[22–24] as exposure is a function of concentration and time. Human exposure to HAP is dependent upon time spent under the condition of exposure,[9] level of ventilation,[2,9] amount and quality of fuel,[9] lighting and extinguishing,[25] distance from pollution source, the number of cooking periods a day[2] and place of cooking,[26] with greatest exposure being associated with cooking in the living area,[27] and lowest exposure with outdoor cooking.[26] Although temperature and humidity can affect the concentration of HAP, the role of seasonality is more likely due to alteration in human behaviour such as indoor cooking, heating or water content of fuels. These behavioural differences, alter the domestic microenvironment, resulting in a global variation of individual human exposure to HAP.[12] Due to the multitude of factors involved in the production and transport of air pollutants, (summarised in Figure 2.2) exposure does not equal the dose of pollutants received.

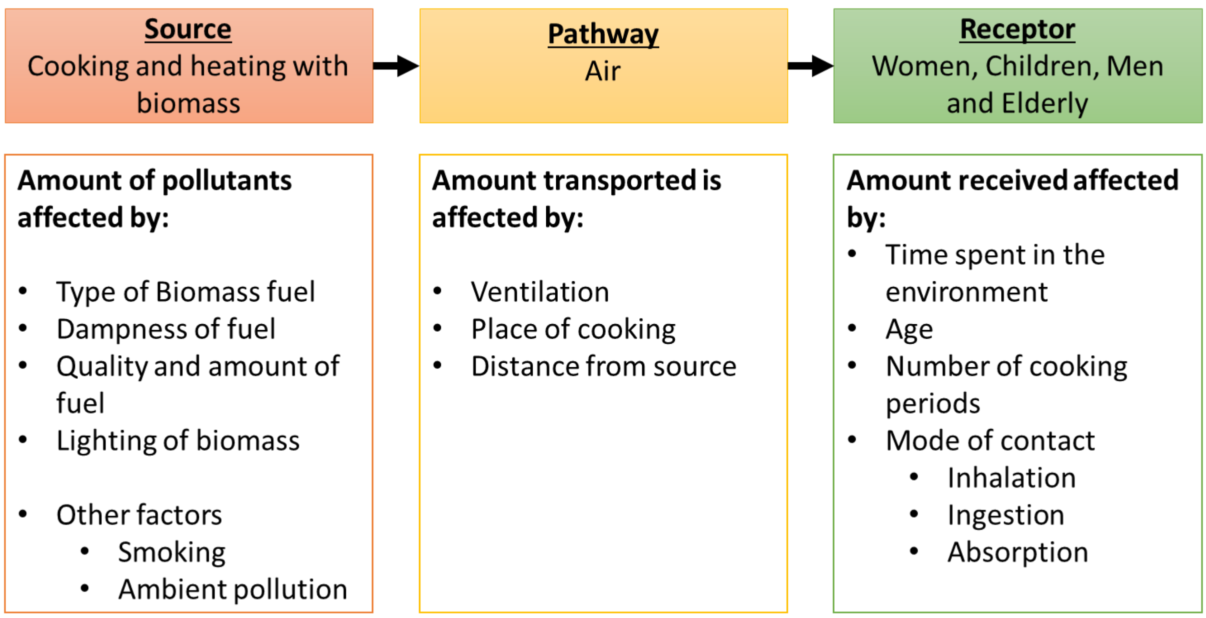

Figure 2.2 Source pathway receptor model of HAP produced from biomass burning for cooking, lighting and heating

2.1.1 Consequence of exposure to HAP

2.1.1.1 Health effects of HAP

HAP presents a significant morbidity and mortality upon the global population, resulting in an estimated 2.31 million premature deaths and 91.5 million Disability Adjusted Life Years (DALYs) in 2019 being attributable to HAP exposure produced from cooking on solid fuels.[28] However, the evidence for the health risk associated with HAP exposure is often of low quality and lacks causal relationships[29] mainly due to methodological issues[30] (such as: cross-sectional studies and use of proxy exposure measures), lack of robust population level statistics and estimates from resource poor setting and other sources of HAP not being considered within studies; especially as HAP levels tend to be more heterogenous that outdoor air pollution. Nevertheless, there is consistent evidence for an association with many disease outcomes, arising from cohort studies, randomised control trials and real-time exposure assessments,[31] even if the results probably underestimate actual associated risk. Variation between health outcome studies also occurs due to multiple confounding factors at household and individual levels including socioeconomic status, culture, gender and age[23] of the target population. Figure 2.3 show the health effects through the life course, illustrating the need for targeting intervening at an early stage (e.g., during pregnancy and the early years).[32] Mechanism of health events include: inflammatory response;[15] oxidative stress,[33] macrophage response; irritation; alterations to coagulation;[34] formation of carboxyhaemoglobin.[35]

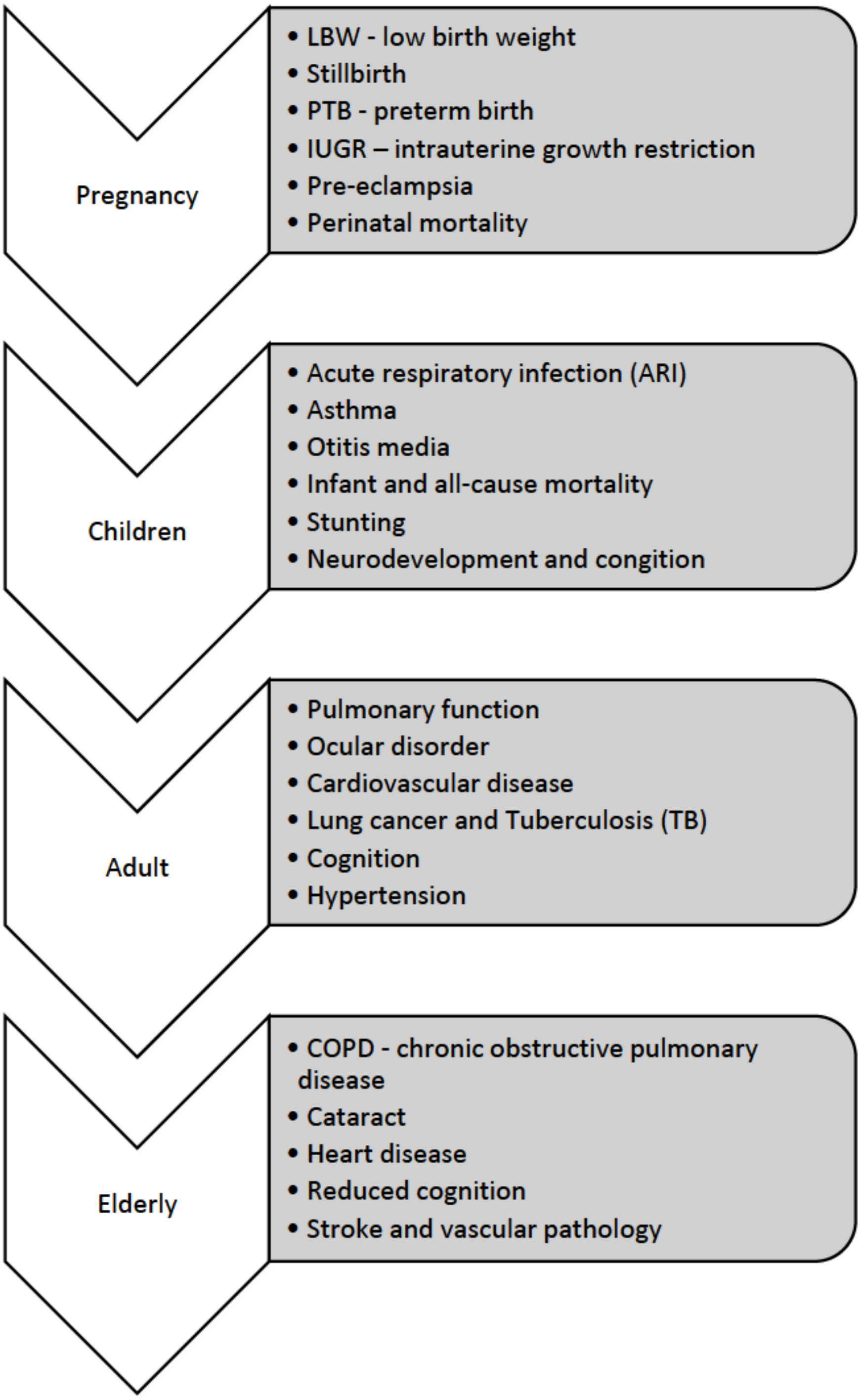

Figure 2.3 Health events associated with HAP exposure through the life course. References: [20,36,45,46,37–44]

2.1.1.2 Environmental and socioeconomic factors

Biomass burning has significant environmental impacts, emphasised by East Africa being situated in a wood fuel depletion hotspot[47] where 27-34% of harvested wood is obtained from unsustainable sources, due to demand outweighing supply.[48] This overburden of environment capacity results in landslides[49] and increased flood risk due to environmental degradation, including soil erosion and desertification.[48] In addition, biomass burning produces greenhouse gasses (CO, CO_2, CH_4), which has a direct contribution to climate change and indirect contribution due to deforestation, however, the net climate benefit from HAP interventions is potentially minimal, due to the indirect climate contributions from use of fossil fuels in the energy generation system (e.g., electricity and transportation) or directly though the burning of fossil fuel (e.g., LPG).[50]

Socioeconomic implications of biomass fuel reliance include the wider and indirect costs of time spent collecting fuel[51] and healthcare,[52] resulting in less available resources for development activities such as education and employment.[53] In addition, cognitive impairment due to HAP exposure has the potential for reducing work place productivity and educational attainment, thus limiting job prospects. The resultant poor health, both disability and illness, impacts on already overburdened healthcare systems in LMICs, thus exerting wider economic impacts;[54] therefore trapping especially the most disadvantaged households in the poverty cycle.[23,55] This leads to households being unable to transition up the energy ladder towards cleaner fuel use. Transition to cleaner fuels occurs with greater economic development,[56] through the “energy ladder” hypothesis, but the transition can be non-linear in process.

2.1.2 HAP and the sustainable development goals

Biomass reliance features strongly in the United Nation's (UN) Sustainable Development Goals (SDGs), which are targets set by the UN in 2015 to be achieved by 2030.[57] With biomass cooking having socio-economic, environmental and health consequences, relevant SDG goals include 3 – Good health and wellbeing, 5 – Gender equality, 7 – Affordable clean energy, 13 – Climate action and 15 – Life on land (Figure 2.4).[58] However, it can be argued that HAP could be incorporated into all 17 SDGs. Given the disruptions caused by COVID-19, SGD 13 is likely to be missed[59], which is essentially a commitment to stopping biomass fuel use to reduce HAP.

Figure 2.4: Sustainable Development Goals pertinent to HAP[57]

2.2 Study setting

The setting for this research is Rwanda, a densely populated[60] landlocked country within Eastern Africa (Figure 2.5), commonly known for the tragic genocide in 1994.[61] In just over two decades Rwanda has rapidly developed its economy and population, achieving a GDP per capita of US$ 797.9,[62] a population of ~13 million in 2020[63] and a life expectancy of 67 years,[64] which is higher than neighbouring East African countries[63] (Table 2.2). Rwanda has already demonstrated its ability to deploy effective health interventions to improve maternal and child health through achievement of 90% measles vaccination coverage, community health workers, 70% use of bed nets among children and 100% HIV testing in antenatal care.[65]

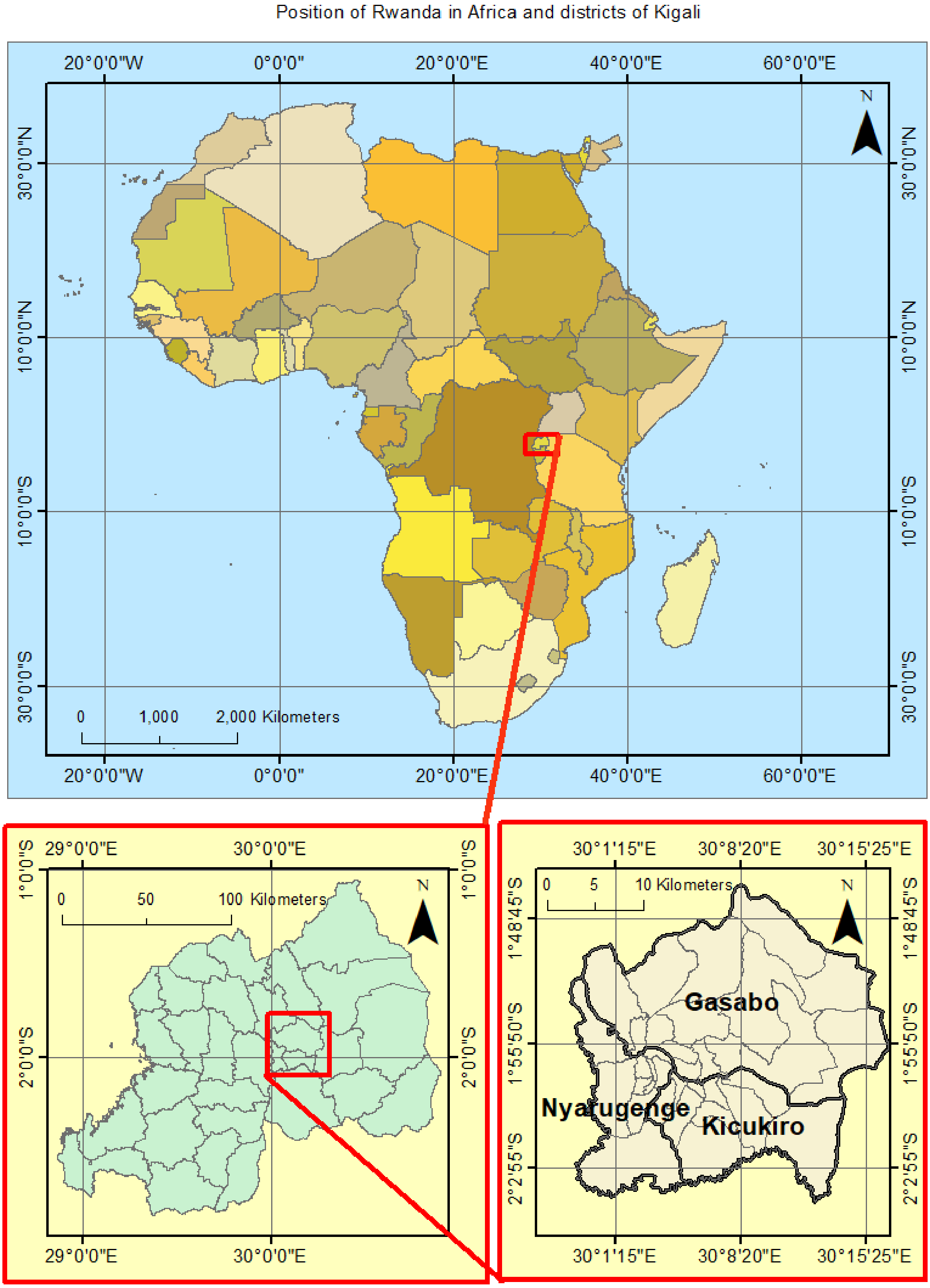

Figure 2.5 Position and map of Rwanda and study location within Rwanda.
Adapted using data from The World Bank Group.[66] Top Image: Location of Rwanda within Africa. Bottom Left: Location the City of Kigali region. Bottom Right: The three districts (black outline) that make up the City of Kigali, with the sectors illustrated within (grey outline). The red cross represents the location of study area.

Table 2.2 Key statistics for selected East African countries

	Rwanda	Ethiopia	Uganda	Kenya	Burundi	Tanzania
Population	12,925,209[63]	114,963,583[67]	45,741,000[68]	53,711,300[69]	11,890,781[70]	59,734,313[71]
Population density (/ km^{2})	525[72]	101.8[67]	228.1[68]	94.5[69]	436.0[70]	67.4[71]
Life expectancy (Years)	69[63]	66[67]	63[68]	66[69]	62[70]	65[71]
GDP per capita (US$)	797.9[63]	936.3[67]	817[68]	1,838.2[69]	274.0[70]	1,076.5[71]
Main Sector	Agriculture[73]	Services[74]	Services[75]	Agriculture[76]	Agriculture[77]	Services[78]
Poverty headcount ratio at $1.90 per day (%)	56.5[63]	30.8[67]	41.3[68]	37.1[69]	72.8[70]	49.4[71]
Rate of biomass use for cooking (%)	95[79]	91[79]	95[79]	75[79]	99[79]	93[79]

Superscript numbers are references.

Rwanda’s main industries are agriculture, mining, construction and services, with the service industries being focused in the centrally located capital Kigali. Rwanda has a high employment rate with 77.7% (2014-15) of women employed compared to 86.1 % in men;[80] with an unemployment rate of 17%.[81] The issues of poverty are mainly located within rural areas, which make up 75% of the population.[73] The government aims to increase urbanisation 35% by 2024 up from 27% in 2015,[82] to transform Rwanda’s economy to be industry based from its current agricultural base. Industry only made up 19% of GDP in 2015, but the Rwandan government aims to reach 38% by 2035, through the exploitation of natural resources, improving private investment[60] and participation of the East African community (EAC) to improve trade. Investment, in both public and private areas, is aimed to increase from 22.6% (2017) to 31.1% (2024) of GDP, with a focus on education and improving capital.[82]

2.2.1 Urban Rwanda

Rwanda is comprised of 30 districts, three of which make up the city of Kigali (Gasabo, Kicukiro and Nyarugenge – Figure 2.5),[83] which hold an expanding population of 1,057,800 people in 2018.[84] 4% of land in Rwanda is built up area,[85] with Kigali being the main urban area in Rwanda, holding half of the urban population, and the remaining urban population being held in six secondary cities (Huye, Muhanga, Ruzizi, Nyagatare, Musanze, Rubavu). These six secondary cities feature strongly in the Rwanda government's 2014 green model city plans,[72] due to urban areas currently being characterised by peri-urban sprawl and increasing informal settlements.[73] In addition, air pollution (predominately ambient) is a key feature in the urbanisation strategy,[73] with waste combustion, transport, industry, domestic cooking and soil-blown dust being identified as major emission sources.[72]

The Nyarugenge district, one of the three districts that makes up Kigali (Figure 2.5), is made up of ten sectors (Gitega, Kanyinya, Kigali, Kimisagara, Mageragere, Muhima, Nyakabanda, Nyamirambo, Nyarugenge and Rwezamenyo), which in turn are comprised of cells; with cells being made up of villages. Nyarugenge is the most densely populated,[86] with a population of 215,069 in 2015.[83] Primary education within Kigali is higher than the national average being achieved by 61% of men and 58% of women however, secondary education is only achieved by 25% of women and 22% of men.[83]

2.2.2 Trends in fuel use for cooking

Although there has been a global increase in cleaner fuel use, the change in SSA has been marginal (Figure 2.6), due to the increase of cleaner fuel use being offset by higher fuel demand created by population growth.[6,79] In 2019-20 95.2% of Rwanda's population were reliant on solid biomass, predominantly charcoal (16.2%) and wood (63.3%)[80] for cooking, with urban areas predominately using charcoal (53.9%).[79] However, urban solid biomass usage decreased from 96.4% in 2000 to 80.3% in 2019-30, which is reflected in the increase in LPG use.[79] By 2024 the government aims to have only 42% of the Rwandan population reliant on biomass cooking fuel,[82] further decreasing HAP emissions. Biomass cooking in Rwanda is usually undertaken on a three stone stove or on portable metal and ceramic stoves (Figure 2.7).

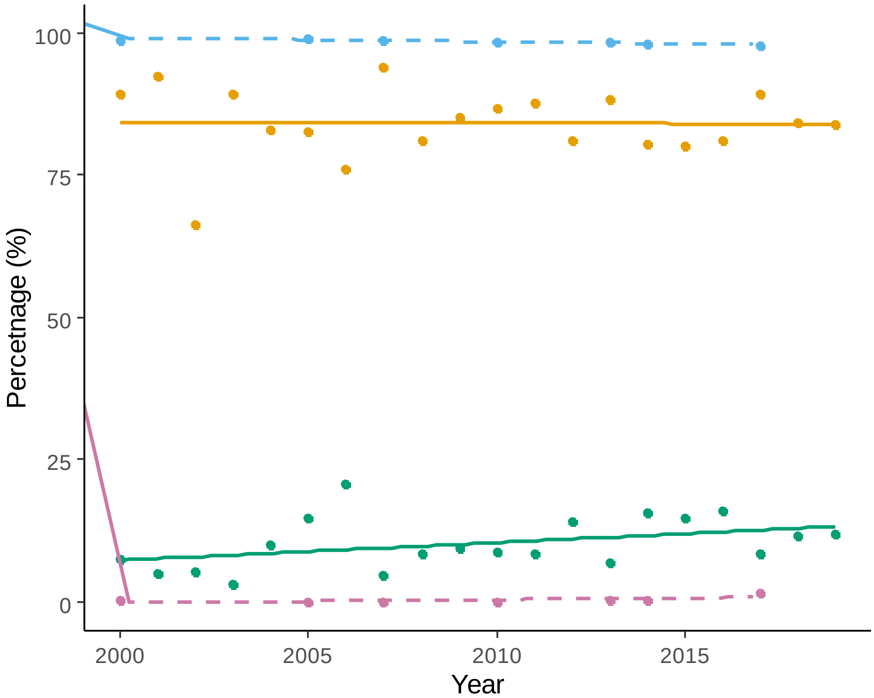

Figure 2.6: Change in rate of household's cleaner and biomass fuel use within SSA, compared with Rwanda. Key: Orange solid line = Biomass cooking fuel usage in SSA, green solid line = cleaner cooking fuel usage in SSA, blue dashed line = biomass cooking fuel use in Rwanda, purple dashed line = cleaner cooking fuel use in Rwanda. Data contained from the DHS Statcomplier.[79]

Figure 2.7 Traditional charcoal cookstove in a kitchen in Rwanda

2.3 Past, present, and future policies for combating HAP in Rwanda

Policies for tackling HAP in Rwanda have been incorporated into larger energy and national development targets. Vision 2020 was a policy document setting ambitious targets for Rwanda to become a middle-income country by 2020 and aimed to reduce consumption of wood for energy to 50% from 90% and have an urbanisation rate of 35%.[72] A full evaluation has yet to take place but progress toward this target has been slow, partly due to a lack of alternatives (LPG, biogas or electricity), but Rwanda is not alone, as this problem has been seen across the international platform.[85]

Vision 2020 has now being superseded by vision 2050, which has aspirational aims to reach upper-middle-income status by 2035 and high-income status by 2050.[60] Tackling HAP is contained within phase 1 of Vision 2050 through reducing households cooking on biomass to 66.6% (2020/21) and 42% (2023/24) from the baseline of 79.9% (2016/17), and promotion of cleaner fuels (LPG, Biogas), especially within rural areas. However, for Vision 2050 to be successful, the weaknesses in Vision 2020 will need to be addressed.

Other large scale policies where HAP have been indirectly included, are the greening of the charcoal values chain (2008-09), which included the production and promotion of alternatives;[87] in addition, to the domestic biogas program (NDBP), at a domestic and institutional level.[88] This $14.1 million project aimed to build 15,000 units by 2011 to decrease reliance on biomass. However, by 2011 only less than half were built[89] and by 2015 only 52% of those installed were operational, indicating a need for better implementation strategies,[90] including educational support and economic development to attract investment.[89] Finally, there has been a USD $4 billion investment to generate methane gas from Lake Kivu, which will reduce the reliance on LPG import.[91]

Policies that specifically address reduction of biomass use for cooking include proposals for a charcoal ban in Kigali city[92], LPG subsidies[88] and increased uptake of improved cookstove (ICS) among biomass users from 50% to 80% (2008-2020).[93] VAT exemptions on LPG are currently in place[94] but a start date for a charcoal ban has yet to be released. However, there is a lack of policy regarding implementation of biomass pellets and briquettes (forms of process improved biomass fuels), with the main supply company, Inyenyeri, going into liquidation; along with a lack of education necessary to support and sustain these fuel switches.

2.4 Health interventions for reducing HAP exposure – the public health perspective

Health interventions are strategic acts aimed at promoting or improving the health status of individuals and the population, either proactively or reactively;[95] in this case the prevention of HAP exposure and health harms. Public health intervention delivery requires a complex mix of science, practice and politics,[96] and frequently comprises four key challenges, which include: addressing all key determinants of health, gaining public visibility, increasing capacity to develop policy and plans and working with people and organisations to improve health.[96] Within the area of HAP intervention delivery there is great potential for health improvement, and wider improvements in gender equality, economic gains and climate protection. However, there is often a weakness in the political environment and understanding of user perceptions and needs, therefore multi-sectorial communication and actions need to occur for effective delivery.[97]

2.5 Interventions

2.5.1 Types of Interventions

Interventions to reduce HAP exposure range from short-term (harm reduction) (e.g., improved cookstove (ICS), improved fuels (pellets and briquettes), outdoor cooking) to long-term solutions (harm avoidance) (e.g., LPG, solar stoves, electricity). As poorest communities with limited resources hold the greatest HAP burden sustained cleaner fuel transition may take years,[98] hence the need for short-term culturally appropriate interventions. Studied interventions, ranging from observational to randomised trials, have been relatively limited to date with mixed results;[8] with Table 2.3 illustrating how interventions work and the extent of their research. Interventions researched in LMICs have focused on structural interventions such as ICS[31] and LPG, with a few studies of improved fuels,[99] education and behavioural change,[100,101] ventilation[102] and biogas;[103,104] within a single country or multi- country.[105] The settings for such studies are mainly in rural communities, with a predominance of cross-sectional small scale studies.[31,106]

Table 2.3: Description of HAP interventions that have been studied within the literature

Type of intervention	How the intervention reduces HAP?	Exposure assessment taken place?	Are the levels below WHO guidelines	Health outcomes assessment?	Quality of Evidence *
Improved cookstove (ICS)	A cookstove designed to reduces the amount of incomplete combustion by increasing air flow	Yes	No	Yes	Good
Ventilation	Allows removal and/or dilution of air pollution in the microenvironment	No	?	Yes	Weak
LPG **	LPG, classified as a cleaner fuel, produces significantly less HAP	Yes	?	Yes	Good
Ethanol stoves	Ethanol is another fuel that produce less HAP when burnt but is not as clean as LPG	Yes	No	Yes	Moderate
Biogas	Biogas is a cleaner fuel and has a similar status to ethanol	Yes	No	Yes	Weak
Improved fuel	These are refined biomass fuels that have been created to burn more efficiently and reduce the amount of HAP produce e.g., biomass pellets or briquettes	Yes	?	Yes	Moderate
Education and behaviour change	Aims to reduce the level of exposure through changing attitudes and behaviour using education e.g., moving cooking outdoors, removing child from kitchen while cooking.	Yes	?	No	Weak
Solar	Using solar energy to create electricity to power cookstove	No	No	Yes	Weak

* Classified as weak, moderate of good quality of evidence based on subjective assessment

** LPG and electricity, under current conditions, is the end game results in tackling HAP via energy transition and would occur as a result of economic improvements; therefore, it could be argued that LPG is not in fact an intervention. However, due to the burden of HAP and need for accelerated roll of out LPG, gaining community reliance as a source of fuel, LPG has been included as an intervention.

2.5.2 Interventions in Rwanda

Two interventions (ICS[107] and biomass pellets[108]) are known to have been undertaken in Rwanda, with one early stage RCT being conducted across four countries (Rwanda, India, Peru, Guatemala) called the HAPIN trial involving 3,200 households, comparing the use of LPG to traditional cooking with pregnancy, perinatal and child outcomes [109] (ClinicalTrials.gov Identifier: NCT02944682). The biomass pellets and ICS have shown a significant reduction in overall HAP concentrations,[99,110] with only a documentation of ARI reduction in children under five with ICS use.[111] Encouraging reductions in $PM_{2.5}$ have been documented within the pilot study for the HAPIN trial, to levels which could have health benefits.[112]

2.5.3 Appraisal of previous interventions

2.5.3.1 Reduction of pollutant concentrations

Overall, interventions implemented globally among solid fuel using households have shown an improvement in PM and CO exposure in children and adults,[31] but the measured levels still exceed the WHO guideline levels.[31,113] However, there are challenges with inadequate technical capabilities for capturing exposure estimates, reliance on proxies and typically highly heterogenous exposure patterns,[114] resulting in high variability requiring careful interpretation.[31] In addition, there is limited research available for Rwanda, hence the need for translation from other settings.

Interventions which successfully reduce pollutant levels in the laboratory setting are frequently not transferable or effective within the field[23] due to a lack of consideration of contextual and behavioural factors, such as fuel type and moisture content, stove type and combustion temperature.[114] Efficiency of laboratory tests cannot therefore be assumed[115] as such evaluation only considers fuel use (efficiency), emissions, indoor emissions, and safety[116] and conversely, field controlled cooking test[117] are often representative of a typical cooking session. Few existing studies have investigated emissions outside of the home,[23] mixing of pollutants between homes or long-term impacts of intervention measures upon cooking behaviours. Variation is also present in methods of assessment of field exposure,[114] which includes fuel choice/stove type, real time measurement of area/kitchen, real time personal pollutants measurement, combining person and area/kitchen measurement and personal dose/biomarkers (Table 2.4).[118] Accurate exposure measurements should characterise the magnitude, frequency and duration of exposure at a human level to give the most comprehensive estimate; as well as a trade-off between short term and long term monitoring.[114] For these reasons, proxy measures (e.g., fuel type, stove type) for pollutant levels have been widely used[119] and are the weakest form of evidence, however these are relatively low cost and enable achievement of a large sample size (Table 2.4). Conversely, proxy measures lack detailed inference concerning exposure-response and are subject to misclassification bias and increased subjectivity of outcome assessment. In addition, there are issues with temporal resolution, reducing generalisability due to site-specific characteristics. However, limitations can be reduced by measurement of time activity, pollutant source, behaviours, stove type, and fuel quality.[114]

Table 2.4: Change of evidence and field practicality in different types of field measurement for HAP exposure assessment (information interpreted from Clark et al., 2013[114])

Measurement type	Low Cost	Large Sample size	Risk of misclassification High	Time Low	Low invasion	No exposure-response
Proxy measures (fuels/stove type)	↓	↑	↓	↑	↑	↓
Proxy measures with semi quantitative measures						
Real times area measurements						
Real-time personal measurement						
Combined personal and area measurement						
Biomarkers/ Internal dose						
Measurement type	High cost	Small Sample size	Risk of misclassification Low	Time High	High invasion	Dose-response

The results of real time measurements have been mixed,[31,113] often limited by costly equipment and small sample sizes.[118] Personal measurements, although not showing HAP reductions arising from interventions,[31] provide the best indication of exposure; however the variability due to temporal and spatial gradients around the cookstove is not captured,[114] as well as use of measurements being limited by the size and weight of the monitors.[120] Finally, internal dose and biomarkers[121,122] are the best indication of exposure, but have revealed little conclusive evidence for reductions in exposure and are rarely done. These measurements are dependent upon the type of biomarker and may not be source specific; as well as being invasive and costly.[114] Gaining the most accurate estimate of exposure within the limitations of research is key to being able to assess the effectiveness of interventions at reducing HAP exposure and the amount of suggestive evidence of causality.[4]

2.5.3.2 Impact on health outcomes due to intervention

HAP interventions aim to improve health through reduction in pollutant levels, however, evidence of health benefits from standalone HAP interventions is limited.[31] But given that many interventions do not lower pollutant levels to below the WHO guidelines, any significant health benefits cannot be anticipated.[39] In addition, any reduction maybe beneficial based on the exposure-response curves but strong conclusions of health risk reduction[23] are often not made, due to the difficulty in interpretation of the exposure-response relationship due to complex nature of the study settings. Health outcomes are influenced by factors[123] such as socioeconomic,[124] nutrition,[125] household characteristics,[126] education, exposure to ambient air pollution[127] and smoking status[124] as well as pre-existing susceptibility which are often not successfully controlled.[124]

RCTs provide the most accurate comparison of health outcomes, however, conflicting and non-comparable results could be introduced in the methodology used to obtain the health outcome measure, with a range from subjective measurements to use of defined instruments and protocols being used.[119,128] Self-assessments and self-report introduce response bias, whereas use of differing instruments (e.g., spirometry vs peak flow test for pulmonary function) can introduce information bias. Finally, there is a lack of understanding of the biological pathway, scale within studies and quantity of evidence,[23] which make it difficult to conclude the attributable cause of the health event being due to HAP exposure.

2.5.3.3 Uptake and sustained use of interventions

Within the literature there is a lack of assessment of the levels and reasoning behind uptake and sustained use of HAP interventions, however, these factors present an important component in assessing effectiveness of interventions; with most studies being quantitative rather than qualitative, which can result in a lack of deeper understanding. In addition there are a range of interrelated factors which include: setting and household characteristics; taxes and finance; market opportunities; knowledge and perceptions; fuel and technology; policy mechanisms.[129] Studies often only focus on one factor, reducing the completeness of situational assessment into the effective of interventions.

The focus of the outcomes of the interventions varies between studies, from health to climate outcomes, which affect the portrayal of the interventions, the participant and the description of the desired outcomes. However, Lewis and Pattanayak[130] suggest that health, the quality of the local environment and climate should all be seen as factors and outcomes in interventions implementation, making it difficult to focus research. Inherent issues, such as education, are barriers to research as greater education and awareness of HAP have been noted to have a positive impact on intervention attainment, through understanding why an intervention is needed.[131]

Although participants' views of interventions have often been positive, with reports of smoke reduction,[132] easier to use, more efficient and fuel saving;[133] behaviours such as stove and fuel stacking[i] influence the sustained use and effectiveness of the interventions.[134] These behaviours are often due to a lack of understanding or the interventions being culturally inappropriate. Stove and fuel stacking and continued use of traditional stoves have ranged from 40% to 26%, in previous studies,[135,136] which potentially underestimates exposure reduction and health benefit.[137]

2.5.4 Barriers to interventions

Barriers to interventions appear when the implementation and development of the interventions do not take into consideration the wider context of social, environmental and economic situations.[138] The right environment is needed to form the foundation of effective policy; with enabling factors being policy, regulation and political stability,[139] which is often a barrier within LMICs. In addition, the enabling environment is influenced by the interlinking factors of: industry structure and services; energy pricing and cost; user and community needs and perceptions; and consumer demand.[139] With HAP interventions within LIMCs, many of these factors are weak or missing. In Rwanda, there is a need to improve awareness, consumer demand and energy pricing; although there is a strong political will to tackle HAP.

There are multiple factors influencing the dependency relationship on solid biomass fuels including the socio-cultural factors and determinants of health that facilitate uptake of HAP interventions. The Dahlgren and Whitehead model (Figure 2.8), with the relevant factors for health interventions for HAP, illustrates the complex situation and interrelated factors that HAP have on society and the varying levels upon which interventions can be placed. Bruce *et al.*,[106] also, stated the interrelationship between dependence of polluting fuels and poverty needs to have greater recognition. Implementation and adaption to the local context of interventions[140] that have been shown to reduce exposure remains a challenge.

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[i] Stove and fuel stacking is defined as concurrent use of multiple stoves and/or fuels[134]

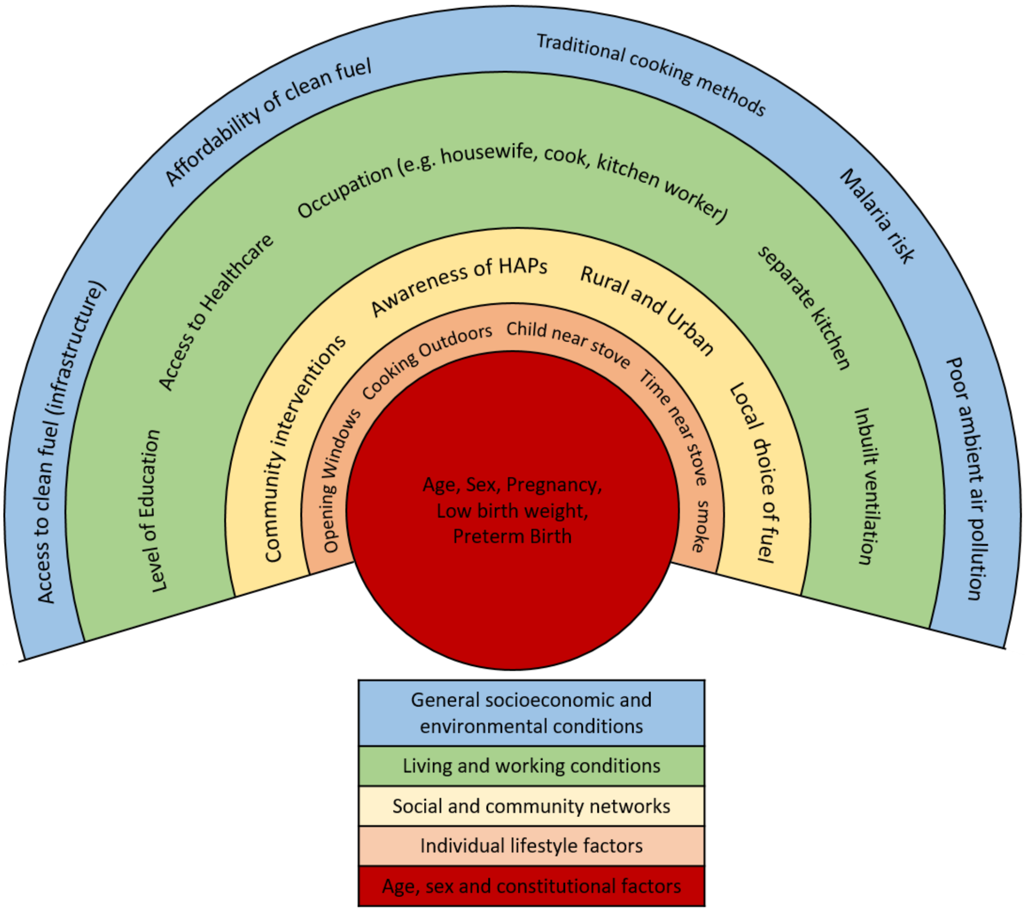

Figure 2.8: Dahlgren and Whitehead social determinant of health applied to the context of HAP

The political/policy situation within Rwanda, illustrated by a Walt and Gibson (1994) triangle (Figure 2.9), shows that the government and NGOs are keen to introduce policy change to tackle the large problem of exposure to HAP. Although the long-term interventions have the evidence behind them there is still a lack of understanding around the effectiveness of the short-term interventions. In addition, there is a need for evidence that is applicable to Rwanda as cultural differences may alter the effectiveness of the interventions. For example, ICS may not be fully versatile in the local context due to differences in how food is cooked.[136] Finally, there are potential barriers to interventions within individuals and communities due to a lack of awareness,[141] to be able to gain significant uptake and sustained use of the interventions for the policy to be effective at having a health benefit.

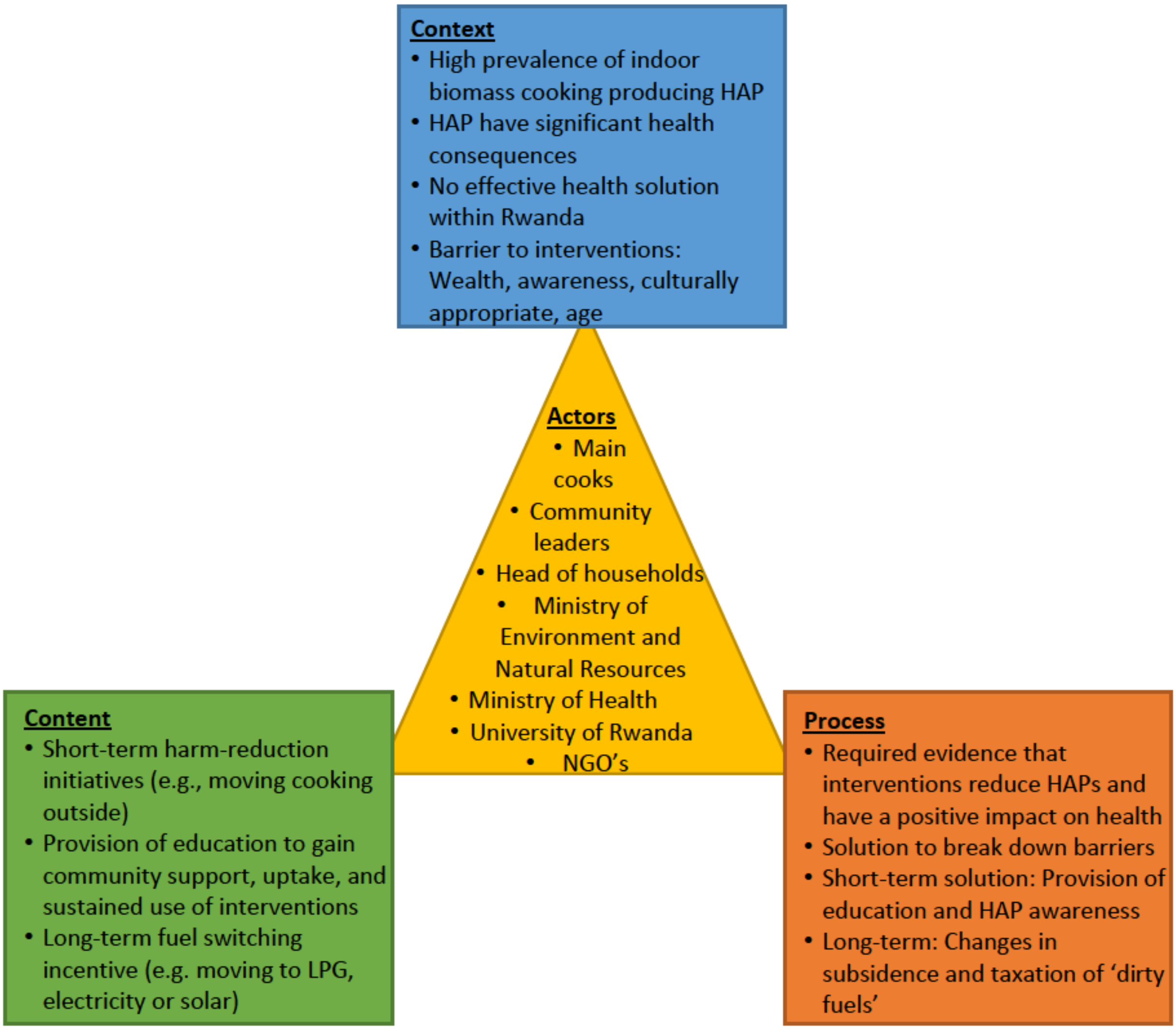

Figure 2.9: Walt and Gibson (1994) triangle which systematically illustrates the difference factors present in formulating a policy for HAP interventions in Rwanda. NGO = non-governmental organisation.

2.6 Complex interventions

Complex interventions for important health challenges are formed due to various interconnecting components and commonly used in public health research.[142,143] As a result of these interacting and often multi-disciplinary components, complex interventions present multiple challenges and therefore need for careful consideration in the design, implementation and evaluation.[144] Qualitative and quantitative methods are needed to provide a theoretical undertaking, to investigate a lack of impact, individual level outcome variability and use of multiple outcome measures to help develop study design and implementation through a phased approach;[144] thus increasing the generalisability and impact of the results. Interventions for HAP are complex by nature of being multi-disciplinary and have interacting health, socioeconomic and environmental components; and therefore, intervention development and evaluation should be undertaken from a complex intervention approach.

The MRC have developed (updated in August 2021) a framework (Figure 2.10) to help guide complex intervention design, monitoring and evaluations;[142] using iterative and often non-linear approaches.[144,145] Firstly, identification of evidence through feasibility, including unintended consequences and potential barriers, will help determine if the intervention will produce the desired effect[144] and help ascertain and refine the research questions, methodological and clinical procedures through preliminary studies.[146] Effectively developed interventions use community engagement,[147] which will enable user-centred design, taking into consideration environmental, social and health factors.[148] As well as identification of the population of interest (e.g., communities or individuals)[149] and understanding how the interventions may link into existing structures and behaviours.[147]

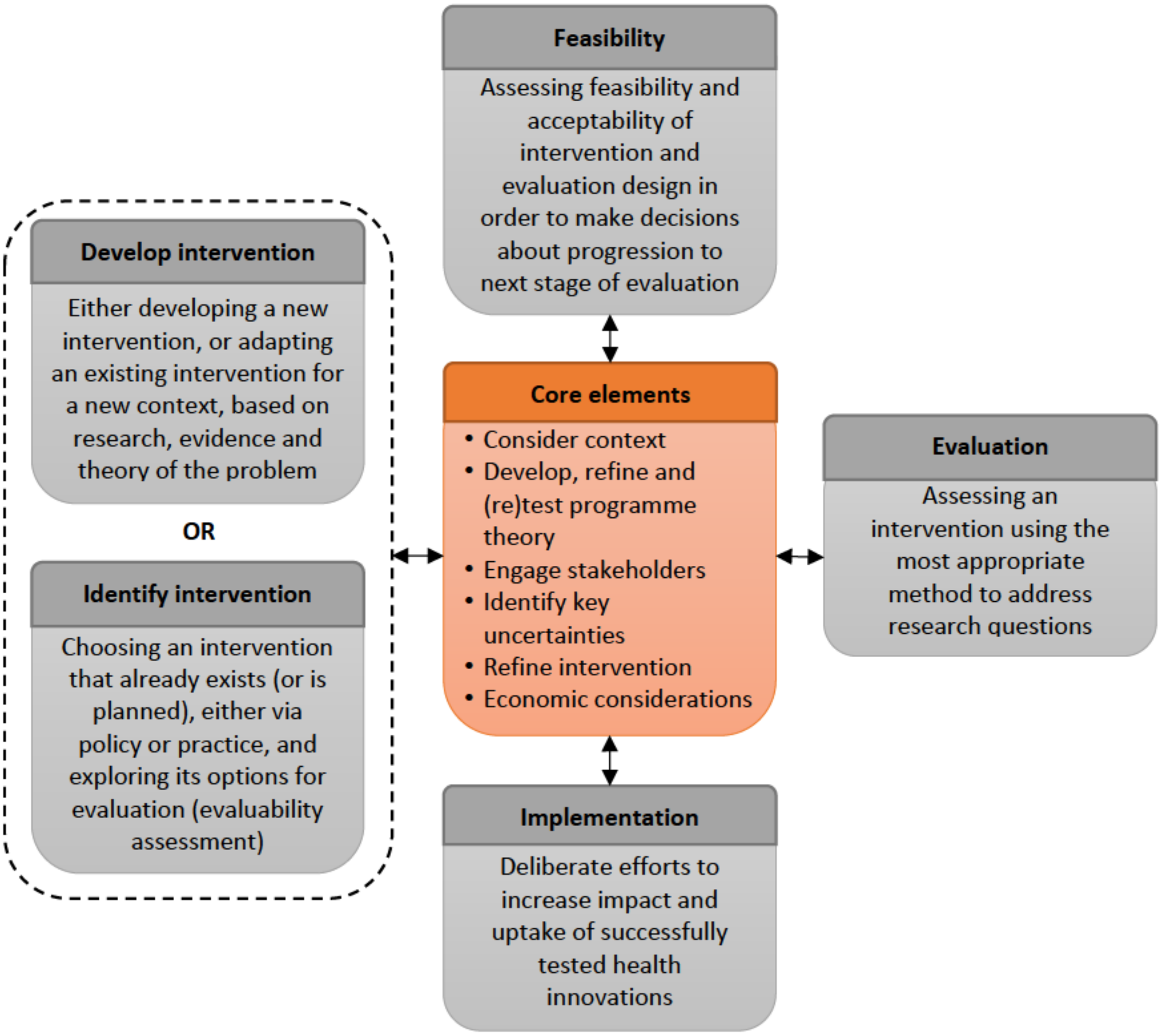

Figure 2.10: MRC process framework.[143]

Development and identifying interventions, including the acceptability, feasibility and outcomes of interest, often receives little attention, due to its challenging nature.[150] Development of interventions requires the use of formal or explicit knowledge, weighing up scientific knowledge and practical wisdoms, all of which can sometimes be conflicting.[150] The evidence formulated in the development has benefits and challenges,[150] however, should be able to increase certainty around the predictive effectiveness of the proposed intervention.[147] Overall, interventions in resource poor settings need to be designed focused in their implementation (e.g., interlinking design, implementation and improvement of interventions),[146] in addition to being investigated and implemented using an holistic approach to prevent real-world shortfall, thus reducing the potential financial and social burden on communities where the intervention has been implemented.[147]

This thesis focuses on the development and core elements, investigating the potential for an intervention, before starting on a lengthy and expensive trial process and identifying unintended consequences. The need for community input into interventions development enables identification of problems within the wider picture (e.g., fuel accessibility, view of household members, cost etc.) and improves community acceptability.

2.7 Summary

Tackling HAP from cooking on solid biomass fuel is of global importance, due to associated health effects seen throughout the entire life course, with associated socioeconomic and environmental impacts. Rwanda provides a unique study setting because of its current political agenda to tackle HAP. Although a sustainable cleaner fuel transition is the ideal scenario which typically accompanies transition to high-income country status there are multiple barriers to achieving widespread adoption, therefore there is a need for harm-reduction and education initiatives to run alongside clear fuel policy interventions. However, the effectiveness of such interventions has not been widely evaluated. The main objective of the thesis is to inform future interventions to effectively reduce the health harms of HAP using a convergent mixed-methods approach,[1] structured with the MRC framework for complex interventions. The results gained will provide the foundations for a HAP intervention to be implemented and evaluated as future research within the urban setting of Kigali; in addition to informing and driving policy change for both short- and long-term solutions.

CHAPTER 3 METHODS: SYSTEMATIC REVIEW PROTOCOL

This chapter details the protocol for the systematic review (CHAPTER 4) to assess the effectiveness of previous interventions at reducing pregnancy, infancy and child health outcomes and is presented in the style for publication in *BMC Systematic Reviews*. The manuscript was accepted for publication in *BMC Systematic Reviews* in January 2021.

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Systematic Reviews

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Effectiveness of interventions to reduce household air pollution from solid biomass fuels and improve maternal and child health outcomes in low- and middle-income countries: a systematic review protocol

Check for updates

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Abstract

Background: A variety of public health interventions have been undertaken in low and middle income countries (LMICs) to prevent morbidity and mortality associated with household air pollution (HAP) due to cooking, heating and lighting with solid biomass fuels. Pregnant women and children under five are particularly vulnerable to the effects of HAP, due to biological susceptibility and typically higher exposure levels. However, the relative health benefits of interventions to reduce HAP exposure among these groups remain unclear. This systematic review aims to assess, among pregnant women, infants and children (under 5 years) in LMIC settings, the effectiveness of interventions which aim to reduce household air pollutant emissions due to household solid biomass fuel combustion, compared to usual cooking practices, in terms of health outcomes associated with HAP exposure.

Methods: This protocol follows standard systematic review processes and abides by the PRISMA P reporting guidelines. Searches will be undertaken in MEDLINE, EMBASE, CENTRAL, WHO International Clinical Trials Registry Platform (ICTRP), The Global Index Medicus (GIM), ClinicalTrials.gov and Greenfile, combining terms for pregnant women and children with interventions or policy approaches to reduce HAP from biomass fuels or HAP terms and LMIC countries. Included studies will be those reporting (i) pregnant women and children under 5 years; (ii) fuel transition, structural, educational or policy interventions; and (iii) health events associated with HAP exposure which occur among pregnant women or among children within the perinatal period, infancy and up to 5 years of age. A narrative synthesis will be undertaken for each population intervention outcome triad stratified by study design.

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(Continued from previous page)
Clinical and methodological homogeneity within each triad will be used to determine the feasibility for undertaking meta analyses to give a summary estimate of the effect for each outcome.

Discussion: This systematic review will identify the effectiveness of existing HAP intervention measures in LMIC contexts, with discussion on the context of implementation and adoption, and summarise current literature of relevance to maternal and child health. This assessment reflects the need for HAP interventions which achieve measurable health benefits, which would need to be supported by policies that are socially and economically acceptable in LMIC settings worldwide.

Systematic review registration: PROSPERO CRD42020164998

Keywords: Indoor air pollution, Interventions, Low and middle income countries, Pregnancy outcomes, Child health, Maternal health, Environmental health, Biomass, Infant health

Background

Household cooking, heating and lighting with solid biomass fuel (e.g. wood, dung, charcoal, crop residues) [1] is common in low- and middle-income countries (LMICs) [2] worldwide, producing hazardous levels of household air pollution (HAP) (e.g. carbon monoxide (CO) and particulate mMatter (PM)) [3], and exposure to results in significant morbidity and mortality. The greatest burden of HAP exposure is recognised to be among women of child-bearing age [4] and children under 5 years, due to a disproportionate amount of time spent in the house, with women performing or assisting with household duties [5]. Intrauterine, infancy and early childhood are critical periods of organ development when individuals are particularly vulnerable to the harms of HAP exposure [6]. Adverse health events associated with HAP exposure can occur throughout the life course from conception to old age, but specifically during pregnancy, with evidence for increased risk of low birth weight, preterm birth, stillbirth, gestational hypertension, intrauterine growth retardation (IUGR) and perinatal mortality [7]. Early life health events among infants and children under 5 years include increased risks of acute lower respiratory infection (ALRI), asthma, otitis media, impaired neurodevelopment and all-cause mortality [8, 9]. In context, 31.75 per 100,000 acute respiratory infection (ARI) deaths and 11.68 per 100,00 preterm birth deaths were attributable to HAP globally in 2019 [10].

Ultimately, economic development is associated with clean fuel transitions (e.g. to ethanol, liquid petroleum gas (LPG), electricity), which are fuels that have been recognised to reduce HAP levels to below World Health Organization indoor air quality (WHO-IAQ) guideline levels (CO 7 mg/m^3 24-h average, $PM_{2.5}$ 25 mg/m^3 annual average) [11]; however, socio-cultural factors can contribute to fuel/stove stacking and mixing (where traditional fuels/stoves are used alongside the intervention) which may reduce the efficacy of clean fuel policy implementation [12]. Interim interventions, prior to sustained cleaner fuel availability, to mitigate HAP exposure levels within the household setting are broad ranging, including improved cookstoves (ICS) (e.g. rocket stoves, plancha) [13], solar stoves [14], improved biomass fuels (e.g. briquettes, biomass pellets) [13] and behavioural changes (e.g. removal of the child from the cooking area, outdoor cooking, opening windows) [12]. LPG, for example, has the potential to reduce HAP levels below the WHO-IAQ guideline levels; however, not all interventions achieve this [15–17] or interim targets ($PM_{2.5}$ 35 mg/m^3 annual average) [18] and are therefore typically harm mitigation measures, with some interventions not reducing exposure at all. In addition, there are often multiple barriers [19] to implementation, uptake and sustained use of interventions, such as fuel affordability and accessibility, cultural and social preferences or lack of relevant infrastructure [20]. Previous systematic reviews have detailed the change in HAP levels [13] and health outcomes (low birth weight, preterm birth, perinatal mortality, paediatric ALRI and chronic obstructive pulmonary disease (COPD)) attributed to ICS interventions [21], in addition to systematic reviews investigating a wider range of HAP interventions for specified symptoms (e.g. blood pressure) [22] and general respiratory and non-respiratory health outcomes [17]. However, to the best of our knowledge, there is a paucity of evidence synthesis concerning the overall benefits to maternal and child health outcomes arising as a consequence of household solid biomass fuel interventions.

The objective of the systematic review protocol outlined here is to assess, among pregnant women, infants and children (under 5 years) in LMIC settings, the effectiveness of interventions which aim to reduce household air pollutant emissions due to household solid biomass fuel combustion, compared to usual cooking practices, in terms of health outcomes associated with HAP exposure. In addition, any information regarding measures of sustained uptake of the intervention within the selected studies will be extracted and discussed. The findings will inform future intervention studies and policy changes, by generating knowledge of effectiveness for achieving improved pregnancy, perinatal, infant and under 5 years child health outcomes in resource-poor settings worldwide.

Methods

Established systematic review methods will be used. This protocol has been registered on the International Prospective Register of Systematic Reviews (PROSPERO) (ID: CRD42020164998) [23] and is presented in accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocol (PRISMA-P) guidelines [24].

Eligibility criteria

The following Population-Intervention-Comparator-Outcome-Study design (PICOS) criteria will be used to determining primary study inclusion.

Population

Pregnant women (no limitation to trimester or number of previous pregnancies), children in infancy and children under the age of 5 years who are exposed to HAP originating from biomass solid fuel sources, used for cooking, heating and lighting within LMIC settings (World Bank definition 2020) [25]. HAP exposure can be determined through direct objective measurement (e.g. personal, kitchen area) of pollutant concentration (e.g. PM, CO) or use of a proxy measure (e.g. self-reported biomass fuel use, classification of 'cleaner' and 'dirty' fuels by household survey).

Intervention

Any intervention implemented which aims to reduce household air pollution emissions arising from indoor cooking or heating using solid biomass fuel. This includes interventions such as those which seek to improve access and take-up to cleaner fuels (e.g. refined biomass, ethanol, LPG, solar, electricity); structural interventions such as improved cookstoves (ICS), inbuilt stoves (e.g. plancha), ventilation and chimney hood; fuel policy; and behavioural/educational interventions (e.g. moving cooking outside, reducing time spent in the kitchen, removing children from the cooking area during cooking, altering fuel or food preparation). There will be no limitation to the length of duration of interventions or timing of deployment of intervention (e.g. anytime during pregnancy through to the fifth year of a child's life).

Comparator

Alternative HAP intervention (e.g. any other intervention within inclusion criteria) or no intervention (e.g. exposure to standard HAP through using the current method of cooking, heating or lighting).

Outcomes

Health outcomes relating to pregnancy and perinatal period (e.g. IUGR, birth weight, preterm birth, pre-eclampsia, pregnancy-induced hypertension, maternal mortality, perinatal/infant mortality, stillbirth and miscarriage) and early life (e.g. upper and lower respiratory tract infections, pneumonia, asthma, respiratory distress syndrome, otitis media, impaired neurodevelopment, mortality and burns) which have been previously associated with HAP exposure. There will be no limits to the follow-up duration of outcome measures.

Study type

Eligible study designs are randomised control trials (RCTs), non-randomised control trials and quasi-experimental or natural experimental studies (before-after studies, interrupted time-series studies). Time-series or before-and-after studies will need to compare the same health outcomes in the same population pre- and post-intervention. It is recognised that before-and-after studies assessing pregnancy outcomes are unlikely to exist due to the difficulties in assessing changes in pregnancy outcomes within subsequent pregnancies, but will not be excluded if present.

Exclusion

Any study that did not meet the inclusion criteria in all five areas (population, intervention, comparator, outcomes and study design) will be excluded.

Information sources

The following databases will be used to search for published, in progress and grey literature: MEDLINE (in process and 1947–date), EMBASE (1947–present), The Cochrane Central Register of Controlled Trials (CENTRAL), WHO International Clinical Trials Registry Platform (ICTRP) [26], ClinicalTrials.gov, The Global Index Medicus (GIM) [27] and Greenfile [28]. Furthermore, the use of manual searches of all reference lists in the included studies and previous systematic reviews related to the topics will ensure capture of all available literature. The systematic reviews will be identified whilst screening the search results for included studies and additionally searching Epistemonkios [29].

Search strategy

The search strategy, where the database platform allows, will include free-text terms and index terms that are contained within the following structure: "Population" AND ("Intervention" ("Household Air pollution" AND "LMICs")) (Appendix), with population being defined as pregnant women and children under 5 and interventions being any intervention that aims to reduce the level of household air pollution. There will be no restrictions in place for the date of publication, language of publication, type of publication (e.g. conference abstracts) or type of study design.

Study records

Selection process

Two reviewers (KEW, EDC) will independently conduct article selection using the eligibility criteria, within Mendeley, after removal of duplicates. Relevant articles will be determined initially by title and abstracts, followed by retrieval and full paper assessment for selection of papers as per the inclusion criteria, with reasons for exclusion noted at each stage (including the screening stage). Authors will be contacted for clarification if required. Any difference in selected articles between reviewers will be discussed using a third independent reviewer (SEB) to adjudicate any remaining disagreements. The selection process will be graphically illustrated using a PRISMA flow diagram [24].

Data extraction

Data will be independently extracted from included studies by two reviewers (KEW, EDC) using an adapted (to type of study design) Cochrane Public Health Group data extraction form [30], in a Microsoft Excel spreadsheet (Microsoft Cooperation). The data extraction form will include critically appraisal of paper quality within the assessment process. Extracted data will include, but not be limited to:

- Study characteristics
  - Article title, author and year, geographical setting, study population characteristics (sex, age, residential setting), inclusion and exclusion criteria, funding sources
- Intervention details
  - Type of interventions and comparators, length of intervention, baseline imbalances, issues with uptake and adoption
  - Type of air pollution measurements, length of measurement, equipment used and results (if any)
- Health outcomes
  - Health outcomes and definitions, method of measurement/classification scales, appropriateness of method, time points measured

Given the likely variability between studies included in the review, in terms of design, population, intervention, comparator, outcomes and data type, the data extraction process will be piloted and then modified if required. Any differences between reviewers in data extracted will be discussed and using a third independent reviewer (SEB) to adjudicate any remaining disagreements.

Quality and bias assessment

Risk of bias will be assessed using the Effective Public Health Practice Project (EPHPP) quality assessment tool for quantitative studies [31] by two reviewers independently (KEW, EDC), assigning low, medium and high risk of bias for each individual study. For trials where a parallel control group is used, it is accepted that random allocation and the blinding of participants and outcome assessor may not be always possible, due to the nature of the interventions and settings.

Data synthesis

A narrative synthesis will be undertaken for each population-intervention-outcome triad (as indicated in Fig. 1) stratified by study design. Data collected will be tabulated reporting study characteristics, intervention, HAP exposure measurements (if any) and outcome details. It is likely that data may be reported in a mixture of formats for the same outcome (e.g. continuous data mean, proportion meeting a fixed change, risks/relative risks, odds ratios). In addition, there will be a range of health outcomes reported, as well as a mixture of type of interventions,

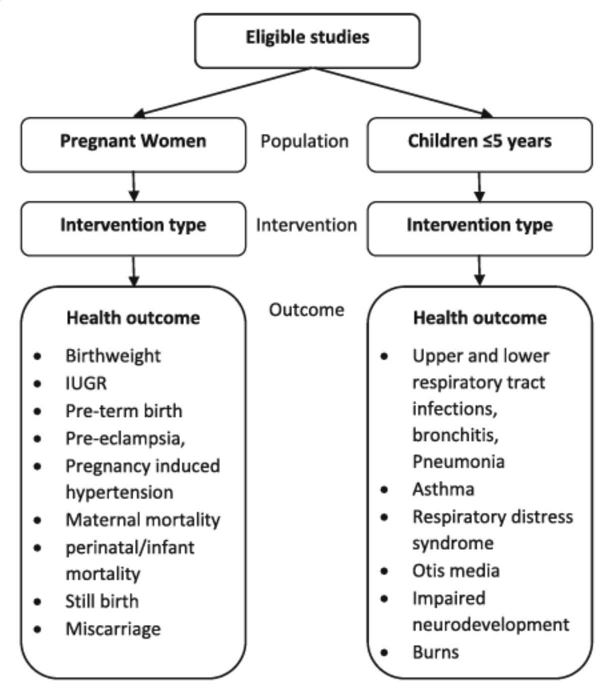

Fig. 1 Flow diagram of study grouping (population intervention outcome) for synthesis. *IUGR* intrauterine growth retardation

geographical regions and social contexts reported, which are likely to not be directly comparable.

Following on from the narrative analysis, meta-analysis will be considered within each triad, for each outcome measure, stratified by study design and the type of data available for the outcome. Clinical and methodological homogeneity within each triad will be used to determine the feasibility for meta-analysis where two or more studies in the same grouping report data in the same format at the same/similar time points. Any meta-analysis will be undertaken using a random effects model, due to an assumption that the studies represent a distribution of true effects. Determination of the level of between-study variation not attributable to chance will be calculated and displayed as an I^2 value with 95% confidence interval.

It is not anticipated that there will be more than a few studies in each meta-analysis, if even such an analysis is possible. The potential for additional sub-group analysis, sensitivity analysis or the assessment for the existence of small study effects using a funnel plot, will likely not exist. Risk of bias information will be used descriptively to contextualise the findings for each outcome whether a meta-analysis is undertaken or not. Recommendation for the improved conduct of studies in the field will be made.

Discussion

Alternatives to standard practices of household biomass fuel use for cooking, heating and lighting are required within LMICs to combat the morbidity and mortality presented by HAP, with implications for maternal and child health and sustainable economic development. National and local policymakers increasingly recognise the need for effective policy changes to mitigate the health burden associated with HAP exposure; however, there is a lack of evidence regarding affordable, effective and culturally acceptable interventions. This may restrict the progress of such changes, notably in countries which lack widespread access to mains electricity or gas for household cooking, heating and lighting, in addition to limits in transferability of effectiveness of interventions from one context to another. Harm mitigation approaches would bridge the gap before there is widespread affordable access to electricity or gas, but the efficacy of such an intervention requires evaluation. Therefore, this proposed review aims to report the contemporary scientific evidence concerning the effectiveness of HAP mitigation interventions to improve maternal and child health, thus identifying existing research gaps and informing future research and impact activities.

Appendix

MEDLINE Search strategy

Population

1 (Child* adj3 (young or pre school)).ti,ab. (72952)
2 child, preschool/ or infant/ (1228593)
3 (pregnan* or birth).ti,ab. (706117)
4 (neonat* or infant or perinatal or newborn).ti,ab. (517748)
5 exp Infant, Newborn/ (607223)
6 foetus.ti,ab. (7397)
7 Fetus/ (78154)
8 fetus.ti,ab. (64247)
9 (baby or babies).ti,ab. (69248)
10 exp Pregnancy/ or exp Pregnant Women/ (894010)
11 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10 (2660727)

Intervention

12 ((clean* or modern) adj7 (energ* or fuel)).ti,ab. (2920)
13 (renewable* adj7 (energ* or fuel)).ti,ab. (4618)
14 (polic* adj7 (energ* or fuel)).ti,ab. (969)
15 (chang* adj7 (energy* or fuel)).ti,ab. (23059)
16 exp Renewable Energy/ or exp Biofuels/ (31360)
17 ((solar or wind or hydro*) adj5 (energ* or power*)).ti,ab. (19581)
18 (behavio$r adj9 (fuel or cook* or vent*)).ti,ab. (2091)
19 (transition adj7 (energ* or fuel)).ti,ab. (8426)
20 (electricit* adj7 energ*).ti,ab. (932)
21 ((hous* or home or domestic) adj7 (energ* or fuel)).ti,ab. (2213)
22 low polluting fuel*.ti,ab. (3)
23 (air adj7 ventilation).ti,ab. (3055)
24 (air pollution adj7 intervention).ti,ab. (73)
25 chimney.ti,ab. (1420)
26 "outdoor cook*".ti,ab. (9)
27 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25 or 26 (93856)

Household air pollution

28 ((household or indoor) adj3 air).ti,ab. (6933)
29 (HAP or IAP).ti,ab. (11561)
30 exp Air Pollution, Indoor/ (13569)
31 exp Particulate Matter/ (62709)
32 ("particulate matter" or "black carbon").ti,ab. (19909)
33 exp Carbon Monoxide/ (17931)
34 "carbon monoxide".ti,ab. (26660)
35 ((solid fuel or wood or charcoal or cook*) adj3 smok*).ti,ab. (1071)
36 (cookstove or stove).ti,ab. (1014)
37 Cooking/mt [Methods] (2210)
38 Household Articles/ (2254)
39 exp "Cooking and Eating Utensils"/ (1231)
40 26 or 27 or 28 or 29 or 30 or 31 or 32 or 33 or 34 or 35 or 36 or 37 or 38 or 39 (222736)

LMICs

41 (LMIC or "lower adj3 middle income" or "developing countr*").ti,ab. (60345)
42 exp Developing Countries/ (74829)
43 exp Africa, Western/ or exp Africa, Northern/ or South Africa/ or exp Africa, Eastern/ or exp Africa, Central/ or exp "Africa South of the Sahara"/ or exp Africa/ or exp Africa, Southern/ (266418)
44 Africa.ti,ab. (109048)
45 exp South America/ (161665)
46 exp Asia, Central/ or exp Asia, Northern/ or exp Asia/ or exp Asia, Western/ or exp Asia, Southeastern/ (835914)
47 south America.ti,ab. (14583)
48 Latin America.ti,ab. (13762)
49 Asia.ti,ab. (59583)
50 (Afghanistan or Albania or Algeria or Angola or "Antigua and Barbuda" or Argentina or Armenia or Azerbaijan or Bangladesh or Belarus or Belize or Benin or Bhutan or Bolivia or "Bosnia and Herzegovina" or Botswana or Brazil or Burkina Faso or Burundi or Cabo Verde or Cambodia or Cameroon or Central African Republic or Chad or China or Colombia or Comoros or Democratic

MEDLINE Search strategy (Continued)

Republic of Congo or Congo or Cook Islands or Costa Rica or Cote d'Ivoire or Cuba or Djibouti or Dominica or Dominican Republic or Ecuador or Egypt or El Salvador or Equatorial Guinea or Eritrea or Ethiopia or Fiji or Gabon or Gambia or Georgia or Ghana or Grenada or Guatemala or Guinea or Guinea Bissau or Guyana or Haiti or Honduras or India or Indonesia or Iran or Iraq or Jamaica or Jordan or Kazakhstan or Kenya or Kiribati or Democratic People's Republic of Korea or Kosovo or Kyrgyzstan or Lao People's Democratic Republic or Lebanon or Lesotho or Liberia or Libya or Former Yugoslav Republic of Macedonia or Madagascar or Malawi or Malaysia or Maldives or Mali or Marshall Islands or Mauritania or Mauritius or Mexico or Micronesia or Moldova or Mongolia or Montenegro or Montserrat or Morocco or Mozambique or Myanmar or Namibia or Nauru or Nepal or Nicaragua or Niger or Nigeria or Niue or Pakistan or Palau or Panama or Papua New Guinea or Paraguay or Peru or Philippines or Rwanda or Saint Helena or Samoa or "Sao Tome and Principe" or Senegal or Serbia or Sierra Leone or Solomon Islands or Somalia or South Africa or South Sudan or Sri Lanka or Saint Lucia or "Saint Vincent and the Grenadines" or Sudan or Suriname or Swaziland or Syrian Arab Republic or Tajikistan or Tanzania or Thailand or Timor Leste or Togo or Tokelau or Tonga or Tunisia or Turkey or Turkmenistan or Tuvalu or Uganda or Ukraine or Uzbekistan or Vanuatu or Venezuela or Vietnam or "Wallis and Futuna" or "West Bank and Gaza Strip" or Yemen or Zambia or Zimbabwe).ti,ab. (1000461)
51 41 or 42 or 43 or 44 or 45 or 46 or 47 or 48 or 49 or 50 (1807589)

Grouped terms

52 11 and 27 (2227)
53 40 and 51 (25902)
54 11 and (27 or 53) (4306)

Abbreviations

ALRI: Acute lower respiratory infection; ARI: Acute respiratory infection; CENT RAL: The Cochrane Central Register of Controlled Trials; CO: Carbon monoxide; EPHPP: Effective Public Health Practice Project; GIM: Global Index Medicus; HAP: Household air pollution; ICS: Improved cookstove; ICTRP: International Clinical Trials Registry Platform; IUGR: Intrauterine growth retardation; LMICs: Low and middle income countries; LPG: Liquefied petroleum gas; RCT: Randomised control trial; PM: Particulate matter; PICOS: Population Intervention Comparator Outcome Study design; PRIS MA: Preferred Reporting Items for Systematic Reviews and Meta Analyses; PRISMA P: Preferred Reporting Items for Systematic Reviews and Meta Analyses Protocol; PROSPERO: International Prospective Register of Systematic Reviews; WHO: World Health Organization

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Authors' contributions

KEW and EDC initiated the aims and scope of the review under the supervision of SEB, GNT and SMH. Search strategy support was provided by AC. Methodological, support, advice and review were given by DJM. The manuscript was written by KEW and edited by EDC, DJM, GNT, SEB, FDP, SMH, RD, TO, BK, STM, TK, AS, WRA and DW. All authors have read and approved the manuscript for publication. GNT will be the guarantor for this review.

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Availability of data and materials

Not applicable, as no data was generated for this article

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Competing interests

The authors have no competing interests to declare.

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CHAPTER 4 RESULTS: SYSTEMATIC REVIEW: ARE INTERVENTIONS EFFECTIVE? CURRENT STATE OF EVIDENCE

The following chapter details the results from the systematic review, investigating the current state of intervention development within the literature for pregnancy and child health outcomes. The chapter was published in *Indoor Air* and is written in the style for publication in *Indoor Air*.

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CHAPTER 5 METHODS: QUANTITATIVE

This chapter gives a detailed account of the methods for the quantitative elements of the thesis, which draw together evidence for differences between cooking fuel type and cooking location; providing quantitative information on both the health benefits and potential unintended health consequences. The first section describes the methods for the quantitative health risk assessment for acute respiratory infection (ARI) for biomass fuel type (CHAPTER 6) and cooking location (CHAPTER 7) and malaria risk assessment (CHAPTER 8), using the DHS data. The second section details the primary data collection methods investigating the impact of the COVID-19 public health protection measures due to economic and market change and instability on cooking fuel switching (CHAPTER 9).

5.1 Quantitative methods 1: Health risk assessment – Acute Respiratory Infection

5.1.1 Introduction

Interventions to tackle high level of HAP from the burning of biomass include transition to cleaner fuels, by moving up the fuel ladder, using improved fuels, improving ventilation and reducing the level incompletion combustion by using improved cookstove.[31] Although harm prevention interventions (e.g., LPG, electricity), are the best long-term solution, there are multiple barriers (affordability, accessibility) of uptake of such an interventions in LMIC settings. Harm mitigation approaches are therefore required to bridge this gap in the context of sustained biomass usage, with behaviour change interventions (e.g., location of child while cooking, ventilation, cooking duration,[151] outdoor cooking) having the potential to reduce HAP levels.[152] In addition, interventions can have unintended consequences, which require attention when developing and deploying HAP interventions. For example, a charcoal ban restricts charcoal use, intending that more households would adopt cleaner fuels. However, such fiscal policies also risk unintended consequences, such as households switching to relatively more polluting but readily available fuels further down the fuel ladder such as wood.

Solid fuel exposure among preschool children is associated with pneumonia, but the role of specific pollutants is hard to determine due to a lack of standardised exposure measurements.[153] Two solutions to reducing HAP exposure are to restrict charcoal use and moving cooking outdoors,[26,110,154,155] but there remains a paucity of evidence regarding the potential health benefits of outdoor cooking and the potential health harms from banning charcoal. The only studies available comparing health events in wood and charcoal cooking households are three small scale community based cross sectional studies in Sub-Saharan Africa[156–158] showing an increased risk of ARI or respiratory symptoms with wood/crop residue cooking compared to charcoal cooking. Conversely, of the two published population based cross-sectional studies, one in Tanzania[159] and the other in Uganda;[160] only Uganda showed an increased risk of ARI with wood compared to charcoal cooking. On the other hand outdoor cooking compared to indoor cooking has been shown to be associated with reduced ARI in children under five residing in firewood cooking households, in one global cross-sectional analysis of DHS survey between 2004-2014.[161]

ARI in children under five years, a leading cause of mortality in children under 5 years old,[162] is known to be associated with HAP exposure,[23,163] with evidence from Nepal suggesting 39.8% of ARI is due to polluting cooking fuels[164] and comparisons in disease incidence for ARI being undertaken between cleaner and solid biomass fuels,[165–168] including kerosene;[169,170] but there remains paucity of evidence at global scale and comparing different biomass fuel types. The occurrence of ARI is also affected by individual characteristics such as HIV status[171] and poor nutrition;[172] in addition to household and socioeconomic factors such as poor ventilation,[173] outdoor cooking,[174] poor maternal education, passive smoking,[171] poverty[175] and crowding.[176]

The routinely collected DHS data is designed to collect monitoring and health impact data on population, health and nutritional determinants, using a standardised questionnaire, at a population level. The DHS data has often been used as a data source for assessing health outcomes with cooking practices due to its widespread and nationally representative coverage and range of health data collected. Previous literature has looked at the association of childhood mortality, stillbirth, birthweight,[177] stunting and blood pressure in adults,[178] with cleaner and biomass fuels. The investigation of ARI in children is a useful outcome to study due to the higher level of reporting than other health outcomes and that the events occur in the two weeks prior to the interview. Studies investigating ARI have highlighted important confounding factors at an individual country level which include, child's age, receipt of vitamin A,[179] season[180] and improved water supply.[181] In addition, educational attainment and wealth have been seen as protective effects,[55,181] however, the effect of wealth was not seen in an analysis of the Afghanistan 2015 DHS-VII data.[182] Among these studies, at country level there were varying confounders (e.g., paternal education, mother's smoking status, breastfeeding and birthweight), and varying difference in ARI definitions, this in part is due to DHS altering their definition from short rapid breaths and cough in phase V-VI, to short rapid breath and problems with chest from phase VII onwards;[183] but also other definitions were used. The change in definition results in a lack of comparability between studies but provides a unique opportunity for provision of new evidence outlining the relationship between biomass fuel usage and of risk of ARI and severe ARI. Within the literature DHS data has been used in two studies to assess ARI at a multi-country level, to the best of the author's knowledge, providing scope for extending the evidence base at a multi-country level. The child, mother and household characteristics of ARI of 40 DHS stage V surveys were assessed previously,[105] but failed to take into account environmental risk factors such as biomass burning and household smoking. The association of ARI with cleaner and dirty fuel was also assessed for sub-Saharan Africa.[180]

Despite these limitations of ARI as an outcome, ARI reduced the potential for recall bias due to the respiratory symptoms occurring two weeks prior to the interview, high data availability, mother likely to report symptoms and not based on cumulative exposure, when compared to other potential health outcomes (e.g., birthweight, stillbirth and mortality). However, there is the potential to use other DHS health outcomes (Table 5.1) and these have been documented within the literature, but are subject to measurement bias, recall bias, or have high levels of missing data, which could reduce the power of the analysis.

Table 5.1 Rationale for not using alternative health outcomes to ARI

Health outcome	**Rationale**
Birthweight	Birthweight was obtained by maternal recall, reporting two measures: (i) weight in in grams and (ii) relative size (very large, larger than average, average, smaller than average, or very small); an additional note is made where a health card has corroborated the birthweight.[183] However, birthweight is subject to recall bias, especially with older children, as well as measurement bias, as the scale or instruments used cannot be verified; and also favour those who accessed healthcare. Reporting the size of the child is also subjective and requires the mother to have prior knowledge. Finally, a global variation with birthweight due to ethnicity[184,185] and other confounding factors,[186] results in difficulties in drawing substantive conclusions at a global scale. In addition, birthweight is subject to knowing the fuel type used across the whole of the pregnancy and birth period, resulting in potential misclassification of exposure if cooking fuel or location has changed overtime.
Stillbirth and pre-term birth	Within the birth history, women were asked to report if they have ever had a termination, with a stillbirth being defined as pregnancy loss after seven months.[183] Women were also asked to report the week of gestation the child was born in. Both measures are subject to women knowing and recalling accurately the weeks' gestation at which these events have occurred; with better reporting in those women who access pre-natal healthcare. In addition, there may be underreporting due to the stigma associated with miscarriage and stillbirth.
Nutritional status	Investigation into the association with HAP and child nutritional status has been widely undertaken using the DHS dataset.[187–192] Although the DHS has standardised protocols for taking anthropometric measurements they are not always collected or have large amounts of missing data [193].
Mortality	Neonatal, infant and child mortality and cooking fuel type has been widely explored using the DHS data.[194–202] Although an analysis using mortality could have impact, there are fewer cases of mortality compared to ARI. In addition, deaths can occur over a range of time prior to the interview but cooking fuel is recorded at time of interview.

Two sets of analysis were therefore undertaken using DHS datasets to investigate relationships with ARI, one for evaluating the differing ARI risks between biomass fuel type and the other cooking location. A multi-country approach was taken to increase the power of the study through a large sample size and create a study that has more impact than a single country study. The methods have been reported together to save duplication of information and any differences have been clearly marked.

At a multi-country level, using data obtained from the DHS, these analyses aim to:

1. Assess the association of under-five respiratory health (respiratory symptoms, ARI, severe ARI), with wood and charcoal, within low- and middle-income countries.
2. Assess the contextual and household determinants of cooking location at a household level, within SSA.
3. Assess the association of under-five respiratory health (respiratory symptoms, ARI, severe ARI), with cooking location, within SSA.

By investigating children under five, it reduces some of the uncertainty around impact of cumulative exposure. In addition, this study takes a novel approach to assessing the symptom of ARI separately, along with assessment of ARI and severe ARI, which will give an indication of the gradient of the benefit of the assesses potential interventions. A reduction in ARI would contribute to reducing morbidity and mortality in children under five years old, supporting the achievement of the sustainable development goal 3 of ending preventable death of new-borns and children under-five.[203]

5.1.2 Methods

5.1.2.1 Data sources

Routinely collected data from the DHS program is freely and publicly available from participating countries.[204] Representative country samples were collected through two-stage stratified sampling where clusters were determined from Enumeration Areas (EAs) based on the previous census and a random proportional sample of households taken from the cluster.[183] Residential households were selected and eligible participants (ever-married women and men age 15-49, who resided in the household the night before the survey) were approached for interview; resulting in a hierarchical data set (Figure 5.1). Excluded from the sample were non-response households at time of data collections and institutional living arrangements (e.g., boarding schools, police camps, army barracks, and hospitals).[183] The standardised questionnaires contained core questions with additional country specific questions to suite the characteristics of the country; which does create variability in available variables from differing countries. Within each country the questionnaires were translated into the main language(s) required within the planning stage and prior to data collection commencing. The questionnaires were also back-translated to maintain validity of questionnaire. "Pre-test" data collection (approx. 100-200 households) was undertaken to check translation of questionnaire, skipping pattern of questions and confirming the interviews and supervisors' manuals are suitable. All surveys and data entry were completed by trained local data collectors, supervised by government agencies and health authorities, who were trained by the United States Agency for International Development (USAID) in a standardised approach. The data from each individual country is provided within separate files called recodes (Table 5.2), which were based content on the household's, woman's and man's questionnaire. Some variables are not present in all recodes therefore some data merging was required to obtain all necessary variables.

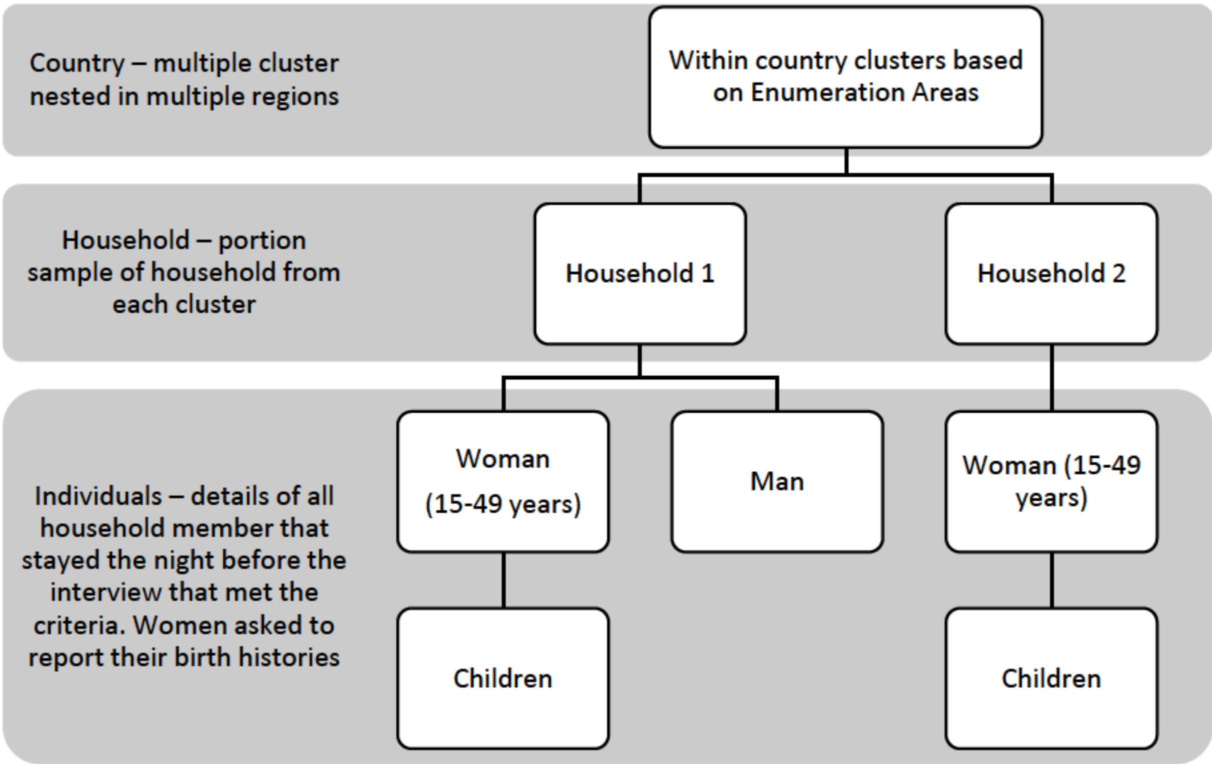

Figure 5.1 Structure of the DHS dataset, adapted from The Guide to DHS statistics [183]
Household level data was used to determine the social determinants of outdoor cooking, whereas individual child level data was used for the determinants the association with ARI.

Table 5.2 Details of the data files available from the DHS online archive

Recode	Data contained in the recode and its structure
Households recode	Each data observation contains information of each household including: household composition, socioeconomic status, cooking fuel, number of household members, region and household level indicators.
Women recode	Each woman interviewed makes up each line of the data set containing information on: Woman's health, birth history (up to 20 births), child health information (up to 6 children), domestic violence questions, education status, employment, fertility preferences, family planning, marriage and sexual activity, anthropometry and anaemia, HIV/AIDS, adult and maternal mortality, malarial prevention.
Birth recode	Every live birth from the women interviewed within the past five years makes up a separate observation containing birth information, whether the child is still alive, pre and postnatal care.
Child recode	Every child alive at the time of interview is a single observation with the recode which contains information on child health (repository symptoms, diarrhoea treatment, and malaria), vaccination status, nutritional status, anthropometric measurements and birth information.
Man recode	Each man interviewed makes up each line of the data set containing information on: education status, employment, HIV/AIDS, domestic violence questions, fertility preference, family planning and marriage status
Person recode	Every household member makes up a single observation and includes basic demographics (e.g., sex, age, education) as well as relevant bio-marker information (i.e., malaria, HIV and anaemia testing result) and household characteristics.
Geographic data	Global Positioning System (GPS) data for each cluster containing latitude, longitude and altitude details.

The DHS data provides data that is of a large sample size and nationally representative; however, like any cross-sectional routinely collected data there were factors (e.g., missing data and variables) that need to be taken into consideration at the analysis stage. Due to the global approach, missing data varies between countries due to differing cultures, situational contexts and scope of the survey; therefore, each country will need to be assessed individually. In addition, the DHS is adapted over time in phases of five years, which allows for survey development and survey scope, however, reduces the ability to compare the original phase survey with more recent surveys. Finally, many of the variables are self-reported within the survey and would be subject to recall bias; and will need to be taken into consideration at the interpretation stage.

For these cross-sectional study within the thesis, the most recent survey for each country which has occurred within the last 10 years (i.e., after 2010) was identified, which will include Phase VI, VII and VIII of the DHS Program models; surveys with restricted access datasets to be excluded (n=0 – post 2010); with variables extracted from the household, woman and children recodes. The remaining surveys were investigated for the presence of the outcome and exposure variables, and excluded if one of the variables is missing or there are low cell counts (<5) in the 2 by 2 cross tabulation; preventing an analysis of logistic regression.

5.1.2.2 Outcome variables

5.1.2.2.1 Cooking location

Each survey has a question on the self-reported location of cooking (inside the house, in a building detached from the house and outdoors). For the purpose of the cooking location analysis cooking inside the house and in a building detached from the house was combined to form an indoor cooking variable, to form a binary outcome variable (indoor, outdoor).

5.1.2.2.2 Health Outcome: Respiratory symptoms, ARI and Severe ARI

Mothers were asked to report the presence of cough, shortness of breath and fever among their children aged under five years, occurring in the two-week period prior to the survey. To assess ARI and severe ARI, a composite measure of the respiratory symptoms was created. ARI was defined as having shortness of breath and cough;[105,173,182,205,206] blocked and stuffy nose was not included to distinguish between upper respiratory tract infections such as common colds and coughs[207] with acute respiratory infection. The WHO[208] and other clinical definitions[209] are varied in regards to the use of fever within the clinical definition. However, it was recognised that fever is an important factor in the severity of an infection, due to a systemic inflammatory response;[205] therefore, a composite measure for severe ARI (shortness of breath, cough and fever)[210] was used in conjunction with ARI. All five (shortness of breath, cough, fever, ARI and severe ARI) of these health outcome variables were modelled as binary outcomes (yes, no).

5.1.2.3 Measures of HAP exposure

5.1.2.3.1 Difference between wood-charcoal cooking analysis

Exposure to HAP was determined through fuel use, with each house reporting the main cooking fuel (electricity, LPG, natural gas, biogas, kerosene, coal/lignite, charcoal, wood, straw/shrubs/grass, agricultural crop, animal dung). Those children who live within wood and charcoal cooking households were extracted, to use as a proxy exposure measure.

5.1.2.4 Cooking location analysis

Households using solid biomass fuel cooking fuel (kerosene, coal/lignite, charcoal, wood, straw/shrubs/grass, agricultural crop, animal dung), were extracted, with location of cooking (indoor and outdoor) being used a proxy exposure measure.

5.1.2.5 Modified wealth index

The wealth index is a composite measure calculated through principal component analysis (PCA) into five relative wealth categories and is composed of wealth factors including household asset (e.g., possession of bike, radio) and utility services (e.g., sanitation and access to water, housing material, cooking fuel).[211] However, as the "exposure of interest" is cooking fuel, there is the potential for under inflation of the effect estimates due to circularity.[212] As wealth is an important indicator of both the outcome and exposure of interest it was necessary to include it within the analysis, therefore a new modified wealth index[213] with SPSS[214] was created at a country level using the step provided by DHS, to remove cooking fuel as an indicator variable. These steps included:

1. **Indicator construction**: Creating categories and standardising binary variables.
2. **Factor analysis of common variables:** Undertaken after eliminating of indicator was no variation, for the whole dataset.
3. **Factor analysis of urban areas:** Repeating step two but for urban areas only.
4. **Factor analysis of rural areas:** Repeating step two but for rural areas only.
5. **Estimation of composite wealth score:** Run rural and urban regression with the common factor score as the dependant variable and using these and the common factor analysis to create a combined score.
6. **Wealth qualities calculation:** Using household weights and the number of household members to create a weight score for number of household members, divide the factor score into five quintiles.

Indicator variables included within the PCA differed by country but broadly encompass four areas: (i) assets; (ii) housing material; (iii) source of drinking water; (iv) toilet facilities (Table 5.3). An explanation of the effect of the modified wealth index on the overall effect estimates, compared to the provided wealth index are detailed in Appendix 1.

Table 5.3 Modified wealth index PCA included indicator variables

Area	Indicator variable
Assets	• Main assets: electricity ratio, television, refrigerator, watch, bicycle, motorcycle/scooter, animal-drawn cart, car/truck, boat with a motor, bank account, mobile telephone, computer • Other assets: non-motorised boat, tractor, plough, household furniture,* household electronics,* other assets.*
Housing material	• Roof material • Wall material • Floor material
Source of drinking water Toilet facility	• Household's source of drinking water • Type of toilet facility • Shared toilet facility with other households

*Household furniture (e.g., table, chairs, wardrobe, bed, mattress, lamps, clock)
Household electronics (e.g., washing machine, DVD player, internet, modem/router, satellite, laptop, generator, music system, sewing machine, fan, air conditioning, solar panel, water pump, battery, iron, TV5 antenna, Cable subscription, camera, blender, microwave)
Other assets (e.g., Grain mill, hammer mill, Rickshaw/Chingchi/Tuk Tuk/Htawlargyi/Keke Napep/Bagag, bank account with another institution, credit union, beneficiary of Pantawid Pamilyan Pilipino Program (4Ps), canoe with motor, banana boat, thresher, bedroom available for sleep, floor area of house, dwelling window material, lighting fuel, refused collection, own/rent house)

5.1.2.6 Explanatory variables

Covariates (Table 5.4), where available, were modelled as categorical variables and include individual child, maternal, and household characteristics. In addition, to detailing potential confounding factors that are not possible to include in this analysis, due to lack of reported data, issues with measurements methodology or a large global variation. The results for the social determinants of outdoor cooking informed the variables which were included in the outdoor cooking analysis.

Table 5.4 Details of included and excluded variables including categorisation and epidemiological and biological relevance to the health outcome.

Variable	Categories	Relevance	Contextual and household determinants	ARI	
				W/C	I/O
Individual Child characteristics					
Age	0-11, 12-23, 24-35, 36-48, 48-59 months	The incidence of ARI has been previously reported to decrease with age, due to pulmonary physiology and immune system development[179,215] and potential higher exposure to environmental factors in children ages 2-3 years.[216]	✗	✓	✓
Sex	Male, Female	Boys have previously been shown to be at greater risk of ARI that girls.[160,216]	✗	✓	✓
Mode of delivery	Caesarean, Vaginal	Vaginal deliveries introduced bacteria to the child, thus increasing the immune system to be able to fight infection. Children from caesarean deliveries do not have their immune systems primed and therefore are at greater risk of gaining infections.[217]	✗	✓	✓
Birth order	Frist born, Not first born	Women report all the children from all live births in order, therefore children can be categorised into first born or not first born. Birth order confounds birthweight, along with first born having a greater risk of ARI.[218]	✗	✓	✓
Birthweight	Low, Not Low	Low birth weight was defined as <2500g[219] and is known to increase the risk of respiratory infections in children under five.[220] The DHS data has two birthweight variables, maternal recall of size approximation at birth (very small, smaller than average, average or larger, don't know/missing) and maternal recall of actual birth weight (g). Actual birth weight was used due to the high potential for misinformation bias among size approximation both from maternal recall and differing perception globally of appropriate size at birth.[221]	✗	✓	✓

Breastfeeding status	Ever, Never	Mothers are asked to report if they "ever breastfed, not current", "never breastfed" or "still breastfeeding" their child. Breastfeeding has an important protective effect against ARI[222] and ARI induced from air pollution[223] and mortality,[197] breastfeeding is collapsed to ever breastfed (current or previous breastfeeding) and never breastfed, to prevent low cell counts in previous breastfeeding status.	✗	✓	✓
Vitamin A supplementation in the last 6 months	Yes, No	Vitamin A deficiency increase the risk of infection and death[224] and is also a risk factor of ARI.[172] However, diagnosed Vitamin A deficiency is not available within the DHS dataset therefore Vitamin A supplementation provides a proxy for deficiency.	✗	✓	✓
Iron supplementation	Yes, No	Iron is required for an effective immune response but deficiencies in iron is high in LMICs.[225]	✗	✓	✓
Maternal characteristics					
Age of mother (ARI analysis only)	15-24, 25-35, 36-49 years	Age is an important factor that affects decision-making, as older adults are more likely to have prior experience, but younger adults have received different education.	✗	✓	✓
Age of household head (Social determinants analysis only)	>20, 21-30, 31-40, 41-50, 51-61, 60+ years		✓	✗	✗
ARI analysis: Mother's highest attained education Social determinants analysis: Head of household's education level	None, Primary, Secondary/ higher	Women self-reported level of education (no education, primary, secondary and higher education). Household head education was reported by the woman responding to the main household survey. However, due to the low number of participants reporting higher education a composite category of secondary and higher education was created.	✓	✓	✓
Household characteristics					
Number of household members	≤6, >6	The crowding of a household is a known risk factor for ARI;[176] however, as the measurements of the house were not taken in the survey a crowding index could not be calculated. Therefore, number of household members was used as a proxy for household crowding.	✓	✓	✓

Household smoking	Yes, No	Second hand smoke exposure is another risk factor but also an alternative source of household air pollution.[226–228] Household smoking is covered in the household surveys, asking if any member of the household smoked and the frequency (daily, weekly, monthly, less often than once a month or never). Due to the low number of occasional smoking, the smoking categories was collapsed to Yes, No.	✓	✓	✓
Cooking location	Biomass fuel type analysis = Indoors, Outdoors Cooking location = Indoors, In a separate building, Outdoors	Cooking location effects[174] the level of exposure to HAPs, therefore represents an alternative exposure. Women reported if the cooking was undertaken inside the house, inside in a building detached from the house or outside.	N/A	✓	N/A
Cooking fuel type (cooking location analysis)	Coal/lignite, charcoal, wood, Other biomass (straw/shrub / grass, agricultural crop, animal dung)	Self-reported household biomass cooking fuel at time of interview was used, and split into four categories. Choice of cooking fuel can influence the level of HAP exposure, with increasing exposure higher up the fuel ladder.[38]	✓	N/A	✓
Modified wealth index	Lowest, Low, Middle, High, Highest	Wealth is an important covariate, as wealth equality leads to improved child health outcomes,[229] as well as being able to afford more expensive and cleaner cooking fuels.[230] The lowest category is the poorest and the highest category is the richest.	✓	✓	✓
Type for residence	Rural, Urban	Urban and rural locations often have differing fuel, cooking behaviours[231,232] and previously reported ARI risk differences;[158,160] along with urban areas having higher ambient pollution,[233] which is another potential air pollution exposure which needs to be accounted for.	✓	✓	✓

Altitude	Not High, High	Higher altitude locations have a greater level of rainfall and lower temperatures, therefore households less likely to cook outside. Altitude was recorded as a continuous variable, with any value greater than 2500 m being defined as high altitude.[234]	✓	✗	✓
Woman empowerment	Empowered, Not empowered	Women empowerment is a composite measure where women make or are included in decisions regarding healthcare, visiting family and money, as defined by the DHS.[183]	✓	✗	✓
Country/regional level					
Season (some countries have regional variation which has been accounted for)	Wet, Dry	Data on season for each countries was obtained for the Central Intelligence Agency (CIA) factbook[235] and the World Bank climate change knowledge portal.[236] Season influences both ARI[180] and HAP levels.[237]	✓	✗	✓
Excluded variables					
Nutritional status	Although nutritional status is a risk factor for ARI,[172] the only metric of nutritional status within the DHS data set is height and weight from which z score for stunting, wasting and underweight can be calculated. Stunting and underweight capture different dimensions of nutritional status,[238] however, if used in conjunction in the same model may run the risk of high collinearity. However, not all children have these measurement taken, along with implausible ranges reported causing poor quality data in many DHS countries,[193] often in just a minority of surveys.[239]				
Floor, wall material and WASH facilities	Due to these variables being used to determine the wealth index, there is the potential for issues with collinearity within the models.				
HIV, TB status	Comorbidities such as HIV and TB[171] are risk factors for ARI, however, such data has not been collected among children in the DHS survey				

Abbreviations: W/C = Wood-Charcoal: Biomass fuel type analysis. I/O = Indoor-outdoor: Cooking location analysis. WASH = Water, sanitation and hygiene, TB = Tuberculosis, HIV = Human immunodeficiency virus

5.1.2.7 Dealing with missing data

Missing data in the variables in the dataset was investigated to ascertain if the data is missing completely at random (MCAR), missing at random (MAR) and missing not at random (MNAR). Data that is MCAR or MAR and less than 50% missing[240,241] underwent multiple imputation, at a country level, using the MICE package[242] in R studio. The MICE package uses multivariate imputation by chained equations, which can be used with a low number of iterations (10-20);[242] and cycles through each variable individually, providing the ability to handle different data types.[243] However, the maximising number of iterations minimises the impact of imputation variability,[244] therefore 50 iterations was used, which coincides with the maximum percentage missing[244,245] of 50%. As the data was categorical the following method commands in MICE were used: logreg (Logistic regression) for binary data, polyreg (Multinomial logit model) for categorical data >2 levels and polr (Ordered logit model) ordered, categorical data >2 levels.[242] Proportion of missing variables for variables that contains missing values are documented in Appendix 2 by each country.

5.1.2.8 Data analysis and presentation of results

All data management, manipulation and analysis was undertaken in R studio.[246] Descriptive statistics will include a number of cases (n) and percentage (%) for each categorical outcome variable for the combined dataset, presented in table format, before imputation. Due to the complex sampling strategy (as describes in 5.1.2.1), multivariable logistic l regression was undertaken using the survey package[247] in R studio, using individual sampling weight, household and cluster primary sampling units (PSU); adjusting for individual, household, regional and country level confounding factors.

5.1.2.8.1 Biomass fuel type analysis: ARI analysis

Proportion (%) of fuel use by country was presented graphically as a stacked bar chart by country. Confounders incorporated in the logistic regression model include: age of child, sex of child, birth order, mode of delivery, breastfeeding status, mothers age, mother's education, wealth, location of cooking, household smoking status and rural/urban. Each country will initially be analysed separately, with the risk estimate for health outcome by cooking fuel use populated on a forest plot and presented graphically. The overall estimates for the combined dataset were calculated in a single multivariable logistic regression model. Separate exploratory analyses were undertaken with household smoking, breastfeeding and birthweight due to entirely missing covariates in some countries to investigate the role these covariates have on the overall effect estimate for cooking fuel type. A further stratified analysis was undertaken of rural and urban status and indoor and outdoor cooking status, separately, due to differing fuel, cooking behaviours presenting HAP exposure differences[231,232] and previously reported ARI risk differences;[158,160] along with urban areas having higher ambient pollution.[233] The role of gender was explored as an exploratory analysis, the results of which can be found within Appendix 3 of the thesis. However, an exploratory analysis by age group (years) could not be explored due to low cell counts after the data had been subsetted for each of the individual age categories.

5.1.2.8.2 Cooking location

5.1.2.8.2.1 Contextual and household determinants

Proportion (%) of outdoor cooking was displayed as a heat map by country. In the multivariable model of the pooled dataset, included confounders were head of household's age, head of household's education, wealth, rural/urban residence, number of household members, wealth, type of biomass cooking fuel, season. A further exploratory analysis where altitude is available was undertaken and a stratified analysis by rural, urban, east, west, south and central Africa was undertaken, to investigate the effect on location within SSA on the determinants of outdoor cooking.

5.1.2.8.2.2 ARI

The same methodology as the biomass fuel type analysis in section 5.1.2.8.1 was employed to determine the association between indoor and outdoor cooking. Three additional variables were added including season, female empowerment and cluster altitude (exploratory analysis only). Further exploratory analyses included were for: breastfeeding, birthweight, altitude and smoking, based on the rationale provided in section 5.1.2.8.1.

5.1.2.9 Ethical considerations

Ethical approval for the primary data collection was gained from the country's relevant government authority.[183] Data was subsequently anonymised and aggregated to be made publicly available with authorisation from the DHS online data archive.

5.2 Quantitative methods 2: Unintended consequences – Malaria

5.2.1 Introduction

Any potential complex health promotion intervention can have unanticipated or negative consequences directly linked to the deployment and use of the intervention; including health (physical, psychosocial - e.g., stigmatisation around cooking cessation), environmental, economic and cultural impacts.[248] Therefore, there is a need to understand unintended consequences within the development of any interventions to resolve or mitigate against any negative consequences, thus improving the potential success of an intervention. Adverse health events as a result of HAP interventions within trials are often not included as an outcome, leading to under reporting; therefore, there is a reliance on anecdotal and observational evidence for potential adverse events. Within the target population these perceived adverse events linked to HAP interventions, present barriers against uptake and sustained use, whether or not they are founded judgments. Some interventions, such as LPG stoves, are perceived to increase the risk of burns and explosions,[129] despite evidence to the contrary.[249] ICS have been shown to decrease the risk of burns[250] but there is some evidence (potentially a false positive) from an ICS RCT in Malawi that interventions increase malarial risk.[251] Of those studies that have evidence for adverse events, the interventions are predominantly ICS and LPG, resulting in a paucity of evidence of unintended consequences, one of which is malaria, especially within behaviour change HAP interventions.

The evidence around domestic biomass fuel use and mosquito repellence is limited, often small scale and anecdotal evidence; however burning certain types of plants has been proven to repel mosquitos, with ‘Churai’ specific to Western Africa.[252,253] Therefore it is unsurprising that biomass cooking smoke has been cited by women to deter mosquitos and is seen as favourable to help protect again malarial infection,[254,255] arborvirus and other diseases which use mosquitos as a vector; despite the health harms presented by exposure to HAPs. Malarial prevention strategies encourage behaviours which deter mosquitos but also prevent mosquito reproduction; including housing improvements, closing of windows and eve spaces;[256] which is counter intuitive to some HAP interventions.

The evidence around the impact of HAP interventions and risk of malarial infection is limited; due in part to a reduction in mosquitos and does not necessarily mean a reduction in malarial infection as biting events can occur outside of the home. In Africa studies have shown that there was no increase in malarial infection or mosquito levels with biomass burning;[252] however, these are all small studies, underpowered and locally driven. Conversely, HAP has been shown to reduce arboviral cases in Guatemala.[257]

Due to the paucity and mix of evidence, this study aims to, using available data form Sub-Saharan DHS data at a multi-country level, assess malarial risk in children under five years with:

1. Biomass fuel usage - Cleaner cooking compared to biomass cooking
2. Biomass fuel type - Wood cooking compared to charcoal cooking
3. Cooking location – Indoor cooking compared to cooking in a separate building and outdoors.

This large-scale novel approach to assess the role household air pollution plays on the risk of malarial infection, would shed light on the potential impacts HAP intervention deployment may have on malarial risk. Understanding this risk is particularly prevalent within SSA which has the higher rate of biomass cooking fuel usage[7] and malarial prevalence.[258]

5.2.2 Methods

5.2.2.1 Data sources

The DHS dataset, detailed in section 5.1.2.1, was used for those surveys that had undertaken the optional malaria modules, in addition to the Malaria Indicator Survey (MIS). The MIS is an interim survey often undertaken within the high malarial transmission season, within 19 countries, specifically investigating malarial prevention behaviours, treatment of children under five with high fever and diagnostic testing for malarial infection. The MIS uses the same sampling and data collection methodology as the DHS. Questions include the use and presence of ITN bed nets, household sprays, preventative treatments, type and timing of treatment of children under five with high fever, diagnostic test for malarial infection and anaemia for both children under five and pregnant women; including relevant background details. For both datasets, the relevant information is held within the Person's recode file (see Table 5.2).

Fieldworkers are trained to undertake malaria rapid diagnostic tests (RDT) on children aged 6-59 months within an eligible household; which involves taking a sample of blood from the child's finger and placing it into the well of the test device along with assay diluent to detect malaria antigens within 15 minutes, using SD BIOLINE Malaria Ag tests. Within the MIS the RDT was undertaken on all children with parental or guardian consent; whereas only a sub-sample were approached for a malaria test within the main DHS survey. In addition, not all surveys undertook a blood smear (n=11) for microscopy to gain a malarial diagnosis alongside the RDT (n=17). Diagnosis of malaria by RDT and microscopy have differing specificity, sensitivity and positive predictive values Table 5.5, therefore both have been included within the analysis.

Table 5.5 Specificity and sensitivity of malaria diagnosis by RDT and microscopy

Criteria	Specificity (%)	Sensitivity (%)	Reference
RDT	96.9	94.3	[259]
Microscopy	97.9	95.7	[260]

The DHS and MIS dataset does not contain information on malaria endemicity, therefore details were gained from The Malaria Atlas Project,[261] which maps out malaria to support malaria control planning at national and international levels. Raster maps containing the average malaria prevalence across the course of a year, to 4.5 km^2 grid squares were downloaded for each corresponding country and year of included studies. Cluster geolocation for each survey is available as a point shape file, with each cluster location offset to prevent identification of individuals. Urban clusters are offset at a random angle by 0-2 km and rural by up to 0-10 km.[262] The malarial prevalence assigned was assigned to each cluster using the Spatial analyst tool in ArcMap 10.7,[263] where the corresponding raster value at each cluster point was obtained. The cluster malarial endemicity data and cluster altitude information, were exported into excel, and subsequently merged within the Person's recode file in R studio for each country separately.

5.2.2.2 Outcome variables

Available results of the malaria RDT and microscopy, were positive, negative, unconfirmed or missing. Unknown or unconfirmed values were assigned to missing and the results were modelled as a binary (negative, positive) outcome variable.

5.2.2.3 Proxies for HAP exposure

Three separate analyses were undertaken for the differing HAP exposure proxies.

Biomass fuel usage: This binary variable was categorised from type of cooking fuel. Cleaner fuels were defined as electricity, LPG, natural gas, biogas and biomass fuel were defined as kerosene, coal/lignite, charcoal, wood, straw/shrub/ grass, agricultural crop, animal dung. Kerosene is classified as a polluting fuel, as defined by the WHO[17] (2016), however, it is worth noting that some previous studies using the DHS to investigate HAP has defined kerosene as a cleaner fuel.[264]

Biomass fuel type: Data for children who reside in wood or charcoal cooking households were extracted for this analysis, with cooking fuel (wood, charcoal) being modelled as a categorical variable. Charcoal is higher on the fuel ladder due to being relatively less polluting than wood.[156,265]

Cooking location: Only biomass fuels (coal/lignite, charcoal, wood, straw/shrub/ grass, agricultural crop, animal dung) were included within this analysis, due to the nature of cleaner cooking (e.g., electricity, LPG) more likely to be done inside the house as a result of the equipment and resources required. Cooking location is a categorical variable using the pre-defined categories set out by DHS, which include 'inside the house', 'in a separate building' and 'outdoors'. Cooking inside the house was used as the reference category for all analyses.

5.2.2.4 Explanatory variables

Co-variates have been included for the epidemiological and biological importance, however, not all variables could be included due to high level of missing data or the questions not being asked within the MIS. Table 5.6 shows the included variables, rationale for inclusion and level within the hierarchical structure. All variables are categorical apart from altitude which is a continuous measure in meters (m).

Table 5.6: Details of included and excluded variables with categorisation and epidemiological and biological relevance to the health outcome

Variable	Categories	Relevance
Individual child level variables		
Child's age	<1, 1, 2, 3, 4 years	Children of differing ages will have different activity patterns and therefore susceptibility to being bitten by mosquitos. Increasing age has been shown to increase the risk of malarial infection.[266]
Child's sex	Male, Female	
Birth order	First born, Not first born	
Slept under mosquito net last night?	No, Yes – ITN, Yes – untreated net	Sleeping under a bed net, especially an ITN is protective against malarial infection.[267]
Household level variables		
Cooking fuel†	Coal/lignite, charcoal, wood, other biomass (straw/shrub/grass, agricultural crop, animal dung)	The differing types of cooking fuel emit different HAP concentration, thus effecting the levels of smoke within the households.[38]
Number of household members	≤6, <6	The number of household members, a proxy for crowding and is strongly linked to increased malarial infection,[268] sometimes due to multiple family member sharing one bed net.
Household smoking	Yes, No	Household smoking is an alternative source of HAP [269] but it is also a health-related behaviour.[17]
Cooking location†	Indoors, In a separate building, Outdoors	Cooking location effects the concentration of HAPs, with lowest exposure being out in outdoor cooking followed by cooking in a separate building.[26,270] A separate kitchen has previously been shown to decrease the risk of malarial infection.[271]
Modified wealth index	Lowest, Low, Middle, High, Highest	Wealth influences both cooking fuel choice, household characteristics and malarial risk.[266,268] (see 5.1.2.5 for detail on how the wealth index is formed)
Regional/ country level variables		
Place of residence	Rural, Urban	Rural and urban areas have differing individual and situation characteristics including: cooking behaviours,[231,272] access to education and health care,[273] WASH facilities[274] and levels of standing water.[275] Rural areas have previously been shown to increase the malarial risk.[268,276]
Malaria endemic	Mesoendemic, Hyperendemic, Holoendemic	Areas with high malarial endemicity are going to have a higher incidence of malarial infection. (See section 5.2.2.1 for further details)
Altitude	Meters above sea level	There is a strong correlation between higher altitudes and lower level of mosquitos, due to

		higher climates having lower temperatures; with malarial risk decreasing with altitude.[266]
Season	Wet, Dry	There is a higher malarial prevalence within the wet season, due to greater availability of water sources.[277] In addition, cooking location is also affected by season, with outdoor cooking less likely to occur within the wet season.[249]
Excluded variables – in addition to those documented in Table 5.4		
Stagnant water	Stagnant water provided a breeding site for mosquitos and living near stagnant water increases the malarial risk.[267,271,275,278] However, this information was not available within the survey.	
Animals sleeping in the house, opening windows, eve spaces	Keeping animals in the house and housing characteristics[266] have been shown to increase the risk of malarial infection, however, these questions were not asked within the survey.	

Notes: † included where the variable is not the exposure variable; ITN – insecticide treated net, WASH - Water, sanitation and hygiene

5.2.2.5 Dealing with missing data

The same method for dealing with missing data, detailed in section 5.1.2.7, was also used within this analysis.

5.2.2.6 Data analysis and presentation

Descriptive statistics, for the combined non-imputed data set were presented as the number of observations (n) and percentage (%) for categorical variables, and median and interquartile range (IQR) for continuous variables, in table format. Multivariable logistic regression accounting for the complex sampling strategy was undertaken using the survey package[247] in R studio, adjusting for relevant individual, household and regional confounding factors (Table 5.6). Analyses were undertaken at a country level and combined dataset, for each HAP proxies and presented graphically in a forest plot. Due to the missing data in the MIS dataset with cooking location and household smoking, an exploratory analysis of countries with available data for these two variables was undertaken, to investigate the effect on the outcome variables; as those two variables influence the level of HAPs. Sub-analysis Table 5.7 were also undertaken for rural area, urban areas, mesoendemic areas and wood cooking fuel, the latter being for just the indoor-outdoor analysis.

Table 5.7 Detail of sub-analysis for investigating the association between malarial infection and HAP intervention

Sub-analysis	Rational	C/B	W/C	I/O
Urban areas	As detailed in Table 5.6 rural and urban areas have significant individual and situational characteristics.	✓	✓	✓
Rural areas		✓	✓	✓
Mesoendemic areas only	Malarial endemicity interacts with the outcome of malaria diagnosis, with children in holoendemic area being at greater risk of malarial infection.	✓	✓	✓
Wood cooking only	Cooking fuel interacts with the outcomes due to different types of fuels producing differing levels of HAPs.			✓

Note: C/B = Cleaner vs biomass cooking analysis; W/C = wood vs charcoal cooking analysis; I/O = indoor vs outdoor cooking analysis.

5.2.2.7 Ethical considerations

Section 5.1.2.9 details the ethical approvals for the DHS data. Further authorisation for data access, for MIS dataset and geolocation data, was required for this analysis.

5.3 Quantitative Methods 3: Fuel switching with economic uncertainty

5.3.1 Introduction

Kigali has a high rate of biomass usage for cooking, with urban areas documented to rely on 65.5% charcoal and 24.5% wood,[83] with a previous study within the Kabeza cell, Nyarugenge District showing hazardous level of HAP (CO and $PM_{2.5}$) from indoor domestic charcoal cooking.[279] Supporting this study a questionnaire illustrated a lack of awareness of the health harms of cooking with charcoal in the indoor environment and the feasibility for a structure and education HAP intervention, taking into consideration flexibility to meet the end-user needs.[141] However, fuel switching behaviours have not yet been documented within Rwanda and can influence the sustained and successful uptake of cleaner fuels. Previous studies[280,281] have documented fuel switching behaviours as a result of economic and fuel supply uncertainty during the COVID-19 lockdown in 2020. Combined with this is the charcoal ban and LPG subsides planned by the Rwandan government, which provides a unique opportunity to explore how much households are willing to pay for cooking fuel and what their potential fuel switching behaviour may be. Kenya has banned the sale and production of charcoal, with Uganda and South Sudan banning production in certain areas, all three countries list environmental reasons (e.g., deforestation) for their policies. However, the effect on cooking fuel choices has not been documented.

5.3.2 Aims and objectives

- To understand fuel switching behaviours as a result of economic uncertainty during the COVID-19 lockdowns within Rwanda.
- To understand how much households are willing to pay after a charcoal ban and its influence on fuel switching behaviour.

5.3.3 Methods

5.3.3.1 Study area

The study is set in the Kabeza cell, situated in the Muhima sector, which is one of the ten sectors that make up Nyarugenge district in Kigali, Rwanda (see section 2.2.1). The Kabeza cell is an informal settlement made up of seven villages (Hirwa, Ikaze, Ituze, Imanzi, Ingenzi, Sangwa, Umwezi), with a combined total of approximately 950 households and predominance of charcoal cooking fuel use.[141,279]

5.3.4 Participant selection and eligibility criteria

Only one interview per household was undertaken, with no exclusion based on cooking fuel type. This criterion was chosen in order to capture charcoal using households for the charcoal ban questions and identify participants for interviews; in addition to all households' fuel types being required for the fuel switching questions. A convenience sample[282] of mobile phone numbers were obtained for 132 households from the cell and villages leaders. Each mobile number was contacted, up to two times if there was a non-response on the first attempt at calling. Overall, there was a response rate of 64.4% (85/132), with only 25.8% withdrawing (34/132). Some of the participants could not be contacted (9.8%), due to either not answering the phone, being out of service when the call was made, or an incorrect mobile number being supplied.

5.3.4.1 Semi-structured questionnaire

The English language survey (Appendix *4*) contained open and closed questions[283] covering: sociodemographic and household characteristics; previous fuel switching behaviour due to COVID-19 awareness of charcoal ban and LPG subsidy; charcoal ban willingness to pay (WTP).[ii] Only participants

[ii] Willingness to pay (WTP) is defined as the maximum amount the participant is willing to pay for a product[396]

that cooked on charcoal were asked to complete the questions relating to the charcoal ban. The survey was administered verbally via mobile telephone, through simultaneous translation from English to native language (Kinyarwanda), with responses recorded in English, using the online data collection tool LimeSurvey;[284] a method used in the previous in-person household survey[141] which had been demonstrated to be an effective technique.

5.3.4.2 Field assistants

All fieldwork was undertaken by trained fieldwork assistants, who were students at the University of Rwanda, College of Science and Technology (UR-CST). Fieldwork assistants undertook a two-hour long training session, developed and delivered by KEW virtually, to learn how to undertake the surveys, the aim of the project and appropriate data management. As part of the training and piloting of study methodologies, field assistants were observed and aided by KEW virtually, to ensure competency.

5.3.4.3 Statistical analysis

All data management and analysis was undertaken within R studio.[285] The closed questions were summarised as frequencies, percentages, medians and interquartile ranges. Comparison between groups was undertaking using non-parametric Kruskal-Wallis or Mann-Whitney U test. As participant's occupation was an open question, the variables were categorised into the internationally recognised International Standard Classification of Occupations (ISCO-08)[iii] codes,[286] to effectively group and analysis occupation. Open questions were analysed through inductive thematic anylsis[287] by creating codes from the written text, creating groupings and topics, with each code being counted and visually represented proportionally in a word cloud. To investigate factors

[iii] International Standard Classification of Occupations (ISCO-08) groups are: 1.) Manager, 2.) Professionals, 3.) Technicians and associate professionals, 4.) Clerical support workers, 5.) Services and sales workers, 5.) Skilled agricultural, forestry and fishery workers, 7.) Craft and related trades workers, 8.) Plant and machine operators and assemblers, 9.) Elementary occupation, 10.) Armed forces occupations. [286]

which were associated the response provided from the WTP for cooking fuel questions a linear regression (using the lme4[288] package in R Studio) was undertaken with WTP as the dependant variable and age, gender, occupation, monthly household income and proportions of income spent on cooking fuel as independent variables. The following packages in R Studio were used to create the visual diagrams: lattice[289] (bar charts) ggplot[290], ggpubr[291] (scatter plots), networkD3[292] (Sankey diagram) and wordcloud2[293] (wordcloud).

5.3.5 Data management

All electronic data was kept on the secure University of Birmingham server and backed up using the University of Birmingham BEAR data share. Any data sharing between collaborators was undertaken using the secure BEAR data share. Data will be kept for a minimum of 20 years[294] after completion of the PhD and will then be subsequently destroyed as per the University of Birmingham guidelines.

5.3.6 Ethical approval

Ethical approval for the quantitative and qualitative primary data collection was obtained from the University of Birmingham Central Ethics Committee (ERN_19-0252) and the University of Rwanda College of Medicine and Health Science Institutional Review Board (CMHS IRB) (No 235/CMHS IRB/2020).

5.4 Summary of quantitative methodologies

A mixture of secondary data analysis and primary data collection has been undertaken as part of the quantitative section of the thesis; the methods for which are documented and discussed within this chapter. Firstly, the secondary data analysis of the DHS surveys has been designed to indicate the potential health benefits and harms of potential interventions with ARI (CHAPTER 6, CHAPTER 7) and malaria (CHAPTER 8); which links into both the evaluation of unintended consequences of policy change and community behaviour change interventions. Second, remote primary data collection, aimed at capturing information of fuel switching behaviours in an informal settlement in Kigali, Rwanda, using a semi-structured survey (CHAPTER 9); which links into the factors which may affect sustained intervention uptake.

CHAPTER 6 RESULTS: HEALTH RISK ASSESSMENT: BIOMASS FUEL TYPE

A global quantitative health risk assessment investigated the relative difference in ARI in children under five years between wood and charcoal cooking fuels; illustrating that there is an increase in the occurrence of ARI in East Africa and Asia in children residing wood compared to charcoal cooking households. These results have been published in *International Journal Environmental Research and Public Health* and are presented within the journal style. Detailed methods for this chapter can be found in section 5.1

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Comparison of Respiratory Health Impacts Associated with Wood and Charcoal Biomass Fuels: A Population-Based Analysis of 475,000 Children from 30 Low- and Middle-Income Countries

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Abstract: Background: The World Health Organisation reported that 45% of global acute respiratory infection (ARI) deaths in children under five years are attributable to household air pollution, which has been recognised to be strongly associated with solid biomass fuel usage in domestic settings. The introduction of legislative restrictions for charcoal production or purchase can result in unintended consequences, such as reversion to more polluting biomass fuels such as wood; which may increase health and environmental harms. However, there remains a paucity of evidence concerning the relative health risks between wood and charcoal. This study compares the risk of respiratory symptoms, ARI, and severe ARI among children aged under five years living in wood and charcoal fuel households across 30 low- and middle-income countries. Methods: Data from children (N = 475,089) residing in wood or charcoal cooking households were extracted from multiple population-based Demographic and Health Survey databases (DHS) (N = 30 countries). Outcome measures were obtained from a maternal report of respiratory symptoms (cough, shortness of breath and fever) occurring in the two weeks prior to the survey date, generating a composite measure of ARI (cough and shortness of breath) and severe ARI (cough, shortness of breath and fever). Multivariable logistic regression analyses were implemented, with adjustment at individual, household, regional and country level for relevant demographic, social, and health-related confounding factors. Results: Increased odds ratios of fever (AOR: 1.07; 95% CI: 1.02–1.12) were observed among children living in wood cooking households compared to the use of charcoal. However, no association was observed with shortness of breath (AOR: 1.03; 95% CI: 0.96–1.10), cough (AOR: 0.99; 95% CI: 0.95–1.04), ARI (AOR: 1.03; 95% CI: 0.96–1.11) or severe ARI (AOR: 1.07; 95% CI: 0.99–1.17). Within rural areas, only shortness of breath was observed to be associated with wood cooking (AOR: 1.08; 95% CI: 1.01–1.15). However, an increased odds ratio of ARI was observed in Asian (AOR: 1.25; 95% CI: 1.04–1.51) and East African countries (AOR: 1.11; 95% CI: 1.01–1.22) only. Conclusion: Our population-based observational data indicates that in Asia and East Africa there is a greater risk of ARI among children aged under 5 years living in wood compared to charcoal cooking households. These findings have major implications for understanding the existing health impacts of wood-based biomass fuel usage and may be of relevance to settings where charcoal fuel restrictions are under consideration.

Keywords: acute respiratory infection; biomass fuel; household air pollution; respiratory symptoms; low-and middle-income countries

1. Introduction

Exposure to household air pollution (HAP) is associated with adverse child and maternal health outcomes, including morbidity and mortality in children under five years old [1–3], acute respiratory infection (ARI) [4], child growth failure [5], low birth weight, and stillbirths [6]. Vulnerability to ARI, the leading cause of mortality in children under five years worldwide [7], is high among children due to a greater level of pollutant inhalation from the same external concentration as their adult counterparts, and more susceptible pulmonary physiology [4]. HAP includes carbon monoxide (CO), particulate matter (PM), sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) produced from burning biomass (wood, dung, charcoal and crop residue) for cooking, heating and lighting. Despite the known high HAP exposures in low- and middle-income countries (LMICs), there are few sustainable "cleaner fuel" interventions available to these populations, due to multiple barriers to sustained uptake, including low financial and infrastructural capabilities, lack of awareness, and appropriate policies [8]. Research has indicated harm reduction approaches such as outdoor cooking [9–12] and cooking with charcoal compared to wood [13,14], lowers exposure; with two small scale studies rural/peri-urban and urban settings, providing evidence for a respiratory health difference between wood and charcoal users [15,16]. However, the evidence in support of such approaches in LMIC settings remains limited.

Some governments have adopted legislative approaches to restrict the use of charcoal due to the recognised environmental and health impacts [17]. Evidence from domestic and commercial kitchens suggests that charcoal cooking is associated with high levels of PM [18] and CO [19] above the World Health Organisation's Indoor Air Quality Guidelines (WHO-IAQ) [18,20]. Introduction of charcoal fuel-based legislative changes or fiscal disincentives are typically intended to improve population health, including shifting to cleaner fuels such as electricity and liquid petroleum gas (LPG) alternatives. However, such changes may also generate unintended consequences [21,22], such as substitution with more polluting biomass fuels (e.g., wood, dung, straw) [23] which are typically readily available and cheaper alternatives [24]. Wood is the most common fuel used globally and it is therefore preferred as it suits traditional cooking practices [25]. In addition, LPG adoption is not likely in the imminent future due to multiple barriers, including equipment and fuels access, cost, and safety concerns [26]. Societal and economic issues with uncertainty can also affect fuel choices [27,28], meaning fuel transition often does not occur in a linear fashion [29,30]. In the advent of policy measures to restrict charcoal use, it is possible that charcoal could be replaced by wood fuel by end-users, presenting overall health risks given that wood produces more PM than charcoal [18]. But there remains a paucity of evidence in the relative health effects between wood and charcoal cooking, on a global scale.

We report the association of under-five respiratory health (respiratory symptoms, ARI, severe ARI) with wood and charcoal fuel use for cooking, in over 475,000 children from 30 LMICs, using comprehensive population-based data obtained from the Demographic and Health Survey (DHS).

2. Materials and Methods

2.1. Data Sources

A cross-sectional study across 30 LMIC countries was conducted using data obtained from the most recently available national population-based Demographic and Health Survey (DHS) [31], with LMIC status defined using the Development Assistance Committee (DAC) list 2020 [32]. Criteria for country inclusion included: (i) DHS survey data available from within the last 10 years, (ii) presence of wood and charcoal cooking fuel use (iii) presence of the outcome variables of interest (Appendix A: Figure A1). Each country followed the same two-stage stratified DHS sampling methodology with proportionate random sampling and standardised questionnaires with fieldwork supported by United States Agency for International Development (USAID). Eligible participants were identified through the residential household survey and included ever-married (has been married at least once in their life) women aged 15–49 years and men aged 15–59 years, who resided in the household the night before the survey [33]. Non-response households at the time of data collection and those with institutional living arrangements (e.g., boarding schools, police camps, army barracks, and hospitals) were excluded.

All countries followed the standard core questionnaire from Phases VI, VII, and VIII of the DHS Program model, with country-specific modifications to non-core questions to reflect the population and health issues most relevant to that country. USAID standardises and provides training to government agencies and health authorities to complete surveys, with internal training and supervision of local data collectors and data entry. The questionnaire is translated into the main language(s) for each country and validated on approximately 100–200 households. Data for this current analysis were obtained from (i) household dataset containing situational and household characteristics; (ii) woman's dataset containing maternal characteristics; (iii) children's dataset containing health and individual characteristics. All primary data collection has ethical approval from the relevant government authority within each country, with all data being anonymised and aggregated for DHS online data archive [31]. The archive is publicly available and authorisation for data access has been gained for this study.

2.2. Modified Wealth Index

The wealth index provided by DHS is calculated through principal component analysis, including cooking fuel as an indicator variable [34], therefore to prevent effect underestimation due to circularity, a modified wealth index was calculated [35] following the DHS provided guide [36] using SPSS [37], to calculate a modified wealth index. The new wealth index included indicator variables for the source of drinking water, house construction material (wall, roof and floor), toilet facility and assets. The assets included vary by country [37] and have been documented in Appendix B: Table A1. The wealth index was then ranked by household to provide tertiles of wealth.

2.3. Outcome Variables-Measure of Respiratory Symptoms and Acute Respiratory Infection

Maternal respondents were asked to report the presence of respiratory symptoms (shortness of breath, cough and fever) during the two weeks prior to the survey among all children under the age of five years living in their household. Respiratory symptoms were modelled as binary outcomes (yes, no), included short rapid breaths or difficulty breathing, cough, and fever. These respiratory symptoms were used to form the composite measures for ARI (both shortness of breath and cough [38]), and severe ARI (each of shortness of breath, cough, and fever [39–41]). Composite measures for ARI and severe ARI were then modelled as binary (yes, no) outcomes.

2.4. Measure of Exposure to HAP

Cooking fuel use was recorded from self-report for each household that undertook cooking activities. Fuels were categorised as "Cleaner fuels" (electricity, LPG, natural gas, biogas) and "Solid biomass fuels and kerosene" (kerosene, coal/lignite, charcoal, wood, straw/shrubs/grass, agricultural crop, animal dung). Wood and charcoal cooking household fuels were extracted and modelled as a binary variable.

2.5. Explanatory Variables

Individual child characteristics included child's age (0–11, 12–23, 24–35, 36–48, 48–59 months), sex (male, female), mode of delivery (caesarean, vaginal), birth order (first, not first born), breastfeeding status (ever, never), vitamin A supplementation in the last 6 months (yes, no), iron supplementation (yes, no). Maternal characteristics included age of mother (15–24, 25–35, 36–49 years), mother's highest attained educational level (none, primary, secondary/higher). Household characteristics included: number of household members (≤6, >6), household smoking (yes, no), cooking location (indoor, outdoor), and modified wealth index (lowest, low, middle, high, highest) [34]. Situational variables included geographical region of residence and area of residence (rural, urban). All co-variates were modelled as categorical variables.

2.6. Missing Data

Data that were identified to be missing at random with less than 50% missing data [42,43] underwent multiple imputations of 50 iterations [44,45], at a country level, using the MICE package [46] in R studio [47].

2.7. Data Analysis

Using R studio [47], descriptive statistics were tabulated with the number of cases (n), and percentage (%) for categorical outcome variables within the combined dataset. The association between the health outcome variables and exposure to HAP was assessed using a multivariable logistic regression using the Survey package [48] in R to account for the sampling strategy. Adjusted odds ratios (AOR) and 95% confidence intervals (95% CI) for each country were obtained and presented on a forest plot, with a summary result for the combined dataset. Additional exploratory analyses of a subset of countries were undertaken, incorporating breastfeeding, birthweight, and household smoking, which were missing or incomplete in a number of countries. Stratified analyses were undertaken to investigate the association in rural and urban settings, indoor and outdoor cooking status, geographic location and before or after 2014 (mid-time point of included studies), separately.

3. Results

3.1. Cooking Fuel Usage and Number of Respiratory Outcomes

Out of the 30 included country datasets, there was substantial variation in the type of fuels used within the country (Figure 1), however, wood was the predominant cooking fuel (range: 2.5–94.9%). Indonesia, Afghanistan, Peru, Pakistan and India have a large proportion of "cleaner" fuel use (range: 48.9–56.6%), with low charcoal usage (range: 0.4–2.1%). Within the pooled dataset before imputation (N = 475,089), 88.7% used wood cooking fuel compared to 11.1% using charcoal cooking fuel (Table 1). Overall, there were 23,490 cases of severe ARI (5.3%), 36,657 of ARI (8.3%), with shortness of breath being reported in 38,703 children (8.8%), cough in 82,523 children (18.7%), and fever in 89,621 children (20.3%) (Table 1).

3.2. Risk of Respiratory Symptoms, ARI, and Severe ARI

After adjusting for individual and situational potential confounding factors, children who resided in wood cooking households were observed to have increased adjusted odds ratios (Figure 2) with fever only (AOR: 1.07; 95% CI: 1.02–1.12), in the pooled dataset. No association was observed with ARI (AOR: 1.03; 95% CI: 0.96–1.11) or severe ARI (AOR: 1.07; 95% CI: 0.99–1.17). However, at a country level Afghanistan (AOR: 4.24; 95% CI: 1.66–10.83), Pakistan (AOR: 2.44; 95% CI: 1.29–4.61), Burundi (AOR: 1.73; 95% CI: 1.21–2.46), Zambia (AOR: 1.62; 95% CI: 1.16–2.26), Philippines (AOR: 1.44; 95% CI: 1.04–2.00) and Uganda (AOR: 1.34; 95% CI: 1.02–1.76), were all observed to have increased adjusted odds ratios of severe ARI in children residing in wood cooking households compared to charcoal cooking. This observed increase in adjusted odds ratios was also present in Afghanistan (AOR: 3.38; 95% CI: 1.23–9.29), Pakistan (AOR: 2.71; 95% CI: 1.45–5.07), Zambia (AOR: 1.43; 95% CI: 1.12–1.83), Burundi (AOR: 1.40; 95% CI: 1.06–1.84) and Uganda (AOR: 1.26; 95% CI: 1.00–1.58) for ARI. Little change was observed in the effect estimate when controlling for birthweight, breastfeeding and household smoking in those countries with available data (Appendix C: Table A2).

Figure 1. Proportion of clean, kerosene, wood, charcoal, other biomass (dung, crop residue) fuel use within each country, ordered by geographical region.

Table 1. Descriptive statistics before imputation for respiratory health outcomes (N = 475,089).

	Cough (*N* = 442,450, Missing = 6.9%)			**Shortness of Breath (*N* = 442,040, Missing = 7.0%)**			**Fever (*N* = 442,550, Missing = 6.9%)**			**ARI (*N* = 441,987, Missing = 7.0%)**			**Severe ARI (*N* = 441,627, Missing = 7.0%)**		
	No (N = 359,927) n (%)	**Yes (N = 82,523) n (%)**	***p* Value**	**No (N = 403,337) n (%)**	**Yes (N = 38,703) n (%)**	***p* Value**	**No (N = 352,929) n (%)**	**Yes (N = 89,621) n (%)**	***p* Value**	**No (N = 405,330) n (%)**	**Yes (N = 36,657) n (%)**	***p* Value**	**No (N = 418,137) n (%)**	**Yes (N = 23,490) n (%)**	***p* Value**
Household cooking fuel			<0.001			<0.001			<0.001			<0.001			0.790
Charcoal	36,279 (10.1%)	12,296 (14.9%)		43,749 (10.8%)	4799 (12.4%)		37,859 (10.7%)	10,774 (12.0%)		44,033 (10.9%)	4500 (12.3%)		45,933 (11.0%)	2546 (10.8%)	
Wood	323,648 (89.9%)	70,227 (85.1%)		359,588 (89.2%)	33,904 (87.6%)		315,070 (89.3%)	78,847 (88.0%)		361,297 (89.1%)	32,156 (87.7%)		372,204 (89.0%)	20,944 (89.2%)	
Child's sex			<0.001			0.064			<0.001			<0.001			<0.001
Male	183,227 (50.9%)	42,317 (51.3%)		205,018 (50.8%)	20,329 (52.5%)		179,258 (50.8%)	46,364 (51.7%)		206,066 (50.8%)	19,249 (52.5%)		212,678 (50.9%)	12,463 (53.1%)	
Child's Age (months)			<0.001			<0.001			<0.001			<0.001			<0.001
0–11	76,440 (21.2%)	18,754 (22.7%)		85,537 (21.2%)	9575 (24.7%)		75,566 (21.4%)	19,644 (21.9%)		86,053 (21.2%)	9055 (24.7%)		89,380 (21.4%)	5693 (24.2%)	
12–23	69,761 (19.4%)	20,002 (24.2%)		80,043 (19.8%)	9614 (24.8%)		66,964 (19.0%)	22,806 (25.4%)		80,529 (19.9%)	9124 (24.9%)		83,344 (19.9%)	6261 (26.7%)	
24–35	69,555 (19.3%)	16,566 (20.1%)		78,494 (19.5%)	7556 (19.5%)		67,785 (19.2%)	18,370 (20.5%)		78,899 (19.5%)	7140 (19.5%)		81,311 (19.4%)	4671 (19.9%)	
36–47	72,650 (20.2%)	14,756 (17.9%)		80,785 (20.0%)	6552 (16.9%)		71,814 (20.3%)	15,601 (17.4%)		81,120 (20.0%)	6206 (16.9%)		83,422 (20.0%)	3785 (16.1%)	
48–59	71,521 (19.9%)	12,445 (15.1%)		78,479 (19.5%)	5405 (14.0%)		70,799 (20.1%)	13,200 (14.7%)		78,729 (19.4%)	5133 (14.0%)		80,680 (19.3%)	3080 (13.1%)	
Birth order			<0.001			<0.001			<0.001			<0.001			<0.001
Not first born	256,340 (71.2%)	60,619 (73.5%)		288,083 (71.4%)	28,569 (73.8%)		250,638 (71.0%)	66,433 (74.1%)		289,685 (71.5%)	26,928 (73.5%)		299,038 (71.5%)	17,343 (73.8%)	
Mode of delivery *			0.005			<0.001			0.099			<0.001			<0.001
Caesarean	25,107 (7.0%)	6134 (7.5%)		28,378 (7.1%)	2846 (7.4%)		25,064 (7.2%)	6182 (7.0%)		28,487 (7.1%)	2735 (7.5%)		29,437 (7.1%)	1777 (7.6%)	

Table 1. *Cont.*

	Cough (N = 442,450, Missing = 6.9%)			Shortness of Breath (N = 442,040, Missing = 7.0%)			Fever (N = 442,550, Missing = 6.9%)			ARI (N = 441,987, Missing = 7.0%)			Severe ARI (N = 441,627, Missing = 7.0%)		
	No (N = 359,927) n (%)	Yes (N = 82,523) n (%)	p Value	No (N = 403,337) n (%)	Yes (N = 38,703) n (%)	p Value	No (N = 352,929) n (%)	Yes (N = 89,621) n (%)	p Value	No (N = 405,330) n (%)	Yes (N = 36,657) n (%)	p Value	No (N = 418,137) n (%)	Yes (N = 23,490) n (%)	p Value
Birthweight*			<0.001			<0.001			<0.001			<0.001			<0.001
Low	63,970 (28.8%)	11,814 (23.3%)		69,945 (28.0%)	5799 (25.3%)		62,841 (28.6%)	12,935 (24.4%)		70,163 (27.9%)	5578 (25.7%)		72,017 (27.8%)	3687 (26.5%)	
Breastfeeding status *			<0.001			<0.001			<0.001			<0.001			<0.001
Never Breast-fed	14,047 (5.1%)	2197 (3.2%)		15,209 (4.9%)	1021 (3.2%)		13,850 (5.1%)	2402 (3.1%)		15,244 (4.8%)	981 (3.2%)		15,537 (4.8%)	674 (3.4%)	
Vitamin A supplementation			<0.001			<0.001			<0.001			<0.001			<0.001
Yes	193,115 (54.6%)	49,265 (60.9%)		219,310 (55.3%)	22,867 (60.2%)		190,098 (54.8%)	52,338 (59.4%)		220,415 (55.3%)	21,741 (60.5%)		227,872 (55.4%)	14,113 (61.3%)	
Iron supplementation *			0.106			<0.001			0.018			<0.001			<0.001
Yes	63,042 (18.4%)	12,534 (16.6%)		69,285 (18.1%)	6245 (17.5%)		60,992 (18.2%)	14,587 (17.3%)		69,500 (18.1%)	6026 (17.9%)		71,308 (18.0%)	4156 (19.1%)	
Maternal age (years)			0.012			<0.001			<0.001			<0.001			<0.001
15–24	121,452 (33.7%)	27,738 (33.6%)		135,727 (33.7%)	13,329 (34.4%)		119,212 (33.8%)	29,974 (33.4%)		136,313 (33.6%)	12,723 (34.7%)		140,647 (33.6%)	8244 (35.1%)	
25–35	189,953 (52.8%)	42,587 (51.6%)		212,443 (52.7%)	19,888 (51.4%)		186,522 (52.8%)	46,110 (51.5%)		213,507 (52.7%)	18,795 (51.3%)		220,127 (52.6%)	11,987 (51.0%)	
36–49	48,523 (13.5%)	12,198 (14.8%)		55,167 (13.7%)	5486 (14.2%)		47,195 (13.4%)	13,537 (15.1%)		55,509 (13.7%)	5138 (14.0%)		57,363 (13.7%)	3259 (13.9%)	
Maternal education level			<0.001			<0.001			<0.001			<0.001			<0.001
No education	143,818 (40.0%)	25,418 (30.8%)		155,811 (38.6%)	13,185 (34.1%)		136,969 (38.8%)	32,317 (36.1%)		156,599 (38.6%)	12,384 (33.8%)		160,619 (38.4%)	8196 (34.9%)	
Primary	98,665 (27.4%)	30,379 (36.8%)		114,886 (28.5%)	14,076 (36.4%)		98,262 (27.8%)	30,839 (34.4%)		115,753 (28.6%)	13,178 (36.0%)		120,526 (28.8%)	8302 (35.3%)	
Secondary /Higher	117,428 (32.6%)	26,724 (32.4%)		132,623 (32.9%)	11,442 (29.6%)		117,685 (33.3%)	26,461 (29.5%)		132,961 (32.8%)	11,095 (30.3%)		136,974 (32.8%)	6991 (29.8%)	

Table 1. *Cont.*

	Cough (N = 442,450, Missing = 6.9%)			Shortness of Breath (N = 442,040, Missing = 7.0%)			Fever (N = 442,550, Missing = 6.9%)			ARI (N = 441,987, Missing = 7.0%)			Severe ARI (N = 441,627, Missing = 7.0%)		
	No (N = 359,927) n (%)	Yes (N = 82,523) n (%)	p Value	No (N = 403,337) n (%)	Yes (N = 38,703) n (%)	p Value	No (N = 352,929) n (%)	Yes (N = 89,621) n (%)	p Value	No (N = 405,330) n (%)	Yes (N = 36,657) n (%)	p Value	No (N = 418,137) n (%)	Yes (N = 23,490) n (%)	p Value
Household wealth index			<0.001			<0.001			<0.001			<0.001			<0.001
Lowest	100,447 (27.9%)	21,240 (25.7%)		110,928 (27.5%)	10,698 (27.6%)		97,093 (27.5%)	24,616 (27.5%)		111,451 (27.5%)	10,167 (27.7%)		114,771 (27.4%)	6773 (28.8%)	
Middle	80,643 (22.4%)	17,910 (21.7%)		90,194 (22.4%)	8240 (21.3%)		78,956 (22.4%)	19,595 (21.9%)		90,616 (22.4%)	7810 (21.3%)		93,332 (22.3%)	5000 (21.3%)	
Highest	27,563 (7.7%)	8875 (10.8%)		32963 (8.2%)	3434 (8.9%)		28,989 (8.2%)	7464 (8.3%)		33,149 (8.2%)	3237 (8.8%)		34,533 (8.3%)	1811 (7.7%)	
Household smoking *			<0.001			<0.001			<0.001			<0.001			<0.001
Yes	126,552 (36.2%)	24,092 (31.4%)		138,907 (35.6%)	11,612 (32.2%)		123,113 (36.1%)	27,526 (32.2%)		139,279 (35.5%)	11,231 (33.0%)		142,874 (35.4%)	7518 (34.3%)	
Household cooking location			0.118			0.395			<0.001			0.001			<0.001
Indoors	262,449 (73.2%)	60,621 (73.8%)		293,885 (73.1%)	28,871 (75.0%)		258,651 (73.5%)	64,479 (72.4%)		295,282 (73.1%)	27433 (75.3%)		304,800 (73.2%)	17,651 (75.6%)	
Number of household member *			<0.001			<0.001			<0.001			<0.001			<0.001
≤6	174,300 (48.5%)	44,496 (53.9%)		198,285 (49.2%)	20,349 (52.6%)		172,461 (48.9%)	46,326 (51.7%)		199,396 (49.2%)	19,201 (52.4%)		206,328 (49.4%)	12,071 (51.4%)	
Place of residence			0.476			<0.001			0.048			<0.001			0.578
Urban	66,652 (18.5%)	17,978 (21.8%)		77,206 (19.1%)	7349 (19.0%)		67,436 (19.1%)	17,232 (19.2%)		77,496 (19.1%)	7049 (19.2%)		80,271 (19.2%)	4201 (17.9%)	

N = observation number, n = category observation number, % = column percentage for category. *p* value = Chi-Squared. * Missing data = Mode of delivery = 0.7%, Breastfeeding status = 22.8%, Birthweight = 38.3%, Vitamin A supplementation = 1.7%, Iron Supplementation = 534%, Mother's education = 0.004%, Household smoking = 3.6%, Cooking location = 0.4%, Number of household members = 0.06%.

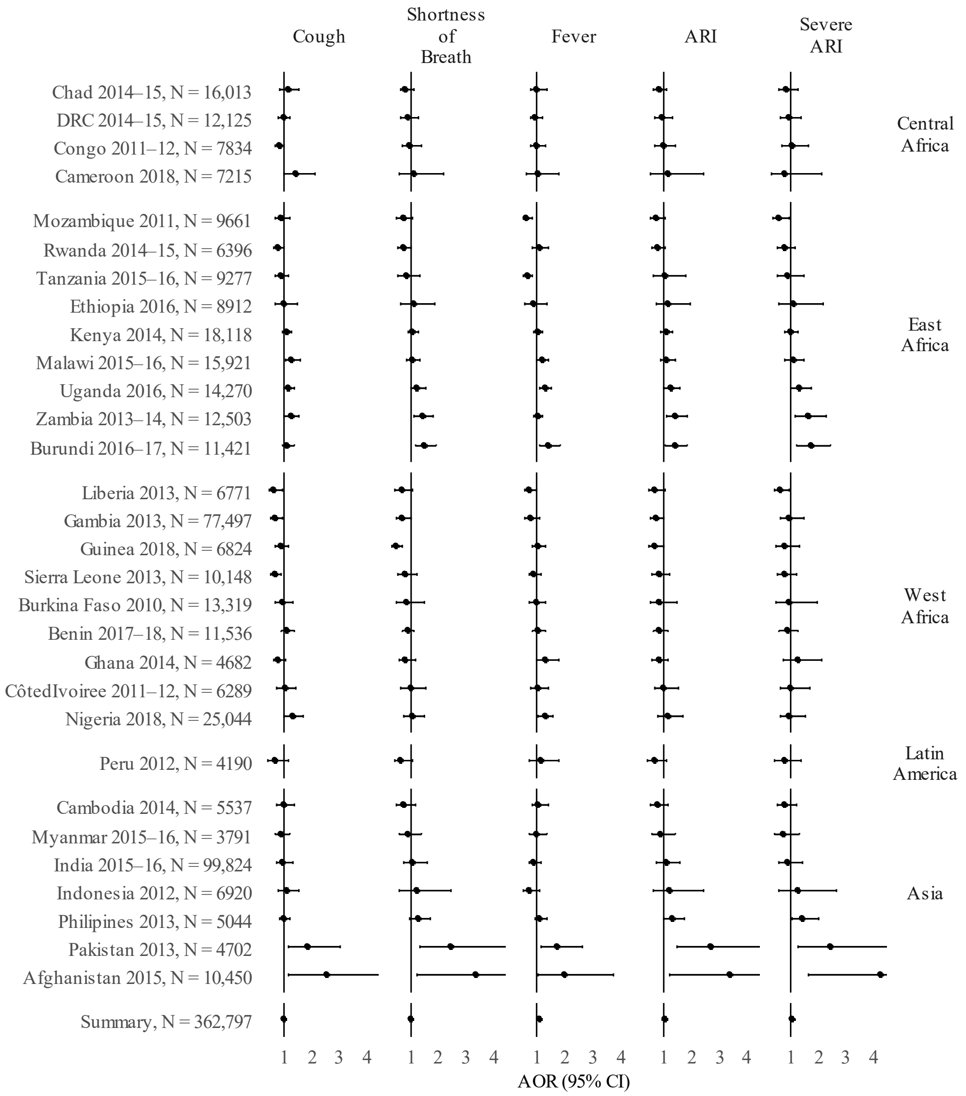

Figure 2. Forest plot illustrating the adjusted odds ratio (AOR) for respiratory symptoms, ARI and severe ARI with wood cooking fuel compared to charcoal for all countries. The summary measure is adjusted for: age, birth order, mode of delivery, vitamin A supplementation, mother's age, mother's education level, wealth status, number of household members, rural/urban residence and location of cooking.

3.3. Role of Rural and Urban Residence

In the rural and urban sub-analysis cough was observed to be associated with an increased odds ratio (AOR: 1.08; 95% CI: 1.01–1.15) among children residing in wood compared to charcoal fuel households in rural areas only.

3.4. Role of Outdoor Cooking

In the analyses of the pooled dataset, for indoor cooking children under five years residing in households using wood had increased adjusted odds ratios of fever (AOR: 1.07; 95% CI: 1.00–1.13). No other differences were observed (Table 2).

Table 2. Summary effects (AOR–95% CI) for respiratory symptoms, ARI and severe ARI with wood cooking of the whole, exploratory and sub-analysis.

Analysis (N)	Cough AOR (95%CI)	Shortness of Breath AOR (95%CI)	Fever AOR (95%CI)	ARI AOR (95%CI)	Severe ARI AOR (95%CI)
Whole (N = 482,644)	0.99(0.95–1.04)	1.03(0.96–1.10)	**1.07(1.02–1.12)** [b]	1.03(0.96–1.11)	1.07(0.99–1.17)
Sub-analysis					
Urban areas (N = 89,661)	0.93(0.87–1.00)	0.99(0.90–1.09)	1.03(0.96–1.10)	0.99(0.89–1.09)	1.02(0.90–1.14)
Rural Area (N = 392,983)	**1.08(1.01–1.15)** [c]	1.00(0.90–1.11)	1.05(0.98–1.13)	1.02(0.92–1.14)	1.05(0.92–1.20)
Indoor (N = 368,647)	1.03(0.97–1.09)	1.05(0.96–1.14)	**1.07(1.00–2.13)** [c]	1.06(0.97–1.15)	1.08(0.97–1.20)
Outdoor (N = 113,997)	0.96(0.89–1.04)	0.98(0.89–1.09)	1.07(0.99–1.16)	1.01(0.91–1.13)	1.10(0.96–1.25)
Africa (N = 245,363)	1.02(0.97–1.08)	1.00(0.93–1.08)	1.02(0.97–1.08)	1.01(0.93–1.09)	1.04(0.94–1.14)
Asia (N = 233,091)	1.05(0.92–1.20)	**1.25(1.04–1.51)** [b]	1.06(0.93–1.20)	**1.25(1.04–1.51)** [c]	1.24(0.99–1.54)
Central Africa (N = 47,710)	0.97(0.86–1.11)	0.99(0.79–1.24)	0.99(0.86–1.13)	0.99(0.79–1.25)	1.04(0.80–1.36)
East Africa (N = 105,543)	**1.09(1.02–1.17)** [b]	**1.10(1.00–1.20)** [c]	1.01(0.94–1.09)	**1.11(1.01–1.22)** [c]	1.10(0.98–1.24)
West Africa (N = 92,110)	0.96(0.87–1.06)	**0.86(0.76–0.97)** [b]	1.00(0.92–1.09)	0.88(0.78–1.00)	0.93(0.80–1.09)
Surveys undertaken during or before 2014 (N = 134,225)	0.97(0.91–1.04)	0.99(0.89–1.09)	1.01(0.94–1.08)	0.99(0.89–1.09)	1.00(0.89–1.14)
Surveys undertaken during or after 2015 * (N = 348,419)	1.04(0.97–1.12)	1.09(1.00–1.20)	**1.18(1.10–1.26)** [a]	**1.11(1.01–1.22)** [c]	**1.17(1.04–1.31)** [b]

AOR = adjusted odds ratio for wood cooking compared to charcoal, 95% CI = 95% confidence interval, a = $p \leq 0.001$, b = $p \leq 0.01$, c = $p \leq 0.05$, bold = $p \leq 0.05$, N = number of observations in the SARI analysis. * Surveys that were undertaken across 2014–2015 (n = 2) were included within during or after 2015 (Total countries = 15).

3.5. Role of Geographic Location

In the stratified sub-analysis by geographic location, an association with ARI in children under five years old living in wood compared to charcoal cooking households was observed in East Africa (AOR: 1.11; 95% CI: 1.01–1.22) and Asia (AOR: 1.25; 95% CI: 1.04–1.51) (Table 2). An increase in the adjusted odds ratio with wood cooking compared to charcoal was also observed with shortness of breath in Asia (AOR: 1.25; 95% CI: 1.04–1.51) and East Africa (AOR: 1.10; 95% CI: 1.00–1.20), whereas a decrease in the adjusted odds ratio was observed in West Africa (AOR: 0.86; 95% CI: 0.76–0.97). An association was observed with cough (AOR: 1.09; 95% CI: 1.02–1.17) in East Africa only.

3.6. Role of Time Period Survey Was Undertaken

In the stratified sub-analysis of those surveys undertaken during or after 2015, an association within an increase in the adjusted odds ratio of fever (AOR: 1.18; 95% CI: 1.10–1.26), ARI (AOR: 1.11; 95% CI: 1.01–1.22), severe ARI (AOR: 1.17; 95% CI: 1.04–1.31) in children under five years old living in wood compared to charcoal cooking households (Table 2). However, no associations were observed in surveys undertaken during or before 2014.

4. Discussion

In our large cross-sectional multi-country study (30 countries; 475,089 participants), increased odds ratios of ARI were observed in Asia (AOR: 1.09; 95% CI: 1.05–1.13) and East Africa only (AOR: 1.04; 95% CI: 1.00–1.08) among children living in wood cooking households compared to charcoal cooking households. The risk of ARI varies between countries, and this may reflect different wood fuel choices, cultural differences, access to healthcare [49], elevation [50] and seasonal or climatic differences [51], which could not be accounted for in our analyses. Moreover, the variation of the observed outcome results between countries indicates the need to take current country and regional level characteristics into consideration when developing HAP interventions for reducing ARI in children aged under five years. This is further highlighted as only the most recent surveys (post-2015) have an observed association with fever (AOR: 1.18; 95% CI: 1.10–1.26), ARI (AOR: 1.11; 95% CI: 1.01–1.22), severe ARI (AOR: 1.17; 95% CI: 1.04–1.31). Prevention of ARI in children aged under five years would reduce child mortality and long-term morbidities, exert health and fiscal benefits; in addition to supporting progress towards the Sustainable Development Goals (SDGs) (namely SDG 3).

Given the wider environmental and health impacts of charcoal production and use, there is an argument for restricting the use of charcoal. However, the clear financial and structural difficulties of provision of clean fuels in many LMIC settings means charcoal restriction could potentially result in health harms by some users reverting to other biomass fuels. Although charcoal use presents significant health harms [52], it has previously been shown to produce lower pollutant levels than wood cooking in laboratory and field studies [15,18], and our results reflect these findings and their effect on child health, indicating that compared to charcoal, wood cooking is associated with increased risk of ARI in East Africa and Asia. It is evident that a package of measures is required for fuel transition policies which include charcoal restrictions, to limit increased uptake of wood alternatives. Adoption of charcoal restrictions should be carefully considered, in terms of the potential health harms, in LMIC settings, in the context of clean fuel access, availability and affordability. Given the volatility of fuel costs, for example in response to disruptive changes such as COVID-19, such policies must also consider the longer-term resilience of domestic fuel supplies, in each specific context.

Fuel choice, preparation, cooking characteristics, and cumulative exposure have been shown to vary between countries [53]. We also explored how cooking location (indoor vs outdoor) and exposure to second-hand smoke from household smoking could potentially contribute to the risk of ARI and severe ARI. In the main analysis outdoor cooking was associated with reduced risk of shortness of breath, cough, fever and ARI (AOR: 0.96; 95% CI: 0.94–0.98]), which is another potential interim harm mitigation behavioural intervention promoted to reduce the adverse health effects of HAP exposure [10]. However, in the sub-analysis of outdoor cooking and indoor cooking separately, an association was only observed with fever (AOR: 1.07; 95% CI: 1.00–2.13) in indoor cooking households, which may have resulted from the small sample size or influence of seasonal factors [51]. However, a more detailed country-specific assessment by differing solid biomass fuels [40] would be required to understand the overall potential benefits of cooking outdoors; in addition, to the combined health effects and pollutants level benefits when changing cooking fuel to charcoal and moving cooking outside.

Household smoking could not be accounted for in the main summary analysis, due to missing data in Peru, the Philippines, and Kenya DHS surveys. In the exploratory analysis, limited effect of household smoking was observed upon outcome measures. Smoking is not only an alternative source of HAP exposure but is also a recognised risk factor for respiratory infections in infants [54]. However, an association was only observed in households with a smoker with cough (AOR: 1.05; 95% CI: 1.01–1.08) and fever (AOR: 1.04; 95% CI: 1.01–1.07), compared to non-smoking households, indicating the limited potential of smoking causing the occurrence of ARI.

Urban and rural areas also have additional differing situational contexts, including housing type, co-inhabiting with livestock, food security, WASH, household crowding, malnutrition, access to healthcare, wealth [55] and ambient pollution levels [56]. Differences in changes over time were investigated through the sub-analysis comparing surveys between 2010–2014 (n = 15) and 2015–2018 (n = 15), which indicated potential differing situational contexts. The role of alternative sources of HAP and differing situational characteristics both within and between countries highlights the complexities that need to be considered to understand the context-specific needs and acceptability of behavioural harm reduction HAP interventions.

Although there is an environmental and health need for reducing the reliance on charcoal cooking fuel, legislative approaches to restricting charcoal use should take into consideration the potential unintended or unanticipated health consequences of targeted fiscal policies. Wood fuels are readily available in most settings, as they are typically free to collect, thus may be reverted to as a fuel of choice [57], along with being strongly linked with poverty [58]; as seen in this study with the wealth index. This combination of factors increases the vulnerability of households to the health-harms of solid biomass cooking. Other approaches to improving the sustainability of charcoal such as improving sustainable production and the use of ICS for improved burning efficiency [17,59,60], could be considered as alternative mitigation measures in the short to medium term. However, the longer-term solution is to support the sustained adoption of cleaner fuels, with maintained strong supply links [61] to prevent fuel switching, as seen in the COVID-19 lockdowns [23,27]; and also provide education for health-harms of using solid biomass cooking fuel. Any policy mitigation measures for HAP to reduce ARIs in children under five should also consider wider protective health behaviours against ARIs, e.g., encouraging breastfeeding, especially within the first 6 months of life [62,63], childhood vaccinations, undernutrition [4], reducing the incidence of HIV, TB [64], and reducing the risk of low birth weight [65].

Although the use of fuel type as a proxy for HAP exposure, self-reported respiratory symptoms, changes over time, weaknesses in the potential to control for all confounding factors and the observational nature of the data generate study limitations, this population-based approach provides a large sample size and global comparison, detailing the widespread impact of a potential harm reduction intervention for HAP exposure. In addition, many potential associations were investigated; therefore, some association would be expected to be down to chance. Further research implications include the need to characterise exposure levels and exposure-response functions for key health outcomes and increased clinical diagnostic confirmation to improve aetiological specificity. Further research is also necessary to understand the specific physiological mechanism between specific pollutant exposure and ARI risk in children aged under five years, including by specific wood and charcoal types and combustion techniques. Further, we recommend consideration of the implications of wood to charcoal transition for climate change, specifically for CO_2 emissions [66] and environmental degradation associated with charcoal production [67]. This study has global implications and provides the evidence to support a clear policy recommendation for safer domestic cooking practices.

5. Conclusions

Our population-based observational study indicates that in Asia and East Africa there is a greater risk of ARI among children aged under 5 years living in wood compared to charcoal cooking households. Users of domestic wood fuels are among the most vulnerable sub-populations worldwide and our findings support the need for ensuring long-term uptake of clean domestic energy alternatives in resource-poor settings worldwide. Policymakers should adopt an evidence-based approach, to ensure long-term sustained uptake of clean domestic energy alternatives and to prevent unintended consequences of biomass fuel restriction policies.

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Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Informed consent for the primary data collection can be found at https://dhsprogram.com/ (accessed on 15 January 2020).

Data Availability Statement: Data is freely and publicly available at: https://dhsprogram.com/ (accessed on 15 January 2020).

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

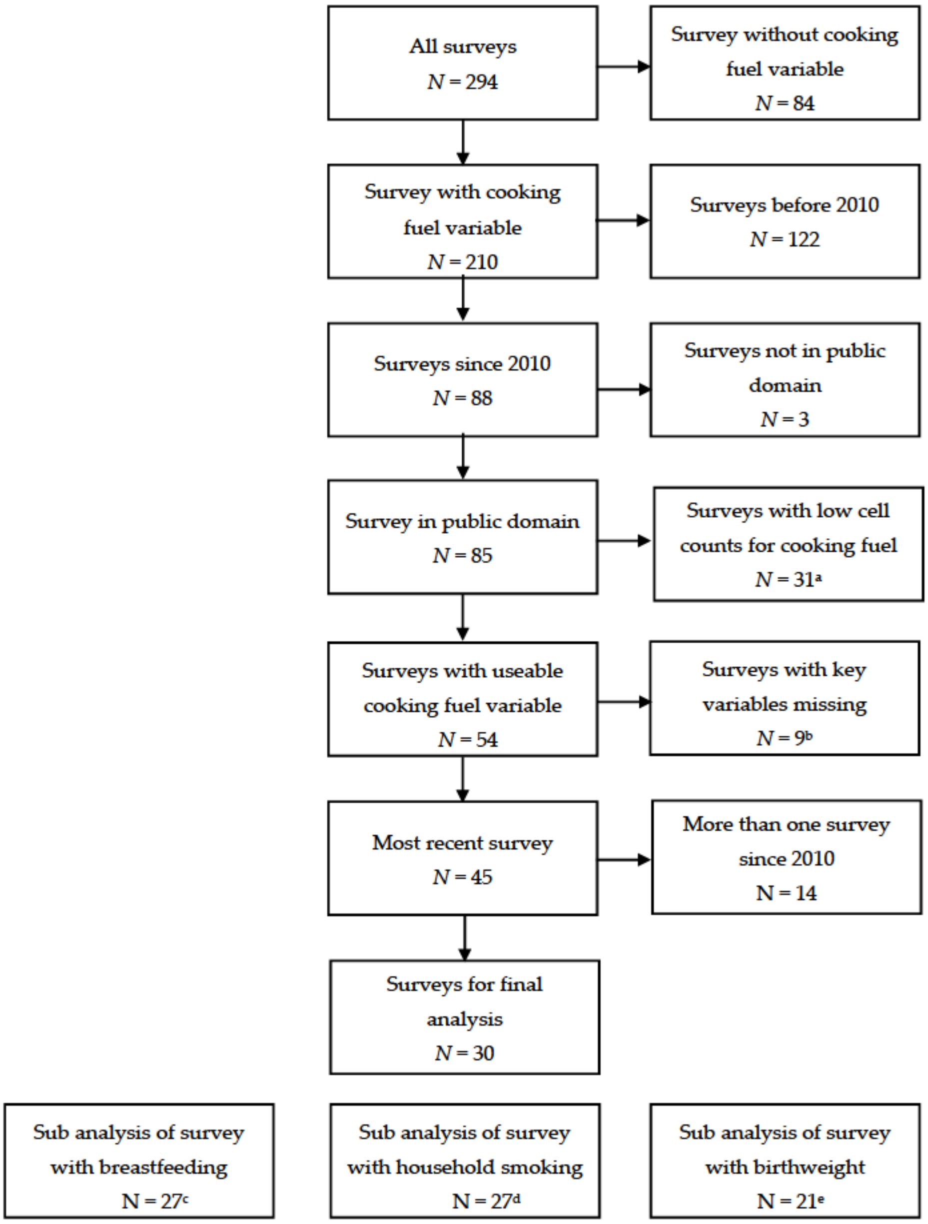

Figure A1. Flow diagram for selection of final dataset for analysis from all household data sets available from the DHS program data archive [31] (**a**) Survey was excluded due to have low cell counts for wood or charcoal cooking (n = 31) included: Comoros 2012, Zimbabwe 2010–2011, Zimbabwe 2015, Senegal 2010–2017 (continuous dataset), Togo 2013–2014, Kyrgyz 2012, Tajikistan 2012, 2017, Papa New Guinea 2016–2017, Bangladesh 2011, 2014, Indonesia 2017, Maldives 2016–2017, Nepal 2011, 2016, Timor-Leste 2016, Albania 2017–2018, Armenia 2010, 2015–2016, Jordan 2012, Yemen 2012, Columbia 2010, 2015, Guatemala 2014–2015, Honduras 2011–2012, South Africa 2016, Namibia 2013, Lesotho 2014. (**b**) Surveys were excluded due to low cell counts with explanatory variable (n = 3) and low cell counts of missing entirely for wealth (n = 3) or three or more key variables (e.g., Breastfeeding, mode of delivery, household smoking) (n = 3). (**c**) Peru, Zambia and Kenya were excluded due to <50% missing data for breastfeeding. (**d**) Household smoking data was not collected for Kenya, Peru and the Philippines. (**e**) Chad, Ethiopia, Kenya, Guinea, Liberia, Afghanistan, Myanmar, Pakistan, Nigeria were excluded due to <50% missing data for birthweight.

Appendix B

Table A1. Predictors included in the principal component analysis for the calculation of the modified wealth index within each country.

Country	Source of Drinking Water	Toilet Facility	House Construction			Assets																		Dwelling Window Material	Lighting Fuel	Refuse Collection	Own or Rent House
			Wall Material	Roof Material	Floor Material	Electricity	Radio	Television	Refrigerator	Watch	Bicycle	Motorcycle or Scooter	Animal-Drawn Cart	Car or Truck	Boat with a Motor	Bank Account	Mobile Telephone	Computer	Non-Motorised Boat or Canoe	Tractor	Plough	Household Furniture *	Household Electronics *	Other Assets *				
Afghanistan 2015	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■		■		■	■	■				
Benin 2017–2018	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■				■	
Burkina Faso 2010	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										
Burundi 2016–2017	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■						
Cambodia 2014	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■					
Cameroon 2018	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■				
Chad 2014–2015	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■	■				
Congo 2011–2012	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■						
Côte d'Ivoire 2011–2012	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
DRC 2014–2015	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■					■
Ethiopia 2016	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■						
Gambia 2013	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■					
Ghana 2014	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■					
Guinea 2018	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■					
India 2015–2016	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■		■	■	■				
Indonesia 2012	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■				
Kenya 2014	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■					
Liberia 2013	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■				■		
Malawi 2015–2016	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■						
Mozambique 2011	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											
Myanmar 2015–2016	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■				
Nigeria 2018	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■					
Pakistan 2013	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■				
Peru 2012	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■		■	■	■	
Philippines 2013	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■				■
	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■									
Rwanda 2014–2015	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■									
Sierra Leone 2013	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■					
Tanzania 2015–2016	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■			■		
Uganda 2016	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■						
Zambia 2013–2014	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■				

* Household furniture (e.g., table, chairs, wardrobe, bed, mattress, lamps, clock). * Household electronics (e.g., washing machine, DVD player, internet, modem/router, satellite, laptop, generator, music system, sewing machine, fan, air conditioning, solar panel, water pump, battery, iron, TV5 antenna, Cable subscription, camera, blender, microwave). * Other assets (e.g., Grain mill, hammer mill, Rickshaw/chingchi/Tuk tuk/htawlargyi/Keke Napep/Bagag, bank account with another institution, credit union, beneficiary of Pantawid Pamilyan Pilipino Program (4Ps), canoe with motor, banana boat, thresher, bedroom available for sleep, floor area of house).

Appendix C

Table A2. Summary effects (AOR–95% CI) for respiratory symptoms, ARI and severe ARI with wood cooking for the exploratory analysis.

Analysis (N)	Cough AOR (95%CI)	Shortness of Breath AOR (95%CI)	Fever AOR (95%CI)	ARI AOR (95%CI)	Server ARI AOR (95%CI)
Controlling for birthweight [1] (N = 405,839)	0.97(0.93–1.03)	1.02(0.94–1.10)	1.08(1.02–1.14) [a]	1.02(0.94–1.10)	1.02(0.94–1.10)
Controlling for breastfeeding [2] (N = 448,769)	0.97(0.92–1.02)	1.01(0.94–1.09)	1.07(1.01–1.12) [b]	1.02(0.94–1.10)	1.07(0.98–1.18)
Controlling for household smoking [3] (N = 455,289)	0.98(0.93–1.03)	1.01(0.94–1.09)	1.06(1.01–1.12) [c]	1.02(0.94–1.10)	1.07(0.97–1.17)

AOR = adjusted odds ratio for wood cooking compared to charcoal, 95% CI = 95% confidence interval, a = $p \leq 0.001$, b = $p \leq 0.01$, c = $p \leq 0.05$, bold = N = $p \leq 0.05$, number of observations in the SARI analysis. [1] = Chad, Ethiopia, Kenya, Guinea, Liberia, Afghanistan, Myanmar, Pakistan, Nigeria were excluded due to < 50% missing data for birthweight. [2] = Peru, Zambia and Kenya were excluded due to < 50% missing data for breastfeeding. [3] = Household smoking data not collected for Kenya, Peru and the Philippines.

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CHAPTER 7 RESULTS: HARM MITIGATION: COOKING LOCATION

This chapter details the contextual and household determinants and the respiratory health impacts in children under five years of cooking location in biomass cooking households in Sub-Saharan Africa. The results of this chapter have been accepted for publication in *Atmospheric Environment* in March 2022 and are therefore presented in this style. Detailed methods for this chapter can be found in section 5.1.

Woolley, K.E., Thomas, G.N., Kirenga, B., Okello, G., Kabera, T., Lao, X.-Q., Pope, F.D., Greenfield, S.M., Price, M.J., Bartington, S.E., on behalf of Global - CLEAR, Association of household cooking location behaviour with acute respiratory infections among children aged under five years; a cross sectional analysis of 30 Sub-Saharan African Demographic and Health Surveys, Atmospheric Environment (2022), doi: https://doi.org/10.1016/j.atmosenv.2022.119055

CHAPTER 8 RESULTS: UNINTENDED CONSEQUENCES: MALARIA

In this chapter is a quantitative health risk assessment within Sub-Saharan Africa investigating the effects levels of biomass smoke have on malaria infection in children under five years; illustrating that there is no increased risk of malaria in cooking practices that have lower biomass smoke exposure. The chapter is written in the style for publication for *BMC Malaria Journal* and has been published at this journal.[iv] Detailed methods for this chapter can be found in section 5.2.

Woolley, K.E., Bartington, S.E., Pope, F.D., Greenfield, S.M., Tusting, L.S., Price, M.J. and Thomas, G.N. (2022) Cooking outdoors or with cleaner fuels does not increase malarial risk in children under 5 years: a cross-sectional study of 17 sub-Saharan African countries. Malaria Journal 21(133) https://doi.org/10.1186/s12936-022-04152-3

[iv] A correction has been made to this published paper where the word “incidence” has been replaced “prevalence” within second sentence of the discussion.

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RESEARCH Open Access

Cooking outdoors or with cleaner fuels does not increase malarial risk in children under 5 years: a cross-sectional study of 17 sub-Saharan African countries

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Abstract

Background: Smoke from solid biomass cooking is often stated to reduce household mosquito levels and, therefore, malarial transmission. However, household air pollution (HAP) from solid biomass cooking is estimated to be responsible for 1.67 times more deaths in children aged under 5 years compared to malaria globally. This cross-sectional study investigates the association between malaria and (i) cleaner fuel usage; (ii) wood compared to charcoal fuel; and, (iii) household cooking location, among children aged under 5 years in sub-Saharan Africa (SSA).

Methods: Population-based data was obtained from Demographic and Health Surveys (DHS) for 85,263 children within 17 malaria-endemic sub-Saharan countries who were who were tested for malaria with a malarial rapid diagnostic test (RDT) or microscopy. To assess the independent association between malarial diagnosis (positive, negative), fuel type and cooking location (outdoor, indoor, attached to house), multivariable logistic regression was used, controlling for individual, household and contextual confounding factors.

Results: Household use of solid biomass fuels and kerosene cooking fuels was associated with a 57% increase in the odds ratio of malarial infection after adjusting for confounding factors (RDT adjusted odds ratio (AOR):1.57 [1.30–1.91]; Microscopy AOR: 1.58 [1.23–2.04]) compared to cooking with cleaner fuels. A similar effect was observed when comparing wood to charcoal among solid biomass fuel users (RDT AOR: 1.77 [1.54–2.04]; Microscopy AOR: 1.21 [1.08–1.37]). Cooking in a separate building was associated with a 26% reduction in the odds of malarial infection (RDT AOR: 0.74 [0.66–0.83]; Microscopy AOR: 0.75 [0.67–0.84]) compared to indoor cooking; however no association was observed with outdoor cooking. Similar effects were observed within a sub-analysis of malarial mesoendemic areas only.

Conclusion: Cleaner fuels and outdoor cooking practices associated with reduced smoke exposure were not observed to have an adverse effect upon malarial infection among children under 5 years in SSA. Further mixed-methods research will be required to further strengthen the evidence base concerning this risk paradigm and to support appropriate public health messaging in this context.

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Keywords: Malaria, Household air pollution, Children under 5 years, Low and middle-income country, Sub-Saharan Africa, Biomass

Background

Smoke arising from solid biomass cooking (wood, dung, charcoal, crop residue) is widely perceived to act as a mosquito repellent among communities [1–3], therefore protecting against mosquito-borne disease. However, solid biomass cooking produces health harming levels of household air pollution (HAP), estimated to be responsible for around 450,000 deaths in children aged under 5 years worldwide [4], compared to only 274,000 estimated deaths from malaria in 2019 [1]. This discordance in perceived compared to actual health risks associated with malarial transmission could impact upon uptake of structural interventions (e.g., cleaner fuel transition [LPG, electricity, biogas]) and behavioural changes intended to reduce harmful HAP exposure, notably among those living in endemic malarial regions.

Sub-Saharan Africa (SSA) has the highest malarial prevalence globally with 94% of cases and deaths, caused by predominantly by *Plasmodium falciparum* [5]. Identified risk factors for malarial infection include poor household construction [6–8] (e.g., open eaves), animals sleeping in the house [9] and presence of standing water near the house [10, 11]. The use of mosquito nets, household insecticidal spraying, and larval source management [12] have become common practice advocated in malarial prevention, driven in part by the World Health Organization's (WHO) coordinated response [5]. Another, common preventive measure is use of mosquito repellent smoke from the burning of certain types of plant materials, such as *churai* in West Africa [2, 13].

There is little evidence supporting reduced mosquito infiltration [14, 15] or malarial transmission associated with solid biomass fuel cooking [2, 16]; although there is some evidence that solid biomass cooking reduces the risk of arboviruses in Guatemala [17]. Therefore, to better understand this disease risk paradigm, this study investigates the association of malarial acquisition among children aged under 5 years with regard to: (i) cleaner or solid biomass fuels and kerosene cooking; (ii) charcoal or wood fuel usage; and (iii) indoor and outdoor cooking, within households in 17 SSA countries using the population-based Demographic and Health Survey (DHS) data.

Methods

Data sources

This cross-sectional study uses publicly available survey data for 17 malarial-endemic SSA countries with available malarial data (Fig. 1), obtained from the DHS program supported by the United States Agency for International Development (USAID) within the last 10 years (2010–2020). The DHS undertakes full surveys every 5 years, and intermediate Malaria Indicators Surveys (MIS) [18]; only some of the full DHS survey modules undertake malarial testing. For those DHS surveys including malaria modules, malarial testing is undertaken by trained fieldworkers on a sub-sample of eligible children aged 6–59 months using a malarial rapid diagnostic test (RDT) [18]. A two-stage stratified sampling technique was employed to obtain a representative population-based sample, with residential households randomly selected. Eligible households included those with an ever-married (married, widowed or divorced) woman aged between 15 and 49 years and resident the night before the survey. Ethical approval for data collection was gained from the relevant government authority [18], and authorization for data access was provided by the DHS.

Malarial endemicity was generated for each cluster by assessment of malarial prevalence obtained from the open source Malaria Atlas Project [19] within eligible countries, and defined as holoendemic (> 75%), hyperendemic (51–75%), mesoendemic (11–50%), hypoendemic (< 10%) [20]. Those data points that fell within hypoendemic areas were excluded from the analysis due to lower rate of malarial infection and testing. Malarial prevalence data were geocoded to the cluster geographic coordinates using the spatial analyst tool in ArcMAP 10.7 [21]; a method that has been previously used for this purpose [22].

As the wealth index provided by DHS contains cooking fuel as an indicator variable, a new modified wealth index was calculated in SPSS [23] using principal component analysis [24] to prevent circularity [8]. The index indicator variables included source of drinking water, house construction material, provision of a toilet facility and household assets, which varied by country (Additional file 1).

Predictor and outcome variables

Proxies for household air pollution (HAP) exposure levels

Three analyses were undertaken (Table 1), undertaking comparisons by the main type of cooking fuel used and cooking location respectively: cleaner vs solid biomass fuels and kerosene fuels; charcoal vs wood fuels; outdoor vs indoor cooking (indoors, in a separate building).

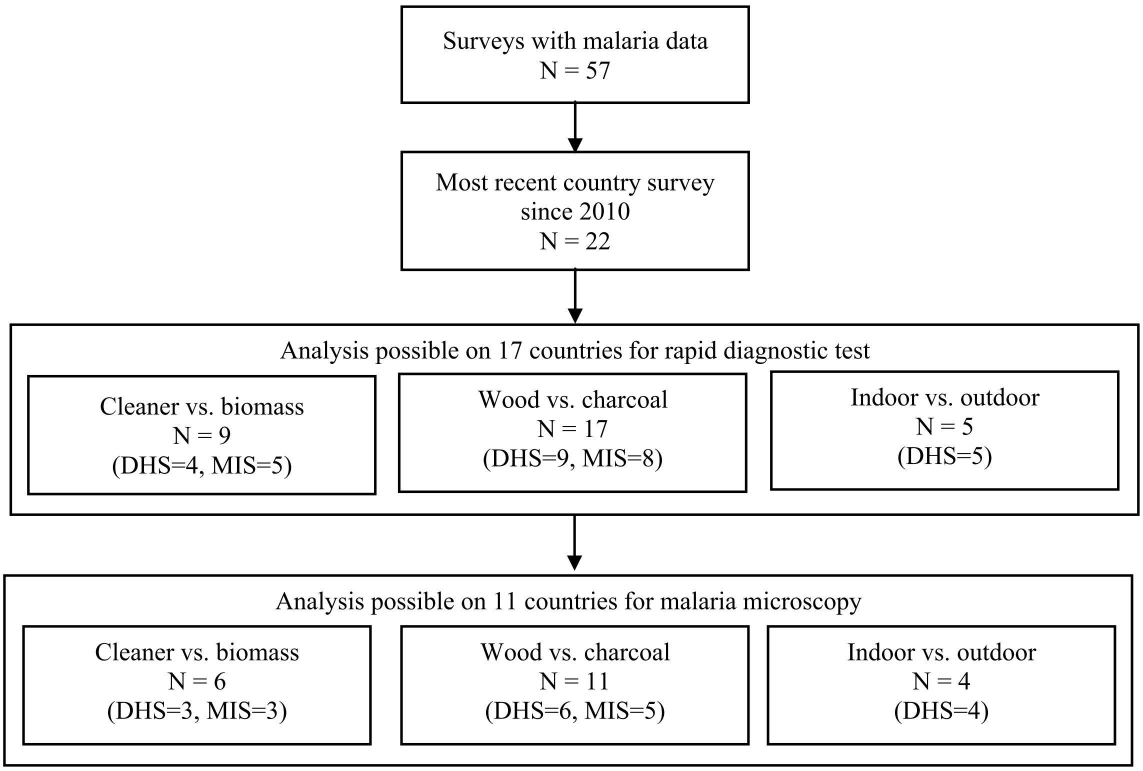

Fig. 1 Flow diagram for included countries. *N* Number of countries

Measure of malarial diagnosis

A malarial infection was determined by a positive RDT (n = 17 countries) and in some countries a subsequent blood smear test via microscopy taken at the point of interview (n = 11 countries), both of which were modelled as a binary (negative, positive) outcome variable, in separate analysis within this study. The RDT was undertaken using the SD BIOLINE Malaria Ag test, in all countries, which has estimated sensitivity of 99.7% and specificity of 99.5% [25]. Whereas, only certain countries collected blood samples which were collected with the parasites detected in the blood at time of survey using microscopy [18], with estimated sensitivity of 95.7% and specificity of 97.9% [26].

Explanatory variables

Covariates were included for the relevant contextual, household and individual factors identified as influencing both HAP exposure and malarial risk. Covariates were included in regression models as categorical variables other than household altitude, which was modelled as a continuous variable. Regional level variables were: malarial endemicity (mesoendemic, hyperendemic and holoendemic), season (dry, wet), rural or urban residence (rural, urban), cluster altitude (metres). Household level variables were: number of household members (≤ 6, > 6), household smoking (no, yes), modified wealth index (lowest, low, middle, high, highest), biomass cooking fuel type (where applicable; kerosene, coal/lignite, charcoal, wood, straw/shrubs/grass, agricultural crop, animal dung), household insecticide spraying within the last 12 months (no, yes) and dwelling construction (traditional, modern). Child variables were: age (< 1, 1, 2, 3, 4 years), birth order (first born, not first born), child's sex (male, female), slept under mosquito net last night (no, yes—treated (ITN) net, yes—untreated net). The season variable is created using regional and country level information from the CIA fact book [27] and the World Bank climate change knowledge portal [28]. The household construction variable is a composite variable derived from the wall, roof and floor material. Firstly, each of the three materials were categorized into natural, rudimentary and finished construction material using the criteria outlined by Tusting et al. [8], followed by the creation of the household construction variable where modern household construction was define as wall, roof and floor being made of finished materials.

Table 1 Analyses, sub-analyses and exploratory analyses undertaken with detail on categorisation of the exposure of interest

Analysis	Exposure of interest	Categories	Adjusted for	Sub-analysis	Exploratory analysis controlling for[‡]
Analysis 1	Biomass usage	• Cleaner (electricity, LPG, natural gas, biogas) • Solid biomass fuels and kerosene (kerosene, coal/lignite, charcoal, wood, straw/shrubs/grass, agricultural crop, animal dung)	• Child's age, child's gender, birth order, Child slept under slept under mosquito net last night, modified wealth index, number of household members, place of residence, malarial endemicity, season, cluster altitude and cooking location	• Urban areas only • Rural areas only • Mesoendemic areas only	• Household insecticidal spraying • Household smoking and cooking location
Analysis 2	Biomass fuel type*	• Charcoal • Wood	• Child's age, child's gender, birth order, Child slept under slept under mosquito net last night, modified wealth index, number of household members, place of residence, malarial endemicity, season, cluster altitude and cooking location	• Urban areas only • Rural areas only • Mesoendemic areas only	• Household insecticidal spraying • Household smoking and cooking location
Analysis 3	Cooking location[†]	• Outdoors • In a separate building • Indoors	• Child's age, child's gender, birth order, Child slept under slept under mosquito net last night, modified wealth index, number of household members, place of residence, malarial endemicity, season, cluster altitude and biomass cooking fuel type	• Urban areas only • Rural areas only • Mesoendemic areas only • Wood cooking only	• Household insecticidal spraying • Household smoking and cooking location

* Charcoal and wood are the most commonly used type of biomass fuel and are next to each other on fuel ladder, with charcoal being relatively less polluting

† Only Solid biomass fuels and kerosene (kerosene, coal/lignite, charcoal, wood, straw/shrubs/grass, agricultural crop, animal dung) were included in the analysis and included as a covariate

‡ Countries excluded due to the variable being incomplete, high level of missing or low cell counts. For household insecticidal spraying excluded countries were: Burkina Faso 2017–2018, Cameron 2018, DRC 2013–2014, Malawi 2017, Mali 2018, Nigeria 2018, Tanzania 2017 and Togo 2017. For household smoking and cooking location excluded countries were: Burkina Faso 2017–2018, Ghana 2019, Liberia 2016, Malawi 2017, Mozambique 2018 and Sierra Leone 2016

Data analysis

Data preparation and analysis was undertaken in R studio [29]. Each variable was described within the combined dataset using number of cases (n), and percentage (%) and median and Interquartile range (IQR) for continuous variables. The level of missing data ranged from 0 to 48% of clinically relevant variables at a country level, which was imputed using the MICE package [30] with 50 iterations [31, 32]; to prevent bias from list-wise deletion [33]. To test the association between cooking practices and malarial infection, multivariable logistic regression using the survey package [34], was used to account for the complex sampling strategy; reporting adjusted odds ratios (AOR) and 95% confidence intervals (95% CI). The MIS survey did not contain information on cooking location and household smoking, therefore a sub-analysis was undertaken using countries where these variables were available for analysis. Sub-analyses were also undertaken for rural, urban, wood cooking fuel houses and mesoendemic areas. In addition, the analysis was repeated to include additional covariates among a sub-set of countries where additional variables of interest were available. This enabled investigation of the influence of (i) household cooking location; (ii) household smoking; and (iii) household insecticidal spraying, as some of the variables are missing from certain countries.

Results

This study identified 85,263 children aged under 5 years children living in 17 participating countries (DHS = 9, MIS = 7) from 2011 to 2019, with a total of 74,461 RDT and 48,491 microscopy test results. Within the pooled full dataset, median child age was 3 years (IQR: 2–4). The proportion of girls ranged from 48.0% in Guinea (2012) to 51.0% in Cote d'Ivoire (2011–2012), with overall 49.4% in the pooled dataset (Table 2).

Malarial infection was positively identified by RDT among 34.6% of children in the combined dataset at the time of testing, with the highest point prevalence in Guinea 2012 (51.8%) and lowest in Tanzania 2017 (7.07%) (Table 3). However, where microscopy was undertaken malarial infection was identified in 28.2% of children, with the highest prevalence in Guinea 2012 (48.7%) and lowest in Uganda 2018–2019 (11.3%). Of the areas surveyed, most were in mesoendemic areas (Fig. 2), with holoendemicity in Cote d'Ivoire 2011–2012, DRC 2013–2014, Guinea 2012 and Liberia 2016. Of those children with a positive malarial RDT result, 1.3% resided in cleaner cooking households. Whereas, 35.2% in outdoor cooking households and 35.7% in a household where cooking was typically undertaken in a separate building (Table 3).

Analysis 1—Solid biomass fuel usage and risk of malarial infection

In pooled analyses, cooking with solid biomass fuels and kerosene fuels was observed to be independently associated with a 57% increase in the adjusted odds ratio for malarial infection, compared to cleaner cooking (electricity, LPG) (Fig. 3) (RDT AOR: 1.57 [1.30–1.914]; Microscopy AOR: 1.58 [1.23–2.04]) (Table 3). A 61% increase in adjusted odds ratio was also observed when investigating the effect of cooking location and household smoking with solid biomass fuels and kerosene compared to cleaner cooking fuels (RDT AOR: 1.61 [1.28–2.02]; Microscopy AOR: 1.61 [1.20–2.15]. The increased malarial infection adjusted odds ratio associated with solid biomass fuels and kerosene cooking remained in the stratified sub-analysis among rural locations (RDT AOR: 1.41 [1.02–1.95]; Microscopy AOR: 2.10 [1.34–3.32]), urban locations (RDT AOR: 1.58 [1.24–2.03] only) and mesoendemic regions (RDT AOR: 1.58 [1.28–1.95]; Microscopy AOR: 1.59 [1.21–2.08]) (Table 4).

Analysis 2—Biomass fuel type and risk of malarial infection

Among biomass fuel households only, use of wood compared to charcoal fuel was associated with an increased adjusted odds ratio of malarial infection (RDT AOR: 1.77 [1.54–2.04]; Microscopy AOR: 1.21 [1.08–1.37]) (Fig. 4), with a similar effect being observed in the exploratory analysis controlling for cooking location and household smoking (RDT AOR: 1.26 [1.10–1.46] only) and in mesoendemic areas (RDT AOR: 1.77 [1.49–2.09]; Microscopy AOR: 1.26; [1.10–1.44]) (Table 4). In the stratified sub-analysis it was observed that urban areas had a greater adjusted odds ratio of malarial infection associated with wood compared to charcoal cooking (RDT AOR: 2.25 [1.79–2.78]), in comparison to rural areas (RDT AOR: 1.43 [1.21–1.70]).

Analysis 3—Household cooking location and risk of malarial infection

No significant association was observed between household cooking location and malaria adjusted odds ratio (RDT AOR: 0.94 [0.83–1.05]; Microscopy AOR: 0.97 [95% CI 0.83–1.05]) (Fig. 5). In comparison, cooking in a separate building was associated with a reduced adjusted odds ratio of malarial infection by 74% compared to indoor cooking (Fig. 5) (RDT AOR: 0.74 [0.66–0.83]; Microscopy AOR: 0.75 [0.67–0.84]). The same reduced malarial infection adjusted odds ratio associated with cooking in a separate building was observed in stratified

Table 2 Characteristics of included surveys

Country	Survey	N	Positive RDT (%)*	Positive microscopy (%)*	Child's age (years) n (%)					Females (%)
					< 1	1	2	3	4	
Central Africa										
Cameroon 2018	DHS	4417	23.9	–	567 (12.8%)	873 (19.8%)	1056 (23.9%)	1002 (22.7%)	919 (20.8%)	48.7
DRC 2013–2014	DHS	6359	35.9	28.3	868 (13.6%)	1263 (19.9%)	1515 (23.8%)	1390 (21.9%)	1324 (20.8%)	50.1
East Africa										
Burundi 2016–2017	DHS	4309	47.4	33.4	604 (14.0%)	901 (20.9%)	935 (21.7%)	921 (21.4%)	948 (22.0%)	49.5
Malawi 2017	MIS	1929	41.3	–	229 (11.9%)	374 (19.4%)	438 (22.7%)	406 (21.1%)	480 (24.9%)	49.3
Mozambique 2018	MIS	384	45.4	–	507 (13.4%)	769 (20.3%)	944 (25.0%)	810 (21.4%)	753 (19.9%)	49.3
Tanzania 2017	MIS	5882	7.1	–	782 (13.3%)	1197 (20.3%)	1383 (23.5%)	1308 (22.2%)	1212 (20.6%)	49.7
Uganda 2018–2019	MIS	5282	21.0	11.3	631 (11.9%)	1011 (19.1%)	1281 (24.3%)	1228 (23.2%)	1131 (21.4%)	49.5
West Africa										
Benin 2017–2018	DHS	11,981	36.4	39.3	1747 (14.6%)	2390 (19.9%)	2705 (22.6%)	2699 (22.5%)	2440 (20.4%)	49.2
Burkina Faso 2017–2018	MIS	4839	20.8	17.1	645 (13.3%)	877 (18.1%)	1175 (24.3%)	1149 (23.7%)	992 (20.5%)	49.2
Cote d'Ivoire 2011–2012	DHS	3679	50	17.6	550 (14.9%)	749 (20.4%)	932 (25.3%)	808 (22.0%)	640 (17.4%)	51.0
Ghana 2019	MIS	2143	25.9	–	269 (12.6%)	407 (19.0%)	565 (26.4%)	457 (21.3%)	445 (20.8%)	49.1
Guinea 2021	DHS	3022	51.8	48.4	394 (13.0%)	580 (19.2%)	660 (21.8%)	729 (24.1%)	659 (21.8%)	48.0
Liberia 2016	DHS	3074	45.0	–	388 (12.6%)	581 (18.9%)	711 (23.1%)	712 (23.2%)	682 (22.2%)	49.1
Mali 2018	DHS	5159	26.4	–	664 (12.9%)	1117 (21.7%)	1224 (23.7%)	1126 (21.8%)	1028 (19.9%)	49.5
Nigeria 2018	DHS	9791	34.8	21.9	1335 (13.6%)	2017 (20.6%)	2273 (23.2%)	2153 (22.0%)	2013 (20.6%)	49.2
Sierra Leone 2016	MIS	6763	52.7	40.1	946 (14.0%)	1226 (18.1%)	1594 (23.6%)	1587 (23.5%)	1411 (20.9%)	50.0
Togo 2017	MIS	2850	44.3	28.8	401 (14.1%)	566 (19.8%)	666 (23.4%)	630 (22.1%)	588 (20.6%)	50.3

N: Number of child observations, DHS: Demographic and Health Survey, MIS: Malaria Indicators Survey, n: number of child observation with each category

* Percentage for positive results based on those children who received a conclusive result from malaria test

Table 3 Descriptive statistics for the combined dataset (N = 85,263)

	Malaria RDT result (N = 74,461)			Malaria Microscopy results (N = 48,491)		
	Negative N = 48,699 (65.4%)	Positive N = 25,761 (34.6%)	p value	Negative N = 34,802 (71.8%)	Positive N = 13,689 (28.2%)	p value
Proxies for HAP exposure levels						
Cooking fuel			< 0.001			< 0.001
Electricity	247 (0.5%)	47 (0.2%)		196 (0.6%)	22 (0.2%)	
LPG	2404 (4.9%)	295 (1.1%)		1287 (3.7%)	98 (0.7%)	
Natural gas	305 (0.6%)	9 (0.0%)		201 (0.6%)	7 (0.1%)	
Biogas	38 (0.1%)	8 (0.0%)		16 (0.0%)	7 (0.0%)	
Kerosene	1256 (2.6%)	220 (0.9%)		927 (2.7%)	107 (0.8%)	
Coal, lignite	155 (0.3%)	42 (0.2%)		103 (0.3%)	24 (0.2%)	
Charcoal	10,043 (20.7%)	2297 (8.9%)		6368 (18.3%)	1500 (11.0%)	
Wood	33,799 (69.5%)	22,397 (87.0%)		25,288 (72.8%)	11,602 (84.8%)	
Other biomass	370 (0.8%)	417 (1.6%)		358 (1.0%)	307 (2.2%)	
No food cooked in house	15 (0.0%)	8 (0.0%)		7 (0.0%)	2 (0.0%)	
Missing	68	22		50	13	
Cooking location			< 0.001			< 0.001
In the house	7108 (29.0%)	4129 (29.1%)		6326 (31.2%)	2830 (32.2%)	
In a separate building	9170 (37.5%)	5068 (35.7%)		6468 (31.9%)	2627 (29.9%)	
Outdoors	8196 (33.5%)	4994 (35.2%)		7482 (36.9%)	3321 (37.8%)	
Missing	24,226	11,571		14,526	4911	
Contextual and contextual variables						
Place of residence			< 0.001			< 0.001
Urban	17,582 (36.1%)	4683 (18.2%)		11,635 (33.4%)	2669 (19.5%)	
Season			< 0.001			< 0.001
Dry	25,169 (51.7%)	11,776 (45.7%)		20,750 (59.6%)	6583 (48.1%)	
Malarial endemicity			< 0.001			< 0.001
Mesoendemic	42,772 (87.8%)	19,018 (73.8%)		29,351 (84.3%)	9457 (69.1%)	
Hyperendemic	5729 (11.8%)	6286 (24.4%)		5116 (14.7%)	3971 (29.0%)	
Holoendemic	198 (0.4%)	457 (1.8%)		335 (1.0%)	261 (1.9%)	
Cluster altitude			< 0.001			< 0.001
Median IQR	294 (85, 596)	321 (156, 590)		322 (149, 764)	324 (149, 588)	
Household level variables						
Modified Wealth Index			< 0.001			< 0.001
Lowest	8669 (17.8%)	7714 (29.9%)		6633 (19.1%)	3976 (29.0%)	
Low	9618 (19.7%)	7306 (28.4%)		6925 (19.9%)	3722 (27.2%)	
Middle	9919 (20.4%)	5698 (22.1%)		6949 (20.0%)	2908 (21.2%)	
High	10,886 (22.4%)	3802 (14.8%)		7724 (22.2%)	2225 (16.3%)	
Highest	9608 (19.7%)	1241 (4.8%)		6569 (18.9%)	859 (6.3%)	
Household smoking			< 0.001			< 0.001
No	20,049 (81.6%)	10,852 (76.1%)		16,195 (79.5%)	6631 (75.1%)	
Missing	24,119	11,497		14,430	4860	
Number of household members			< 0.001			< 0.001
≤ 6	26,538 (54.6%)	13,007 (50.6%)		18,579 (53.5%)	6631 (48.5%)	
Missing	68	44		51	31	
Household insecticide spraying within last 12 months			< 0.001			< 0.001
No	18,189 (91.1%)	13,044 (94.9%)		17,582 (93.3%)	8527 (95.6%)	
Yes	1779 (8.9%)	703 (5.1%)		1260 (6.7%)	394 (4.4%)	
Missing	28,731	12,014		15,960	4768	
House construction			< 0.001			< 0.001

Table 3 (continued)

	Malaria RDT result (N = 74,461)			Malaria Microscopy results (N = 48,491)		
	Negative N = 48,699 (65.4%)	Positive N = 25,761 (34.6%)	p value	Negative N = 34,802 (71.8%)	Positive N = 13,689 (28.2%)	p value
Traditional	28,361 (58.2%)	19,352 (75.1%)		20,902 (60.1%)	10,056 (73.5%)	
Modern	20,338 (41.8%)	6410 (24.9%)		13,900 (39.9%)	3634 (26.5%)	
Child level variables						
Child's age (years)			< 0.001			< 0.001
< 1	7643 (15.7%)	2282 (8.9%)		5319 (15.3%)	1272 (9.3%)	
1	10,335 (21.2%)	4404 (17.1%)		7359 (21.1%)	2186 (16.0%)	
2	11,266 (23.1%)	6328 (24.6%)		8127 (23.4%)	3239 (23.7%)	
3	10,254 (21.1%)	6497 (25.2%)		7425 (21.3%)	3568 (26.1%)	
4	9201 (18.9%)	6251 (24.3%)		6572 (18.9%)	3424 (25.0%)	
Birth order			< 0.001			
First born	14,376 (33.7%)	5338 (24.5%)		9392 (30.8%)	2553 (22.1%)	
Missing	6102	3993		4306	2164	
Child's gender			0.068			
Male	24,535 (50.4%)	13,112 (50.9%)		17,489 (50.3%)	6971 (50.9%)	
Child slept under slept under mosquito net last night			< 0.001			< 0.001
Did not sleep under a net	20,615 (42.3%)	12,078 (46.9%)		15,858 (45.6%)	6942 (50.7%)	
Only treated (ITN) nets	26,991 (55.4%)	13,204 (51.3%)		18,320 (52.6%)	6525 (47.7%)	
Only untreated nets	1093 (2.2%)	480 (1.9%)		624 (1.8%)	222 (1.6%)	

N: Number of observations; %: column percentage for categorical variables; IQR: interquartile range; ITN: insecticide-treated nets; RDT: rapid diagnostic test

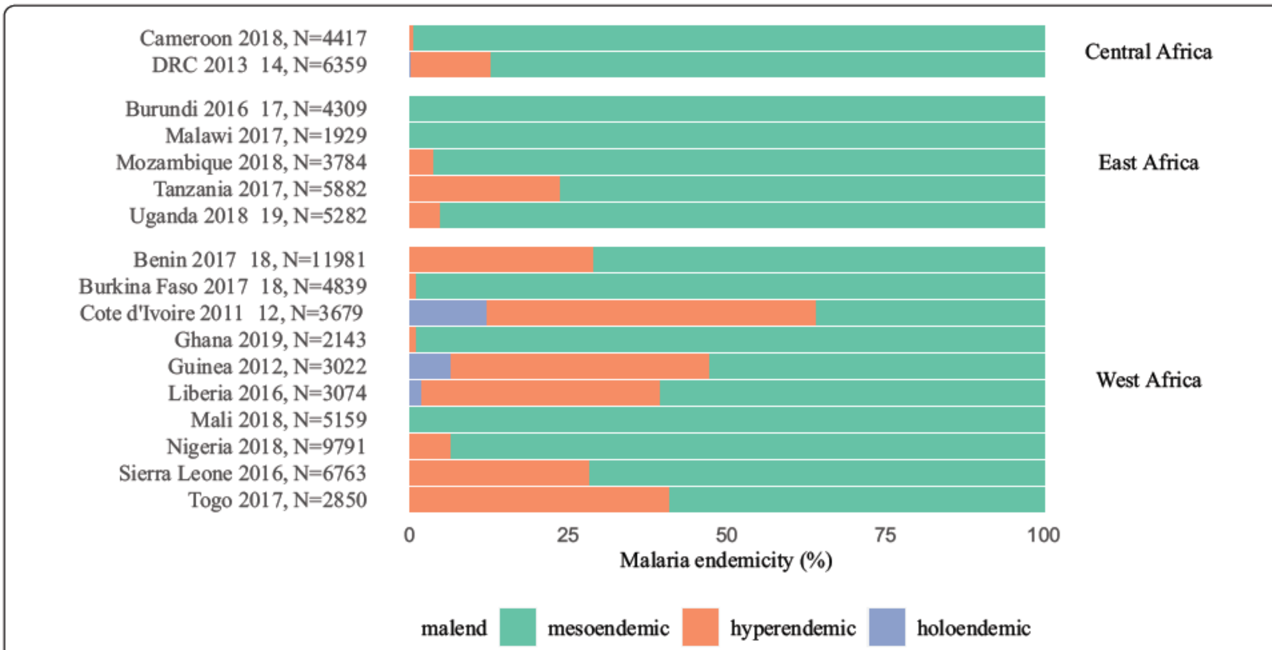

Fig. 2 Malarial endemicity and prevalence among children under five for each country. *N* number of child observations, *PR* prevalence rate of positive RDT result

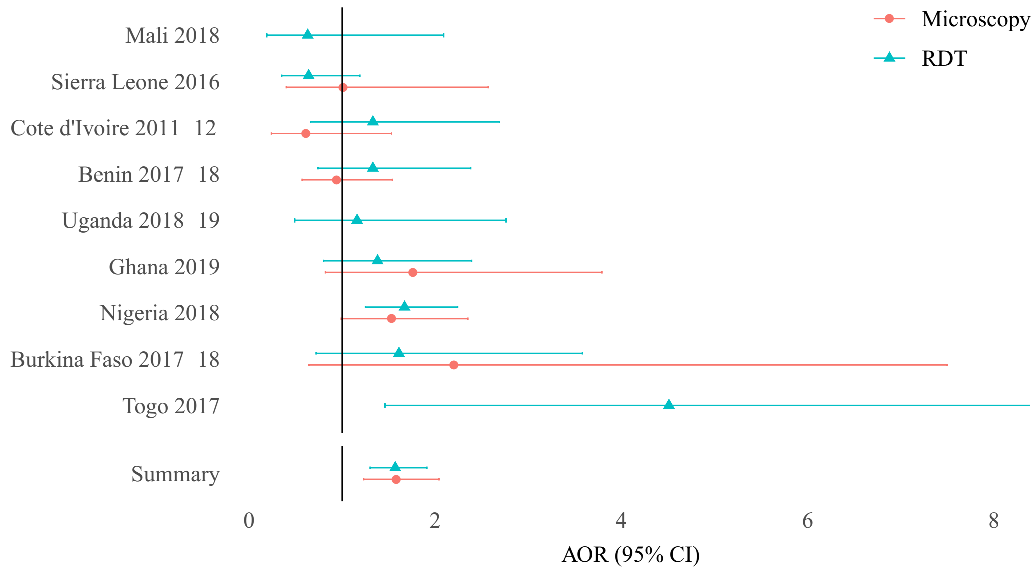

Fig. 3 Adjusted odds ratio of malarial infection with biomass cooking compared to cleaner cooking. *AOR* adjusted odds ratio, *95% CI* 95% confidence interval, *N* Number of child observations. Table of unadjusted and adjusted results can be found in Additional file 2: Table S2.1

sub-analyses for wood cooking (RDT AOR: 0.75 [0.67–0.85]; Microscopy AOR: 0.77 [0.67–0.87]), rural (RDT AOR: 0.70 [0.62–0.80]; Microscopy AOR: 0.73 [0.64–0.84]) and mesoendemic areas (RDT AOR: 0.73 [0.65–0.82]; Microscopy AOR: 0.74 [0.65–0.83) only (Table 4).

Discussion

This large exploratory study of over 85,000 children aged under 5 years living in 17 malaria-endemic SSA found no evidence to suggest that use of cleaner fuels (e.g., LPG, electricity, biogas), charcoal vs wood, or outdoor cooking location are associated with an increased risk of malarial infection. Indeed, the findings suggest that solid biomass fuel usage may be associated with a higher incidence of malarial infection among children in SSA. There are a number of factors that may account for the increase in infections, such as the longer cooking times and thus of carbon dioxide production [35], a major mosquito attractant [36], found with solid biomass fuel cooking [37]. Additionally, the use of solid biomass fuels, particularly wood, crop residue and dung, require women, to typically collect fallen or harvest branches from woods and forests where mosquitoes commonly reside, often taking children under 5 years on their backs, thereby increasing risk of mosquito bites.

It is highly likely that risk of within household acquisition of malaria is also influenced by socioeconomic factors such as household construction characteristics (eaves space, wall type) and living conditions [8, 38–41] which are not fully captured in the DHS composite wealth index. It is also recognized that use of cleaner domestic energy sources, cooking in a separate building and selection of biomass cooking fuel type may reflect socio-economic determinants, also related to malarial microepidemiology at the household level [42, 43]. The child's age is also a key factor in malarial infection risk, with an observed increased risk with increasing age, potentially reflecting behavioural, nutritional or exposure differences. In terms of modifiable factors for malarial infection prevention and control, there is strong evidence supporting the sustained use of ITN bed nets, larval source management and household insecticide spraying [12]; of which only ITN bed nets could be controlled for in the main analyses. The importance of household insecticide spraying can be seen in the subsidiary analysis undertaken among countries for which this information was available, identifying that there was no association with type of biomass fuel and malarial infection risk (RDT: AOR 1.23 [0.94–1.61]; Microscopy AOR: 1.07 [0.77–1.47]; Table 4); however, this sub-analysis is likely to be underpowered and should be interpreted with caution.

The analyses presented also did not explore broader contextual factors associated with household or village level clustering of malarial transmission, including position of households in relation to mosquito sites and local attitudes to malarial treatment which are recognized to influence local variations in malarial prevalence [44]. The DHS dataset did not contain information on cooking practices such as timing or duration, both of which

Table 4 Odds ratio of malarial infection for each cooking practices for the combined dataset, exploratory and sub-analysis

Analysis	Outcome	Analysis 1 Biomass vs cleaner cooking				Analysis 2 Wood vs charcoal cooking				Analysis 3 Cooking location			
		Cooking fuel	AOR [95% CI]	*p* value	N	Cooking fuel	AOR [95% CI]	*p* value	N	Type of cooking location	AOR [95% CI]	*p* value	*N*
Combined dataset*	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.57 [1.30–1.91]**	**<0.001**	43,759	Wood	**1.77 [1.54–2.04]**	**<0.001**	73,072	In a separate building	**0.74 [0.66–0.83]**	**<0.001**	23,754
										Outdoor	0.94 [0.83–1.05]	0.26	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.58 [1.23–2.04]**	**<0.001**	30,007	Wood	**1.21 [1.08–1.37]**	**0.001**	46,206	In a separate building	**0.75 [0.67–0.84]**	**<0.001**	21,383
										Outdoor	0.97 [0.86–1.09]	0.58	
Sub-analysis													
Rural areas	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.41 [1.02–1.95]**	**0.04**	31,100	Wood	**1.43 [1.21–1.70]**	**<0.001**	54,473	In a separate building	**0.70 [0.62–0.80]**	**<0.001**	16,988
										Outdoor	0.91 [0.79–1.04]	0.17	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**2.10 [1.34–3.32]**	**0.001**	20,290	Wood	1.09 [0.91–1.30]	0.36	34,693	In a separate building	**0.73 [0.64–0.84]**	**<0.001**	15,193
										Outdoor	0.92 [0.80–1.07]	0.28	
Urban areas	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.58 [1.24–2.03]**	**<0.001**	12,659	Wood	**2.23 [1.79–2.78]**	**<0.001**	18,599	In a separate building	0.96 [0.78–1.19]	0.72	6766
										Outdoor	0.99 [0.81–1.21]	0.90	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	1.30 [0.96–1.76]	0.09	9717	Wood	**1.40 [1.20–1.64]**	**<0.001**	11,513	In a separate building	0.86 [0.69–1.07]	0.17	6190
										Outdoor	1.08 [0.90–1.31]	0.40	
Mesoendemic areas	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.58 [1.28–1.95]**	**<0.001**	35,167	Wood	**1.77 [1.49–2.09]**	**<0.001**	57,814	In a separate building	**0.73 [0.65–0.82]**	**<0.001**	20,349
										Outdoor	0.92 [0.81–1.05]	0.22	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.59 [1.21–2.08]**	**0.001**	23,519	Wood	**1.26 [1.10–1.44]**	**0.001**	35,898	In a separate building	**0.73 [0.65–0.83]**	**<0.001**	18,209
										Outdoor	0.94 [0.83–1.08]	0.37	

Table 4 (continued)

Analysis	Outcome	Analysis 1 Biomass vs cleaner cooking				Analysis 2 Wood vs charcoal cooking				Analysis 3 Cooking location			
		Cooking fuel	**AOR [95% CI]**	***p* value**	**N**	**Cooking fuel**	**AOR [95% CI]**	***p* value**	**N**	**Type of cooking location**	**AOR [95% CI]**	***p* value**	***N***
Wood only	RDT									Indoor	*Ref.*		
										In a separate building	**0.75 [0.67–0.85]**	**< 0.001**	19,406
										Outdoor	0.90 [0.79–1.02]	0.10	
	Microscopy									Indoor	*Ref.*		
										In a separate building	**0.77 [0.67–0.87]**	**< 0.001**	17,244
										Outdoor	0.94 [0.82–1.08]	0.36	
Exploratory analysis													
Controlling for household mosquito spraying†	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	1.23 [0.94–1.61]	0.14	26,778	Wood	**1.94 [1.62–2.33]**	**< 0.001**	36,898	In a separate building	**0.85 [0.73–0.99]**	**0.03**	9951
										Outdoor	0.95 [0.81–1.10]	0.47	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	1.07 [0.77–1.47]	0.69	18,102	Wood	**1.30 [1.13–1.49]**	**< 0.001**	27,115	In a separate building	**0.76 [0.65–0.88]**	**< 0.001**	9676
										Outdoor	0.92 [0.79–1.07]	0.29	

AOR Adjusted odds ratio, *95% CI* 95% confidence interval, *N* Number of observations, *RDT* Rapid diagnostic test, *Ref* Reference group. Results in bold are statistically significant. Unadjusted results are in Additional file 3: Table S3.1

* Controlled for: Child's age, child's gender, birth order, Child slept under slept under mosquito net last night, modified wealth index, number of household members, place of residence, malarial endemicity, season and cluster altitude

† Burkina Faso 2017–2018, Cameron 2018, DRC 2013–2014, Malawi 2017, Mali 2018, Nigeria 2018, Tanzania 2017 and Togo 2017 were excluded due to the household mosquito spraying variable being incomplete, high level of missing or low cell counts

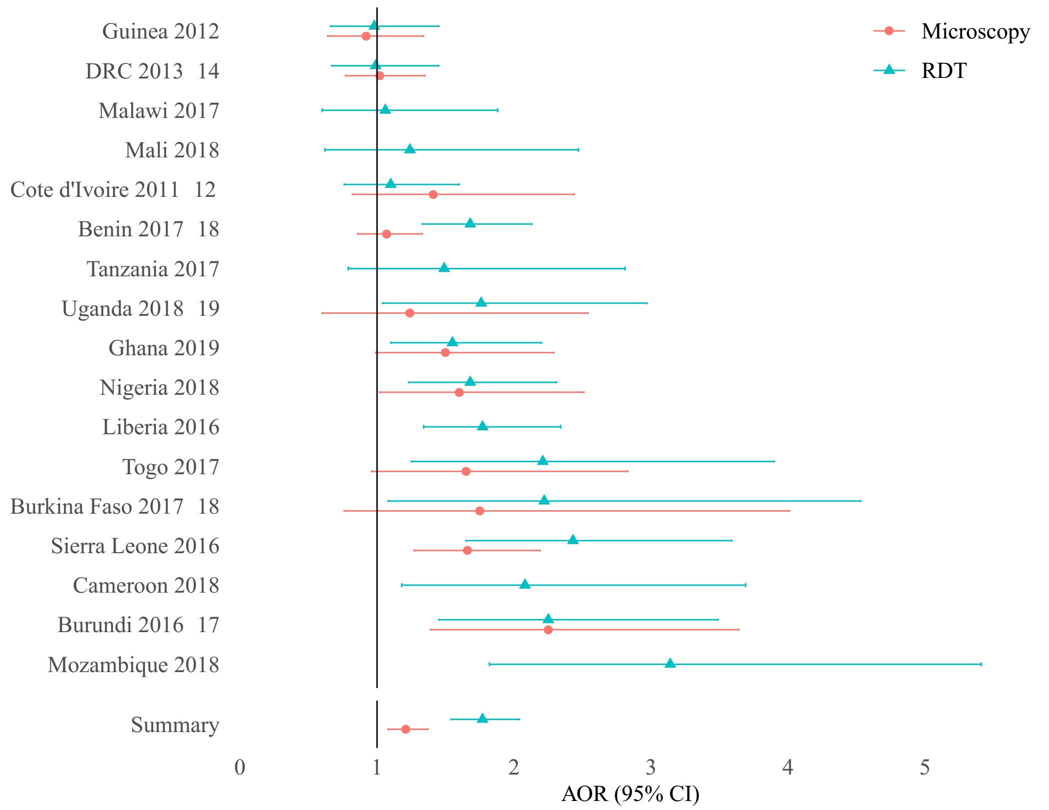

Fig. 4 Adjusted odds ratio of malarial infection with wood cooking compared to charcoal cooking. *AOR* Adjusted odds ratio, *95% CI* 95% confidence interval, *N* Number of child observations. Table of unadjusted and adjusted results can be found in Additional file 2: Table S2.2

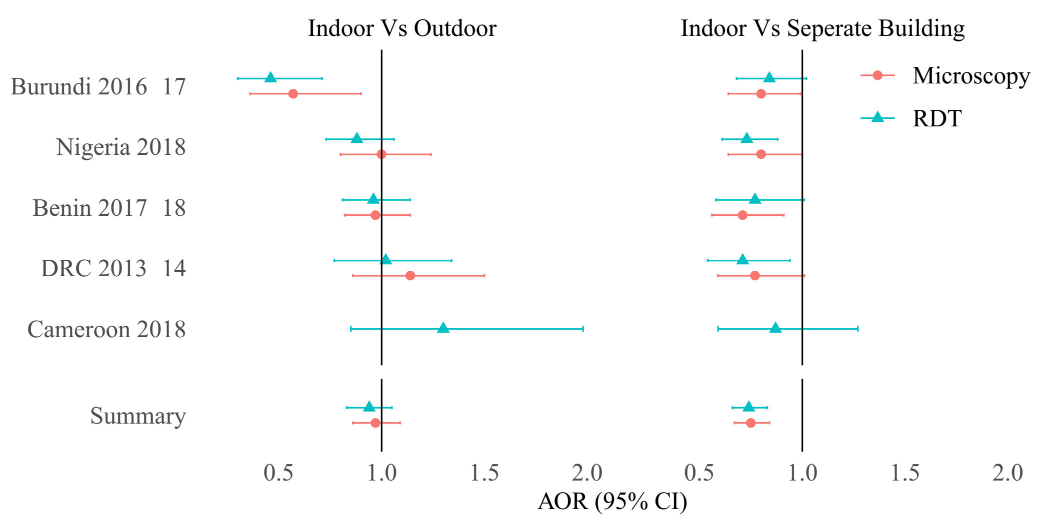

Fig. 5 Adjusted odds ratio of malarial infection with cooking location (outdoor, in a separate building) compared to indoors. *AOR* Adjusted odds ratio, *95% CI* 95% confidence interval, *N* Number of child observations. Table of unadjusted and adjusted results can be found in Additional file 2: Table S2.3

influence the amount of smoke produced and therefore HAP exposure, and may also generate higher localized levels of indoor CO_2 [35] thereby attracting mosquitoes into the home [36]. In addition, season could only be accounted for at country or broader regional level, which does not take into account microclimates, in addition, the DHS is normally undertaken in the dry season and the MIS in the wet season when the malarial transmission risk is increased [18]. HAP interventions should be developed to include activities which communicate that cooking practices which produce less smoke do not increase risk of malaria transmission to residents. It is also important to reinforce health protection advice regarding evidence-based measures for mosquito control. Further qualitative and quantitative research is merited, for a detailed investigation of the relationships between cooking location, fuel choice and risk of malarial acquisition, considering a wider range of transmission risk factors at a local level.

The rural–urban differences in cooking activity patterns, which can be most clearly noted within the differences observed in distribution between fuel types, is likely to reflect relative economic development, improved access to cleaner fuel sources in urban areas and reduced potential for cohabitation with livestock [45]. However, the rural–urban divide was not as distinct within the cleaner fuel or cooking location sub-analysis, indicating that other contextual and compositional factors exist which may influence malarial infection risk (e.g., nutrition). Although season, malarial endemicity and altitude were captured as confounding factors within our analyses, information was not available for other contextual factors of relevance to malarial infection risk, such as temperature [46].

Additionally, although the cooking practices are reported at the time of interview, this survey question does not take into consideration longer-term trends which may vary on a seasonal basis. Further prospective research is required to better understand environmental influences upon malarial microepidemiology including objective pollutant exposure assessment, capture of household design characteristics, lifestyle and time-activity factors to assess relationships with mosquito breeding conditions, malarial parasitaemia and outcomes among adults and children.

Conclusion

This large-scale observational study suggests that use of cleaner fuels and outdoor cooking practices typically associated with lower levels of household smoke, were not associated with an increased malarial acquisition risk among children living in SSA. Further mixed-methods research is required to better understand the relationships between cooking practices, cooking fuel emissions, mosquito activity and risk of malarial acquisition at household and community levels in this world region.

Abbreviations

AOR: Adjusted odds ratio; DHS: Demographic and Health Survey; DRC: Democratic Republic of Congo; HAP: Household air pollution; ITN: Insecticide-treated net; LPG: Liquefied petroleum gas; MICE: Multiple imputation by chained equations; MIS: Malaria indicator Survey; RDT: Rapid diagnostic test; SSA: Sub-Saharan Africa; USAID: United States Agency for International Development; 95% CI: 95% Confidence interval.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12936-022-04152-3.

Additional file 1: Table S1.1. Predictors included with the PCA analysis for the modified wealth index by country.

Additional file 2: Table S2.1. Unadjusted and adjusted odds ratio of malarial infection with solid biomass fuels and kerosene cooking compared to cleaner cooking—Analysis 1. **Table S2.2.** Unadjusted and adjusted odds ratio of malarial infection with wood cooking compared to charcoal cooking—Analysis 2. **Table S2.3.** Unadjusted and adjusted odds ratio of malarial infection with cooking location (outdoor, in a separate building) compared to indoors—Analysis 3.

Additional file 3: Table S3.1. Unadjusted odds ratio of malarial infection for each cooking practices for the combined dataset, exploratory and sub-analysis.

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Author contributions

KEW: Conceptualization; methodology; data curation, formal analysis, visualization and roles/writing—original draft. SEB and GNT: conceptualization; supervision and writing—review and editing. MJP: methodology and writing—review and editing. FDP and SG: supervision and writing—review and editing. LST: writing—review and editing. All authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study freely and publicly available from https://dhsprogram.com/data/ and https://malariaatlas.org/.

Declarations

Ethics approval and consent to participate

Not applicable as no data was collected as part of this study; authorization was given by DHS to access the online data archive. Details on ethical approval and consent are available from https://dhsprogram.com.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

Additional File 1

Table S1.1: Predictors included with the PCA analysis for the modified wealth index by country

Country	Source of drinking water	Toilet facility	House construction			Assets																			Dwelling window material	Lighting fuel	Refuse collection	Own or rent house
			Wall material	Roof material	Floor material	Electricity	Radio	television	refrigerator	Watch	Bicycle	Motorcycle or scooter	Animal-drawn cart	Car or Truck	Boat with a motor	Bank account	Mobile telephone	Computer	Non-motorised	Tractor	Plough	Household furniture*	Household electronics*	Other assets*				
Benin 2017-18	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■				■	
Burkina Faso 2017-18	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■						
Burundi 2016-17	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■						
Cameroon 2018	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■	■	■				
Côte d'Ivoire 2011-12	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
DRC 2014-15	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■	■					■
Ghana 2019	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■					

Guinea 2012	■	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■			■	■						
Liberia 2016	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■						
Malawi 2017	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				■						
Mali 2018	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■						
Mozambique 2018	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■											
Nigeria 2018	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■					
Sierra Leone 2016	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■									
Tanzania 2017	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■					
Togo 2017	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					■					
Uganda 2018-19	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			■						

*Household furniture (e.g., table, chairs, wardrobe, bed, mattress, lamps, clock)

*Household electronics (e.g., washing machine, DVD player, internet, modem/router, satellite, laptop, Generator, music system, sewing machine, fan, air conditioning, solar panel, water pump, battery, iron, TV5 antenna, Cable subscription, camera, blender, microwave)

*Other assets (e.g., Grain mill, hammer mill, Rickshaw/Chingchi/Tuk tuk/Htawlargyi/Keke Napep/Bagag, bank account with another institution, credit union, beneficiary of Pantawid Pamilyan Pilipino Program (4Ps), canoe with motor, banana boat, thresher, bedroom available for sleep, floor area of house)

Additional file 2

Table S2.1: Unadjusted and adjusted odds ratio of malarial infection with solid biomass fuels and kerosene cooking compared to cleaner cooking – Analysis 1

Country	Outcome	UOR [95% CI]	*p* value	AOR [95% CI]	*p* value	N
Benin 2017-18	RDT	**5.13[2.79-9.43]**	**<0.001**	1.33[0.74-2.38]	0.35	6118
	Microscopy	**2.02[1.28-3.20]**	**0.003**	0.94[0.57-1.54]	0.80	5829
Burkina Faso 2017-18	RDT	**4.19[2.00-8.77]**	**<0.001**	1.61[0.72-3.58]	0.25	4845
	Microscopy	**5.49[1.69-17.86]**	**0.005**	2.20[0.64-7.50]	0.21	4840
Côte d'Ivoire 2011-12	RDT	**7.31[4.63-11.56]**	**<0.001**	1.33[0.66-2.69]	0.43	3383
	Microscopy	**4.45[2.25-7.85]**	**<0.001**	0.61[0.24-1.53]	0.29	3248
Ghana 2019	RDT	**3.54[2.11-5.94]**	**<0.001**	1.38[0.80-2.39]	0.25	2354
	Microscopy	**3.81[1.90-7.64]**	**<0.001**	1.76[0.82-3.79]	0.15	2356
Mali 2018	RDT	1.04[0.44-2.50]	0.92	0.63[0.19-2.09]	0.45	2322
Nigeria 2018	RDT	**5.10[3.90-6.67]**	**<0.001**	**1.67[1.25-2.24]**	**0.001**	9697
	Microscopy	**5.20[3.52-7.70]**	**<0.001**	1.53[0.99-2.35]	0.05	7065
Sierra Leone 2016	RDT	0.88[0.30-2.57]	0.81	0.64[0.35-1.19]	0.16	6659

	Microscopy	1.03[0.44-2.40]	0.95	1.01[0.40-2.57]	0.98	6669
Togo 2017	RDT	**27.29[9.83-75.76]**	**<0.001**	**4.51[1.46-13.9]**	**0.01**	2905
Uganda 2018-19	RDT	1.30[0.60-2.80]	0.50	1.16[0.49-2.76]	0.73	5476

Abbreviation: UOR = Unadjusted Odds Ratio, AOR = Adjusted Odds Ratio, 95% CI = 95% confidence interval, N= Number of observations, RDT = Rapid diagnostic test. Results in bold are statistically significant.

The reported odds ratios are from solid biomass fuels and kerosene cooking with the reference group being cleaner cooking

Table S2.2: Unadjusted and adjusted odds ratio of malarial infection with wood cooking compared to charcoal cooking –Analysis 2

Country	Outcome	UOR [95% CI]	*p* value	AOR [95% CI]	*p* value	N
Benin 2017-18	RDT	**4.14[3.35-5.12]**	**<0.001**	**1.68[1.33-2.13]**	**<0.001**	5670
	Microscopy	**1.95[1.60-2.38]**	**<0.001**	1.07[0.86-1.33]	0.54	5829
Burkina Faso 2017-18	RDT	**3.70[1.80-7.60]**	**<0.001**	2.22[1.08-4.53]	0.03	4697
	Microscopy	**3.04[1.31-7.04]**	**0.01**	1.75[0.76-4.01]	0.19	4840
Burundi 2016-17	RDT	**4.82[3.14-7.39]**	**<0.001**	**2.25[1.45-3.49]**	**<0.001**	3739
	Microscopy	**4.62[2.88-7.40]**	**<0.001**	**2.25[1.39-3.64]**	**0.001**	3743
Cameroon 2018	RDT	**2.73[1.68-4.44]**	**<0.001**	**2.08[1.18-3.69]**	**0.01**	3367
Côte d'Ivoire 2011-12	RDT	**2.97[2.10-4.19]**	**<0.001**	1.10[0.76-1.60]	0.61	3105
	Microscopy	**3.82[2.30-6.34]**	**<0.001**	1.41[0.82-2.44]	0.22	2980
DRC 2014-15	RDT	1.36[1.00-1.86]	0.05	0.99[0.67-1.45]	0.95	6181
	Microscopy	1.19[0.92-1.54]	0.20	1.02[0.77-1.35]	0.91	6171
Ghana 2019	RDT	**2.30[1.65-3.22]**	**<0.001**	**1.55[1.10-2.20]**	**0.01**	2098
	Microscopy	**2.17[1.56-3.02]**	**<0.001**	1.50[0.99-2.29]	0.06	2101
Guinea 2012	RDT	**2.26[1.64-3.11]**	**<0.001**	0.98[0.66-1.45]	0.93	2948

	Microscopy	**1.79[1.31-2.43]**	**<0.001**	0.92[0.64-1.34]	0.68	2949
Liberia 2016	RDT	**5.63[4.25-7.46]**	**<0.001**	**1.77[1.34-2.34]**	**<0.001**	2785
Malawi 2017	RDT	**2.24[1.36-3.68]**	**0.002**	1.06[0.60-1.88]	0.84	1358
Mali 2018	RDT	2.20[0.98-4.92]	0.05	1.24[0.62-2.47]	0.54	2244
Mozambique 2018	RDT	**6.95[4.08-11.84]**	**<0.001**	**3.14[1.82-5.41]**	**<0.001**	3141
Nigeria 2018	RDT	**2.56[1.90-3.46]**	**<0.001**	**1.68[1.23-2.31]**	**0.001**	7487
	Microscopy	**2.70[1.82-3.99]**	**<0.001**	**1.60[1.02-2.51]**	**0.04**	5423
Sierra Leone 2016	RDT	**6.23[4.66-8.34]**	**<0.001**	**2.43[1.65-3.59]**	**<0.001**	6612
	Microscopy	**3.67[2.92-4.61]**	**<0.001**	**1.66[1.27-2.19]**	**<0.001**	6622
Tanzania 2017	RDT	**5.42[3.05-9.62]**	**<0.001**	1.49[0.79-2.81]	0.22	4903
Togo 2017	RDT	**6.01[4.24-8.51]**	**<0.001**	**2.21[1.25-3.90]**	**0.01**	2791
	Microscopy	**4.18[2.90-6.02]**	**<0.001**	1.65[0.96-2.83]	0.07	2800
Uganda 2018-19	RDT	**3.09[1.73-5.51]**	**<0.001**	**1.76[1.04-2.97]**	**0.03**	5426
	Microscopy	**2.63[1.18-5.85]**	**0.019**	1.24[0.60-2.54]	0.57	5421

Abbreviation: UOR = Unadjusted Odds Ratio, AOR = Adjusted Odds Ratio, 95% CI = 95% confidence interval, N= Number of observations, RDT = Rapid diagnostic test. Results in bold are statistically significant.

The reported odds ratios are from wood cooking with the reference group being charcoal cooking

Table S2.3: Unadjusted and adjusted odds ratio of malarial infection with cooking location (outdoor, in a separate building) compared to indoors – Analysis 3

Country	Outcome	Type of cooking location	UOR [95% CI]	*p* value	AOR [95% CI]	*p* value	N
Benin 2017-18	RDT	In a separate building	**0.74[0.58-0.94]**	**0.02**	0.77[0.58-1.01]	0.06	5932
		Outdoor	1.15[0.97-1.36]	0.11	0.96[0.81-1.14]	0.63	
	Microscopy	In a separate building	**0.69[0.54-0.87]**	**0.002**	**0.71[0.56-0.91]**	**0.01**	5653
		Outdoor	1.07[0.91-1.25]	0.43	0.97[0.82-1.14]	0.67	
Burundi 2016-17	RDT	In a separate building	**0.52[0.44-0.62]**	**<0.001**	0.84[0.68-1.02]	0.08	4019
		Outdoor	**0.30[0.20-0.44]**	**<0.001**	**0.46[0.30-0.71]**	**0.001**	
	Microscopy	In a separate building	**0.55[0.46-0.66]**	**<0.001**	**0.80[0.64-0.99]**	**0.04**	4023
		Outdoor	**0.36[0.24-0.56]**	**<0.001**	**0.57[0.36-0.90]**	**0.02**	
Cameroon 2018	RDT	In a separate building	0.94[0.64-1.37]	0.73	0.87[0.59-1.27]	0.46	3385
		Outdoor	1.16[0.76-1.76]	0.49	1.30[0.85-1.98]	0.23	
DRC 2014-15	RDT	In a separate building	0.78[0.59-1.02]	0.07	**0.71[0.54-0.94]**	**0.02**	6214
		Outdoor	0.83[0.64-1.07]	0.15	1.02[0.77-1.34]	0.89	
	Microscopy	In a separate building	0.80[0.62-1.03]	0.09	0.77[0.59-1.01]	0.06	6204

		Outdoor	0.88[0.69-1.13]	0.33	1.14[0.86-1.50]	0.36	
Nigeria 2018	RDT	In a separate building	**0.69[0.57-0.73]**	**<0.001**	**0.78[0.61-0.88]**	**0.001**	7589
		Outdoor	0.88[0.74-1.06]	0.17	0.88[0.73-1.06]	0.18	
	Microscopy	In a separate building	**0.71[0.57-0.88]**	**0.002**	1.00[0.80-1.24]	0.97	5503
		Outdoor	0.94[0.76-1.16]	0.57	0.80[0.64-1.00]	0.05	

Abbreviation: UOR = Unadjusted Odds Ratio, AOR = Adjusted Odds Ratio, 95% CI = 95% confidence interval, N= Number of observations, RDT = Rapid diagnostic test. Results in bold are statistically significant.

The reference group is indoor cooking for all reported odds ratios.

Additional file 3

Table S3.1: Unadjusted odds ratio of malarial infection for each cooking practices for the combined dataset, exploratory and sub-analysis

Analysis	**Outcome**	**Analysis 1 Biomass vs cleaner cooking**				**Analysis 2 Wood vs charcoal cooking**				**Analysis 3 Cooking location**			
		Cooking fuel	AOR [95% CI]	*p* value	N	Cooking fuel	AOR [95% CI]	*p* value	N	Type of cooking location	AOR [95% CI]	*p* value	*N*
Combined dataset*	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**4.75[3.95-5.71]**	**<0.001**	43759	Wood	**3.06[2.71-3.44]**	**<0.001**	73072	In a separate building	**0.71[0.64-0.88]**	**<0.001**	23754
										Outdoor	**0.80[0.72-0.79]**	**<0.001**	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**5.13[4.07-6.48]**	**<0.001**	30007	Wood	**1.94[1.73-2.18]**	**<0.001**	46206	In a separate building	**0.65[0.58-0.72]**	**<0.001**	21383
										Outdoor	**0.89[0.80-1.00]**	**0.50**	
Sub-analysis													

Rural areas	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**2.39[1.72-3.31]**	**<0.001**	31100	Wood	**1.73[1.46-2.05]**	**<0.001**	54473	In a separate building	**0.63[0.56-0.71]**	**<0.001**	16988
										Outdoor	**0.78[0.68-0.89]**	**<0.001**	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**3.84[2.42-6.12]**	**<0.001**	20290	Wood	1.26[1.05-1.52]	0.015	34693	In a separate building	**0.62[0.54-0.70]**	**<0.001**	15193
										Outdoor	0.89[0.77-1.02]	0.10	
Urban areas	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**3.49[2.74-4.45]**	**<0.001**	12659	Wood	**2.82[2.33-3.43]**	**<0.001**	18599	In a separate building	1.02[0.83-1.27]	0.83	6766
										Outdoor	1.19[0.99-1.41]	0.61	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**3.57[2.70-4.72]**	**<0.001**	9717	Wood	**1.77[1.52-2.06]**	**<0.001**	11513	In a separate building	**0.75[0.60-0.94]**	**0.01**	6190
										Outdoor	1.13[0.94-1.36]	0.20	
	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		

Mesoendemic areas		Biomass	**4.26[3.50-5.19]**	**<0.001**	35167	Wood	**2.78[2.43-3.17]**	**<0.001**	57814	In a separate building	**0.72[0.64-0.80]**	**<0.001**	20349
										Outdoor	**0.74[0.66-0.84]**	**<0.001**	
		Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
	Microscopy	Biomass	**4.72[3.67-6.06]**	**<0.001**	23519	Wood	**1.77[1.57-2.00]**	**<0.001**	35898	In a separate building	**0.66[0.59-0.73]**	**<0.001**	18209
										Outdoor	**0.84[0.74-0.95]**	**0.005**	
										Indoor	*Ref.*		
Wood only	RDT									In a separate building	**0.66[0.59-0.74]**	**<0.001**	19406
										Outdoor	**0.77[0.68-0.87]**	**<0.001**	
										Indoor	*Ref.*		
	Microscopy									In a separate building	**0.63[0.56-0.72]**	**0.001**	17244
										Outdoor	**0.86[0.75-0.99]**	**0.03**	
Exploratory analysis													
	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		

		Biomass	**4.70[3.59-6.15]**	**<0.001**	26778	Wood	**3.88[3.32-4.53]**	**<0.001**	36898	In a separate building	**0.67[0.58-0.77]**	**<0.001**	9951
										Outdoor	**0.73[0.63-0.85]**	**<0.001**	
Controlling for household mosquito spraying†	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**4.80[3.58-6.45]**	**<0.001**	18102	Wood	**2.20[1.91-2.53]**	**<0.001**	27115	In a separate building	**0.59[0.51-0.69]**	**<0.001**	9676
										Outdoor	1.00[0.87-1.15]	0.99	

Abbreviation: AOR = Adjusted Odds Ratio, 95% CI = 95% confidence interval, N= Number of observations, RDT = Rapid diagnostic test. Ref = Reference group. Results in bold are statistically significant.

*Controlled for: Child's age, child's gender, birth order, Child slept under slept under mosquito net last night, modified wealth index, number of household members, place of residence, malarial endemicity, dwelling construction, season and cluster altitude.

† Burkina Faso 2017-18, Cameron 2018, DRC 2013-14, Malawi 2017, Mali 2018, Nigeria 2018, Tanzania 2017 and Togo 2017 were excluded due to the household mosquito spraying variable being incomplete, high level of missing or low cell counts.

CHAPTER 9 RESULTS: FUEL SWITCHING WITH ECONOMIC UNCERTAINTY

This chapter details the community's willingness to pay for charcoal after the announcement of the charcoal ban in Rwanda. In addition, it documents fuel switching that occurred during the COVID-19 health protection measures, illustrating a movement down the energy ladder towards firewood. The chapter is currently under-peer review at *Energy for Sustainable Development* and is presented in this style. Detailed methods for this chapter can be found in section 5.3.

Domestic fuel affordability and accessibility in urban Rwanda; policy lessons in a time of crisis?

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Abstract

Background: Cooking fuel choice and fuel switching behaviours can be influenced by both social and economic contextual factors; with implications for household air pollution exposure. The Rwandan government have recently proposed a charcoal sale ban to reduce domestic reliance upon charcoal fuels and reduce associated respiratory health harms.

Methods: A semi-structured mobile telephone survey administered to 85 participants in Kigali, Rwanda to identify (i) fuel switching as a result of COVID-19 emergency health protection 'lockdown' measures (ii) awareness of proposed charcoal sale restrictions and willingness to pay for alternative domestic cooking fuels.

Results: Of the 85 interviewed participants, 15 (17.6%) reported a change in primary cooking fuel since the first national COVID-19 emergency 'lockdown' period (March – May 2020), with Liquid Petroleum Gas (LPG) users moving to charcoal (n=3; 20%), and charcoal users to firewood (n=7; 46.7%) or LPG (n=4; 26.7%) and one firewood user to charcoal (n=1; 6.6%). Awareness of the forthcoming LPG subsidy (81.5%) and charcoal ban policy proposals was high among all participants (81.5%), with 90.7% indicating they would change their cooking fuel as a consequence. LPG was the preferred alternative fuel of choice (89.8%), with cost, ease of use and cleanliness reported as rationale. Forty-four percent of participants reported a willingness to pay less, thirty-eight percent to pay the same and twenty-five percent to pay more than their current cooking fuel expenditure for a cleaner alternative fuel.

Conclusion: Domestic fuel switching as a result of economic and energy market volatility, was observed in urban Rwanda as a consequence of COVID-19 emergency measures, most notably by substitution of firewood for charcoal, reflecting a regressive step in the energy ladder. Our findings demonstrate a high level of awareness and engagement with forthcoming domestic fuel policy changes in Kigali, and a large proportion of those interviewed would consider transition to cleaner domestic energy sources. This novel research has implications for developing domestic energy resilience to disruptive economic impacts and ensuring effective clean fuel policy implementation in East Africa.

Key words: Solid biomass cooking; household air pollution; charcoal ban; fuel switching; COVID-19; Willingness to pay

Highlights:

- COVID-19 restitution measures in Rwanda resulted in energy uncertainty
- Households switched from charcoal to wood cooking fuel during COVID-19 lockdown
- Switching to more polluting biomass fuels has major health and environmental risks
- There is high awareness of forthcoming domestic fuel policy changes in Rwanda

1. Introduction

Domestic cooking using solid biomass fuels (wood, dung, charcoal and crop residue) causes harmful levels of Household Air Pollution (HAP) [1]; associated with adverse health effects throughout the life course including increased risk of low birth weight, pregnancy complications [2], acute respiratory infections [3–5], respiratory impairment [6], cardiovascular disease [7] and cognitive impairment [8]. HAP includes carbon monoxide (CO), particulate matter (PM), amongst other pollutants, typically generated by burning solid fuels using inefficient cooking stoves in poorly ventilated domestic environments. With over three million solid biomass fuels users worldwide and a substantial contribution to carbon emissions, reduction in reliance upon solid biomass fuels is integral to achievement of the United Nation's Sustainable Development Goals (SDGs) (specifically SDG 7 - Ensure access to affordable, reliable, sustainable and modern energy for all) [9], and rapid, sustained transition to clean energy alternatives are urgently required worldwide.

The fuel ladder (figure 1) illustrates that the most polluting fuels are also typically the most affordable and most readily accessible, with economic development typically associated with cleaner fuel transition (e.g., to electricity, solar energy and LPG). However, transition up the fuel ladder is recognised to often not be undertaken as a linear process among those living in low- and middle-income countries (LMICs) with household level fuel choices determined by a complex range of factors including local availability (e.g., reliability of access), affordability, cultural preferences and household and situational contextual [10]. Fuel switching behaviour varies between different countries influenced by local and national factors [11], including wealth, level of education [12], cost of fuel, cleanliness, ability to cook traditional dishes [13], safety concerns and knowledge of health benefits [11]. In addition, any reduction in HAP associated with cleaner fuel usage can be attenuated by 'stove' or 'fuel stacking', whereby traditional cooking methods are used alongside cleaner fuels [14], or by ongoing use of solid biomass fuel sources among neighbouring households [15] contributing to ambient air pollution exposure. However, accelerating transition to cleaner sustainable fuels would deliver significant health [16] and socio-economic benefits for LMICs (e.g., reduced opportunity costs associated with fuel collection [17]), in addition to a reduction in the environmental impacts associated with charcoal and firewood use (e.g. deforestation, erosion, increased flooding risk [18]) and carbon emissions. It is anticipated that with rapid economic development, cleaner fuel use as a proportion of domestic energy will continue to increase worldwide, however, total coverage is negated by rapid population growth notably in sub-Saharan Africa where the total number of biomass fuel users is at an all-time high [19]. Further periods of global economic uncertainty (e.g., COVID-19) and disruptive economic changes may also impact on trends towards cleaner fuel transition even among rapidly emerging nations in the global south [20].

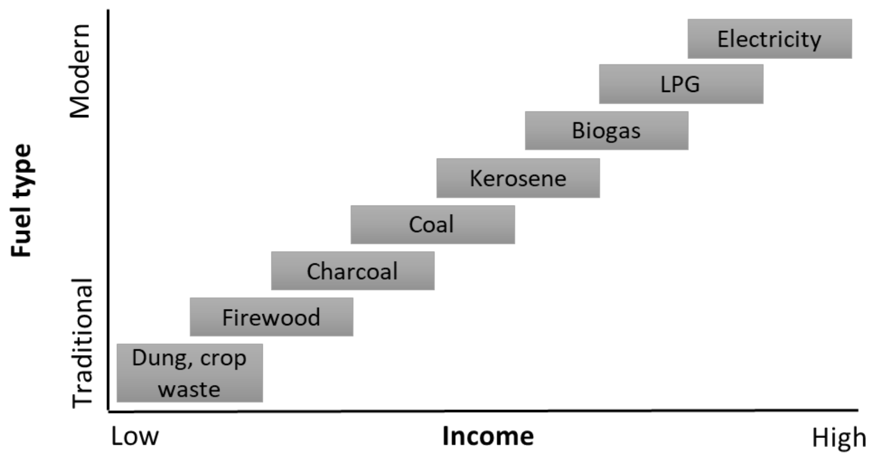

Figure 1: The energy ladder depicting fuel within increase energy efficiency, cleanliness and cost with increasing income. Adapted from Smith 1994 [14]

Cost of cleaner cooking fuels and technologies is a large barrier to sustained uptake [21] and therefore there needs to be an understanding of how much households are willing to pay (WTP) [22]. WTP is defined as the maximum amount the participant is willing to pay for a product [23] and has previously been used within intervention studies post-implementation for improved cookstove (Bangladesh, Malawi) [22,24] and a LPG pay as you cook (PAYC) scheme (Kenya) [25]. WTP for improved cook stove was undervalued [22] due to affordability [24], however, participants on the LPG PAYC scheme reported a higher WTP than the non-PAYC users [25].

Rwanda is an ambitious, rapidly developing (GDP per capita: US$ 797.9) [26] East African country, with a high population density of 498.7 people per km2 [27] and a population of ~13 million in 2020 [28]. In 2014, charcoal was the predominant cooking fuel used in urban Rwanda (65.5%), with only 1.8 % of households in urban areas using cleaner cooking fuels such as LPG or electricity [29]. Implementation of emergency public health restrictions, referred to as 'lockdown' measures were implemented from March - May 2020 and January-February 2021 to control the COVID-19 pandemic, with COVID-19 exerted disruptive impacts and energy market instability in sub-Saharan Africa with evidence for regressive fuel switching undertaken by informal settlement dwellers in Nairobi, Kenya reflecting changes in household circumstances, employment patterns and falling petroleum prices [30]. Further, in May 2020 the Rwandan Government announced planned proposals to ban the use and supply of charcoal in Kigali City, to address adverse health and environmental impacts [31] and increase the availability and uptake of LPG through a subsidy scheme. Therefore, this study aims to (i) characterise cooking fuel switching as a result of the COVID-19 emergency health protection measures; (ii) explore potential cooking fuel switching as a result of the proposed charcoal ban; (iii) investigate WTP for alternative cooking fuels, in urban Rwanda.

2. Materials and methods

2.1. Study setting and participants

The study area was an urban informal settlement in Kigali, Rwanda, within the Kabeza cell, situated within the Muhima sectors of the Nyarugenge district. The Kabeza cell comprises seven villages (Hirwa, Ikaze, Ituze, Imanzi, Ingenzi, Sangwa, Umwezi), with a cell total of ~950 households, and predominant charcoal fuel reliance [32,33]. A convenience sample [34] was identified by communication with the Kabeza cell local leader who provided mobile telephone contact numbers for eligible households (i.e., any residence situated in the Kabeza cell) and those who consented to have their number shared. One participant in each household was eligible for study participation. Of the 132 mobile telephone contact numbers provided, and contact was made 119 unique residents. Of these, 85 residents completed the study questionnaire (71.4%) and 34 (28.6%) declined to participate.

2.2. Data collection

A semi-structured questionnaire (Appendix 1), including open and closed questions [35], comprising sociodemographic characteristics, fuel usage patterns, awareness of charcoal ban and LPG subsidy proposals and willingness to pay for an alternative cooking fuel was administered by trained fieldworkers. The WTP question asked participants to state the maximum amount they would be willing to spend a month for an alternative cooking fuel, with response provided on a payment scale from 0-24000 RWF, with the option to add in a value if the amount was not present on the scale. Each interview was undertaken by a single mobile telephone call on a weekday between April 2021-July 2021 during the hours of 09:00-17:00. The survey was administered verbally by simultaneous translation from English to native language (Kinyarwanda), with responses recorded in English; a method used in a previous household survey [32] which had been demonstrated to be an effective technique.

2.3. Statistical analysis

All data collation, cleaning and analysis was undertaken within R Studio [36]. Participant characteristics included: Age (15-24, 25-34, 35-44, 54-54, 55-64, 65-74, 85+ years), gender (male, female), household incomes per months in Rwandan Francs (RWF). Participants' occupational details were categorised using the internationally recognised ISCO-08 code classification [37], with housewife classified as an elementary occupation and an additional category for no occupation. Cooking fuel options included charcoal, firewood, ethanol, LPG, biomass pellets and none of the above. Quantitative descriptive statistics provided frequencies, percentages, medians and interquartile ranges, with univariate statistics (Kruskal-Wallis or Mann-Whitney U) undertaken to determine differences between two groups. Additional R package were required in the development of the bar chart (Lattice package [38]), scatter plot (ggplot [39] and ggpubr [40]) and Sankey diagram (networkD3 [41]). The open questions (n=2) were qualitatively analysed using inductive thematic analysis [42], with coding of answers into summary topics, which were summarised in a word cloud using the wordcloud2 package [43] in R Studio. Factors that were associated with the WTP for cooking fuel were determined through linear regression, using the lme4 package [44].

2.4. Ethical Approval

Ethical approval for this study was received from the College of Medicine and Health Science Institutional Review Board at the University of Rwanda (No 235/CMHS IRB/2020) and the University of Birmingham Ethics Committee (ERN_19-0252B). Fully informed consent was obtained from each study participant at the start of the survey. Participants we free to withdraw at any point during the study and have their data destroyed.

3. Results

3.1. Participant characteristics

A total of 85 mobile telephone surveys were completed among 67 (78.8%) women and 18 (21.2%) males, of age range 25-74 years (figure 2). Overall, 42 (49.4%) participants were employed in elementary occupation (Females: 40; Males: 2), 22 (25.9%) as professionals (Females: 16; Males: 6), 19 (22%) (Females: 9; Males: 10) in other occupation (services, craft, agriculture or technicians); and two (2.4%) participants, both female, noting unemployment (at time of interview). Median household income was 60,000 RWF; IQR: 40,000-120,000 RWF with proportion of monthly household income spent on cooking fuel in the range of 3-60% (Female: 3-60%; Male: 6-20%). Cooking fuel costs comprised a higher proportion of the total income in low-income households compared to high-income households (p=<0.001 – Appendix 1).

Three cooking fuel types were reported to be in use at time of interview: LPG (n=23), charcoal (n=54) and firewood (n=8). A significant relationship between fuel type (at time of interview) and household income was observed (*p*=<0.001), with LPG users having the highest household incomes compared to those using firewood, who were more likely to be in the lowest household income group (Figure 1). Among charcoal fuel users, the majority purchased charcoal from the local market (n=48), with fewer individuals purchasing charcoal from wholesalers (n=4), mobile sellers (n-3) friends or family members (n=1).

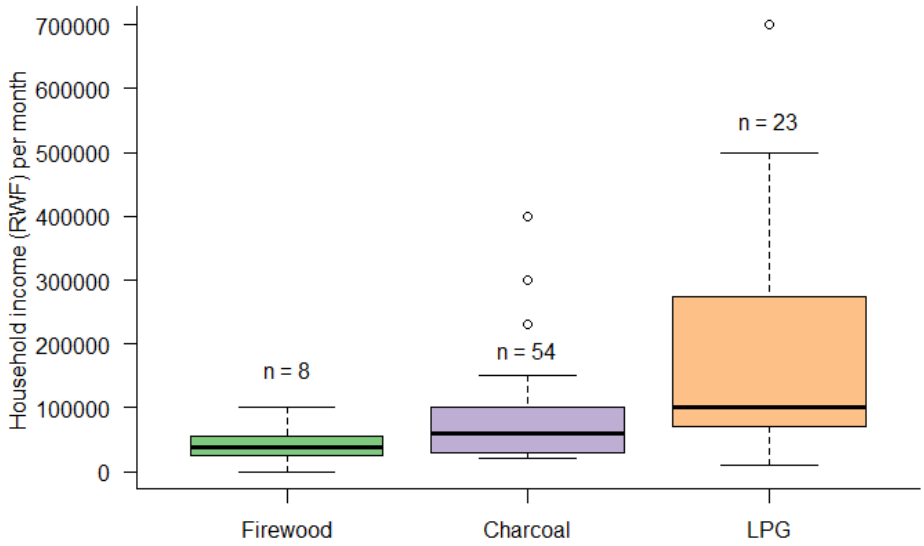

Figure 2: Box plot of cooking fuel use at the time of interview by household income per month (median values represented by black horizontal line, maximum and minimum values represented by whiskers). A significant association was observed (H (2) = 15.7; *p*=<0.001), assessed using the Kruskal Wallis test.

3.2. Fuel switching

3.2.1. Fuel type changes during COVID-19 restrictions

Prior to the COVID-19 pandemic and associated lockdown measures the majority of survey participants (n=61; 71.8%) reported using charcoal fuel for cooking, 22 (25.9%) LPG and two (2.3%) firewood. However, during the restrictions 15 (17.6%) participants switched their cooking fuel, with three (20%) LPG users switching to charcoal, seven (46.7%) charcoal users switching to firewood, four (26.7%) charcoal users switching to LPG and one (6.6%) firewood users switching to charcoal (figure

3). Most respondents (79; 92.9%) reported the quality of fuel to have changed during this period including 13/15 respondents who switched cooking fuels.

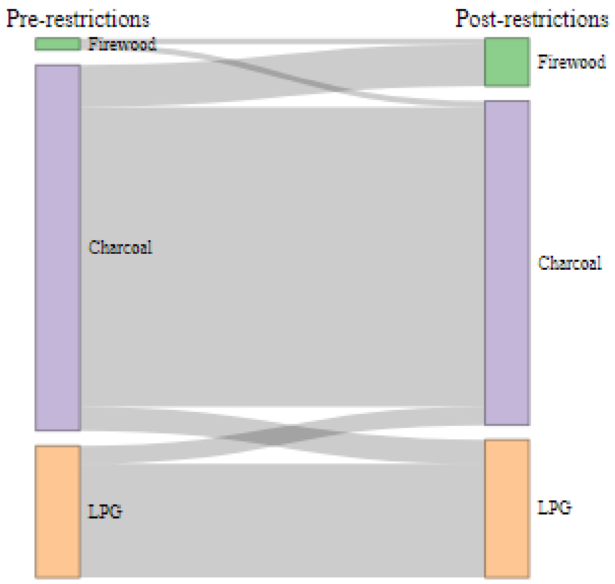

Figure 3: Cooking fuel changes occurring among 15 study participants during a period of COVID-19 emergency health protection measures in March – May 2020

3.2.2. Awareness of forthcoming domestic energy policy proposals

Out of the 54 participants (Female: 49; Male: 5) who cooked using charcoal fuel, 44 (81.5%) were aware of the proposed charcoal ban with 49 out of 54 (90.7%) reporting that they would change their fuel if a charcoal ban was implemented. Awareness of the LPG subsidy proposals was also high among the 54 charcoal users with 44 (81.5%) aware of specific proposals. LPG (44/49 – 89.8%) was the fuel of preference for future use, with cleanliness the main reason provided (n=23), along with speed of use (n=16), ease of use (n=9), cost (n=7), personal knowledge (n=7), availability (n=6), good of the environment (n=4), knowledge in the neighbourhood (n=2) and they aspire to have LPG in their home (n=1) (figure 4). However, one participant indicated they would switch to firewood due to cost constraints (Quote: “cheap and affordable”) and another reported switching to an electric cooker for safety reasons (Quote: “change to the electric cooker because has low risk of fire accidents compared to LPG “). Finally, three participants reported they would switch to biomass pellets reporting ease of use (n=2) and equivalence to using charcoal (n=1).

Figure 4: Word cloud for the rationale stated by participants (n=49) for alternative fuel choices arising from charcoal ban implementation (clean=23, quick=16, easy=11, cost=8, personal knowledge=7, available=6, environment=4, neighbourhood knowledge=2, equivalent=1, aspiration=1, safety=1).

3.3. Willingness to pay for alternative clean cooking fuel sources.

Participants who cooked on charcoal were asked about the maximum they would be willing to pay per month for an alternative cooking fuel if a ban is implemented. Of the 54 charcoal users, WTP for cooking fuel ranged from 500-20,000 RWF, with most common reason behind the amount chosen stated to be affordability (n=40 out of 54) (figure 5). Participants on higher incomes were willing to pay more for cooking fuel than those on lower incomes (p=0.001 – Appendix 2). Overall, to change their cooking fuel to a cleaner source, 13 (25.0%) were willing to pay more, 16 (30.8%) the same amount for cooking fuel and 23 (44.2%) stated they wanted to pay less. Figure 6 illustrates that those participants who currently spend the most on charcoal are willing to pay less for cooking fuel after a charcoal ban. There was no observed difference in the amount users were willing to pay for cooking fuel and the choice of alternative cooking fuel if the charcoal ban came into force (p=0.795 – appendix 3); nor by gender (p=0.085 – appendix 3). However, in a regression analysis after adjusting for confounders (Table 1), for every increase (1 RWF) in WTP the participant's income increases by 0.2 RWF (95% CI: 0.00 – 0.04). In addition, participants aged 65-74 years were WTP 11060 RWF (95% CI: 2498– 19621) more for alternative fuels than those aged 25-34 years.

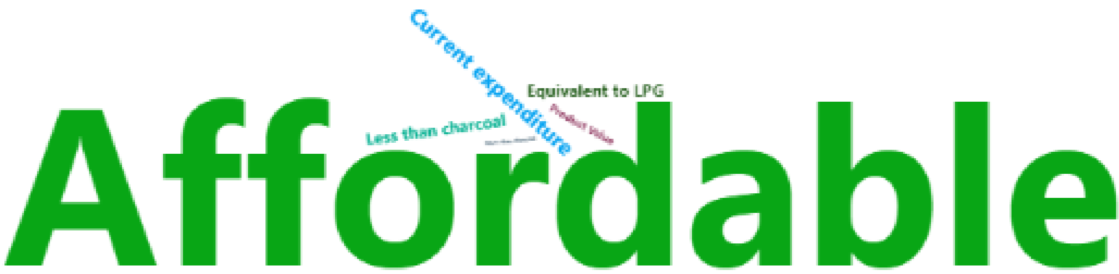

Figure 5: Word cloud illustrating the reasons given for the chosen amount of money participants (n=53) are willing to pay for alternative cooking fuels. (Affordable=40, Current expenditure on fuel=4, Equivalents to LPG or other fuels=3, Less than charcoal=23 Product value=2, More than charcoal=1)

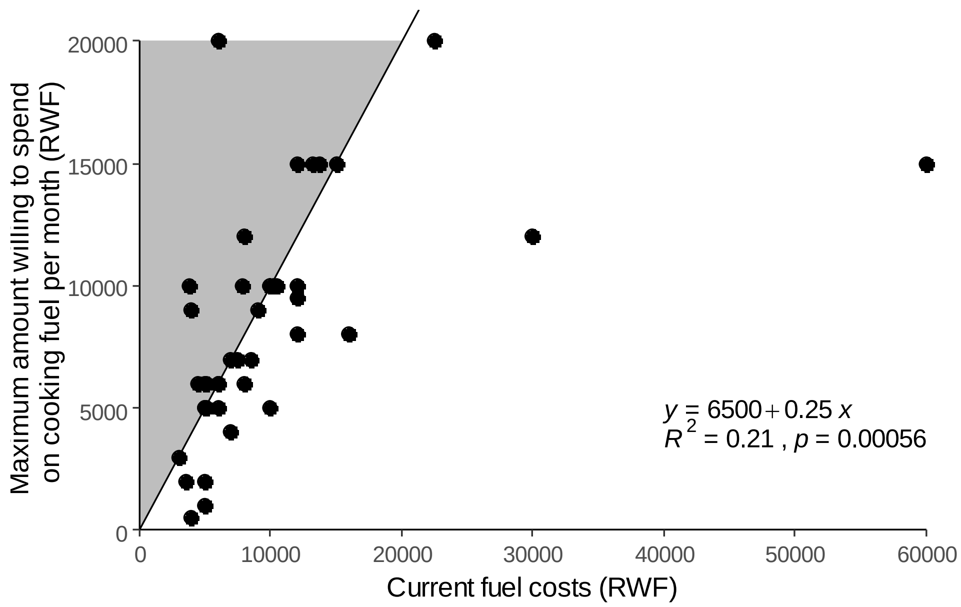

Figure 6: Relationship between current fuel expenditure and WTP for alternative fuels (RWF) per month. (Grey area designates participants who are willing to pay more for cooking fuel than they currently do)

Table 1: Unadjusted and adjusted linear regression for the association between WTP for alternative cooking fuels and participants' characteristics (n=52).

	Unadjusted		**Adjusted**	
	β (95% CI)	*p* value	β (95% CI)	*p* value
Monthly household income (RWF)	**0.03 (0.01-0.04)**	**0.001**	**0.02 (0.00 – 0.04)**	**0.027**
Proportion of income spent on cooking fuel monthly (%)*	-94.9 (-267-76.9)	0.272	16.3 (-161 – 194)	0.854
Age (years)				
25-34	*Ref.*		*Ref.*	
35-44	1381 (-1523 – 4285)	0.344	434 (-2368 – 3235)	0.756
45-54	-324 (-3908 – 3260.8)	0.857	564 (-2815 – 3944)	0.738
55-64	3510 (-2123 – 9142)	0.216	4445 (-754 – 9643)	0.092
65-74	**12177 (2922 – 21431)**	**0.011**	**11060 (2498 – 19621)**	**0.013**
Gender				
Female	*Ref.*		*Ref.*	
Male	4311 (-477 – 9100)	0.077	1785 (-3136 – 6705)	0.469
Occupation				
Elementary	*Ref.*		*Ref.*	
Non-elementary	2132 (-526 – 4786)	0.113	1311 (-1392 – 4014)	0.333

Footnote: 95% CI = 95% confidence interval, Ref. = reference group for categorical variables. * = missing data – two participants did not provide a proportion of income spent of cooking fuel

4. Discussion

Our cross-sectional study of 85 participants residing in urban Kigali has shown evidence of fuel switching (17.6%) coinciding with the COVID-19 pandemic as reported previously elsewhere in sub-Saharan Africa. The evidence of fuel switching during the COVID-19 highlights the potential reversal of progress towards SDG-7 in sub-Saharan Africa, due to economic and societal consequences of the pandemic. The announcement of the charcoal ban in Kigali by the Rwanda Government will require charcoal using households to switch fuel. Encouragingly, a high proportion of survey participants were aware of the charcoal ban proposals and most were willing to change to using cleaner fuels (89.8%), with the most common reasons stated being cost and cleanliness of the fuel. This indicates flexibility in fuel usage behaviour, suggesting responses can occur to both external economic impacts and underlying personal considerations, including health impacts. These approaches will help mitigate unintended consequences of policy proposals, such as switching to alternative more polluting but readily available fuels in the context of national policy measures.

Domestic fuel switching may be due to economic situational factors (e.g., fuel market volatility, income, energy access [21]) as previously documented within Nairobi's informal settlements during the first COVID-19 lockdown in 2020 [30]. In this large scale mobile telephone survey of 194 residents, the largest switch was from LPG to kerosene as a consequence of falling petroleum prices and therefore affordability [30]. We find that income may influence cooking fuel choice, which may have contributed to 17 users changing to firewood, from kerosene and LPG, which is readily and freely available by collection. Our findings support these previous observations, with evidence for movement towards more affordable fuels associated with reduced household income with 46.6% households switching from charcoal to firewood fuel. However, an approximately equal proportion switched from charcoal to LPG and LPG to charcoal, which could reflect the relative expense of charcoal compared to LPG in Rwanda. However, charcoal remains the dominant fuel used in Kigali due to lesser start-up costs, traditional cooking practices and being able to purchase in small amounts [32]. In addition, the pay as you go (PAYGO) LPG scheme in Kenya supported cleaner cooking throughout the COVID-19 lockdown [45]; however, there is currently no equivalent scheme within Rwanda. Interestingly, no participants reported switching to kerosene as a cooking fuel, which dominated the findings from Nairobi [30]; however kerosene is more typically used for lighting in sub-Saharan Africa. Nevertheless, there was some indication of impacts upon fuel quality although the extent to which this factor influences fuel switching behaviour is beyond the scope of the current study. These findings are therefore indicative of the need to improve understanding and improve monitoring of fuel switching behaviour for example by longitudinal and qualitative studies in this context, as well as approaches to encourage sustained cleaner fuel switches.

We also identified flexibility in response to forthcoming domestic fuel policy proposals, with most residents indicating their readiness to switch to clean cooking alternatives. In some cases, cooking fuel expenditure makes up to 60% of the participant's income, indicating the vulnerability of household to economic change and uncertainty, which will ultimately affect choice of cooking fuel and food security. Our findings may be influenced by social acceptability bias in this study context. In addition, there is a widespread aspiration to cook using LPG, but actual uptake may be influenced by external factors such as price of fuel, market availability and national economic situation [17,46]. Understanding the patterns of fuel switching, including potential for stove or fuel stacking (where polluting cooking fuels are used alongside cleaner interventions) is important given the potential for negative unintended consequences arising from fuel restriction proposals [47,48]. Although stove and fuel stacking has not been explored within this study, it is important to recognise the ongoing access to cheap and readily available biomass is likely to increase the risk of reversion to more polluting fuels [49]. Households experiencing financial difficulty or reduced incomes may switch to freely available firewood fuel, as indicated in the COVID-19 lockdown period. This has been documented previously in other settings and risks proposals, which are negating the desired health [50] and environmental [51]. Willingness to pay less than their current fuel expenditure for cleaner fuel alternatives was reported by 44.2% of participants. Some participants explained that the amount they are WTP was equivalent to the price of LPG suggesting that there is a level of awareness of fuel costs, and that the responses given were based on the price of cooking fuel, rather than personal choice. However, the price and WTP for cooking fuel does not address the issue of the start-up costs for LPG equipment, which requires further exploration.

Aside from cooking fuel costs, personal motivations towards fuel choice were dominated by availability, ease and speed of use, familiarity and knowledge; reasons which are reflected within the literature [52]. The identification of the value of community knowledge in cooking fuel choice, presents a potential opportunity for community initiatives to support cleaner fuel transition. However, barriers to LPG use could also be identified as those participants who did not choose LPG as their choice of fuel after the charcoal ban is introduced cited “safety” and “similarity of fuel to charcoal” as reasons for their choice of fuel. Therefore, there is a need to address and reduce these barriers to cleaner fuel use, to complement legislative fuel restrictions. Supporting sustained use of cleaner fuel use to reduce HAP exposure is a complex public health policy intervention requiring a multifaceted approach. The Rwandan Government has proposed a LPG subsidy to complement the charcoal fuel restrictions thereby providing support from a financial perspective during the transition phase. The need for such provision is supported by encouraging results from the PAYGO LPG pilot, which highlighted the benefits of being able to buy small amounts of LPG and help with equipment costs; but high levels of stove and fuel stacking remained [53]. Therefore, without the support of knowledge and education a long-term uptake of cleaner fuels could be sub-optimal.

Despite the complexities of undertaking remote research in a pandemic, 85 surveys were undertaken, with a responses rate of 64.4%. However, as a result of undertaking telephone surveys there is the potential that the non-respondents were unavailable due to work commitments, and could explain the higher proportion of women respondent than men; in addition, to potentially missing households without a mobile telephone. Although this study is of a small scale, undertaken in one cell within Kigali, the ability to conduct rapid and responsive research via mobile phone has the potential to easily scale-up coverage to wider areas across urban Rwanda to compare and contrast different fuel switching behaviours. Further research is required to better understand long-term trends in transient fuel usage and switching, both prior to and after the charcoal ban thereby capturing both negative and positive consequences. Investigating these patterns has implications for formulating successful fuel transition policies which improve both access and uptake whilst minimising potential for harmful or negative outcomes, thereby optimising health and environmental benefits.

5. Conclusion

We identified evidence of domestic fuel switching among residents in an urban informal settlement during the early phase of the COVID-19 pandemic in Kigali Rwanda; notably towards more polluting fuels. Households are evidently highly vulnerable to fuel price volatility, with a high proportion of income spent on cooking fuels, particularly among existing biomass fuel households. Long-term policy proposals to phase out charcoal and subsidise LPG access will require careful consideration to mitigate risk of unintended consequences arising from switching to more polluting solid fuels (e.g., firewood) and to enable cleaner fuel to be affordable at a household level.

The authors declare no conflict of interest.

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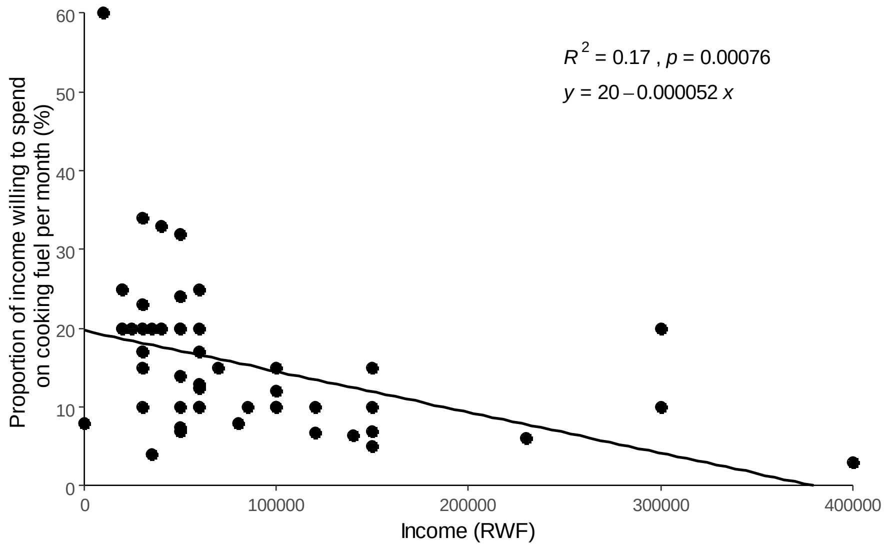
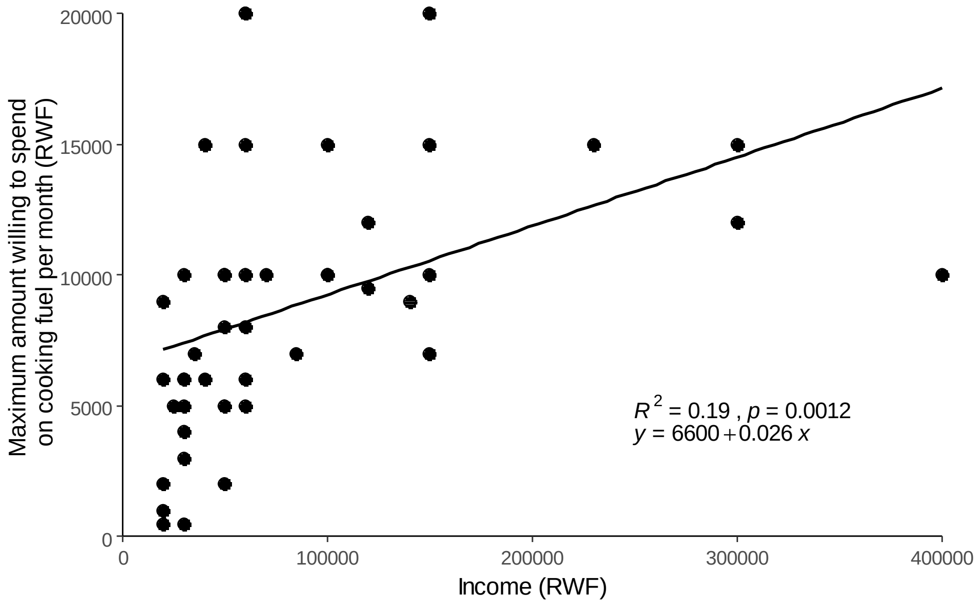
53. Perros, T.; Buettner, P.; Parikh, P. Understanding Pay-As-You-Go LPG Customer Behaviour - Modern Energy Cooking Services; 2021;

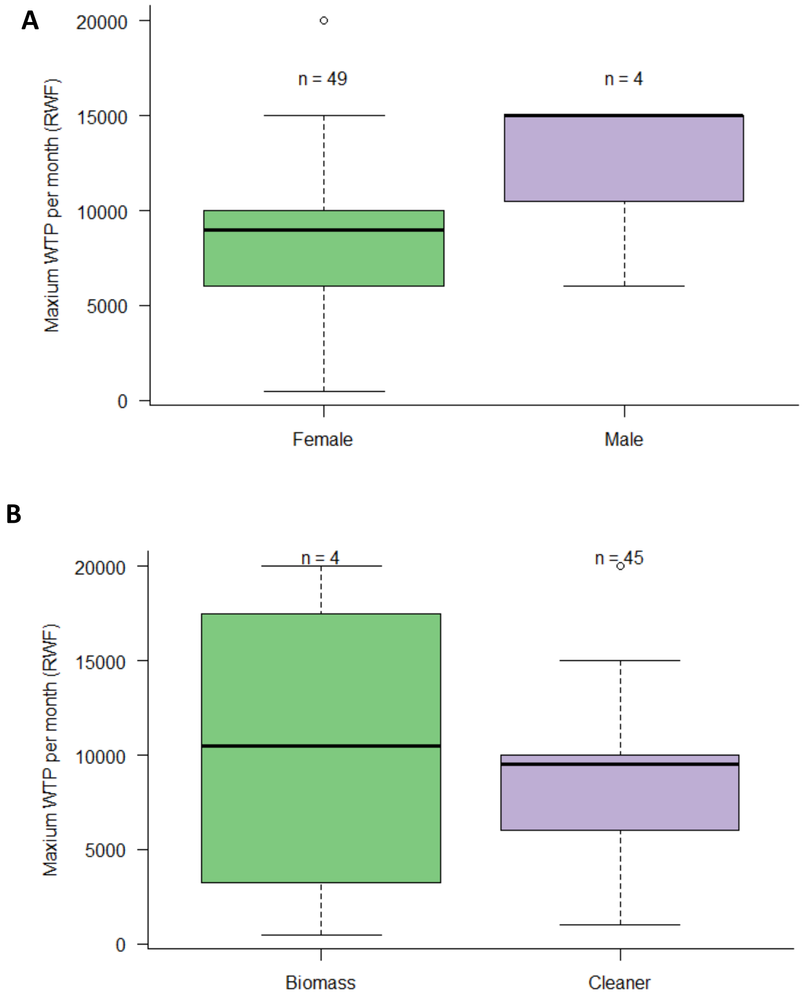
Appendix 1: Relationship between the proportion of income willing to spend and current income per month



Appendix 2: Relationship between willingness of pay for cooking fuel and participant's income per month.



Appendix 3: Box plots of the different in the amount willing to pay for cooking fuel per month against (A) Gender (B) Proposed fuel type to change to when the charcoal ban is enforced. Difference between groups determined with a Mann-Whitney U test (A) $U = 97.5$; $p = 0.795$ (B) $U = 47$; $p = 0.085$. (Abbreviation: WTP - Willingness to pay)



CHAPTER 10 METHODS: COMPLEXITIES OF CROSS-CULTURAL RESEARCH AND DEVISING APPROPRIATE QUALITATIVE METHODOLOGY

10.1 Introduction to chapter

Undertaking qualitative research in cross-cultural settings, such as HAP intervention research in LMICs, presents practical and methodological challenges. Therefore, to try and facilitate successful cross-cultural qualitative research it is imperative to consider both general challenges and those specific to the research topic area and setting. In order to effectively explore qualitatively the role of facilitators and barriers to HAP interventions in Rwanda within the thesis, this chapter discusses, appraises and critiques existing literature on the value of, complexities and challenges of undertaking cross-cultural qualitative research in LMICs which need to be taken into consideration when undertaking research into designing and developing HAP interventions. The chapter firstly discusses the use of qualitative methods in HAP intervention development, and subsequently discusses the use of qualitative HAP intervention research and cross-cultural research literature. Results from a pre-planning analysis of previously collected data from Rwanda and Ethiopia, have been used to inform the design and development of qualitative research methodology for a behavioural change HAP intervention (e.g., question development, data collection and analysis) within the study setting of Rwanda. The COnsolidated criteria for REporting Qualitative research (COREQ) checklist,[295] a journal endorsed qualitative reporting checklist for interviews and focus groups, has been used to aid and guide the appraisal of qualitative literature and pre-planning analysis. This chapter aims to:

- Appraise the use of qualitative methodology in HAP intervention research.
- Appraise the complexities for undertaking qualitative research in LMICs and cross-cultural research; taking into consideration complexities presented by the COVID-19 pandemic.

- Undertake a pre-planning analysis and appraise pre-planning qualitative methods to inform and develop the methodology for the qualitative aspect of the thesis.
- To describe the proposed methods for the qualitative aspects of the thesis; taking into consideration adaptation required due to the COVID-19 pandemic.

10.2 Use of qualitative methods in development or pre-deployment of HAP interventions

Qualitative methodologies are often underrepresented in HAP research, but can provide richer and more in-depth information on adoption, use, and barriers to HAP interventions than their quantitative counterparts.[296] In addition, qualitative methodology is often added as a subsidiary section to form mixed-methods research; resulting in qualitative methodology that is not robust or integrated as much as it could be.[297] Although mixed-methods research is required due to the complex nature of understanding and monitoring of HAP initiatives,[297] it should not be at the sacrifice of good quality qualitative methodology. Previous qualitative HAP intervention research has focussed on HAP awareness,[254,255] understanding traditional cooking practice[298] or accessibility and suitability of interventions[299–301] after they have been put in place or during trial conditions. However, little has been undertaken in the pre-intervention stage to enable end-users of the intervention to influence and express their preferences about a proposed intervention.

Interviews, focus groups,[300,302] surveys,[303] photovoice[304] and artwork[254] have been previously used in qualitative HAP research with end users; with the majority being undertaken within the past 10 years. However, a broad range of factors including stakeholders at a local, regional and national level[297,302] should be considered as stakeholders that can all influence the supply chain, with the differing levels having variation in power and resources.[305] Stakeholders are often under represented due to focus on the "end-user".[296] As a result of country and global variation in cooking practices[30] and socio-economic conditions many of the findings are highly context-dependant resulting in reduced transferability,[302] reinforcing the value of incorporating qualitative methods into HAP research. In addition, there is huge potential for innovative participatory qualitative research methods to understand HAP perception in development of interventions within community driven initiatives;[306] which has been shown to play a valuable role in the resource poor and challenging research setting within the CAPS trial in Malawi, by enabling women to share through photographs their perspective and priorities for cooking.[304]

Participatory qualitative research methods have been effectively used in intervention development prior to a HAP intervention trial. These studies include a potential LPG intervention in Cameroon using photovoice,[v] interviews and focus groups[307] and formative research for the HAPIN trial, in India, Guatemala, Peru, and Rwanda, using direct observation, in-depth interviews, semi-structured interviews and focus groups to create visual messages which could aid the uptake and continued use of LPG.[308] These studies in Guatemala, India, Peru, and Rwanda also identify factors that influence cooking fuel choice and contextual factors that direct behaviour change towards exclusive use of LPG.[309] All three demonstrated that participatory methods were valuable in identifying opinions and barriers to LPG interventions to inform an effective approach to improve uptake within the main trial; as well as improve community and stakeholder engagement.

To the best of the author's knowledge there has only been one published qualitative study for a behaviour change intervention regarding using existing traditional cooking methods, investigating women's knowledge and reported change in behaviours following a midwife-led education and behaviour change intervention in Kenya. This study of 88 participants and 41 village health teams reported that women's knowledge on biomass smoke improved and women were motivated to change and share information within the community.[310] However, there remains a paucity of evidence around use of qualitative methods within behaviour change intervention development and

[v] Photovoice participatory research method, which empowers participants to share knowledge with the researcher without the need for translation.[369]

subsequent uptake and sustained use. Gaining a greater understanding of opinions and barriers to a potential interventions would improve the cultural acceptability of any intervention,[129] as seen with nutritional interventions within Africa.[311]

10.3 Challenge of undertaking qualitative research:

10.3.1 In LMICs and cross-cultural settings

The term LMIC is used as a way of classifying global wealth with category levels determined by the country's gross national income (GNI) per capita.[312] As a result of lower wealth, research becomes more complex due to a lack of formal systems, infrastructure and resources. In addition, there are the added complexities of cross-cultural research, where human behaviours are compared across two or more cultures to understand variation as a result of cultural context;[313] and that research in the global south is often led by the global north. Consequently, there are considerations within research methodology, data collection logistics, data management, analysis and interpretation, when undertaking research in these settings. COVID-19 has presented further challenges, but also opportunities, in undertaking remote or "COVID-safe" data collection, which will also be discussed throughout this section.

In any research, the question and problem needs determining and defining, but requires further consideration in cross-cultural research; to address the interests of both the researcher and communities.[314] Pre-planning, including identifying collaborators at an early stage, appreciating cultural differences [315] and piloting both data collection and analysis[316] can enable identification of clear objectives and the research problem; supporting the justification of the type of qualitative research and methods to be undertaken, thus improving methodological quality.

When choosing qualitative research methodologies the researcher needs to consider the appropriateness of the research design, participant recruitment, justification for method of data collection, and robustness of data analysis within an iterative process.[317] Traditional qualitative research methods (e.g., face-to-face interview, focus groups and ethnographic observations)[318] have often been undertaken in these settings. However, alternative methods such as telephone interviews.[319] email conversations,[320] chat room conversation,[321] photovoice[322,323] and auto ethnography[324,325] are not often widely used in LMICs due to technology poverty, educational level and difficulties being able to form a researcher-participant relationship.[326,327] However, these techniques have proved successful in high-income countries where cross-cultural or sensitive qualitative research has been undertaken.[326,327] Therefore with a move towards remote research delivery as a result of COVID-19[328,329] and less carbon intensive travel there is an opportunity to investigate the potential for using these methods within cross-cultural and LMIC settings.

Recruitment strategies include sampling (convenience, snowball, purposive) and methods of approach (face-to-face, email, telephone, flyers), with factors affecting recruitment including participant characteristics, researcher characteristics, nature of research and infrastructure.[330] Due to lack of formal systems and technological access requirements convenience[331] or snowball[332] sampling is often used, with participants being approached face-to-face, through strong collaborations with the community.[333] This requires the researcher to be on the ground and in the communities to build rapport with participants to enable recruitment. Successful recruitment has been reported to have occurred by taking into consideration the cultural context, building trust and 'knowing and being known'.[333] In addition the researcher must remain adaptive and invest time and resources into the process.[334] However, there is little evidence for the efficacy of remote recruitment within these settings, therefore there is a reliance on collaborators and trusted community figures to aid recruitment.[333–335]

Collaborators are essential to help with translation and interpretation as language barriers are one of the biggest methodological challenges in undertaking qualitative cross-language research;[316] due to difficulty in verifying errors and interpretation biases with simultaneous translation and interpretations. Analysis is often undertaken in English,[336] but data collection has been undertaken and recorded in the native language, where verbatim translated transcripts verified by back-translation is required.[337] Due to cost of professional translation, in-country collaborators who are confident in both languages are often used, but this can result in inaccuracies in the text.[316] Conversely, professional translators have not experienced the discussion that took place, which can be useful in their interpretation of the language, especially where there is dual meaning.[338] Careful thought about the use of translations within cross-cultural research, can reduce the potential for misinterpretation and introduction of potential biases through improving accuracy of the hard to translate words or concepts.

Further bias can occur due to the participant-researcher relationship being influenced when data collection is being led and/or undertaken by a “western” researcher or “outsider” (e.g., different age, gender, shared experience).[339] This can result in differences in participants’ response, feeling and opinions;[340] especially in culturally sensitive topics in settings often unfamiliar to the researcher. Mutual respect between participants and researcher reduces the power differential and can be tackled through recruitment and opportunity to refuse to participate or withdraw; along with being flexible in language and data collection time.[340] Research design can also be “western” in style, and may need to be adapted to suit the cultural setting, which has previously been done successfully in Fiji.[341] The role and expertise of lead researcher, collaborators and field assistants, is often under reported or discussed explicitly which is a limitation, despite being a part of the COREQ checklist; in addition to cultural consideration and adoption of predominantly western research methods. Both of these factors have a large bearing on the reliability and integrity of cross-cultural qualitative research and should be discussed explicitly.

Cross-cultural qualitative research requires effective collaborations. The knowledge and expertise that researchers bring to developing countries can be beneficial given the right collaborations and capacity building. However, with the advent of "tokenism[vi]" leading to undertaking a particular aspect of the research just to please external criteria,[342] power imbalance in the research partnership,[343] only taking the interests of the researcher and not the interest of communities;[314] highlights potential ethical considerations. Conversely, moving towards remote research[vii] has the potential to reduce the influence of the "western research", through local leadership and empowerment to lead data collection on the ground, and if done effectively can enable local researcher capacity building.

Capacity building is essential in LMICs to address the gap in skills to conduct and implement research, which includes scientific knowledge, knowledge of data collection methods, appropriate handing of data and participant and time organisation; and should be equally valued as a research output.[344] However, caution should be maintained that true capacity building is taking place, as capacity building is the "process of developing and strengthening the skills, instincts, abilities, processes and resources that organizations and communities need to survive, adapt, and thrive in a fast-changing world" as defined by the UN;[345] not just the enablement of local field assistants to collect the data on behalf of the researcher. In addition to giving local researcher the appropriate credit for their work (e.g., named authors on publications), rather than persuading "parachute science" where there is no engagement or acknowledgement of the role local researchers played in the research.[346]

[vi] Tokenism – "A show of accommodation to a demand, principle, etc. by small, often merely formal concessions to it" [397]. For example only undertaking public and participant engagement to please funders [342]
[vii] Remote research –The process of data collection where study participants and researchers are physical distanced, using phone, online or other virtual platforms.[328]

10.3.2 Qualitative research in Rwanda

As discussed in section 2.3 Rwanda is an ambitious country with household air pollution at the forefront of the government's agenda,[60] implementing a top-down legislative approach with a proposed charcoal ban and LPG subsidy, providing an enormous opportunity to undertake natural observational research. There is an under representation of qualitative research within Rwanda in general, with a literature search in December 2021 showing the majority are recent (2017-2021) publications and led by visiting researchers, although in recent years there has been an increase in the proportion of in country researchers conducting qualitative research. An under representation of qualitative research within Rwanda could be due to Kinyarwandan being a specialist language making translation harder, lack of qualitative collaborators and the presence of sensitive topics, such as the Rwandan genocide in 1994; presenting ethical and logistical barriers (e.g., harder to recruit participants and obtain research permit).

Interviews and focus groups have mainly been used, using captive audiences (e.g., clinics or health care workers), and the majority conducted in Kinyarwanda; with two reporting the participants could use a language of their choice;[347,348] this allows the participants to freely express themselves. However, multiple languages add complexities in comparing participants due to loss of meaning in translation, especially where a second language has then been translated into English.[349]

Reporting on transcription and translation was poor, with only two studies reporting back-translation,[350] accuracy checking[301] or the use of professional translators;[350–352] with reasons for choice of transcription and translation not being transparent. Only one study was transparent in regard to the experience of data collectors.[353] The weaknesses in the published literature may be as a result of the challenges faced when undertaking qualitative research within Rwanda.

Despite these challenges two studies have investigated HAP interventions in Rwanda. A trial investigating the barriers and facilitators to the uptake and use of ICS and biomass pellets between users and non-users in urban Rwanda has been undertaken using in-depth interviews, led by US-based investigators.[301] The investigation was part of a large RCT of biomass pellets in urban Rwanda,[108] and therefore used a sub-sample from the trial, recruiting until data saturation.[301] Local field assistants fluent in both English and Kinyarwanda were recruited and provided with rigorous training over the course of three days. Interviews were recorded and transcribed verbatim and translated into English by a research assistant, with 10% of transcripts checked for accuracy. Due to being part of a large trial, participants where prior information is given could have been more aware of the research question causing positive feedback and influencing the responses given, which may explain some of the complex and contradictory results. Conversely, the lack of knowledge around use of LPG in Rwanda provided a unique opportunity to develop behaviour change material with the formative research for the HAPIN trial.[309] However, no information about recruitment, language of interview, researcher-participant relationship or translation was provided. Both of these studies have provided rich and detailed information about their specific HAP intervention within Rwanda and the ability to undertake qualitative research within these settings; indicating the valuable role this type of research can play in informing HAP interventions in this topic area and setting.

10.3.3 Summary

Developing and planning qualitative research in cross-cultural and LMIC settings requires further thought beyond that of just the research methods. Logistical and cultural challenges require consideration and mitigation within the research methods to enable effective and non-biased data collection. These processes are often restricted by time and cost constraints to be able to undertake research to the “gold standard”. Moving towards novel remote data collection in these settings could revolutionise the way research is approached in LMICs and cross-cultural settings. Undertaking qualitative research in these settings has a huge potential in HAP intervention development, if used effectively, but at the same time acknowledging the potential limitations.

10.4 Preparation and planning

10.4.1 Why undertake pre-planning analysis?

For a qualitative study pre-planning analysis provides justification of selected qualitative research methods,[354] including the direction of the research question, rationale for data collection and analysis, the role of the research team and effective reporting;[355] to provide a holistic and exclusive perspective for the research problem.[354] Pre-planning analysis of similar or pilot qualitative data helps identify any potential issues and highlights the specific complexities of cross-cultural research that may present within the specific, or a comparable setting; to be able to mitigate problems and learn from early findings. This dynamic and iterative approach[355] can consider a range of analysis approaches and allow for prioritisation of the research question; as well as providing explicit learning opportunities.

10.4.2 Pre-planning analysis in context of the behaviour change wheel

The aim of behaviour change within HAP interventions is to prevent disease, but it is a complex intervention compounded by the wider ecological context and the multiple interactions of confounding factors affecting the effectiveness and sustainability.[356] Strategic frameworks can be used to structure behavioural intervention research[356] to produce effective intervention, with policy outcomes and community empowerment.[357] The Behaviour Change Wheel (Figure 10.1) shows a layered approach to the interaction between behaviours and target policy areas to achieve a successful outcome to an intervention.[358] In the behaviour change wheel the behaviour system comprises four conditions; ‘capability’, 'opportunity', 'motivation' and 'behaviour', which is termed the COM-B system. Capability is defined as the ability (physical and psychological) for an individual to engage in the chosen activity (e.g., skills and knowledge). Factors which are beyond the individual to make behaviour change possible defines opportunity. Motivation is the brain processes (e.g., habitual process, decision making, emotional response) that energise and direct behaviour.[358] The behaviour change wheel helps design interventions through stages; (i) understanding behaviours (e.g., defining the problem, identifying and defining target behaviours and changes required) (ii) identification of options (e.g., intervention function and policy layers) and (iii) identify context and implementation options (e.g., mode of delivery and techniques).[359] Qualitative study will provide evidence to aid stages 1 and 2, through in-depth understanding of reasons for community behaviour, awareness of the problem and the community's perception of a potential intervention;[359] to develop hypotheses for a potential solution. The behaviour change wheel can be applied to intervention development through identifying target behaviour, behavioural diagnosis, selection of intervention strategy, selection of implementation strategy, identifying specific behaviour change techniques and designing the full intervention specification.[360] This will help conclude the possibility of an effective behavioural intervention for women within biomass cooking households in urban Rwanda and which policies would be needed to support such an intervention.[358]

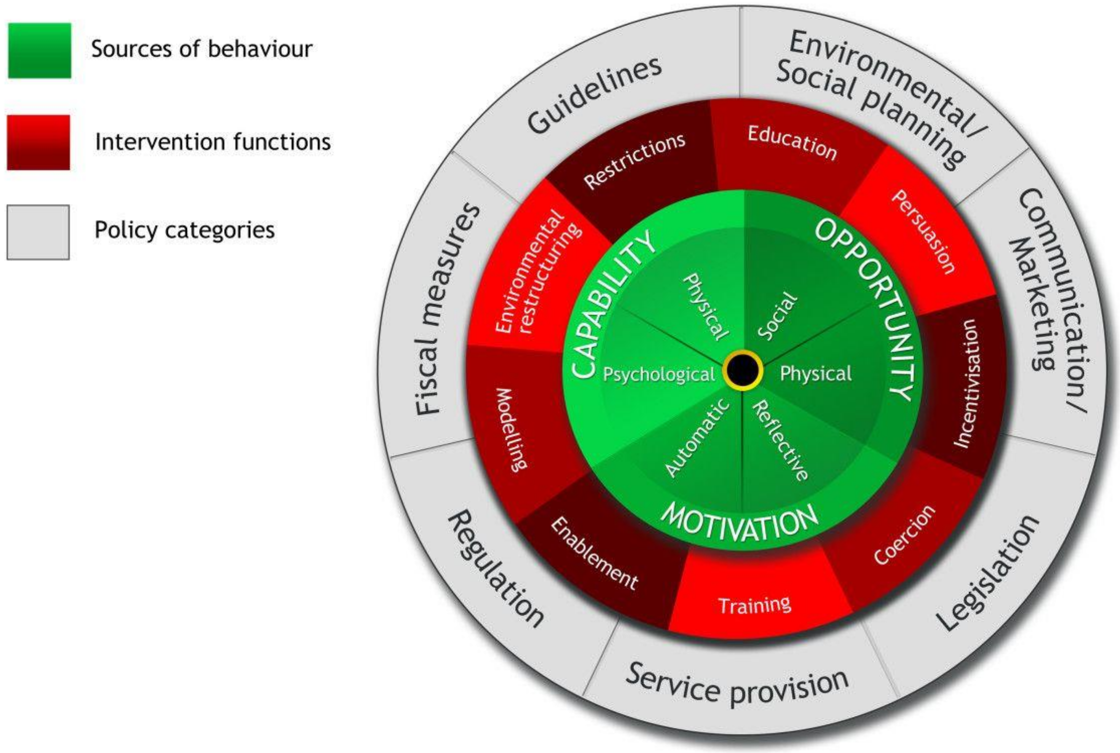


Figure 10.1: The Behaviour change wheel [358]

10.4.1 Aims of pre-planning analysis

The main aim of the preplanning analysis in this thesis was to analyse two previously collected qualitative data sets to identify HAP intervention opportunities and barriers using the COM-B wheel for (i) research questions, (ii) qualitative methods, (iii) logistical features; to enable a dynamic and iterative approach to inform the methods of the qualitative section of the thesis and learning from early research findings.

10.4.2 Methods

Two previously collected data sets have been obtained through the supervisory team, to undertake a preplanning analysis, the first was open questions from a household survey investigating cooking activity patterns and perceptions of air quality interventions in Rwanda[141] and the second, responses (thoughts and perceptions) on the back of postcards from Ethiopia that held photographs illustrating air pollution using a light painting technique, to make the invisible visible. Details of these two datasets are discussed in sections 10.4.2.1 and 10.4.2.2. These two datasets were chosen for their similar contexts or their methods used, to provide information on cross-cultural research, effectiveness of research methods and identify research gaps. This section introduces these datasets, including how and when they were collected; followed by methods of analysis.

10.4.2.1 Dataset 1 - Open questions from household survey

A semi-structured questionnaire was undertaken within the Kabeza cell (described in section 5.3.3.1), investigating women's cooking activities, awareness and perceptions of household air pollution and improved cookstoves (ICS). This survey of closed and open questions was undertaken by a University of Birmingham medical student as part of an intercalation degree, with fieldwork undertaken in early 2018 the results of which have subsequently been published[141] in the *International Journal of Environmental Research and Public Health*. The open questions (Table 10.1) were asking participants to expand on their answer to a closed question apart from the final question, which gave women the opportunity to express their thoughts and feelings about ICS and alternative fuels more widely. However, the open questions exploring HAP interventions had never undergone qualitative analysis, which provided a unique opportunity and was an appropriate data source to investigate the requirements and impact of the chosen methods of qualitative analysis, participant-researcher interaction and translation; in addition, to directing the research question and feasibility of qualitative research with the study area.

Table 10.1: Open question within the household survey relating to HAP interventions

Removing child from the cooking area to reduce exposure
Is the cooking done in the same place all year round? No – please provide details
Are children less than 5 years allowed into the cooking area? No – Please comment why
What is the main reason for your child spending time in the cooking area?
Do you currently do anything to reduce your child/children's exposure to cooking smoke? Yes – please specify
Switching to LPG
Would you be interested to use gas as cooking fuel? Yes - please comment on why
Would you be interested to use gas as cooking fuel? Yes – do you have any concerns about using gas?
Would you be interested to use gas as cooking fuel? No – Why not?
Improved cookstove and alternative fuels
What are your thoughts on improved cookstoves and alternative fuels and why? Please tell us about anything else you feel is important to you about your experiences of cooking, type of stove and fuel.

Questionnaires were undertaken by a stratified convenience sample[331] of households that (i) cooked on wood or charcoal, (ii) had a female main cook ages 15-55 years, and (iii) a child under five. Forty-one women were interviewed face-to-face within their homes, by a female University of Birmingham intercalating medical student, with simultaneous translation of questions from English into Kinyarwanda by trained fieldworkers (masters student at the University of Rwanda College of Science and Technology). Responses were also simultaneously translated and written down in English and any clarification on the answer, either with translation or with understanding, was obtained at time of noting answers. Data collection took place in February 2018. The survey had ethical approval from the University of Rwanda, College of Medicine and Health Sciences Institutional Review Board (No. 317 CMHS IRB) and the University of Birmingham, Internal Research Ethics Committee (IREC2017/1413634).

10.4.2.2 Dataset 2 – Postcards

As part of the DFID funded 'All Systems Approach to air pollution'[361] – ASAP light project, led by one of the supervisors, Francis Pope (Professor of Atmospheric Science) and Robin Price (artist-inventor), to visualise air pollution with photographs, qualitative data was collected on the back of postcards describing posters situated outside the University of Addis Ababa in Ethiopia. Images produced by Robin Price (Figure 10.2) used an MkII Pollution Painter feat Alphasense OPC-N2, attached to the photographer's wrist, to measure the level of particulate matter within the air. The level of particulate matter detected is then translated, using a raspberry pi 0w, into the intensity of LED lights placed along a 3m pole, and walked across the camera frame, with the lights being captured using a long exposure camera setting. These photographs were placed onto posters and postcards, with differing text identifying pollution and how it can be reduced (Figure 10.2). Participants were approached outside the University of Addis Abba Institute of Technology and asked by local facilitators (staff form the Institute of Technology) to write their anonymous comments about the images on a back of the postcard[362,363] in regards to three key questions:

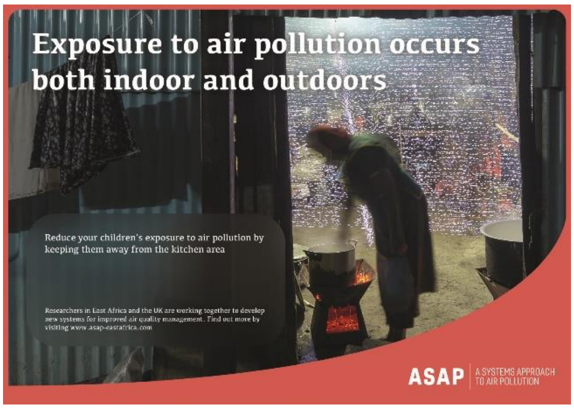
1. What do you think about air pollution?
2. What action should be taken to address air pollution?
3. Who should address air pollution?

Responses were recorded in Amharic (Ethiopia's principal language) and translated verbatim into English by local facilitators. There were no participant characteristics collected with the responses. This data collection had ethical approval from the University of Birmingham Ethical Committee (ERN_17-0994B).

A

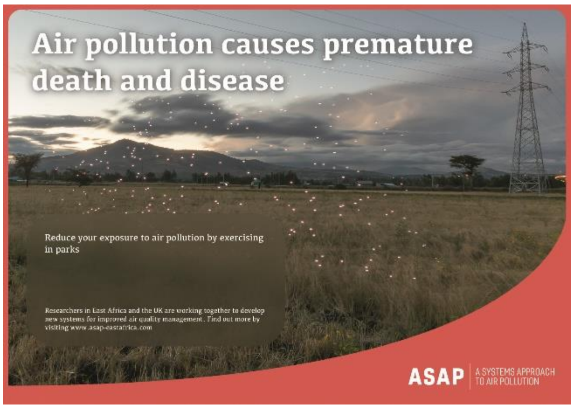
"Reduce your exposure to air pollution by avoiding major raods and uing public transport when possible"

B



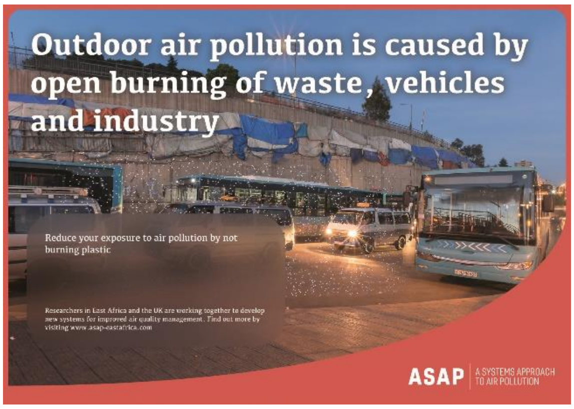
"Reduce yourchildren's exposure to air pollution by keeping them away from the kitchen area"

C



"Reduce your exposure to air pollution by exercising in parks"

D



"Reduce yor rexpousre to air polltion ny not burning plastic"

E

"Reduce your exposure to air pollution by spending less time by the fire while cooking"

F

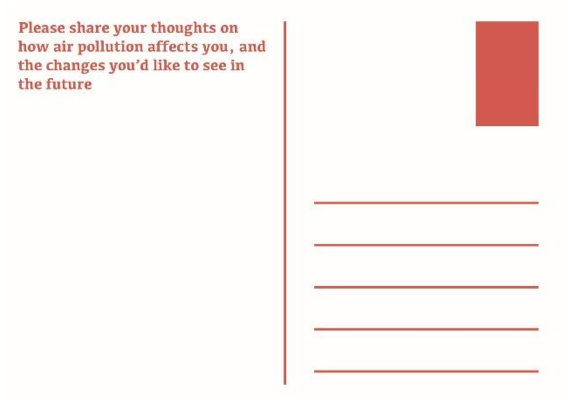


Figure 10.2: Illustrated the two types of postcards produced.
A.) Depicts the level of air pollution on Airport Road, Addis Ababa, Ethiopia, recording $PM_{2.5}$ levels of 10-20 mg/m^3. B.) Depicts the level of air pollution of biomass burning in a commercial kitchen at the University of Addis Ababa, Ethiopia, recording $PM_{2.5}$ levels of 150-200 mg/m^3. C.) Depicts level of air pollution in an open area D.) Depicts level of air pollution at a bus station in Addis Ababa, Ethiopia E.) Depicts level of air pollution during a traditional Ethiopian coffee ceremony F.) Back of postcard

10.4.2.3 Analysis methods

Deductive thematic analysis, where existing ideas are used in coding and theme development,[287] was used using the COM-B model, and NVivo,[364] for data management. Initially codes were formed from the data, with themes of 'capability', 'opportunity' and 'motivation' being assigned to the codes. A robustness check was undertaken where all four members of the supervisory team independently analysed the data from two participants from each dataset, the results of which were then discussed to confirm interpretation.

10.4.3 Results

The results of the two data sets for the pre-planning analysis are presented separately below, and structured, for consistency, using the three major themes 'capability', 'opportunity' and 'motivation' defined in section 10.4.2. Direct quotes are presented alongside the results to corroborate the points made.

10.4.3.1 Analysis 1 - Open questions from household survey

10.4.3.1.1 Background characteristics

Responses were collected from 36 women aged between 20-49 years (median 31 years), with 97.2% cooking on a mobile charcoal stove. Number of meals cooked per day ranged from 1-3 meals, with 63.8% cooking outdoors and 22.2% of women attending the stove for more than 4 hours a day.

10.4.3.1.2 Capability

Enablers and barriers were found in all discussed interventions (behavioural changes, LPG, ICS) with regards to having the necessary knowledge and skill to have the capacity to engage with an intervention. Women reported concern about using LPG due to costs, lack of awareness and knowledge and safety of gas. Although LPG fuel is cheaper than charcoal, participants reported that it was more costly, in part due to the largest barrier being the cost of installation of the equipment needed to use LPG fuel.

> *Participant 8: "Sometimes people who sell gas stoves sell them on loan but they can't afford it (costs 80,000 rwf) to install in total plus pay for gas requirements on top."*
>
> *Participant 35: "She would be very happy top use gas because it is quicker and fast and cheaper than charcoal."*

Fuel cost and environmental benefits were also cited as a benefit of using ICS stoves, due to more efficient burning leading to lower charcoal usage, which provides greater capacity and motivation to change cooking practices.

> *Participant 17: "The current type of stove they have often breaks even if it is bought new. The ICS is stronger as it is made of stronger materials. The worst thing about cooking with charcoal is the smoke. Having to change the stove position when raining and also getting the charcoal is becoming harder because the government restrict the amount produced because they are trying to limit deforestation. Therefore, sometimes the quality of the charcoal is poor"*

However, external factors such as renting and non-home ownership present a barrier to installation of structural interventions such as chimneys, reducing the physical capacity for women to engage in such interventions.

> *Participant 8: "Whatever will help to reduce the health problems she would be happy to do if possible but renting makes it harder to make changes to house."*

Some women reported that the child was not allowed within the cooking area, with some citing health reasons (e.g., burns), indicating a capacity to engage with a harm reduction intervention. However, forcing the child to remain out of the cooking area, was reported to be a challenge due to the child misbehaving or that the mother did not want the child to be alone. In addition, some women cited that the child is accompanying the mother or socialising in the cooking area, which reduces the woman's capability to remove the child from the room while cooking is taking place.

Participant 14: "mother prevents her child being near the stove so that she doesn't get burnt because in the village there was a child who died from burns injuries."

Participant 9: "Socialising, there is no way to keep the older child (still<5) away from the cooking area as it is right outside the front door of house"

10.4.3.1.3 Motivation

Conscious and unconscious decision-making enables the process of behaviour changes. Women reported attempts to remove children from the cooking area due to risk of burns or smoke exposure, at peak exposure times, indicating women have a level of awareness of how to reduce their child's exposure to HAP, and are motivated to try and protect their children. However, women only "attempt" to make these changes, indicating that there are other factors (such as those associated with capability) which reduce the motivation to remove the child from the cooking area.

Participant 8: "Tries to prevent child going into cooking area but the child is a child and so sometimes does wonder in"

Participant 3: "Tries to stop children and tells them to go away from the smoke, especially when lighting the stove"

Motivation can also be seen with some women reporting no concern for using LPG, but they lacked an explanation as to why, which could be a result of reporting bias. One woman reported that they had *"no concerns as they knew people who used gas"*, indicating the power behind shared knowledge via social networks (e.g., family and friend networks). Another effective way of sharing knowledge is through mass media, with one participant reporting that they learn from and like to listen to the radio. Having no concerns about using an intervention, suggests that women are motivated to change cooking practices.

Participant 17: "They like to listen to the radio which sometimes tells them about the harms of cooking smoke - it says that smoke can affect the lungs and pollutes the atmosphere"

Another motivation towards alternative cooking practices is the dislike of current cooking methods including the cost of fuel, smoke and dirt produced from cooking, stove breakages, time requirements, associated health effects and food tasting of charcoal. Likewise, these factors were all reported as perceived potential benefits of the interventions. Women were able to link the interventions to improved health; despite this there was one report of a woman not being aware cooking smoke was harmful.

> *Participant 26: "The worst part of using charcoal is that when boiling water to drink it tastes of smoke and they have health problems like a cough from the smoke."*
>
> *Participant 21: "Charcoal stoves when used to boil water makes the water taste of smoke so gas is better as it doesn't."*
>
> *Participant 8: "She is interested to know if the ICS releases smoke at the beginning - the way it is lit is it similar to traditional stove because she is not sure how much benefit it would provide"*
>
> *Participant 15: "For the ICS she would be interested to use it because she thinks it would reduce her symptoms from the respiratory disease (sinutisitis)."*
>
> *Participant 10: "The worst thing about cooking with charcoal is the ash and smoke. Even when loading the stove with charcoal she has breathing problems because of the fine particles that are released from charcoal."*
>
> *Participant 6: "She wants to know more about how disease from smoke can directly/indirectly impact on health. She was not aware of the health effects - wants me to explain more."*

Although health benefits were positively reported there were concerns over the health benefit of interventions in regard to the intervention's safety, risk of burns and explosions and some participants were unsure of the health benefit. The negative perceptions of poor health events associated with the interventions may reduce the effectiveness of interventions, however, these are mainly due to a lack of knowledge reducing the women's motivation to make change. Motivation towards using HAP interventions is a key enabler in gaining uptake and sustained use.

> *Participant 23: "She is worried about burns because she met someone at the hospital who was severely burnt by gas."*
>
> *Participant 10: "Safety concerns - she heard there can be explosions but she heard this about maintenance and security but she would take care of this and keep gas locked away securely to prevent accidents."*

Participant 25: "Not interested to use gas because of the safety concerns, she has heard that gas is explosive and dangerous for children. She has also heard about lots of accidents."

Participant 14: "Primary concern is about the cost as she knows gas is expensive. Her secondary concern is about the safety of using gas in the house. She has heard about gas leaks, explosions and fires."

Participant 11: "Because gas is fast at cooking food but she doesn't know anything about it."

10.4.3.1.4 Opportunity

Barriers reported that were outside the individual's control included the need to cook and eat, feeling gas is inappropriate for cooking methods and children being too young as the women may not have the opportunity for the children to be supervised elsewhere.

Participant 34: "Using charcoal she knows you can get health problems but there is no choice about using it because they have to cook in order to eat and live."

Participant 4: "Some foods gas is not suitable for cooking (e.g., beans) as they take a long time to cook and would use a lot of gas whereas charcoal can burn for longer."

Participant 9: "She carried young child on her back when cooking. There is no way to stop the children being exposed because they are always together with mother."

The weather (e.g., when it is raining) was also reported to be a large barrier to always cooking outdoors. The existing practice of cooking outdoors, indicated there is already motivation towards this practice, however, a solution is required to provide women with the opportunity to cook outdoors, despite the external weather factor.

Participant 11: "If the ICS is mobile she would like it so when it is raining she can bring it inside still."

One woman reported that cooking with LPG would solve the problem of the weather as cooking would always be done inside, suggesting that women do not perceive there is currently a solution to enabling sustained outdoor cooking whatever the weather. However, there is the opportunity for education through mass media enabling uptake of interventions through female empowerment.

Participant 1: "Charcoal requires her to cook outside which means there are lots of flies which might contaminate the food. If she had gas she could cook inside the house and it would be more efficient."

10.4.3.1.5 Summary

A mixture of barriers and facilitators were identified through this analysis summarised in Table 10.2, with each of the differing intervention types. The largest enabler was motivation towards reducing household air pollution, whether that be to improve health, reduce the negative aspect of current fuel use or cost; meaning that these factors could be used in advertisement of HAP interventions. Although there was a mix of enablers and barriers within the capability theme, behaviour change was limited due to housing restriction, fuel and installation costs, and level of awareness. A few external factors (e.g., weather, young children) were cited as barriers to employing HAP interventions, which requires further investigation of how opportunities can be provided to enable women to take up HAP interventions.

Table 10.2 Summary of thematic analysis of the open questions form the household survey by intervention type

Intervention	Code	Theme	Enabler	Barrier
Harm reduction behaviour change				
Removal of child form the cooking area	Child allowed in cooking area – accompanying mother, socialising	Capability		X
	Child allowed in cooking area – cannot be left alone or too young	Opportunity		X
	Child is not allowed in cooking area	Capability	X	
	Attempts are made to remove child from the cooking area	Motivation	X	X
Outdoor cooking	Impact of the weather	Opportunity		X
Structural changes				
ICS	ICS are more practical	Motivator	X	
	Reported willingness to change	Motivator	X	
LPG	Concerns about using LPG	Capability		X
	Cost of installation	Capability		X
	No concerns about using LPG	Motivation	X	
General comments	Negatives perceptions of current cooking practices	Motivation	X	
	Health benefits of interventions	Motivation	X	
	Not aware smoke was harmful	Capability		X
	Health negatives for interventions	Motivation	X	
	Education through mass media	Opportunity	X	
	Necessity cook and eat	Opportunity		X
	Housing restrictions	Capability		X

10.4.3.2 Analysis 2 – Postcards

10.4.3.2.1 Capability

Participants were aware of sources of household and ambient pollution as well as being able to suggest solutions at an individual, government and international level. Having an awareness of sources of pollution suggest that individuals have the knowledge to be able to engage with the problem and identify the root sources of air pollution. This enables cause and effect to be linked, which would support behaviour changes, with some of the participants already linking the sources with the solution or effect. However, participants identified different direct sources of air pollution, but only a few participants provided information in regard to how pollution can be mitigated, suggesting a lack of capacity to intervene with air pollution. Participants were able to provide details of potential solutions and which stakeholders need to advocate for change; which suggests they have the knowledge to engage with and bring about change. In addition, some of these changes require fiscal measures and regulations to change, however only a few participants identified this suggesting knowledge is not widespread.

> *A17: "The United Nations and other authorities should give awareness to people and make an effort to solve this global problem"*
>
> *A8: "The government should give awareness to the people about air pollution. Alternatives for charcoal should be used"*
>
> *D2: "There should be a local meeting in villages on how to make the environment safe and clean"*
>
> *C18: "The changes I want to see in the future is: put in place a public transportation system that actually works and discourage people from everybody owning and driving their own car which is a huge pollution factor. Also encourage the use of clean transportation like building bike lanes and promoting cycling. Promote and encourage people to use electricity for cooking etc. to save the trees and the air from burning wood for fire. Make or subsidise electricity make it cheaper and assemble proper quality stoves etcs for zero tax"*

10.4.3.2.2 Motivation

Awareness of the problem, environmental impact and health effect shows a deep reflective and automatic process, to aid conscious and analytical decision making. Although there were unspecific comments in regard to awareness of air pollution it suggests an unconscious understanding which could motivate people towards behaviour change. Many participants were able to cite the impact of both environmental and health factors, often unspecific (e.g., *"causes disease", "causes climate change"*), which motivates them towards changing their behaviours to reduce air pollution.

> *A19: "I want to move around freely without getting polluted"*
> *B8: "There's a lot of people burning waste nearby my house"*
> *C7: "Air pollution is being terrifying and need to be handled crucially"*

10.4.3.2.3 Opportunity

The opportunity for participants to make behaviour change was not often widely reported, apart from mentioning external factors such as governmental influence and often air pollution being made by other people (e.g., factories); all of which infer external factors. Due to the unspecific nature of many of the participants' comments they have not reached a stage where there is enough knowledge to express what physical and social opportunity is required to enable behaviour change; education alone would not solve the physical constraints. One participant identified that air pollution was a global problem, suggesting that control of air pollution is out of each individual's control. The absence of information regarding opportunity or even details on lack of opportunity, reduces the individual's ability to change their behaviour for reducing air pollution.

> *A1: "Air pollution has become a global issue"*
> *C16: "Everyone's worried about pollution but until human needs are met, humans will see resources as ways to meet their needs"*

10.4.3.2.4 Summary

The use of photographs as a medium for initiating discussion on both ambient and household air pollution showed that there were multiple barriers and opportunities for individual behaviour change focused around capability and motivation towards improving air quality (Figure 10.3). However, a greater understanding for the opportunity for behaviour change could not be gained from the data, suggesting that there is a potential need to focus on external factors to enable behaviour change.

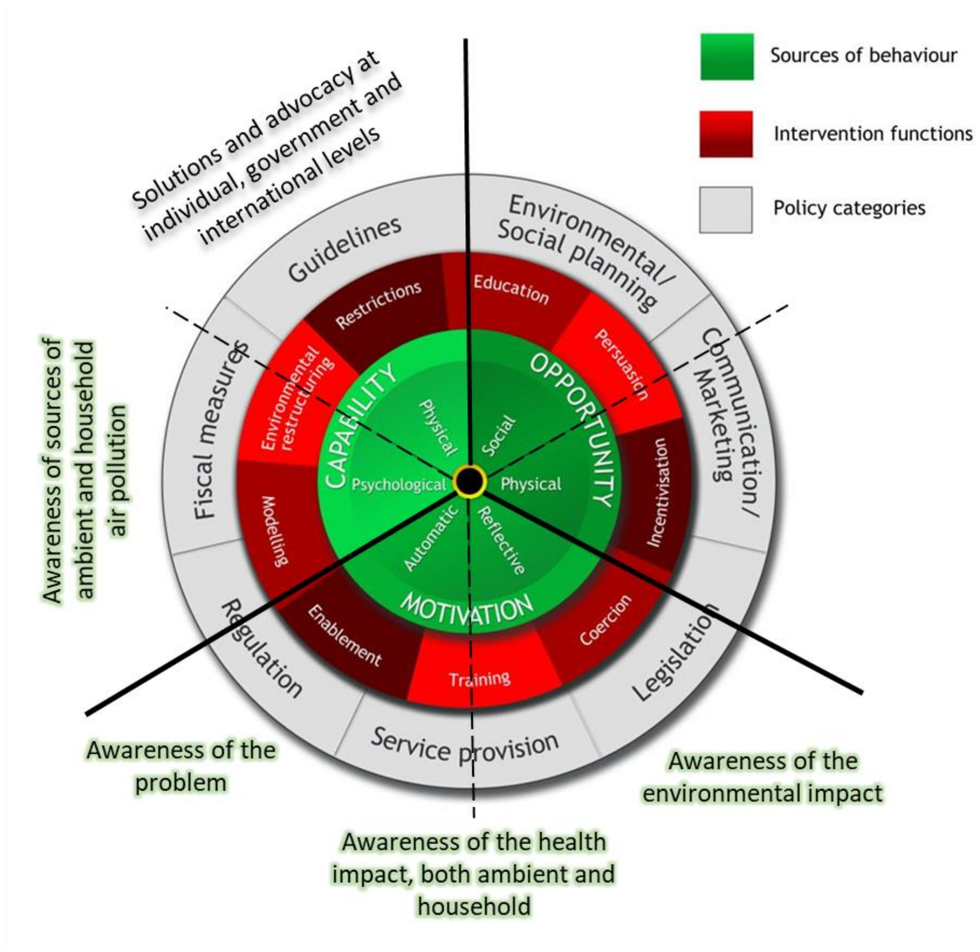


Figure 10.3 Result of the thematic analysis of the postcard data applied to the COM-B wheel

10.4.4 Critique of methods used in analyses 1 and 2 and identification of the direction of future work

10.4.4.1 The data

These two datasets used for the analysis, provided a unique opportunity in qualitative and cross-cultural research to explore qualitative methodologies relevant to the topic area of the thesis, which had been used in LMIC settings. There is potential for response bias and translation errors, as the data was designed from a quantitative perspective, and as the data was collected for another purpose data saturation[365] was not looked at within the analysis.[366] In addition, translations were the fieldworker's interpretations, and discussions were not recorded and could not be validated. Despite this, preceding closed questions enable the formation of a participant-researcher relationship, but this provides participants with knowledge or prompts about HAP interventions from the preceding question that could introduce responses biases. On the other hand, verbatim translation and data collection by Ethiopian researchers was a strength of the postcard data; however, there may be a responses bias as the opportunistic sample was dominated by educated university students.

10.4.4.2 The analysis

Using a deductive thematic analysis,[367] based on COM-B,[358] provided a greater understanding of the barriers and enablers within target areas for an intervention for behaviour changes to reduce air pollution. Although there was a very small amount of potential overlap between themes, such as "the impact of the weather" which was coded as 'opportunity' as weather is an external factor, but rain also reduces the women's physical capability to engage with outdoor cooking, therefore could be interpreted as a 'capacity'. However, the interpretation was confirmed through a robustness check. The inner circle of the COM-B wheel (source of behaviour) could be used effectively in the analysis, but there was not enough detail within the data to provide themed categories for intervention functions and policy categories of the wheel, which reduces the extent to which this complex issue can be explained. An inductive[287] approach would have also enabled the identification of enablers and barriers however, would not have enabled the identification of which areas (e.g., capability, opportunity or motivation) to target within an intervention to change cooking behaviours.

10.4.4.3 Identification of knowledge gaps

The results from these data sets have provided details on the capability, motivation and opportunity, for some behaviour, structural and policy interventions (Table 10.3) and it has allowed for the identification of knowledge gaps and direction for further research questions for short, medium and longer-term intervention. A large range of behavioural, structural and policies research areas have been identified (Table 10.3) with both stakeholders and end-users indicating the complex nature of find potential solutions to HAP; and as a result, some of the intervention discussed within the table are beyond the scope of the PhD, which focuses on harm-reduction behaviour change.

Table 10.3 Summary of potential interventions applied to the study area, with identification of knowledge gaps

	Interventions	Summary of information gained	Potential in study area	Questions remaining/ gaps identified
Behavioural	Removing child from the cooking area	Women reported multiple barriers to removing children from the cooking area due to children being too young or misbehaving. However, they presented motivation towards removing children from the cooking area for health reasons.	Short-medium term	What provision can be put in place to provide women with the opportunity of cook without their children in the cooking area?
	Cooking outdoors	Cooking outdoor is an existing behaviour with the study area used by a high proportion of women, however, the weather plays a major barrier in being able to continually cook outdoors.	Short-medium term	What provision can be put in place to provide women with the opportunity of cook outdoors?
	Opening doors and windows	Although not discussed the setup of the study area means that there are few functioning windows and this would then impact neighbours air quality.	Limited potential	
	Drying wood and crop residue	Charcoal is the main fuel of the study area therefore was not discussed by women.	Limited potential	
Structural	ICS	Women report a high willingness to change to an ICS stove, reporting that they are more practical than their current stove.	Short-medium term (due to charcoal ban)	Why have women not taken up ICS even though they are motivated to do so? Investigation of capacity and opportunity
	LPG	Many women reported concerns (safety, cost etc.) for using LPG.	Long-term	How can these concern about LPG be overcome? How can knowledge about using LPG be provided?
	Biomass pellets	Women did not mention biomass pellets, however, they were not prompted. Previous work has been	Short-medium term	What are the differences between the barriers and facilitators for biomass pellets and other interventions (e.g.,

		undertaken in urban Rwanda indicated that peer communication, training, cost and cleanliness are key factors in adoption of biomass pellet clean cookstoves.[301]		behaviour change, LPG) within Urban Rwanda? How can these results be applied/ transferred into wider HAP interventions in urban Rwanda?
	Chimney	The main barrier to chimneys was lack of homeownership.	Limited potential	
	Solar Stoves	Solar stoves did not arise in the survey however, due to the setting, there is limited outdoor space of stoves to be used along with the household's situation (non-home ownership and poor constructed house) mean solar panels would be difficult to install.	Limited potential	
Policies	Educational and social campaigns	Although these analyses have indicated that education is only part of the puzzle, it is required to support interventions.	Long-term	Engagement of stakeholders (government, community leaders) and end-users to design and target appropriate education and social campaigns.
	Reducing stove/fuel stacking	Stove stacking is a very common phenomena, especially when producing traditional meals. In this setting LPG has been reported not be appropriate for cooking beans.	Long-term	Understanding of why women stove/fuel stack in this setting? Do they understand why it is not a good idea? What tools can be created to facilitate sole use of the intervention? Engagement with stakeholder and end-user to provide education against stove/fuel stacking, alongside interventions.
	Charcoal restrictions and bans	Individuals in both the postcard data and open question report that reducing charcoal use will improve health and deforestation.	Long-term	What fuel would people turn to if charcoal was restricted or banned? What are the potential consequences of restricting charcoal?
	LPG subsidies. Microfinancing, lease	Financing both the start-up and cost of fuel has highlighted the variation in	Long-term	Engagement with stakeholders and end-users to provide schemes which enable uptake

	programs and Pay As You GO (PAYG)	methods that can be used as financial support	of cleaner fuels that are appropriate for all parties. How can these interventions be maintained so that they are always market competitive? How do you prevent fuel switching away from cleaner fuels in time of economic instability?

10.5 Informing the methods for the qualitative component of the thesis

The pre-planning analysis and evaluation of the challenges presented by undertaking cross-cultural qualitative research has identified areas within the research scope for this thesis, which need to be taken into consideration at the planning, data collection and analysis stage (Figure 10.4). The pre-planning analysis enabled learning early lessons including the limitations of the data, the strengths and limitation of the analysis, resulting in improvements to the overall methodological quality of the proposed study for the thesis.

Planning

- Format, direction and structure of topic guide
- Effective fieldworker training to gain in-depth rich data through encourage and exploring discussion
- Sourcing appropriate translators

Data collection

- Reducing western influence by a Rwanda national leading interview
- Build up participant-research relationship through undertaking prior survey
- Use of photos to stimulate discussion and breakdown barriers

Analysis

- Fulfilling data saturation
- Effective organisation of codes and themes
- Benefit of robustness check and results discussion

Figure 10.4: Learning points from the pre-planning analysis to be taken forward into the planning, data collection and analysis stage of the main qualitative component

The result of the preplanning analysis influenced the direction of the topic guide for the in-depth interview within the thesis, both analyses highlighted that there was a high level of motivation for changing women's behaviours to improve air quality. However, the women lacked opportunity in which to undertake these behaviours, which was particularly prevalent with outdoor cooking. This confirmed the need for further investigation into the opinions about and barriers to a behaviour change intervention of moving cooking location and moving children out of the cooking area, supporting investigations at a pilot level to inform the structure and layout of such an intervention. Highlighted in the limitations of the pre-planning analysis were the method of translation and lack of in-depth exploration, which emphasised the need to plan for appropriate translation and provide effective field assistant training to enable in-depth discussion.

Both analyses showed the benefit of building-up a rapport through prior survey and the use of photos to stimulate discussion; indicating that interviews and photovoice would be effective methods in understanding the enablers and barriers of behavioural interventions within the context of the thesis. However, the need for data collection to be undertaken by Rwandan nationals was noted, due to the potential bias of a western researcher undertaking the interviews.

The pre-planning analysis allowed a novice in qualitative data analysis to learn the benefit of effective code organisational and robustness check, which would improve the quality of the main qualitative thesis analysis. However, it could not be ascertained if data saturation had been met within the pre-planning analysis, making this a consideration point in the main thesis qualitative methodology. In addition, the postcard data was collected in a very different context and went beyond HAP to include ambient air pollution.

As the data for the pre-planning analysis was collected face-to-face, further methodological considerations were required to accommodate the complexities or remote research as a result of COVID-19. Table 10.4 highlights the actions taken, for each point of consideration, and the accepted limitations under the given circumstances (e.g., exclusion of participants without a mobile phone), to maintain methodological rigour and quality.

Table 10.4 Methodological aspects which require consideration, action and accepted limitations due to remote research due to the COVID-19 pandemic

Consideration point	**Action**	**Accepted limitation**
Technology poverty	Undertake telephone interviews rather than interview via video link	• Potential lower engagement and ability to form participant-researcher relationship • Will be unable to observe body language
Maintaining research integrity	To provide detailed training, observer fieldworkers, and check data affect every collection	• There could be slower reactions to data quality issues and to solve problems
Maintaining community engagement (Including loss to follow up)	Confirm participant's telephone numbers and ask for time/day they would be available.	• There is a greater potential for loss to follow up
Representative sample	To take an opportunity sample, rather than convenience sample	• May not be representative of study area, especially as the poorest may not have access to mobile phones or data.
Informed consent	Take verbal consent	

10.6 Proposed methods

The following section describes the proposed methods for the qualitative section of the thesis informed by undertaking the pre-planning analysis, which included photovoice data collection and in-depth interviews. As this section is a proposal it is written in the future tense. The qualitative component enables a holistic and robustness assessment of the potential of developing a behaviour change intervention in urban Rwanda, with the results detailed in 0.

10.6.1 Aims and objectives

To qualitatively understand among women:

- The awareness of HAP and the associated health harms
- The awareness of HAP interventions
- The opinions and barriers to the behaviour change intervention of cooking outside and removing children from the cooking area

10.6.2 Study area and population

The study area is the same as that described in the fuel choice survey (section 5.3). A convenience sample[282] was gained by asking participants who met eligibility criteria (Table 10.5) at end of the fuel choice survey if they would like to participate in (i) photovoice research or (ii) an interview. Participants will be randomly selected out of those who indicate a willingness to participate, interviews will be undertaken until data saturation[365] has been reached defined as the point at which no new information is being obtained.[366]

Table 10.5: Eligibility criteria for photo voice and interviews

Photovoice	Interviews
➢ Resident of Kabeza cell. ➢ Aged over 18 years.	➢ The main household cook is a woman aged 18-55 years (reproductive age).* ➢ There is a resident child under the age of 5 years.† ➢ Charcoal and/or wood are the main cooking fuel(s). ‡ ➢ Has taken part in the photovoice.

Rational for eligibility criteria:
* Women of reproductive age are at high risk from HAPs are they are most likely to be the household member undertaking cooking activity[368] and have a child under five years.
† Children under five are also vulnerable to the effects of HAPs, due to spending more time that their older siblings or households members in the house.[368]
‡ Wood and charcoal are the main biomass cooking fuels used within urban setting in Rwanda.[80]

10.6.3 Data collection

10.6.3.1 Visual participatory methods (Photovoice)

Photovoice is a participatory research method, which empowers participants to share knowledge with the researcher without the need for translation.[369] Both men and women, who express an interest in participation at the end of the fuel choice survey (Section 5.3), will be provided with verbal instructions in Kinyarwanda and verbal consent taken. Participants will be asked to take one photograph, using a personal smart phone camera, of what they think air pollution is and the impact air pollution has; and submit this photo to the research team using a dedicated WhatsApp number, including a short description describing the photograph. Participants will be asked to gain written consent from any individuals featuring in the photos (unless within a crowd) and to avoid taking pictures of individuals under the age of 18 unless they are a relative; following the recommendations within the literature.[370,371] As an incentive for participation, all photographs would be entered into a competition, and the winner published in a local media channel.

10.6.3.2 Interviews

Interviews will enable participants to express knowledge and experiences, and provide discussion among members of the community.[372] Women will be asked to initially discuss their photograph, taken as part of the photovoice, followed by discussion on the following questions (Topic guide – Appendix 5):

- What do you feel are the health effects of cooking smoke?
- Where should cooking take place?
- What would you think about moving cooking outside?
- Do you know of any other behaviours you could change to reduce you or your children's exposure to cooking smoke?
- How would you like to learn more about behaviour changes to cooking practices to improve the health of your family?

All interviews will be undertaken by telephone in Kinyarwanda, using trained local fieldworkers, supervised virtually by teleconference (Zoom) by a member of the research team (KEW). KEW will provide detailed training in qualitative data collection methods to the local fieldworkers who are masters' students at the University of Rwanda Collage of Science and Technology, who have no previous experience of qualitative data collection. The same fieldworkers who undertook the fuel choice questionnaire will also be undertaking the interview, to continue the established participant-researcher relationship. Interviews will be recorded via Zoom, with consent verbally taken and recorded separately. Recordings will be professionally translated into English during transcription;[349] and this method will be accepted as a potential limitation due the inherent complexities in multi-language qualitative research.[373] Data analysis will occur in parallel to the data collection and form an iterative process, with development of the interview topic guide to include new relevant topics in subsequent interviews.[374] In addition an assessment of the accuracy of transcriptions and translation of the interview recordings[316] will occur in parallel, to maintain high data quality.

10.6.4 Data analysis

Deductive thematic analysis, using the COM-B behaviour change wheel, will be used to analyse the data collected within both the photo voice and in-depth interviews, in order to allow a thick description of the dataset, generate valuable insights and produce useful results to potentially help inform policy.[367] NVivo will be used to store codes, categories and themes derived using the 6-step process of developing and refining themes describe by Braun and Clarke,[367] where transcripts undergo first cycle coding (descriptive and value codes),[375] and these codes are then sorted/categorised in potential themes. Coding and theme identification will be undertaken by KEW, and a sub-sample (10%) analysed by the supervisory team with discussion of themes for validation[375] and to solve discrepancies; to check that themes are internally coherent, consistent, and distinctive.[367]

Results for the in-depth interviews will be narratively displayed, by theme, 'capability', 'opportunity' and 'motivation', with grouped codes being applied and presented to the behaviour change wheel. These grouped codes will also be tabulated, to identify enablers and barriers to behaviour change HAP interventions.

The photovoice results, where codes and themes are applied to each image, will also be narratively displayed by theme, and presented on the behaviour change wheel. Additional comparative analysis will be undertaken and presented in tabulated form to compare and contrast any differences between participant characteristics. These comparative analyses include:

- **Gender differences** – Grouped codes in males compared to females. Gender differences are important to understand differing perceptions, as often the male heads of the household are the decision makers,[376] which could indicate how the interventions may be targeted (e.g., just women or a mixture of men and women).

- **Fuel type** – Solid biomass (e.g., charcoal, firewood) group codes compared to cleaner cooking fuel types (e.g., LPG). Differences by cooking fuel use may indicate the role HAP perception may play in choice of cooking fuel.

10.6.5 Data management and ethical approval

The data management and ethical approval process is the same as the quantitative primary data collection and can be found in section 5.3.5 and 5.3.6.

10.7 Summary

Mixed-methods and qualitative methodologies have successfully been used in HAP intervention research investigating the drivers behind uptake and sustained use of mainly structural interventions and are required to provide a holistic approach into intervention development. However, cross-cultural research presents many logistical and cultural challenges in data collection and analysis, which requires additional consideration within the planning process and interpretation of results, such as use of translators and influence from "western researchers". Despite the data limitation presented with the two data sets used, the pre-planning analysis has provided a unique opportunity for a qualitative novice to develop skills, identify research gaps to build on with the main qualitative thesis component and learn from early research findings; critiquing the data; analysis methods; and identification of knowledge gaps. The analysis successfully employed the use of deductive thematic analysis[367] using the COM-B wheel,[358] and indicated that there was a lack of 'opportunity' for individuals to make changes to their behaviours. Further research should focus on how opportunities can be provided to break down these barriers with stakeholders and end-users. The detailed qualitative photovoice and in-depth interview proposal, takes into consideration the lessons learnt form the pre-planning analysis and details limitations of undertaking remote qualitative data collection as result of COVID-19. In addition, the qualitative proposal complements the quantitative research which will provide a greater in-depth understanding of thoughts and perception of HAP interventions.

CHAPTER 11 RESULTS: QUALITATIVE: OPINIONS AND BARRIERS OF BEHAVIOUR CHANGE INTERVENTIONS

Within this chapter are the results of the qualitative in-depth interviews among women in biomass using households in the Kabeza cell, illustrating the facilitators and barriers to behaviour change interventions; mapped out onto the behaviours change wheel.[358] The chapter has been published in *Sustainability* and is presented in this style.

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sustainability

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Article

Women's Perceptions and Attitudes to Household Air Pollution Exposure and Capability to Change Cooking Behaviours in Urban Rwanda

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Abstract: Household air pollution (HAP) from cooking on biomass fuel presents significant health, environmental and socioeconomic consequences worldwide. However, there is a lack of understanding of the factors influencing cooking behaviours that affect HAP exposure in Rwanda (e.g., cooking location, removing children from the cooking area). Sixteen qualitative in-depth interviews were undertaken with women living in an underprivileged neighbourhood in Kigali, Rwanda. Deductive thematic analysis was carried out using the Behaviour Change Wheel (*Capability*—ability to engage with chosen activity, *Opportunity*—factors which are beyond the individual's control and *Motivation*—brain processes which direct behaviour: COM-B) to determine the thoughts and perceptions around cooking location and removing children from the cooking area. Facilitators and barriers were subsequently identified within the COM-B framework for the following HAP mitigation interventions: outdoor cooking, removing children from the cooking area and Liquid Petroleum Gas (LPG) use. Of the 16 interviewed, 12 cooked outdoors (75%), two (12.5%) cooked indoors (in the main home) and two (12.5%) in a separate kitchen. Despite the majority cooking outdoors, this was reported not to be a favourable cooking location. Levels of awareness of HAP sources and knowledge of the health effects of air pollution were observed to be limited, reducing women's capability to change, along with stated barriers of cost, housing constraints and safety. Factors out of the individuals' control (opportunities) included weather, socio-economic and educational factors. Preconceived beliefs, experiencing smoke reduction and the briefly described short-term health effects, directed motivation. Furthermore, participants identified a need for community-based education as a facilitator to changing their behaviour. Despite a high level of observed motivation towards reducing HAP exposure, many women lacked the capability and opportunity to change their behaviour. There are research and policy implications concerning development of community-based interventions which involved end-users and relevant stakeholders in the development process.

Keywords: household air pollution; behaviour change wheel; biomass cooking; LPG; Rwanda

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1. Introduction

Over half of the global population cook using solid biomass fuels (wood, dung, charcoal, crop residue) in the indoor environment, causing harmful levels of household air pollution (HAP) responsible for approximately 4 million premature deaths each year [1], with women being the primary cooks. Biomass fuel cooking has major health implications throughout life course (e.g., low-birthweight, respiratory infections, chronic obstructive pulmonary disease (COPD)), cognitive impairment, etc.) [2–5] and also exerts adverse environmental (e.g., deforestation, erosion, greenhouse gas emissions etc.) [6,7] and socioeconomic impacts (e.g., gender inequalities, healthcare costs, opportunity costs etc.) [8,9]. There is a pressing need to develop and implement HAP interventions, with the ultimate long-term goal of cleaner fuel transition (e.g., Liquid Petroleum Gas (LPG), electricity, solar) in low-and middle-income contexts. However, cleaner fuel transition is often not complete or follows the “energy ladder” model with transient fuel switching and stove or fuel stacking [10] due to multiple barriers to clean fuel provision including access, financial costs and traditional cooking behaviours and cultural considerations [11–14]. During the transition period, structural or behavioural interventions which reduce HAP exposure may be introduced, such as improved cookstoves (ICS), outdoor cooking, removing children from the cooking area and improved ventilation; although it is recognised, changes in pollutant concentrations will not meet World Health Organisation indoor air quality guidelines (WHO-IAQ) [15].

Qualitative research provides a valuable tool in HAP intervention research, to understand awareness, attitudes and perceptions around biomass cooking and potential interventions, as well as enablers and barriers to change. Both traditional [16–19] and participatory [20,21] qualitative research methods have previously been used in HAP intervention research, highlighting facilitators of growing awareness of LPG [20], but barriers of cost [19–21], safety concerns with LPG [22], and possibly surprisingly a lack of knowledge regarding the long-term reductions in health risks associated with the cleaner fuel interventions [17,20]. A midwife-led behaviour change intervention introduced in health centres in rural Kenya indicated the important role of education in motivating women to change their cooking behaviour and share information within the community [18]. By identifying barriers at an early stage of intervention development, effective policies can be formulated to improve sustained adoption and change [16,19].

Rwanda is a small landlocked densely populated country in East Africa, with a population in 2020 of ~13 million [23]. Although classified as a low-income country, with a current GDP per capita of US$ 797.9 [24], the Rwandan Government is economically ambitious, aiming to achieve upper-middle-income status by 2035 [25]. This rapid phase of economic development and population growth in recent decades has led to mass urbanisation and the rise of unregulated settlements, especially within Kigali, the capital. In urban areas in 2019, biomass was used for cooking by 80.3% of households, with a prominence of charcoal [26]. In May 2021 the Government of Rwanda announced proposals to phase out the sale of charcoal in Kigali due to its adverse health and environmental impacts [27]. The COVID-19 pandemic presented periods of economic uncertainty which led to cooking fuel switching in East Africa due to a change in market availability and household income [28]. Previous research undertaken in Kigali, Rwanda suggested that women are keen to adopt HAP mitigation interventions, especially ones that can suite a range of cooking patterns, and had positive attitudes towards educational initiatives [29]. In addition, the role of positive peer attitudes upon the uptake of biomass pellets [30] and the use of dynamic HAP concentration feedback with air quality sensors has proven an effective push tactic towards HAP lowering behaviours [31]. However, there is a research gap for the in-depth understanding of women’s perceptions of behaviour changes during the development of such interventions; addressing this research need has the potential for an increased intervention acceptability and uptake.

Therefore, to understand the role of behaviour change to inform potential cleaner cooking interventions in Rwanda, this study aims to explore (i) awareness of HAP exposure and associated health harms, (ii) awareness of HAP interventions and (iii) the facilitators and barriers to (a) outdoor cooking and (b) removing children from the cooking area.

2. Materials and Methods

2.1. Theoretical Grounding

The Capability, Opportunity, Motivation, Behaviour (COM–B) and Behaviour Change Wheel (BCW) framework were originally created to help inform the design of behaviour change interventions [32] and in this study was used to understand the theoretically derived determinants of behaviour change in cooking practices. The three components, 'capability' (ability to engage with chosen activity), 'opportunity' (factors which are beyond the individual's control), 'motivation' (brain processes which direct behaviour), determine the ability for behaviour change [32]. Each of the sources of behaviour can then been divided into nine categories to further understand how the intervention may function (Figure 1), allowing the identification of areas to target [32,33]. Within this study, all three sources of behaviour are used to inform contextually specifical behavioural strategies for HAP reduction.

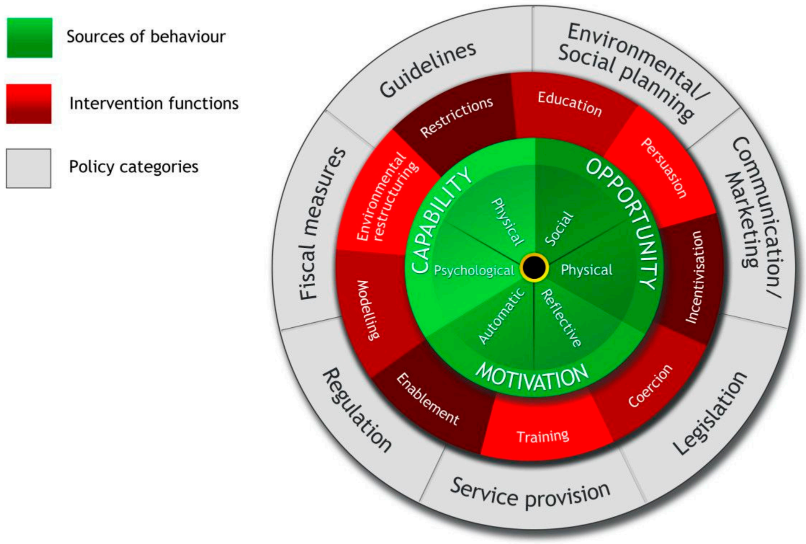

Figure 1. The Behaviour change wheel [32].

2.2. Study Setting

The study was set in the Kabeza cell, which is a group of villages situated in the Nyarugenge district of Kigali city; an informal settlement comprising ~950 households in 7 villages (Hirwa, Ikaze, Ituze, Imanzi, Ingenzi, Sangwa and Umwezi), with a predominance of charcoal cooking on mobile single-pot stoves (Figure 3) [29,34]. Residents were eligible for participation if they (i) were the main female household cook aged 18–55 years (reproductive age), (ii) had a resident child under the age of 5 years and (iii) cooked mainly on charcoal and/or wood fuel(s). Eligible women were identified from a wider study on fuel switching which included a convenience sample [35] of mobile numbers provided by the cell and village leaders, who hold a list of mobile numbers of each household (Figure 2). Of 17 eligible women identified by the survey responses, all agreed to participate in the present study. There was one subsequent withdrawal, resulting in a total of 16 completed interviews. Participants were asked at the end of the semi-structured survey to submit a photographic depiction of air pollution prior to the interview which was used as descriptive context to support the analysis. All 16 interviews were undertaken between April–July 2021. Data saturation, where no new information is obtained within the analysis [36], could not be determined at the time of undertaking the interviews due to the time required for transcription and translation, compounded by delays caused by COVID-19 and expiry of ethical approval. Despite this, data saturation was achieved, and was determined during the data analysis of all collected interviews.

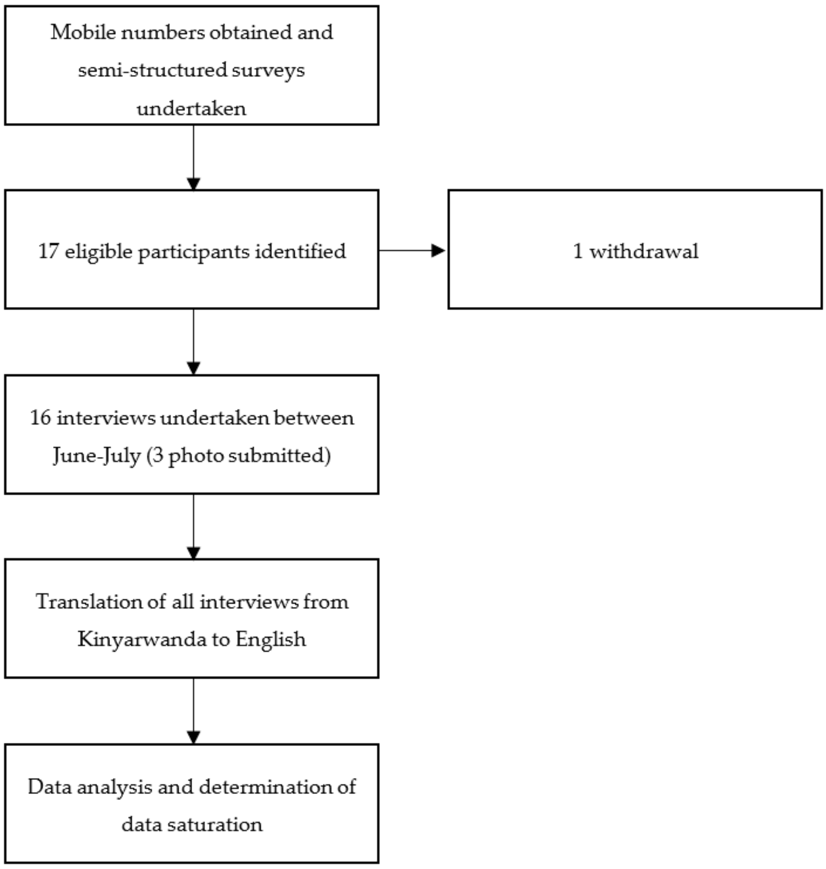

Figure 2. Flow diagram of the research process.

2.3. In-Depth Interviews

Participants were contacted to organise a convenient day and time for the interview, which all took place between 9 a.m.–5 p.m. on a weekday (June–July 2021), via mobile telephone. The interviews were undertaken by trained field workers (A.M., C.M. and O.A.; trained by K.E.W.) in Kinyarwanda, who were undergraduate students studying water and environmental engineering in the University of Rwanda College of Science and Technology and who also undertook the previous semi-structured surveys. Interviews were based on a topic guide (Table S1), which first asked participant to describe and explain the photo they had taken, to stimulate discussion. If the participant had not taken a photo, they were asked to describe what they thought air pollution was and why. The questions which followed covered the awareness of the health effect of household air pollution, views on behaviours to reduce exposure (e.g., moving cooking location and removing the child from the cooking area), what would enable them to make these changes and how they would like to learn more. Verbal informed consent was recorded prior to the interview. All interviews were recorded and professionally translated and transcribed by PageSix Transcription Services Ltd. (Isle of Wight, UK).

2.4. Data Analysis

Deductive analysis [37] was undertaken using the COM-B behaviour change wheel, with coding being undertaken while reading through the interventions, with allocation into the COM-B themes being undertaken using NVivo [38] to manage the data by K.E.W. Data on cooking location and health events were quantified from the interviews. A random sample of 10% of the responses were analysed by S.E.B, G.N.T., F.D.P. and S.M.G. for validation [39] and to check for discrepancies in the coding.

2.5. Ethical Approval

Ethical approval for data collection was obtained from the University of Rwanda College of Medicine and Health Science Institutional Review Board (CMHS IRB) (No. 235/CMHS IRB/2020) and the University of Birmingham (ERN_19-0252). Participants were free to withdraw at any point and fully informed verbal consent was obtained.

3. Results

3.1. Participant Characteristics

Demographic information on the participants was obtained from the prior semi-structured survey (Table 1). The 16 participants were aged 25–55 years and had a median household income of 60,000 RWF (IQR: 37,500–112,500). The majority were employed in elementary occupations (e.g., cleaner, waiter, housekeeper) (n = 11; 68.8%) and other occupations included service and sales workers (n = 3; 18.8%), technician and professional (n = 2; 12.4%). Charcoal was used by most participants (75%, n = 12) with firewood used by four (25%). The majority of participants cooked outdoors (75%) with two (12.5%) cooking indoors and two (12.5%) in a separate kitchen. All three photo submissions were of cookstoves in outdoor (n = 2) and indoor (n = 1) cooking locations, describing the smoke produced from cooking (Figure 3).

Data from the interviews are presented in this section in the three major themes, 'capability', 'opportunity' and 'motivation' followed by a final section which presents the facilitators and barriers to behaviour change interventions. Out of each of the three themes, capability dominated the data, followed closely by motivation; however, little data in comparison was coded to the opportunity theme. Participant quotes are used to support the view presented by participants. Participants can be linked back to Table 1 which illustrated the individual characteristics of each participant.

Table 1. Basic participant characteristics for each interviewed woman.

Participant	Age (Years)	Occupation	Income (RFW)	Cooking Fuel	Cooking Location
Participant 1	35–44	Teacher	180,000	Wood	Outdoors
Participant 2	35–44	Housewife	60,000	Charcoal	Outdoors
Participant 3	35–44	Security worker	100,000	Charcoal	Outdoors
Participant 4	25–34	Casual worker	300,000	Charcoal	Separate kitchen
Participant 5	25–34	Housewife	60,000	Charcoal	Separate kitchen
Participant 6	35–44	Casual worker	20,000	Wood	Indoors
Participant 7	55–64	House cleaner	50,000	Charcoal	Outdoors
Participant 8	35–44	Casual worker	30,000	Charcoal	Outdoors
Participant 9	45–54	Housewife	100,000	Charcoal	Outdoors
Participant 10	35–44	Hair dresser	250,000	Charcoal	Indoors
Participant 11	25–34	Casual worker	40,000	Wood	Outdoors
Participant 12	35–44	Casual worker	30,000	Charcoal	Outdoors
Participant 13	35–44	Mobile seller of vegetables	60,000	Wood	Outdoors
Participant 14	35–44	Casual worker	20,000	Charcoal	Outdoors
Participant 15	25–34	Casual worker	50,000	Charcoal	Outdoors
Participant 16	25–34	Business woman	150,000	Charcoal	Outdoors

Participant 7:
"You saw that the smokes are all over the kitchen, when you are cooking the smoke goes outside when your woods are not very dry. I was cooking as usual"

Participant 1:
"When I was lighting, too much smoke sprayed"
"That's what I photographed and sent it to you; those gases when they rise and disperse in the air are the ones that pollute"

Participant 5:
"The meaning of those pictures, if a person uses charcoals or woods those smokes given off may affect lungs or pollute the air. And the environment, because when the air is not good, we also don't breathe good air"

Figure 3. Pictures and associated captions provided by participants documenting the traditional charcoal stoves in an outdoor setting (**A**,**B**) and indoor setting (**C**).

3.2. Capability

The capability theme covered the ability to engage with behaviours that can reduce HAP exposure, which includes psychological (e.g., awareness of the problem) and physical (e.g., housing and financial constraints). Women reported a lack of clear awareness of the source of air pollution, with nine identifying briefly that cooking fuels cause air pollution, describing it as smoke from cooking. Two participants identified two alternative sources of smoke exposure including plastic bags used as firelighters, lighting and grass burning. One participant claimed that charcoal production generated air pollution rather than the burning of fuel for cooking.

Participant 9: "Smoke from cooking wood pollutes the air"

Participant 11: "The first thing is the smoke from the grass they burn. The second thing is the charcoal we burn and what we use to start the fire, like the plastic bags. The third thing is the cars that use petrol, I don't know, they emit gases that pollute the air we breathe"

Identification of other sources was lacking and could only be gained with further prompting. The health effects of HAP exposure were also vaguely described by providing few substantive or known health events, reporting events including headaches, dizziness, eye irritation and respiratory issues among the women.

Participant 13: "Sometimes I bend down to fetch food from the pot or turn the food, and then the smoke rises in my face causing dizziness, tears, and mucus to run from the nose, and it becomes clear that the smoke is causing issues"

However, there was a lower level of knowledge of the health harms affecting children observed, with one woman reported that her child did suffer from respiratory issues but did not think this was attributable to cooking smoke.

Participant 11: "I have a child among mine who suffers sinusitis, but that [smoke] wasn't the cause"

Respiratory complaints (n = 4), burns (n = 3), headache (n = 2) and heat (n = 1) were the commonly reported health events due to HAP exposure in children, otherwise no events were reported. One woman did identify the difference in the vulnerability between herself and the children stating

Participant 3: "For me it takes time to be contaminated but the child not"

This lack of knowledge of both the sources and health effects of air pollution indicated that women have a lack of capacity to make informed decision about their cooking fuel use.

Participant 15: "What I can tell you now is that I now have a sick child at the hospital with breathing difficulties. I don't know if it is because of the smokes"

Women also reported a general lack of ability to change their cooking practices. The ability to cook outdoors was affected by: safety issues, housing constraints, belief that cooking location should be determined by stove type and belief that outdoor cooking was a last resort. The safety of outdoor cooking was mainly a concern to women in regards to children, typically the risk of burns from playing near the stove, or being by the door; but one woman cited security and potential risk of sabotage with outdoor cooking.

Participant 6: "The reason is that if I cook from outside the children, who are playing, can be burnt. That's why I don't cook from outside"

Participant 13: "The method that could help me would be to find something that doesn't emit smoke or excessive heat, so that I can start cooking inside the house. Because cooking outside the house isn't a good practice. Sometimes dirt does fall into the pot, and it's also possible that bad people might come and add dangerous stuff to the food and endanger the whole family. Cooking outside is good in terms of preventing smoke but it's not generally a great thing"

Participant 5: "It is the security of the house, because you have a place to cook from and prepare things"

The lack of space and housing constraints are reported reasons why women cook outside; they would prefer cooking areas within a kitchen in a separate building, which they currently do not have. However, there was a lack of identification of solutions to enable them to cook outdoors, as women saw it as the last resort, and saw LPG as the solution; but they lacked the capacity to change to LPG.

Participant 3: "No, where I cook is not where I want to cook, this is because of the lack of capacity. Because if I had the means, or if I was the owner of the house because I am the tenant, I should build for the gas in the right place and to cook there. This kitchen also, I will move it away from the door. In short, it's the lack of means that forces me to cook where I cook today"

Barriers to LPG cooking were strongly portrayed by the women. These included a lack of equipment, the fact that gas comes in large volumes, that gas cannot be used outside and the cost of gas.

Participant 10: "The first thing is that I can't carry gas and place it outside"

Participant 1: "It is the problem of high price. Gas is expensive and to find it is also expensive because they sell a big gas bottle, there is no small bottle with fewer kilograms"

One participant noted that they had security issues with gas, recounting her previous experience of her equipment being stolen. However, financial constraints (n = 11) mainly in regards to LPG, was highly cited as a barrier to cooking fuel access: one woman reported that charcoal was expensive; two women reported that they would like to purchase gas in the same way they buy charcoal, in small amounts. In addition, the women stated that they require more information about the cost and equipment for gas. Financial restrictions limit women's capability of switching to cleaner fuels.

Participant 1: "The suggestion is that the government would help us and reduce these gas prices and set up a way for one to go and put in a little gas he can afford, as we do when we buy a bucket of charcoal"

The ability to keep children away from the cooking area elicited mixed responses, indicating various capacities to reduce their child's exposure to air pollution. Seven women stated that they were able to keep children away from the cooking area, with one woman stating that it is the parents' responsibility to keep children occupied so that they stay away from the cooking area. However, the woman did state that they were only able to keep children away most of the time. Only one woman clearly said that she was unable to keep children out of the cooking area.

Participant 13: "There haven't been any consequences except that when I am going to cook, I keep them at a distance and I tell their older sibling to keep them away so they don't risk getting burned or spill something hot on themselves. So, there have been no consequences, because they don't come near the fire"

Participant 12: "You can't be able to keep children away when you are cooking"

3.3. Opportunity

Environmental factors, socioeconomic factors and lack of education reduce the opportunities for women to take up behaviour change interventions, on top of the necessity to cook. The ability to cook outdoors was reported to be limited by wind and rain; however, when asked what could facilitate them to be able to cook outdoors, no suggestions were given, only that cooking with gas was a better solution.

Participant 8: "So, when it rains, in the case of us who are renting houses without a kitchen, we who are poor, you just move the cooking stoves into the house when it rains"

Participant 15: "Cooking from outside, some time there is wind or charcoal are burnt quickly, but I do it to protect myself from the smokes of the stove. Because I had problems when I placed it, I cannot do it again"

Housing constraints also reduced women's opportunity to cook outdoors due to a lack of space, with women suggesting that building open spaces and better housing would facilitate outdoor cooking.

Participant 7: "But if you have the ability you can build the one with an open space, to reduce the disease you can cook from outside. It is good"

Women have little control over their housing due to a reported low socio-economic standing. One participant noted that sickness prevents the ability to work and this subjects them to a healthcare cost, therefore, they do not have any spare money to go towards paying for more expensive fuel. Support from the government was also cited to help with access to LPG and develop intervention support.

Participant 3: "So when a person is sick, or physically damaged in that way, that person cannot work for development, because he is always sick and always at the doctor. And the money he had, it will be used to treat his illness"

Participant 16: "It can be better while government help its citizens to have access to Liquid Petroleum Gas"

Women stated that they required more knowledge of HAP exposure and consequences, forthcoming fuel restrictions and alternative options that are available to them. Community meetings, newspapers, radio, television, leaflets, phone messages, linking producers and consumers together and face-to-face training were all suggested by the women as formats in which they were willing to learn more about reducing HAP exposure. However, some women noted that not all households have access to a television and radio and it is therefore not always convenient.

Participant 13: "Yes, I feel like I want to know more about this issue, the danger of it, and how one can protect oneself from it, and the ultimate consequences that it leads to"

Participant 7: "Talks on the radio, some may not have TV but many listens to the radio"

Participant 16: "I also like to use telephone too, because it can be on radio while I am not around, so that can be lost"

3.4. Motivation

The motivation theme covers the automatic and reflective brain process that influence the behaviours that can reduce exposure to HAP (e.g., previous experience and beliefs). Women were generally motivated towards reducing pollution, though limited education, as described above, mean polluting fuels can still be chosen, with one woman citing that she has switched to charcoal from wood to reduce pollution.

Participant 7: "Yes, we switched to charcoals, now I won't try any other thing"

In addition, there were mixed beliefs as to where cooking should take place, with four reporting that cooking should be done in the house as this was the seen as the social norm, six reported outdoors or in a ventilated space and five reported in a kitchen, indicating underlying assumptions in the motivation behind cooking location. Women demonstrated a motivation to cook outdoors due to the negative aspects of cooking within the house, which included making the house hot, dirty and bad smelling. Conversely, there was some awareness of the benefits associated with cooking outdoors, including reducing pollution, being away from children and protecting children.

Participant 12: "Cooking outside shouldn't be happening, people should be cooking in kitchens"

Participant 11: "Because it allows the smokes to get away and avoid polluting the house and disturb children"

Women expressed negative opinions concerning outdoor cooking including impact upon neighbours.

Participant 7: "When you start a fire the smoke spread all over and reach the neighbour"

Participant 12: "Cooking outside is difficult, it's not easy. And it spreads smokes that pollute the atmosphere"

This concern was also reflected in one of the submitted photographs, when one woman said she identified the closest form of air pollution to her, which was a burning charcoal stove situated outdoors. In addition, outdoor cooking was cited as not being easy, nor was it good practice, which indicated a reduced motivation to cooking outdoors. Despite this, the benefits which motivated women to cook outdoor were more widely reported among participants than the negatives.

Participant 13: "Because cooking outside the house isn't a good practice. Sometimes dirt does fall into the pot, and it's also possible that bad people might come and add dangerous stuff to the food and endanger the whole family. Cooking outside is good in terms of preventing smoke but it's not generally a great thing"

LPG was considered the ultimate option for reducing smoke exposure, and although the negatives of LPG featured more heavily than the positives, it was recognised that LPG reduced the child's exposure to HAP. However, women were concerned about the risk of explosions, the safety of the gasses produced from LPG and their lack of experience using it. Encouragingly, they were motivated to change due to previous or neighbour experience.

Participant 14: "Cooking on gas generates bad smoke in the house"

Participant 16: "lack of experience of using Liquid Petroleum Gas for cooking"

Participant 13: "The reason why I cook outside is that when you place the cooking stove on the house's cemented floor, the fire burns quickly. And it could be possible that smoke can cloud the entire house and prevent you from breathing, causing you to cry and to drip mucus and sneeze a lot. It might also cause death to people, depending on who has a low tolerance to smoke, and that person might suffer consequences. That's why I stopped cooking in the house and decided to cook outside. However, after realising that lesson, I started taking care of the situation, so it doesn't lead to problems anymore"

3.5. Summary of Barriers and Facilitators

Each behaviour change type was dominated by barriers (Table 2), with a few facilitators (n = 5). Of the five facilitators three were motivators and two came under the 'capability' theme. However, all opportunity themes were barriers, indicating the current limiting factors were around women not having the 'opportunity' or 'capability' to change their behaviour. The benefits of outdoor cooking and impacts of indoor cooking were seen as facilitators to cooking outdoors, but despite this motivator, there remained barriers around the belief of where cooking should take place and the negatives of outdoor cooking. Other barriers to outdoor cooking were presented as a lack of capability (e.g., housing constraints and safety) and opportunity (e.g., weather). Conversely, capability was both a facilitator and a barrier to keeping children out of the cooking area in terms of outdoor cooking enabling children to be out of the cooking area and keeping children occupied. In addition, education was both a barrier and facilitator in providing capability for women to change their behaviours. The only facilitator observed with LPG was the motivation towards health improvements; however, barriers remained within women's capability (e.g., financial and equipment availability) and opportunity (e.g., poverty cycle and governmental help) to take up the use of LPG.

Table 2. Barriers and facilitators identified from in-depth interviews, categorised by theme, cooking behaviour and fuel type.

Cooking Behaviour	Code	Theme	Barrier	Facilitator
Outdoor cooking	Weather	Opportunity	X	
	Housing constraints	Capability	X	
	Benefits of outdoor cooking	Motivation		X
	Negatives of outdoor cooking	Motivation	X	
	Safety	Capability	X	
	Belief about where cooking should take place	Motivation	X	
	Impact of indoor cooking	Motivation		X
Keeping children out of the cooking area	Outdoor cooking	Capability		X
	Keeping children occupied	Capability	X	
LPG	Ability to use LPG –equipment, security, safety	Capability	X	
	Financial constraints	Capability	X	
	Health improvements	Motivation		X
	Governmental help	Opportunity	X	
	Poverty cycle	Opportunity	X	
Education	Awareness of sources, consequences and options	Capability	X	X
Previous experience and neighbours' experience		Motivation		X

4. Discussion

This novel in-depth interview study, using mobile phone technology in an informal settlement in Kigali, investigated women's perception of HAP and their views on cooking behaviours, identifying factors which influence the capability, opportunity and motivation on cooking behaviour (e.g., outdoor cooking) that reduces HAP exposure. To the best of our knowledge there have been no other qualitative studies investigating behavioural change HAP interventions in Rwanda. Barriers to reducing exposure to HAP were seen within factors associated with capability (e.g., housing and financial constraints and safety concerns) and opportunity (e.g., weather and lack of governmental support), compared to motivation which included the largest number of enabling factors (e.g., health improvements associated with outdoor cooking, previous personal experience and neighbours' experiences). Encouraging behaviour which reduced HAP exposure could have potential health benefits for women and children, with supportive education informing women of the options to switch to cleaner cooking.

Descriptions of sources of air pollution and associated health effects were vaguely described within this study, with very few reported health effects among children. Of those health effects identified, they were either short-term (e.g., eye irritation, dizziness or headaches) or respiratory, which corresponds with previously published literature [17,21]. Conversely, positive perceptions towards activities that reduce pollution exposure identified within the interviews included cleanliness and lower smoke production, which have previously been reported within the literature as motivators towards intervention adoptions [30]. Health benefits have not always been seen as the driving force behind behaviours to reduce exposure [17,40] and maybe this is due to a lack of clear awareness in both individual and child health benefits, as demonstrated by this study.

Women wanted to cook with LPG indoors; however, due to being unable to do this, they chose to cook outdoors to reduce their exposure due to their awareness of the consequences of HAP, suggesting a level of agency within their decision making. Direct benefits of lower pollution, less dirt and location away from the children were identified as motivators for outdoor cooking; however, no health benefits were mentioned by the participants. This observation of less focus on health effects and more towards immediate impacts such as cleanliness and short-term symptoms has also been documented in previous studies from Latin America [17,41]. External factors (e.g., weather, security and housing constraints) limit women's capability to engage with outdoor cooking; however, women were unable to identify solutions to enable them to cook outdoors when raining such as a covered area. Being unable to identify solutions may be due to women rationalising and accepting their current situation resulting in a lack of agency to change their current conditions [42]. An alternative behaviour change is to remove children from the cooking area, and the women in this study reported that they were capable of removing children from the cooking area, which was also aided by cooking outdoors. However, previous research showed that women often struggled to keep children out of the cooking area [29], suggesting that there may be situational factors, such as time of year, cooking location and data collection methodology, along with a potential response bias which may explain the difference in these results.

Even though the focus of this study was on cooking location and removing children from the cooking area, women highlighted the use of LPG, which could be a reflection that women have a desire to move towards LPG, rather than change their current cooking behaviour with charcoal. Although women do want to transition to LPG, which is also documented within the literature [43], there remain barriers in women's opportunity and capacity to use LPG, despite being motivated by the benefits of LPG. Previous studies have shown that an awareness of the benefits of LPG is often not the limiting factor but instead financial capacity in being able to afford the equipment and gas cylinders. In this study women report wanting to pay for LPG in small amounts, which has also been documented with in a recent successful pay-as-you-go LPG pilot study in urban Rwanda [44]. Although barriers included financial capacity and safety concerns, which are previously documented within the literature [16,22,29,43], it is likely that there are multiple interconnected barriers that need to be overcome to enable sustained adoption. In addition, female empowerment, also documented in the literature [45,46], and female cooks [47] are factors of a successful uptake of cleaner cooking, and, therefore, factors that address gender disparities and improve empowerment within the household environment should be considered in future studies [48]. Governmental policy to break down financial barriers to access to LPG should take into consideration energy supply disruptions and economic instability, as seen with the COVID-19 pandemic, to enable continued and sustained supply [13]. In addition, taking feedback in an iterative way to stakeholders should reduce some of the barriers, such as buying LPG in the same way as buying charcoal in small quantities.

However, financing, governmental support and situational factors are not enough on their own to ensure changes in cooking behaviours [16] and, therefore, should be supported by adequate education to improve individual empowerment and agency. Community perception of interventions is key [49] to enabling women to be capable, motivated and have the opportunity to change this behaviour. Women in this study were keen to learn about HAP, its consequences and options, via a variety of different information sources, which should be considered within the service provision. Therefore, explaining different methods and options to break down barriers, including the relative benefits of different fuels and differences in cost are required and have previously been shown to be effective [17,50]. In addition, the role of previous experience and neighbours' experience should not be underestimated, with the use of platforms to share previous knowledge facilitating this, which has been identified in earlier literature [51]. A previously suggested solution was to encourage community leaders to adopt cleaner fuel to convince community members to transition to cleaner fuels [17,52], which was shown to be effective in sanitation interventions [53]. Without further knowledge of HAP and alternative options, supplied in an accessible format, the women do not have the opportunity to make changes themselves. Therefore, our research indicates the need for local policies to improve community-based initiatives—such as education regarding the harms of poor air quality at Umuganda—that can empower behavioural changes to reduce HAP exposure.

Strengths and Limitations

In depth-interviews via mobile telephone, undertaken by Rwandan nationals, gave rich information pertaining to cooking behaviours. Mobile telephones provided an important mechanism for remote research during COVID-19 restrictions, however, there were distraction and connection issues, which could have taken the participants' attention away from the interview. In addition, only three photovoice responses were gained, highlighting the issue of technology poverty within the study area, as some of the reasons provided for not taking a photo were that the participant did not have access to a phone camera; however, no obvious participant characteristic differences were noted. Those photos submitted could be affected by response bias as they were all of cookstoves and the fact that they had access to a phone with a camera could imply they had a relatively higher socio-economic standing. Despite the limitations of photovoice submission within this study, the detail provided within the pictures and description gave more detail and understanding than those participants who were asked to describe air pollution, illustrating the benefit of participatory research, if barriers to technology are accounted for in the study design. Some of the western researcher influence of the interviews, which ranged from 7–27 min, would have been reduced by being conducted by Rwandan nationals. However, the interviewers, though trained, were not qualitative experts, and some of the nuances in meaning may have been lost in translation though professional translators were used. Cooking location responses could have been influenced by the fact that interviews were undertaken at the end of the rainy season and beginning of the dry season, when outdoor cooking is more prevalent, although social acceptability bias may have led to the higher than expected levels of outdoor cooking participants. We did not collect information describing concurrent use of multiple fuel or stove types, however, there was no indication of fuel or stove stacking behaviour in the survey or interviews. This aligns with our existing knowledge obtained by primary field observations that the mobile single-pot charcoal fuel stove is the dominant cooking practice in the Kabeza cell [29,34].

The COM-B wheel provided a useful tool in identifying which factors that influence behaviour need targeting in an intervention; however, there was some potential overlap between the themes. For example, the awareness of the sources of HAP and the consequences were coded as 'capability' due to women being unable to engage with an intervention, but it could have been an 'opportunity' as provision of education is out of the individual's control. In addition, the data could not provide any information on the further layers (intervention function, policy categories) of the COM-B wheel; which would have provided more details on the design of an intervention.

Future research should consider rural and urban differences, views and perceptions of stove stacking and differences in perception between males and females, as male heads of household often make purchasing decisions [43].

5. Conclusions

Within this study, women were motivated (e.g., health improvements and previous personal and neighbours' experiences) to reduce their exposure to HAP but felt they lacked the capability (e.g., housing, financial, safety and ability to use LPG) and opportunity (e.g., weather, governmental, health and poverty cycle) to change their cooking behaviours and therefore reduce HAP exposure. There was a willingness to learn and adopt new behaviours as a community in this context, which has implications for the implementation of community-based initiatives. Policies to address both sociocultural and structural barriers are required to support individuals to make behaviour changes to reduce HAP exposure.

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CHAPTER 12 DISCUSSION

12.1 Introduction

The purpose of this chapter is to draw together all components of the thesis to discuss and evaluate the findings within the context of developing an intervention to household air pollution for urban Rwanda. The main aim of the thesis was to take a convergent mixed-methods[1] approach to informing an effective health intervention to HAP in urban Rwanda. Therefore, the thesis lies in the development stage of the MRC framework for complex intervention,[142,143] drawing together each set of results, including unintended consequences, to discuss the formulation of potential health interventions. There is currently a lack of sustainable HAP interventions that have substantive and consistent health benefits, due to multiple barriers to sustained uptake and continued exposure to both household and ambient air pollution. By using large global data sets, exploring current situational factors and involving end-users early, the thesis identified behavioural changes to cooking practices (e.g., outdoor cooking) which could have a health benefit (CHAPTER 7), with no impacts of risk of malarial infection (CHAPTER 8). However, outdoor cooking was observed to be unpopular among women in Kigali, who would prefer to transition to LPG (CHAPTER 11). This desire switch to LPG was also documented to be the cooking fuel of choice after the charcoal ban was introduced, despite fuel switching towards firewood being observed during the economic and market instability as a result of the COVID-19 emergency health protection ‘lockdown’ measures (CHAPTER 9). An increased use in firewood could present unintended health consequences from the charcoal ban if residents switch from charcoal to wood (CHAPTER 6). The thesis took a reactive approach to the impacts of COVID-19 on data collection, transferring to remote data collection, a novel approach that has not previously been used in the context of Rwanda.

12.2 Evaluation and appraisal of the thesis

12.2.1 Introduction to the appraisal

Undertaking this PhD has been full of challenges and rewards, in terms of project management, data collection, statistical methods and research design but it has been an enormous learning experience. I have come from a quantitative background with a BSc in Environmental Geoscience and Masters in Public Health, which has formulated my interests in the interaction between the environment and human health and how the health consequences can be mitigated. Prior to undertaking the PhD I had no previous qualitative experience but have enjoyed the challenge and have gained a greater appreciation for the need for mixed-methods research, especially in the context of HAP interventions. This section will discuss if the aims and objective of the thesis were met, as well as appraising the methods used for the primary and secondary data analysis, in terms of the challenges faced, justification for final methodological decision and what has been learned throughout the process of undertaking the PhD.

12.2.2 Were the aims and objectives of the thesis met?

The broad scope of the thesis aims and objectives (documented in section 1.1) allowed flexibility in the content and the HAP interventions investigated. Firstly, the systematic review identified the complexities of undertaking research into HAP interventions, but also identified a research gap in the use of behavioural intervention to improve maternal and child health (CHAPTER 4). The subsequent analysis using the DHS data provided evidence for the potential health benefits and unintended consequences of changing cooking location and relative difference between wood and charcoal cooking fuels (CHAPTER 6, CHAPTER 7). Complementing this was the primary data collection, with the semi-structured survey highlighting the issues with fuel switching due to economic uncertainty (CHAPTER 9) and the qualitative in-depth interviews revealed the opinions and barriers around women changing the behaviours in terms of cooking practices (CHAPTER 11). The addition of investigating malaria impacts highlights the complexities of HAP interventions, both in identifying and disproving unintended consequences (CHAPTER 8).

COVID-19 had a large impact on the ability to undertake data collection. The original plan was to undertake HAP exposure monitoring within solid biomass using households to compare indoor and outdoor cooking, to provide details on the different levels of exposure. However, a decision was made not to complete data collection for both the safety of the participants and the fieldworkers from COVID-19, meaning that HAP monitoring is still an outstanding research area in the appraisal of behavioural change HAP interventions. Despite this, remote research could be undertaken, including remote training, due to international travel restrictions leading to an altered research direction through identification of current situational factors (e.g., charcoal ban and COVID-19 restrictions) which provided timely and valuable information on the 'enabling environment' which could influence intervention uptake and success (CHAPTER 9).[377]

The thesis was never designed to develop, deploy and trial a HAP intervention due to funding and time constraints; especially as HAP interventions are complex, with multiple interconnecting parts, making it difficult to ascertain the actual effectiveness of such measures. Overall, the thesis has focused on theory and evidence from both qualitative and quantitative data sources rather than the design of an intervention, which needs further investigation. The thesis has highlighted the role of education within any intervention deployment, to improve uptake and therefore the effectiveness of an intervention. Within this setting the need for education is particularly prevalent due to the lack of community enthusiasm for outdoor cooking.

12.2.3 Challenges and learning points from the secondary data (DHS) analysis

There are a multitude of benefits from using secondary data including: low cost, provide a large sample sizes and solve issues around the complexities of obtaining own data or linking hospital records in a resource poor setting and ground work required by trained fieldworkers.[378] The DHS data allowed for large-scale analysis, across multiple countries, routinely collected with standardised protocols and sampling strategies. CHAPTER 5 provides details on rational of choice of methods, strengths and limitations of the use of the DHS data. The DHS provides large-scale evidence from multiple countries enabling the evaluation of health implications for different cooking practices, which may not have been possible if a single-country approach (e.g., Rwanda) was taken due to the lowered statistical power. Although the sub-analysis by geographic regions did highlight some geographic variations, displaying the need for individual context to be considered in forming interventions.

There were methodological challenges that had to be overcome, due to two-stage complex sampling strategy, formulation of wealth index and quantity of missing data. Firstly, a multilevel analysis approach was initially considered to be able to account for the natural clustering of the data set, which included children clustered in households, with households clustered in enumeration areas, which would account for multiple children per household. However, this method could not be used due to not having sampling weights for each level, therefore the complex sample design weighting method (e.g., survey package) was used which took into account individual child weights, primary sampling unit and stratification variable. Overall, little change in the effect estimate was observed, with a widening of the confidence interval with the survey methods at the combined dataset level. Secondly, the calculated wealth index provided by DHS included cooking fuel as a predictor variable. Although there was no evidence of collinearity and little overall difference in the effect estimate by using the recalculated wealth index it was important to use and prevent circulinarity.[212]

Finally, the quantity of missing data (e.g., >50%) within some countries and variables, meant that multiple imputation could not be undertaken, resulting in these variables not being used within the models (e.g., breastfeeding, birthweight and household smoking), resulting in exploratory analysis to understand the effect of not including these variables. This issue of data quality is also reflected in the fact that not all confounding factors could be accounted for (e.g., the occurrence of stagnant water as a breading site for mosquitoes, which would of increased the risk of malarial infection) and the reliance of use of proxies as an exposure measure. This evaluation supports the recommendation by Odo *et al.,*[264] for the DHS survey to capture and provide information on cookstove type, fuel stacking, heating methods, lighting sources, level of household ventilation, HAP monitoring and ambient air pollution. All of this would provide a better understanding of the alternative factors that influence HAP that could be exploited within an intervention, but could also give an indication as to why HAP may not be able to be reduced to an appropriate level, even with an intervention.

12.2.4 Challenges and learning points from the primary data collection

Planning, starting and conducting research in a resource poor country is inherently challenging, especially as a researcher with no prior experience of conducting primary data collection of this type. The preliminary qualitative analysis (CHAPTER 10) was hugely beneficial for learning from early research findings, identifying research gaps and developing appropriate methodologies. However, the preliminary analysis did not investigate remote data collection and the self-collection of photographs as discussion points, and the use of participant's mobile phones to collect photos was not evaluated. Previous studies[304,307,379,380] have used photovoice within a resource poor setting, during the intervention development stage, but cameras and training were usually provided to participants, which resulted in successful data collection. However, due to the COVID-19 restrictions and the use of a remote methodology providing cameras was not an option, therefore mobile phones were used as cameras as smart phone use is high in Rwanda.[381] The low number (n=5) of photovoice submissions (Appendix 6) in comparison with the number that opted in (n=33), could be as a result of a misunderstanding by the participants of what they were opting in for and that some of the participants reported not being able to take a photo. All participants were followed up if they had not submitted a photo but there may have been a lack of urgency or priority by the participants.

Therefore, this remote method within this setting is probably not appropriate and having fieldworkers on the ground with cameras would probably improve the participation rate.

The in-depth interviews (CHAPTER 11) and semi-structured survey (CHAPTER 9) were also subject to the issue of technology poverty, as those households without a mobile phone could have been missed, on top of the fact that some of the uncontactable participants may not have been able to answer their phone due to work commitments. The reliability of the in-depth interviews could have also been affected by the fact that some of the interviews were interrupted due to connection issues, participants being on work breaks, and being disturbed by children; although participants were asked for a time in which they would not be disturbed. In a normal face-to-face interview this distraction can normally be controlled more by the interviewer.[382]

There were multiple logistical challenges, which has provided a greater insight into project management and organisation. Gaining local research approvals and ethical clearance took up a large proportion of the research time, partly due to a reliance on collaborators who have different cultural timescales and deadlines, to help provide information on what was required due to a lack of publicly available information, although this has now improved as a result of the move to online submission of the research approval application due to the pandemic. COVID-19 also led to delays in research data collection, resulting in the need to renew the research permit. These delays due to the COVID-19 restrictions also meant that the semi-structured survey was not taken during the COVID-19 restriction period which may have introduced recall biases.[383] Logistical challenges were not just within country as difficulties in setting up professional translation in a timely way to be able to translate and transcribe the in-depth interviews, as they were collected, meant data saturation could not be determined during data collection, which could not afford any further delays due to the expiry of the ethical approval. Therefore, saturation was instead determined during the analysis stage, and was achieved. Despite the challenges of data collection in a resource poor setting and remotely due to COVID-19, rich, detailed and informative data was successfully collected within the deadlines, as well as being an enormous learning opportunity to undertake data collection in difficult circumstances.

12.3 Interpretation and implications of findings

12.3.1 Introduction

With a focus on the development phase and core elements of the MRC framework for complex interventions[143] (described in section 2.6), this thesis has through a variety of data sources and methods, provided evidence towards the potential feasibility of a short-term harm reduction intervention within the setting of urban Rwanda (setting describing in section 2.2.1), which has implications for HAP policy, especially within the provision of a suite of interventions to be given alongside cleaner cookstove messages and solutions.[384] As documented in section 12.1 there are both potential benefits and unintended consequences to a behavioural change health intervention. Although further intervention development is required there are implications for improved health and wellbeing (SDG 3), gender equality (SDG 5) and clean and affordable energy (SDG 7) (section 2.1.2).

12.3.2 Application to the MRC framework for developing complex interventions

When embarking on the development of a HAP intervention using the MRC framework for complex intervention, the initial stages to conduct include a systematic review, and fully describing the intervention, including who it is aimed at. This stage is then followed by a discussion on the variability, content and environment in which the evaluation is taking place to understand the role of situational, economic and environmental factors in formulating an intervention and determining its potential effectiveness.

Not only did the systematic review (CHAPTER 4) highlight the complexities of the development and trialling HAP interventions, but it also identified a research gap of behavioural change interventions. It is imperative to note that harm-reduction behaviour change interventions do have issues, as they do not move away from the use of polluting fuels, so HAP levels are not lowered to the WHO target values. Nor does it recognise that a large proportion within LMICs have successfully transitioned to cleaner fuels. Despite this, the subsequent intervention of interest explored was changing individuals' cooking behaviours (e.g., outdoor cooking, removing children from the cooking area and fuel switching) in a harm reduction approach, which is aimed at solid biomass cooking households in urban informal settlements within Kigali, Rwanda. Although this population needs a solution to help mitigate the health harms of HAPs, due to high levels of solid biomass fuel use, it does mean that this intervention is limited to poor urban areas and may not be applicable to rural locations. In addition, only one site was investigated, therefore future research should expand into other informal settlements in Kigali to capture situational variability which may include; differing access to LPG, charcoal and wood, type of housing and socioeconomic status. However, any further development and trialling of this intervention should take into consideration the systematic review recommendation (CHAPTER 4) of outcome definitions standardisation, improving time of deployment, follow-up, and compliance; including clear reporting of compliance. This would mean that interventions trialled within Rwanda require a greater interdisciplinary focus on the design of the intervention,[150] methods of determining effectiveness[302] and generating evidence to inform policy making due to the nature of behaviours and sources involved in HAP resulting in a lack of health efficacy in intervention trials.[385]

Along with situational variability affecting cooking fuel access, cost, choice and behaviours, cooking practices can change over time, as seen with fuel switching during the COVD-19 lockdown (CHAPTER 9). Although globally there has been a gradual reduction in the percentage of the population using biomass fuel over the last three decades, there has been a large increase in the number of people using biomass fuels especially in SSA, with charcoal increasing in popularity in urban areas,[6] highlighting the effect of time and geographic location. Additionally, the urban-rural divide in access to fuels, cooking behaviours[386] and poverty related factors[32] can also create situational variability within a potential intervention. Documented in the literature is evidence of seasonal fuel switching and reverting to traditional methods when it becomes more accessible or affordable than the cleaner methods currently being used.[387] Furthermore, situational variability in the effectiveness and willingness to take up an intervention due to consumer demand, could be influenced by the time spent cooking, number of cooking sessions and the quantity cooked.[388] Therefore, there is a need to understand longitudinal behaviours of type of primary fuels use, secondary fuels use and stove/fuel stacking across differing areas within Kigali; including detailing the responses to change in cooking practices in the context of wider situational driving forces and pressures.

This thesis has shown the impacts of the economic environment on cooking fuel choice, however, this also limits the comparability of the research findings of the WTP questions (CHAPTER 9) and in-depth interviews (CHAPTER 11), as they were undertaken in time of unprecedented economic uncertainty. In addition, the charcoal ban was announced in May 2020, in the first wave of COVID-19 in Rwanda, which may have reduced individuals' awareness and opposition to such a policy. Therefore, external validity may be affected, however, internal validity should be consistent as all primary data collection was undertaken within a four-month period. The charcoal ban has not yet been implemented or evaluated and there may be environmental benefits; however, caution should be maintained as there maybe health harms if households use wood instead of charcoal. Furthermore there are greater climate impacts of using LPG, rather than renewable resources,[50] which could impact Rwanda's climate action plan to reduce emissions by 38% before 2030,[389] and the potential global health burden from climate change.[29] Together with the changing economic situation and the environment in which the primary data collection was undertaken and the potential risk of health harms, policies need to be developed to support both sustainable cleaner fuel access and alongside alternative harm reduction interventions that can potentially reduce HAP exposure.

Gaining and evaluating evidence of the impacts of HAP interventions on public health is key, however application of a standardised method towards evaluation is required[377] to build the evidence base. The process of investigating and delivering effective interventions is limited by a lack of sustainable and productive links between governments, market sections and user/communities,[8] as well as robust processes for economic evaluation. In addition, there is a lack of strong evidence for the multitude of health events that can occur throughout the life course, as health events are often as a result of chronic HAP exposure,[9] and the current focus within the literature is on investigating health events with a short lead-time (e.g., ARI, LBW) . Interventions have potential to achieve healthcare savings,[390] through reduction in health risks;[227] however, assessment of interventions needs to be an outcomes measure of success rather than an output measure.[377] These robust, comprehensive evaluations are key for effective use of resources through use of interventions that have demonstrable public health benefit, within developing countries,[114] alongside strategic and technical public health leadership for science application.

Finally, the MRC framework outlines the need for user and stakeholder involvement to understand their needs and perceptions, along with consideration of how to monitor, evaluate and report. Participants were included from the start through undertaking in-depth interviews, this highlighted that they would ideally like to use LPG and are not keen on outdoor cooking (CHAPTER 11). Similar results have been reflected in a study in Senegal where early engagement with participants highlighted the unpopularity of traditional cooking, despite high use.[391] Therefore, smaller changes may be difficult to make without the support of substantive education and future participants' engagement, given the current barriers and the fact their end game is LPG. Interventions that have had high uptake and sustained use have been able to work with the market and consumer demands,[108] need for household maintenance and repairs [392] and existing household characteristics (e.g., age, wealth,[392] household decision maker[393] and housing tenure). In this case early dialogues with end-users identified the misconception that LPG gasses are harmful, leading to continued used of charcoal. Despite this there are huge benefits to engaging with participants early within the design phase of an intervention, which has been used with the development of the HAPIN trial.[308,309] Rwanda provides a unique environment with urbanisation and cleaner cooking policies, thus developing an education program would increase public visibility, leading to a greater enabling environment working with stakeholders and end-users.

The use of the MRC framework for complex interventions has provided guidance and a structure to developing an intervention with multiple interacting components. Specifically, the framework has enabled a focus on one area of the development and evaluation process, which was the development of an intervention to the situational context, including opinions and barriers to provide evidence for development of specific content. As well as drawing together different aspects of the work the MRC framework provide a tool for the discussion, enabling evaluation around the uncertainties highlighted within the research, which can be used to inform the next steps of developing an intervention. The ability to react and use the COVID-19 situation, enabled the evaluation of the influence economic situations have on household cooking fuel choice, giving greater insight into situations where interventions may or may not be successful based on the economic situation; and the need to development appropriate policy to mitigate against fuel change with economic uncertainty. Although developing complex interventions is a dynamic and iterative process, it goes beyond what is feasible within a PhD timeframe, for example, stakeholder input was an element not covered by this thesis. However, the nature of the process being open to change enables the intervention to morph and develop. For example, the provision of new literature, the updated WHO air quality guidelines and knowledge of the sustainable cleaner energy sources (e.g., solar) need to be employed, has directed the focus away from a standalone intervention but to use behavioural change as part of a suite of interventions as suggested by Stanistreet et al,.[384] However, the fact that HAP interventions deployment is a non-linear process careful consideration is required for the area of first focus and drawing research together into a persuasive story. In addition, to complete a full evaluation requires time and resources, which may be limited in resource-poor context.

12.3.3 Relevance to Rwanda, Africa and beyond

The two types of data (primary and secondary) used have differing contextual relevance. The primary data (CHAPTER 9 and CHAPTER 11) is directly relevant to informal settlements within Kigali Rwanda, but these findings may not be as applicable to other SSA countries and LMICs, due to differing cooking practices, access to cleaner fuels and governmental policies.[139] Despite this, the barriers and facilitators to HAP interventions are fairly universal globally, especially around cost, access and safety.[300,391,394,395] The secondary data analysis (CHAPTER 6, CHAPTER 7 and CHAPTER 8) has wider implication to East Africa, SSA and LMICs, enabling identification of association due to a greater sample size, which would not be available if a single country was investigated. Therefore, no direct conclusions for Rwanda can be obtained from the secondary data analysis due to variation in domestic microenvironments, however having results at both a multi-country and geographic regional level should provide compelling evidence that these associations are seen within Rwanda. Aside for the applicability by data source, this research has implication for both Rwanda and beyond, in terms of provision of education at a community level of encouraging harm prevision initiatives, such as outdoor cooking and dispelling myths. In addition the use of complex intervention methodology early on in the planning process enables early identification of barriers and solution to breakdown these barriers, resulting in the creation of a more directed and defined interventions for the community;[377] as well as adding to the evidence base where current knowledge has conflicting results.[150] Finally, the success and limitations of this thesis can go on to inform the methodological considerations of future research and/or trial, to create impactful research.

12.4 Policy and research implications

Throughout the discussion, policy and research implications have been alluded to in the context of developing effective health interventions to HAP. A summary of these actionable implications are as follows:

Policy implications:

- Rwanda is in a unique position to understand the use of a charcoal ban for health benefit and to pave the way for use of policy interventions in banning unclean fuels and improve access to cleaner fuels. However, and the government needs to consider and develop appropriate policy to prevent unintended consequences of banning charcoal as cooking fuel; such as the scaling up of the PAYGO scheme.
- Provision of community education around increasing awareness of HAP and the health consequences and what individuals can do to reduce the impact of HAP, including dispelling misconceptions such as safety and gasses released by LPG (and provision of research to aid this if needed)
- Development of stronger stakeholder engagement with the government, market/industry and end-users

Research implications:

- Further development into the design of a behaviour change intervention with a focus on the design format of intervention piloting, real life effectiveness, cost-effectiveness and long-term follow-up. Along with consideration that a behaviour change intervention could be a stand-alone harm reduction approach or integrated into wider education and awareness campaigns for the health harms of solid biomass cooking; including the wider socioeconomic benefits.

- Participants and stakeholders should be included early in any further research to exchange knowledge and co-produce behaviour change interventions, enabling increased impact of the research and inform direct of subsequent research activity
- The ability to undertake remote data collection within a resource poor setting has been shown within the thesis, however, further research is required to evaluate the potential differences in results that may arise between in-person and remote data collection.

12.5 Concluding remarks

There is a current need in Rwanda for development of effective HAP intervention to reduce the health harms, for which Rwanda is in a unique policy situation for implementing successful changes. The convergent mixed-method[1] approach, which drew together quantitative and qualitative knowledge provided evidence to be able to start devising a health behaviour and educational focused HAP intervention in Kigali Rwanda. Encouraging outdoor cooking and providing support to enable cleaner cooking fuel choice, could have health benefits if implemented effectively. Findings highlight the importance of early user involvement and co-production to ensure cultural suitability and sustained uptake. Any future policy change should actively consider the potential health harms of HAP interventions and provide educational support to improve effectiveness. There are strong research and policy implications for Rwanda and application to the wider East African context.

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APPENDIX

Appendix 1: Effect of the modified wealth index on analysis results

Comparison between the provided DHS wealth index and recalculated wealth index for the analysis investigating the difference severe ARI in children under five years in wood and charcoal cooking households.

	DHS provided wealth index			Recalculated wealth index		
	AOR	**95%CI**	**P value**	**AOR**	**95%CI**	**P value**
Cooking fuel						
Charcoal	Ref.			Ref.		
Wood	1.08	0.99 – 1.18	0.092	1.07	0.99 – 1.17	0.100
Child's sex						
Female	Ref.			Ref.		
Male	1.10	1.06 – 1.14	**<0.001**	1.10	1.06 – 1.14	**<0.001**
Child's Age (Years)						
<1	Ref.			Ref.		
1	1.13	1.07 – 1.19	**<0.001**	1.13	1.07 – 1.19	**<0.001**
2	0.86	0.81 – 0.91	**<0.001**	0.86	0.81 – 0.91	**<0.001**
3	0.69	0.65 – 0.73	**<0.001**	0.69	0.65 – 0.73	**<0.001**
4	0.58	0.54 – 0.62	**<0.001**	0.58	0.54 – 0.62	**<0.001**
Birth order						
First born	Ref.			Ref.		
Not first born	1.09	1.03 – 1.16	**0.002**	1.09	1.03 – 1.15	**0.003**
Mode of delivery						
Vaginal	Ref.			Ref.		
Caesarean	1.13	1.03 – 1.23	**0.009**	1.14	1.04 – 1.24	**0.005**
Received Vitamin A in last 6 months						
No	Ref.			Ref.		
Yes	1.20	1.15 – 1.26	**<0.001**	1.21	1.15 – 1.27	**<0.001**
Mother's age						
15-24	Ref.			Ref.		
25-35	0.92	0.87 – 0.97	**0.002**	0.92	0.87 – 0.97	**0.002**
36-49	0.90	0.83 – 0.96	**0.003**	0.90	0.83 – 0.96	**0.003**
Mother's education						
No education	Ref.			Ref.		
Primary	0.84	0.79 – 0.89	**<0.001**	0.83	0.79 – 0.88	**<0.001**
Secondary or Higher	0.89	0.84 – 0.95	**<0.001**	0.90	0.85 – 0.96	**0.001**
Wealth index						
Lowest	Ref.			Ref.		
Low	0.96	0.90 – 1.02	0.155	0.97	0.92 – 1.03	0.378
Middle	0.90	0.84 – 0.96	**0.002**	0.87	0.81 – 0.93	**<0.001**
High	0.91	0.84 – 0.99	**0.028**	0.90	0.84 – 0.98	**0.012**
Highest	0.81	0.72 – 0.91	**<0.001**	0.74	0.67 – 0.82	**<0.001**
Number of household member						
≤6	Ref.			Ref.		
>6	0.99	0.95 – 1.04	0.723	1.00	0.96 – 1.05	0.968
Place of residence						
Urban	Ref.			Ref.		
Rural	1.01	0.93 – 1.09	0.878	0.99	0.92 – 1.07	0.802
Cooking location						
Indoors	Ref.			Ref.		
Outdoors	0.96	0.91 – 1.01	0.107	0.96	0.91 – 1.01	0.100

Footnote: Other biomass=Straw/shrubs/grass/agricultural crop/animal Dung, Ref. = Reference category, AOR = Adjusted odds ratio, 95% CI = 95% confidence interval

Comparison between the provided DHS wealth index and recalculated wealth index for the analysis investigating the difference severe ARI in children under five years in indoor and outdoor cooking households.

	DHS provided wealth index			Recalculated wealth index		
	AOR	**95%CI**	**P value**	**AOR**	**95%CI**	**P value**
Cooking location						
Indoors	Ref.			Ref.		
In a separate building	0.84	0.78 – 0.92	**<0.001**	0.85	0.78 – 0.92	**<0.001**
Outdoors	0.86	0.79 – 0.94	**0.001**	0.87	0.80 – 0.94	**0.001**
Cooking fuel						
Coal, Lignite	0.71	0.51 – 0.98	**0.035**	0.69	0.50 – 0.94	**0.021**
Wood	Ref.			Ref.		
Charcoal	0.93	0.84 – 1.03	0.186	0.92	0.83 – 1.02	0.099
Other biomass	0.98	0.83 – 1.15	0.773	0.97	0.82 – 1.15	0.741
Child's sex						
Female	Ref.			Ref.		
Male	1.03	0.99 – 1.08	0.149	1.03	0.99 – 1.08	0.148
Child's age						
<1	Ref.			Ref.		
1	1.09	1.02 – 1.17	**0.008**	1.09	1.02 – 1.17	**0.008**
2	0.83	0.78 – 0.89	**<0.001**	0.83	0.78 – 0.89	**<0.001**
3	0.61	0.57 – 0.66	**<0.001**	0.61	0.57 – 0.66	**<0.001**
4	0.54	0.50 – 0.58	**<0.001**	0.54	0.50 – 0.58	**<0.001**
Birth order						
Frist born	Ref.			Ref.		
Not first born	0.98	0.92 – 1.05	0.636	0.98	0.92 – 1.05	0.624
Mode of delivery						
Vaginal	Ref.			Ref.		
Caesarean	1.14	1.00 – 1.30	0.052	1.14	1.00 – 1.30	**0.045**
Received Vitamin A in last 6 months						
No	Ref.			Ref.		
Yes	1.35	1.28 – 1.44	**<0.001**	1.36	1.28 – 1.44	**<0.001**
Mother's Age						
15-24	1.01	0.95 – 1.08	0.711	1.01	0.95 – 1.08	0.741
25-35	Ref.			Ref.		
36-49	0.96	0.90 – 1.03	0.248	0.96	0.90 – 1.03	0.241
Mother's education						
No education	0.88	0.83 – 0.94	**<0.001**	0.88	0.83 – 0.94	**<0.001**
Primary	Ref.			Ref.		
Secondary or Higher	0.93	0.87 – 1.00	0.063	0.94	0.87 – 1.01	0.086
Wealth Index						
Lowest	Ref.			Ref.		
Low	0.90	0.84 – 0.97	**0.005**	0.90	0.84 – 0.97	**0.006**
Middle	0.90	0.82 – 0.98	**0.015**	0.87	0.80 – 0.94	**0.001**
High	0.87	0.79 – 0.96	**0.005**	0.89	0.81 – 0.97	**0.012**
Highest	0.74	0.65 – 0.84	**<0.001**	0.72	0.64 – 0.81	**<0.001**
Number of household members						
≤6	Ref.			Ref.		
>6	0.99	0.94 – 1.05	0.795	1.00	0.95 – 1.05	0.944
Woman's empowerment						
Not empowered	Ref.			Ref.		
Empowered	1.15	1.08 – 1.22	**<0.001**	1.15	1.08 – 1.22	**<0.001**
Season						
Dry	Ref.			Ref.		
Wet	0.91	0.84 – 0.99	**0.033**	0.91	0.84 – 0.99	**0.035**
Place of residence						
Rural	Ref.			Ref.		
Urban	1.01	0.92 – 1.12	0.786	1.02	0.92 – 1.13	0.703

Footnote: Other biomass=Straw/shrubs/grass/agricultural crop/animal dung, Ref. = Reference category, AOR = Adjusted odds ratio, 95% CI = 95% confidence interval

Comparison between the provided DHS wealth index and recalculated wealth index for the analysis investigating the difference malarial infection (diagnosed by RDT) in children under five years in biomass and cleaner cooking households.

	DHS provided wealth index			**Recalculated wealth index**		
	AOR	**95%CI**	**P value**	**AOR**	**95%CI**	**P value**
Cooking fuel						
Cleaner	Ref.			Ref.		
Biomass	1.27	1.04 – 1.55	**0.019**	1.57	1.30 – 1.91	**<0.001**
Child's age						
<1	Ref.			Ref.		
1	1.65	1.50 – 1.81	**<0.001**	1.66	1.51 – 1.82	**<0.001**
2	2.30	2.09 – 2.52	**<0.001**	2.32	2.12 – 2.55	**<0.001**
3	2.58	2.36 – 2.81	**<0.001**	2.60	2.38 – 2.84	**<0.001**
4	2.93	2.68 – 3.21	**<0.001**	2.94	2.69 – 3.22	**<0.001**
Birth order						
Frist born	Ref.			Ref.		
Not first born	1.07	1.00 – 1.14	**0.047**	1.07	1.01 – 1.14	**0.034**
Child's sex						
Female	Ref.			Ref.		
Male	0.96	0.91 – 1.00	0.075	0.95	0.91 – 1.00	0.054
Wealth Index						
Lowest	Ref.			Ref.		
Low	0.81	0.75 – 0.89	**<0.001**	0.83	0.76 – 0.92	**<0.001**
Middle	0.66	0.59 – 0.74	**<0.001**	0.70	0.63 – 0.79	**<0.001**
High	0.41	0.36 – 0.47	**<0.001**	0.48	0.42 – 0.55	**<0.001**
Highest	0.15	0.12 – 0.18	**<0.001**	0.19	0.15 – 0.23	**<0.001**
Place of residence						
Rural	Ref.			Ref.		
Urban	1.59	1.41 – 1.79	**<0.001**	1.74	1.55 – 1.97	**<0.001**
Number of household members						
≤6	Ref.			Ref.		
>6	1.19	1.12 – 1.26	**<0.001**	1.24	1.17 – 1.32	**<0.001**
Malarial endemicity						
Mesoendemic	Ref.			Ref.		
Hyperendemic	1.58	1.40 – 1.78	**<0.001**	1.64	1.45 – 1.85	**<0.001**
Holoendemic	2.33	1.70 – 3.20	**<0.001**	2.39	1.74 – 3.27	**<0.001**
Season						
Dry	Ref.			Ref.		
Wet	1.07	0.94 – 1.21	0.327	1.08	0.95 – 1.23	0.243
Cluster altitude						
	1.00	1.00 – 1.00	**0.003**	1.00	1.00 – 1.00	**0.007**
Child slept under slept under mosquito net last night						
Did not sleep under a net	Ref.			Ref.		
Only treated (ITN) nets	0.96	0.90 – 1.02	0.175	0.97	0.91 – 1.03	0.365
Only untreated nets	1.19	0.85 – 1.67	0.307	1.18	0.84 – 1.64	0.344
Household construction						
Traditional	Ref.			Ref.		
Finished	0.95	0.87 – 1.04	0.262	0.93	0.85 – 1.02	0.130

Footnote: Ref. = Reference category, AOR = Adjusted odds ratio, 95% CI = 95% confidence interval

Comparison between the provided DHS wealth index and recalculated wealth index for the analysis investigating the difference malarial infection (diagnosed by RDT) in children under five years in wood and charcoal cooking households.

	DHS provided wealth index			Recalculated wealth index		
	AOR	**95%CI**	**P value**	**AOR**	**95%CI**	**P value**
Cooking fuel						
Wood	Ref.			Ref.		
Charcoal	1.47	1.28 – 1.70	**<0.001**	1.77	1.54 – 2.04	**<0.001**
Child's age						
<1	Ref.			Ref.		
1	1.49	1.38 – 1.61	**<0.001**	1.49	1.38 – 1.61	**<0.001**
2	2.11	1.96 – 2.28	**<0.001**	2.12	1.97 – 2.29	**<0.001**
3	2.40	2.22 – 2.58	**<0.001**	2.40	2.23 – 2.59	**<0.001**
4	2.70	2.50 – 2.92	**<0.001**	2.71	2.51 – 2.93	**<0.001**
Birth order						
Frist born	Ref.			Ref.		
Not first born	1.42	1.34 – 1.51	**<0.001**	1.43	1.35 – 1.51	**<0.001**
Child's sex						
Female	Ref.			Ref.		
Male	0.99	0.95 – 1.03	0.705	0.99	0.95 – 1.03	0.655
Wealth Index						
Lowest	Ref.			Ref.		
Low	0.85	0.79 – 0.91	**<0.001**	0.88	0.82 – 0.95	**0.001**
Middle	0.71	0.65 – 0.77	**<0.001**	0.75	0.69 – 0.81	**<0.001**
High	0.51	0.46 – 0.57	**<0.001**	0.59	0.52 – 0.66	**<0.001**
Highest	0.23	0.19 – 0.27	**<0.001**	0.27	0.23 – 0.32	**<0.001**
Place of residence						
Rural	Ref.			Ref.		
Urban	1.23	1.06 – 1.43	**0.005**	1.26	1.08 – 1.46	**0.003**
Number of household members						
≤6	Ref.			Ref.		
>6	1.12	1.06 – 1.18	**<0.001**	1.13	1.08 – 1.20	**<0.001**
Malarial endemicity						
Mesoendemic	Ref.			Ref.		
Hyperendemic	2.02	1.80 – 2.27	**<0.001**	2.03	1.81 – 2.29	**<0.001**
Holoendemic	3.74	2.69 – 5.21	**<0.001**	3.76	2.69 – 5.26	**<0.001**
Season						
Dry	Ref.			Ref.		
Wet	1.56	1.38 – 1.76	**<0.001**	1.57	1.39 – 1.77	**<0.001**
Cluster altitude						
	1.00	1.00 – 1.00	**0.036**	1.00	1.00 – 1.00	**0.046**
Child slept under slept under mosquito net last night						
Did not sleep under a net	Ref.			Ref.		
Only treated (ITN) nets	0.88	0.83 – 0.93	**<0.001**	0.87	0.83 – 0.92	**<0.001**
Only untreated nets	0.86	0.68 – 1.08	0.205	0.85	0.68 – 1.07	0.175
Household construction						
Traditional	Ref.			Ref.		
Finished	0.97	0.90 – 1.05	0.488	0.97	0.89 – 1.05	0.455

Footnote: Ref. = Reference category, AOR = Adjusted odds ratio, 95% CI = 95% confidence interval

Comparison between the provided DHS wealth index and recalculated wealth index for the analysis investigating the difference malarial infection (diagnosed by RDT) in children under five years in indoor and outdoor cooking households.

	DHS provided wealth index			Recalculated wealth index		
	AOR	**95%CI**	**P value**	**AOR**	**95%CI**	**P value**
Cooking location						
Indoors	Ref.			Ref.		
In a separate building	0.74	0.66 – 0.83	**<0.001**	0.74	0.66 – 0.83	**<0.001**
Outdoors	0.94	0.83 – 1.05	0.275	0.94	0.83 – 1.05	0.273
Cooking fuel						
Coal, Lignite	0.79	0.46 – 1.34	0.376	0.71	0.42 – 1.20	0.200
Wood	Ref.			Ref.		
Charcoal	0.86	0.72 – 1.03	0.104	0.76	0.64 – 0.91	**0.002**
Other biomass	1.42	1.15 – 1.76	**0.001**	1.37	1.11 – 1.70	**0.004**
Child's age						
<1	Ref.			Ref.		
1	1.44	1.28 – 1.62	**<0.001**	1.44	1.28 – 1.63	**<0.001**
2	1.90	1.70 – 2.13	**<0.001**	1.91	1.71 – 2.14	**<0.001**
3	2.25	2.01 – 2.52	**<0.001**	2.26	2.02 – 2.53	**<0.001**
4	2.47	2.21 – 2.77	**<0.001**	2.48	2.22 – 2.78	**<0.001**
Birth order						
Frist born	Ref.			Ref.		
Not first born	1.02	0.93 – 1.10	0.709	1.01	0.93 – 1.10	0.762
Child's sex						
Female	Ref.			Ref.		
Male	0.99	0.93 – 1.06	0.859	0.99	0.93 – 1.06	0.845
Wealth Index						
Lowest	Ref.			Ref.		
Low	0.80	0.71 – 0.90	**<0.001**	0.86	0.77 – 0.96	**0.009**
Middle	0.74	0.65 – 0.84	**<0.001**	0.76	0.66 – 0.86	**<0.001**
High	0.56	0.48 – 0.65	**<0.001**	0.59	0.51 – 0.69	**<0.001**
Highest	0.29	0.23 – 0.37	**<0.001**	0.30	0.24 – 0.37	**<0.001**
Place of residence						
Rural	Ref.			Ref.		
Urban	1.17	1.03 – 1.34	**0.019**	1.16	1.01 – 1.32	**0.036**
Household smoking						
No	Ref.			Ref.		
Yes	1.10	0.97 – 1.24	0.123	1.10	0.98 – 1.24	0.115
Number of household members						
≤6	Ref.			Ref.		
>6	1.10	1.02 – 1.20	**0.020**	1.12	1.03 – 1.22	**0.006**
Malarial endemicity						
Mesoendemic	Ref.			Ref.		
Hyperendemic	2.23	1.89 – 2.63	**<0.001**	2.25	1.91 – 2.66	**<0.001**
Holoendemic	2.43	1.34 – 4.42	**0.004**	2.44	1.35 – 4.42	**0.003**
Season						
Dry	Ref.			Ref.		
Wet	1.25	1.08 – 1.44	**0.002**	1.25	1.08 – 1.44	**0.002**
Cluster altitude	1.00	1.00 – 1.00	**0.007**	1.00	1.00 – 1.00	**0.010**
Child slept under slept under mosquito net last night						
Did not sleep under a net	Ref.			Ref.		
Only treated (ITN) nets	0.82	0.75 – 0.90	**<0.001**	0.82	0.75 – 0.90	**<0.001**
Only untreated nets	0.83	0.59 – 1.18	0.300	0.83	0.58 – 1.17	0.280
Household construction						
Traditional	Ref.			Ref.		
Finished	0.78	0.69 – 0.87	**<0.001**	0.81	0.72 – 0.91	**0.001**

Footnote: Other biomass=Straw/shrubs/grass/agricultural crop/animal dung, Ref. = Reference category, AOR = Adjusted odds ratio, 95% CI = 95% confidence interval

Appendix 2: Percentage of missing by country within the DHS analysis

Percentage of missing values for incomplete variables only within the analysis investigating the association between severe ARI and wood compared to charcoal cooking by included country (CHAPTER 6)

Country	Mode of delivery (%)	Breastfeeding (%)	Birthweight (%)	Received Vitamin A in last 6 months (%)	Taking iron pills, sprinkles or syrup (%)	Mother's education (%)	Household smoking (%)	Cooking location (%)	Number of household residents (%)
Afghanistan 2015 (N=7381)	0.28	0.62	91.1	6.29	4.69	0	0.19	1.44	0
Benin2017 18 (N=11642)	0	0	38.12	1.21	0.59	0	0	1.33	0.96
Burkina Faso 2010 (N=13532)	0.26	0.4	35.09	0.27	0.16	0.05	0.03	0.08	0
Burundi 2016-17 (N=11589)	0.44	0	19.14	0.09	0.03	0	0	0.03	0
Cambodia 2014 (N=5804)	0.17	0.14	9.87	0.65	0.52	0	0.03	3.67	0
Cameroon 2011 (N=7435)	0.12	0	41.71	0.5	0.51	0	0	0.03	0.47
Chad 2014 15 (N=15972)	0.21	1.11	88.79	2.47	2.34	0	0.06	0.39	0.39
Congo 2011-12 (N=5915)	0.17	0.14	11.39	1.56	100	0	0.08	0.03	0
Cote d'Ivoire 2011_12 (N=5821)	0.24	0.45	42.11	1.67	0.86	0	0.1	0.15	0.81
DR 2013 14 (N=16407)	0.24	0.58	23.7	0.69	0.77	0	0.01	0.07	0
Ethiopia 2016 (N=9131)	0	0	87.94	2.32	1.87	0	0	0.1	0
Gambia 2013 (N=7272)	0.22	0.8	39.76	0.95	0.63	0	0.12	0.07	0
Ghana 2014 (N=4267)	0	0.07	44.39	1.08	0.94	0	0	0	0
Guinea 2018 (N=6701)	0.34	0	51.16	0.9	0.79	0	0	0.06	0
India 2015-16 (N=166537)	0	44.39	23.33	1.37	0.7	0	0	0.03	0
Indonesia 2012 (N=5682)	0.3	0.21	21.14	10.75	1.04	0	0.04	0.11	0
Kenya 2014 (N=15314)	0.14	81.74	70.39	0.76	52.19	0	51.91	0.05	0
Liberia 2013 (N=5832)	0.27	0.29	75.69	0.79	0.63	0	0	16.22	0
Malawi 2015-16 (N=15946)	0.33	0	15.38	0.31	0.2	0	0	0.01	0

Mozambique 2011 (N=10350)	0	0	48.5	0.4	0.68	0	0	0.46	0
Myanmar 2015-16 (N=3273)	0.4	0	61.26	0.46	0.12	0	0	0	0
Nigeria 2018 (N=24188)	0.3	0	84.44	0.37	0.33	0	0	0.02	0
Pakistan 2017 18 (N=6508)	0.11	0.02	88.08	2.04	0.48	0	0.02	0	0
Peru 2012 (N=3322)	0	63.31	13.64	53.91	0.12	0	100	0	0
Philippines 2013 (N=4582)	0.7	0.35	24.18	0.22	0.35	0	100	0.04	0
Rwanda 2014-15 (N=6459)	0.03	0.26	6.52	0.2	100	0	0.09	0.02	0
Sierra Leone 2013 (N=10328)	25.89	0.81	48.27	2.44	1.43	0	0.11	0.35	0
Tanzania 2015-16 (N=9068)	0	0	37.45	0.64	0.63	0	0.03	0	0
Uganda 2016 (N=14049)	0.38	0	32.24	0.58	0.54	0	0	0.13	0
Zambia 2013-14 (N=11318)	0.21	62.71	35.55	0.44	1.02	0.1	0.02	0.13	0
Total (N=441627)	0.74	21.8	38.27	1.69	5.35	0	3.61	0.39	0.06

Percentage of missing values for incomplete variables only within the analysis investigating the association between severe ARI and indoor compared to outdoor cooking by included country (CHAPTER 7)

	Cooking fuel (%)	Mode of delivery (%)	Breastfeeding (%)	Birthweight (%)	Received Vitamin A in last 6 months (%)	Taking iron pills, sprinkles or syrup (%)	Mother's education level (%)	Household smoking (%)	Cooking location (%)	Number of household members (%)
Benin 2017-18 (N=12083)	0	0	0	38.16	1.24	0.66	0	0	1.3	0.89
Burkina Faso 2010 (N=13581)	0	0.26	0.4	35.07	0.27	0.18	0.05	0.03	0.08	0
Burundi 2016-17 (N=12450)	0	0.48	0	19.24	0.09	0.05	0	0	0.04	0
Cameroon_2011 (N=7463)	0	0.12	0	41.61	0.56	0.58	0	0	0.03	0.46
Chad_2014_15 (N=16194)	0	0.25	1.14	88.76	2.49	2.37	0	0.06	0.39	0.39
Comoros 2012 (N=2509)	0	0.6	3.27	34.95	4.86	3.15	0.32	0	0.24	0
Congo 2011-12 (N=5941)	0	0.17	0.13	11.36	1.55	100	0	0.08	0.03	0
Cote d'Ivoire 2011-12 (N=5886)	0	0.24	0.44	41.96	1.75	0.95	0	0.1	0.15	0
DRC2013_14 (N=16549)	0	0.24	0.57	23.68	0.74	0.86	0	0	0.07	0
Ethiopia 2016 (N=9953)	0	0	0	88.23	2.31	1.88	0	0	0.09	0
Gambia 2013 (N=7307)	0	0.22	0.82	39.85	1.03	0.67	0	0.12	0.07	0
Guinea 2018 (N=7018)	0	0.36	0	50.3	0.93	0.88	0	0	0.06	0
Liberia 2013 (N=5868)	0	0.27	0.29	75.73	0.84	0.7	0	0	16.22	0
Malawi 2015-16 (N=15915)	0	0.33	0	15.41	0.33	0.25	0	0	0.01	0
Mozambique 2011 (N=10480)	0	0	0	48.18	0.4	0.69	0	0	0.48	0
Niger 2012 (N=11981)	0	0.86	0.68	76.34	1.45	1.43	0.1	100	0.11	0
Nigeria 2018 (N=24721)	0	0.3	0	84.58	0.38	0.33	0	0	0.02	0
Rwanda 2014-15 (N=7594)	0	0.03	0.24	7.16	0.18	100	0	0.11	0.05	0
Sierra Leone 2013 (N=6279)	0	27.44	0.88	47.92	2.88	2.28	0	0.1	0.38	0
Tanzania 2015-16 (N=9048)	0	0	0	37.52	0.74	0.81	0	0.03	0	0.44
Togo 2013-14 (N=5935)	0	0.22	0.59	40.42	0.49	0.69	0	0.02	0.08	0

Uganda 2016 (N=13952)	0.07	0.39	0	32.03	0.67	0.67	0	0	0.1	0
Zambia 2013-14 (N=11435)	0	0.24	62.84	35.66	0.49	1.11	0.1	0.02	0.13	0
Total (N=240139)	0	0.97	3.29	46.77	0.96	6.47	0.02	5.01	0.57	0.1

Percentage of missing values for incomplete variables only within the analysis investigating the determinants of outdoor cooking by included country (Chapter 7)

	Education level of household head (%)	Age of household head (%)	Number of household members (%)	Household smoking (%)	Altitude (%)
Benin 2017-18 (N=13250)	1.51	0	0.14	0	0
Burkina Faso 2010 (N=13275)	0.11	0	0.07	0.03	100
Burundi 2016-17 (N=15763)	0.06	0	0	0	0.31
Cameroon 2018 (N=7766)	1.27	0	0.06	0	0
Chad 2014-15 (N=16314)	0.73	0.04	0.08	0.07	100
Comoros 2012 (N=3376)	2.07	0	0	0.03	100
Congo 2011-12 (N=8204)	1.61	0	0	0.07	100
Cote d'Ivoire 2011-12 (N=7554)	0.56	0.05	0.05	0.09	0
DRC 2013-14 (N=17648)	0.24	0	0	0.02	0
Ethiopia 2016 (N=15489)	0.28	0	0	0	0
Gabon 2012 (N=1420)	1.41	0	0	0.21	0
Gambia 2013 (N=5603)	0.5	0	2.12	0.14	100
Ghana 2014 (N=8282)	0.02	0.02	0	0	1
Guinea 2018 (N=7642)	0.55	0	0.09	0	0
Lesotho 2014 (N=5342)	1.65	0	0	0	0
Liberia 2013 (N=9135)	0.03	0	0	0.03	0
Malawi 2015-16 (N=25735)	0.65	0	0	0	0
Mali 2018 (N=9274)	0.75	0	0.12	0	0
Mozambique 2011 (N=13375)	1.62	0	0	0	0
Namibia 2013 (N=5234)	1.28	0.02	0	0.08	0
Niger 2012 (N=10422)	0.81	0	0.07	100	100
Nigeria 2018 (N=27732)	0.07	0	0.02	0	0
Rwanda 2014-15 (N=12461)	0.1	0.01	0	0.06	0
Sierra Leone 2013 (N=12407)	0.5	0	0.02	0.12	100

South Africa 2016 (N=1380)	1.38	0	0	0	0
Tanzania 2015-16 (N=11753)	0.04	0	0.03	0.02	0
Togo 2013-14 (N=8732)	0.32	0.01	0.06	0.05	0
Uganda 2016 (N=18626)	1.57	0	0	0	0
Zambia 2013-14 (N=13949)	0.65	0.01	0	0.04	0.32
Zimbabwe 2015 (N=7184)	1.06	0	0	0	0
Total (N=334325)	0.65	0.01	0.06	3.14	20.87

Appendix 3 DHS stratified sub-analysis by gender

Chapter 6 Results: Health risk assessment: Biomass fuel type

Summary effects (AOR – 95% CI) for respiratory symptoms, ARI and severe ARI with wood cooking within a stratified sub-analysis by gender

	Cough			Shortness of breath			Fever			ARI			Severe ARI		
	AOR [95%CI]	**P value**	**N**	**AOR [95%CI]**	**P value**	**N**	**AOR [95%CI]**	**P value**	**N**	**AOR [95%CI]**	**P value**	**N**	**AOR [95%CI]**	**P value**	**N**
Male	0.98 [0.93-1.04]	0.56	246655	1.04 [0.95-1.13]	0.4	246436	**1.08 [1.01-1.14]**	**0.02**	246747	1.04 [0.95-1.14]	0.38	246396	1.06 [0.95-1.18]	0.29	246211
Female	**1.00 [0.94-1.07]**	0.97	236919	1.01 [0.93-1.11]	0.79	236667	1.05 [0.99-1.12]	0.11	236967	1.02 [0.93-1.12]	0.68	236641	1.09 [0.97-1.22]	0.15	236433

AOR = adjusted odds ratio for wood cooking compared to charcoal, 95% CI = 95% confidence interval, N= number of observations

Chapter 7 Results: Harm mitigation: Cooking location

Summary effects (AOR – 95% CI) for respiratory symptoms, ARI and severe ARI with outdoor cooking within a stratified sub-analysis by gender

		Cough			Shortness of breath			Fever			ARI			Severe ARI		
Analysis		**AOR [95%CI]**	**P value**	**N**	**AOR [95%CI]**	**P value**	**N**	**AOR [95%CI]**	**P value**	**N**	**AOR [95%CI]**	**P value**	**N**	**AOR [95%CI]**	**P value**	**N**
Male	In a separate building	0.91 [0.86-0.97]	0.002	128024	0.95 [0.88-1.03]	0.236	127942	**0.83 [0.79-0.88]**	**<0.001**	128157	0.94 [0.86-1.03]	0.183	127902	**0.89 [0.80-1.00]**	**0.046**	127795
	Outdoors	0.91 [0.85-0.97]	0.002		0.95 [0.87-1.03]	0.208		**0.86 [0.81-0.91]**	**<0.001**		0.92 [0.84-1.00]	0.062		**0.89 [0.80-1.00]**	**0.048**	
Female	In a separate building	**0.90 [0.85-0.95]**	<0.001	126421	0.87 [0.80-0.94]	<0.001	126324	0.84 [0.79-0.89]	<0.001	126508	0.85 [0.78-0.92]	<0.001	126298	0.80 [0.73-0.89]	<0.001	
	Outdoors	**0.90 [0.85-0.95]**	<0.001		0.88 [0.81-0.95]	0.002		0.83 [0.79-0.88]	<0.001		0.86 [0.79-0.93]	<0.001		0.84 [0.76-0.93]	0.001	126183

AOR = adjusted odds ratio for outdoor cooking compared to indoor cooking, 95% CI = 95% confidence interval, N= number of observations

Stratified sub-analysis by gender of Odds ratio of malarial infection for each cooking practices

Analysis	**Outcome**	**Analysis 1 Biomass vs cleaner cooking**				**Analysis 2 Wood vs charcoal cooking**				**Analysis 3 Cooking location**			
		Cooking fuel	AOR[95% CI]	*p* value	N	Cooking fuel	AOR[95% CI]	*p* value	N	Type of cooking location	AOR[95% CI]	*p* value	*N*
Male	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.68[1.31-2.16]**	**<0.001**	22066	Wood	**1.86[1.56-2.21]**	**<0.001**	36785	In a separate building	**0.70[0.61-0.80]**	**<0.001**	11916
										Outdoor	0.93[0.61-0.80]	0.32	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.54[1.13-2.12}**	**0.01**	15104	Wood	**1.36[1.17-1.57]**	**<0.001**	23279	In a separate building	0.72[0.62-0.84]	**<0.001**	10738
										Outdoor	1.00[0.86-1.15]	0.96	
Female	RDT	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.47[1.11-1.94]**	**0.01**	21693	Wood	**1.69[1.45-1.97]**	**<0.001**	36287	In a separate building	**0.78[0.68-0.90]**	**<0.001**	11838
										Outdoor	0.95[0.82-1.09]	0.44	
	Microscopy	Cleaner	*Ref.*			Charcoal	*Ref.*			Indoor	*Ref.*		
		Biomass	**1.63[1.14-2.32]**	**0.01**	18102	Wood	1.08[0.93-1.26]	0.30	22927	In a separate building	**0.78[0.67-0.90]**	**<0.001**	10645
										Outdoor	0.94[0.81-1.09]	0.39	

Abbreviation: AOR = Adjusted Odds Ratio, 95% CI = 95% confidence interval, N= Number of observations, RDT = Rapid diagnostic test. Ref = Reference group.

Appendix 4: Semi-structured questionnaire for CHAPTER 9

Sociodemographic details

1. Age (tick appropriate box)

0-15		45-54	
16-24		55-64	
25-34		65-74	
35-44		85+	

2. Gender

Male	
Female	

3. Please list your average monthly household income (RWF)

____

4. Occupation?

____

Questions regarding COVID-19

The following questions are asking about the main type of cooking fuel you use pre-pandemic and the main type of cooking fuel you are using during the COVID-19 pandemic.

Which fuel did you previously use before the COVID-19 pandemic began?

Ethanol	
LPG	
Biomass pellets	
None of the above	

1. Have you changed the fuel you use for cooking during the COVID-19 pandemic?

Yes		*Answer questions 2.a.)-2.b.)*
No		*Answer question 2.d.)*

If Yes,

a.) If so, which fuel did you change to?

Charcoal	
Fire wood	
Ethanol	
LPG	
Biomass pellets	
None of the above	

If No,

d.) What fuel do you currently use?

Charcoal	
Fire wood	
Ethanol	
LPG	
Biomass pellets	
None of the above	

2. Has the quality and cost of the fuel change due to COVID-19?

Yes	
No	

Questions regarding the proposed Charcoal ban: (only answer if your main cooking fuel is charcoal)

In May 2020 Rwandan Government announced plans to introduce ban on the use of charcoal for cooking in Kigali[viii] and restrict supply to local areas.

The following questions are asking about your views and responses to the forthcoming changes. We are interested in your views and therefore there are no right or wrong answers.

1. Are you aware of the charcoal ban in Kigali?

Yes	
No	

2. What is the maximum amount you would be willing to pay per month for an alternative cooking fuel if a ban is implemented?

- 24000
- 22000
- 20000
- 18000
- 16000
- 14000
- 12000
- 10000
- 8000
- 6000
- 4000
- 2000
- 0 RWF

If it is not listed, please provide the exact amount _________ RWF

3. Can you please explain why you choose that amount of money in the previous question?

____
____
____
____
____
____
____

[viii] https://africa.cgtn.com/2020/06/02/rwanda-bans-charcoal-for-cooking-in-kigali/

4. What proportion of your monthly income do you currently spend on charcoal?

- ___ 100%
- ___ 90%
- ___ 80%
- ___ 70%
- ___ 60%
- ___ 50%
- ___ 40%
- ___ 30%
- ___ 20%
- ___ 10%
- ___ 0 %

5. Where do you normally purchase you charcoal from?

Market	
Mobile charcoal seller	
Wholesaler – (a company that buys large quantities from the produce to sell to retailers)	
Friends/family	
None of the above (please state)	

6. A.) Would you change your fuel if charcoal ban was implemented?

Yes	
No	

B.) If YES: Which fuel will you change to if charcoal is not available to purchase?

Fire wood	
Ethanol	
LPG	
Biomass pellets	
None of the above	

a) Why would you change to this fuel?

____
____
____

____
____
____
____

7. Are you aware of the plans to introduce a LPG subsidy?

Yes	
No	

Extra questions:

The following questions are optional and are to see if you would be willing to take part in further research into cooking practices and household air pollution.

1. Do you have a child under the age of five?

Yes		If yes, and cooking on charcoal, age 15-49 and a female go to 2.)
No		If no, go to 3.)

2. Would you be willing to take part in an interview about opinions and barriers of household air pollution interventions. If you opt in, you will be randomly selected to take part, and there is no grantee that you will be selected.

Yes		If yes, go to 2a.)
No		If no, go to 3.)

   a. Give details and contact will be made to arrange a time for interview

3. Would you be willing to submit a photo, illustrating what you think air pollution is?

Yes		If yes, go to 3a.)
No		If no, go to 4.)

   a. Details of photovoice

Appendix 5: Topic guide for qualitative in-depth interview

Topic guide: Interview to obtain opinions and barrier of behaviour changes to cooking practices as a harm reduction interventions to air pollution in Kigali, Rwanda

Introduction:

- Thank the participant for coming today to discuss cooking and air pollution, which will last 30-60 minutes
- Introduce yourself
- Outline the study and confirm people are in agreement to continue by making sure consent has been given.
- Highlight to the participants that they are free to ask any questions throughout and they have the right to decline to answer any questions
- All responses will be confidential. Explain this is a safe place to talk and views and responses will not be discussed outside of the interview.
- Draw to the participants' attention that a recording will be taken – confirm participants are happy with this.

Main questions

1. **Please describe your photo that you provided to illustrate what you think air pollution is?** *If you don't have a photo please describe what you think air pollution is.*
   a. How do you think this depicts air pollution
   b. Why did you choose this?
   c. Are you aware of other forms of air pollution?

2. **What do you feel are the health effects of cooking smoke?**
   a. Do you feel you have health issues due to cooking smoke – what are these?
      i. *Prompt if necessary with health issues:*
         a. *Respiratory (infections, asthma, COPD)*
         b. *Issues with the heart*
         c. *Pregnancy (low birth weight, still births, pre-term birth)*
   b. Are your children affected by cooking smoke?
      i. *Prompt if necessary with health issues:*
         a. *Respiratory (infections, cough, shortness of breath)*
         b. *Delayed development*
         c. *Burns for cooking stove*

The following questions are going to cover question on cooking practices

3. **Where should cooking take place?** *Prompt with indoor and outdoor cooking suggestion if necessary*
   a. Where do you currently cook?
   b. Why do you think cooking should take place here?
   c. What else determines your cooking location?

4. **What would you think about moving cooking outside?** – *Prompt with description of outdoor cooking if necessary*
   a. Would you take up this practice?
      i. If yes, why would you move cooking outside?
      ii. If no, why wouldn't you move cooking outside?

b. What issues could you foresee with cooking outside?
c. What would you require to be able to move outside?

5. **Do you know of any other behaviours you could change to reduce you or your children's exposure to cooking smoke?**
   a. What about removing children form the cooking area?
   b. Have you considered changing cooking fuels to reduce levels of air pollution?
   c. Have you made any of these changes?
   d. What stops you from making changes to your cooking practices?

6. **How would you like to learn more about behaviour changes to cooking practices to improve the health of your family?**
   a. *Prompt with examples if necessary:*
      i. *Educational sessions (in Umaganda)*
      ii. *Leaflets/advertisement campaigns*
      iii. *Economic incentives*
      iv. *Others…..*
   b. What would you like to gain from it?

7. **Is there anything else you would like to comment on cooking and air pollution?**

END – Thank participants for contributing their time and sum up discussion

Appendix 6: Photovoice submission received

Due to the low response rate (%) from the photo voice submission, an analysis could not be undertaken. This appendix is designed to illustrate the submission received, with a description of each photo being undertaken to summarise what the picture is depicting.

Submission 1

A smoking portable charcoal, stove situated outside.

Submission 2

An alight portable charcoal stove, location unknown.

Submission 3

A smoking charcoal portable stove, with evidence of grass used for firefighting. Location outdoors but adjacent to the door or the property.

Submission 4

A portable charcoal stove, alight and in the indoor environment. Evidence of twigs and paper.

Submission 5

A smoking portable charcoal stove situated outdoors.

Submission 6

A portable charcoal stove,
with only the embers left.
Location unclear.

Appendix 7: Ethical approval letters from the University of Birmingham and the University of Rwanda

UNIVERSITY of RWANDA

COLLEGE OF MEDICINE AND HEALTH SCIENCES

DIRECTORATE OF RESEARCH & INNOVATION

CMHS INSTITUTIONAL REVIEW BOARD (IRB)

Kigali, 14th/July /2020

Katherine Woolley,
University of Birmingham

Approval Notice: No 235/CMHS IRB/2020

Your Project Title ***"Informing Effective Health Interventions to Indoor Air Pollution in Urban Rwanda"*** has been evaluated by CMHS Institutional Review Board.

Name of Members	Institute	Involved in the decision: Yes	No (Reason): Absent	No (Reason): Withdrawn from the proceeding
Prof Kato J. Njunwa	UR-CMHS		X	
Prof Jean Bosco Gahutu	UR-CMHS	X		
Dr Brenda Asiimwe-Kateera	UR-CMHS	X		
Prof Ntaganira Joseph	UR-CMHS	X		
Dr Tumusiime K. David	UR-CMHS	X		
Dr Kayonga N. Egide	UR-CMHS	X		
Mr Kanyoni Maurice	UR-CMHS		X	
Prof Munyanshongore Cyprien	UR-CMHS	X		
Mrs Ruzindana Landrine	Kicukiro district		X	
Dr Gishoma Darius	UR-CMHS	X		
Dr Donatilla Mukamana	UR-CMHS	X		
Prof Kyamanywa Patrick	UR-CMHS		X	
Prof Condo Umutesi Jeannine	UR-CMHS		X	
Dr Nyirazinyoye Laetitia	UR-CMHS	X		
Dr Nkeramihigo Emmanuel	UR-CMHS		X	
Sr Maliboli Marie Josee	CHUK	X		
Dr Mudenge Charles	Centre Psycho-Social	X		

After reviewing your protocol during the IRB meeting of where quorum was met and revisions made on the advice of the CMHS IRB submitted on 14th July 2020, **Approval has been granted to your study.**

Please note that approval of the protocol and consent form is valid for **12 months**.

You are responsible for fulfilling the following requirements:

1. Changes, amendments, and addenda to the protocol or consent form must be submitted to the committee for review and approval, prior to activation of the changes.
2. Only approved consent forms are to be used in the enrolment of participants.
3. All consent forms signed by subjects should be retained on file. The IRB may conduct audits of all study records, and consent documentation may be part of such audits.
4. A continuing review application must be submitted to the IRB in a timely fashion and before expiry of this approval
5. Failure to submit a continuing review application will result in termination of the study
6. Notify the IRB committee once the study is finished

Sincerely,

Date of Approval: The 14th July 2020

Expiration date: The 14th July 2021

[redacted]

Professor GAHUTU Jean Bosco
Chairperson Institutional Review Board,
College of Medicine and Health Sciences, UR

Cc:

- Principal College of Medicine and Health Sciences, UR
- University Director of Research and Postgraduate Studies, UR

Katherine Woolley (PhD App Health Resea FT (A900))

From: Susan Cottam (Research Support Group)
Sent: 30 September 2019 10:17
To: Neil Thomas (Applied Health Research)
Cc: Suzanne Bartington (Applied Health Research); Francis Pope (Earth and Environmental Sciences); Katherine Woolley (PhD App Health Resea FT (A900))
Subject: Application for Ethical Review ERN_19-0252

Dear Professor Thomas

Re: "Informing effective interventions to reduce health harms of indoor air pollution in urban Rwanda"
Application for Ethical Review ERN_19-0252

Thank you for your application for ethical review for the above project, which was reviewed by the Science, Technology, Engineering and Mathematics Ethical Review Committee.

On behalf of the Committee, I confirm that this study now has full ethical approval.

I would like to remind you that any substantive changes to the nature of the study as described in the Application for Ethical Review, and/or any adverse events occurring during the study should be promptly brought to the Committee's attention by the Principal Investigator and may necessitate further ethical review.

Please also ensure that the relevant requirements within the University's Code of Practice for Research and the information and guidance provided on the University's ethics webpages (available at https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Links-and-Resources.aspx) are adhered to and referred to in any future applications for ethical review. It is now a requirement on the revised application form (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-Forms.aspx) to confirm that this guidance has been consulted and is understood, and that it has been taken into account when completing your application for ethical review.

Please be aware that whilst Health and Safety (H&S) issues may be considered during the ethical review process, you are still required to follow the University's guidance on H&S and to ensure that H&S risk assessments have been carried out as appropriate. For further information about this, please contact your School H&S representative or the University's H&S Unit at healthandsafety@contacts.bham.ac.uk.

Kind regards

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Please remember to submit a new Self-Assessment Form for each new project.

Click Research Governance for further details regarding the University's Research Governance and Clinical Trials Insurance processes, or email researchgovernance@contacts.bham.ac.uk with any queries relating to research governance.