GCRF Report Draft

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Project title: Quantifying the impact of innovative biogas technology on air pollution levels in a peri-urban community in Kenya using novel sensing techniques

Scheme *1: Pump-priming Fund (Jan – July 2019)*

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1. Introduction

Exposure to indoor and outdoor air pollution is a leading environmental health risk factor globally resulting in approximately eight million premature human deaths annually.[1] Breathing polluted air is predominantly associated with non-communicable diseases (NCDs) such as cardiovascular and lung diseases which are the primary causes of mortality and morbidity in the developed world, and their rates are accelerating rapidly in less affluent nations.[2] Over the last decades, the disease burden in low-income and middle-income countries (LMICs) has shifted from a profile dominated by infectious disease to one increasingly characterised by NCDs. Nearly 92 per cent of pollution-related deaths occur in LMICs among the poorest and most vulnerable populations. Approximately 76 per cent of air pollution exposure to particulate matter occurs indoors in the developing world.[3] A major part of this problem arises from burning biomass fuels indoors for cooking energy. There is limited detailed primary research available from developing countries into the health benefits of using clean cooking fuels as alternatives to biomass fuels.[4] This study proposes to contribute to this body of research.

In Kenya, it is estimated that indoor and outdoor air pollution causes nearly 18,900 premature deaths annually, the majority attributed to indoor pollution (14,000) and a further 4,710 from outdoor particulate matter.[5] As in most LMICs, the burden of air pollution is likely to be underestimated in

[1] World Health Organisation (2019) Air pollution. Available at: https://www.who.int/airpollution/en/

[2] NCD Countdown 2030 collaborators. (2018) NCD Countdown 2030: worldwide trends in non-communicable disease mortality and progress towards Sustainable Development Goal target 3.4, Lancet 392, https://doi.org/10.1016/S0140-6736(18)31992-5.

[3] Fullerton DG and S. Semple (2008) Air pollution and health: indoor air pollution in the developing world is the real key to reducing the burden of ill health Thorax, 63(3):288 https://thorax.bmj.com/content/thoraxjnl/63/3/288.2.full.pdf

[4] WHO, 2016. Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children. Available at: https://www.who.int/airpollution/publications/burning-opportunities/en/

[5] Health Effects Institute State of Global Air (2019) Health Impact: number of deaths attributable to air pollution https://www.stateofglobalair.org/data/#/health/plot

Kenya because comprehensive, systematic long-term monitoring of air quality is absent.[6] The problem is complex, with multiple pollution sources affecting air quality in multiple settings, requiring major investment in research to adequately inform solutions to this public health challenge. Moreover, the collection and burning of biomass – particularly firewood and charcoal – have significant negative impacts on the environment, principally through deforestation, denudation of the landscape and the release of carbon dioxide emissions. The twin impacts of poor health and land degradation present serious economic challenges to LMICs, including Kenya, compounded by climate change.

Our proof-of-concept study assessed the feasibility of monitoring air pollution in a peri-urban community in western Kenya ('Dunga Beach') with a focus on the cooking technologies utilised by the most vulnerable subpopulation. The site already supports research led by the Cambridge Institute for Sustainability Leadership (CISL) and AstraZeneca into the effects on health and socio-economic status of adopting clean cooking practices, particularly among women. As a consequence of this existing research, the site provided a unique opportunity to test whether households utilising a clean biogas cooking technology indeed experience improved air quality over households burning biomass with more traditional technologies.

The aims of the study were to:

(1) measure outdoor and indoor gaseous pollutants and particulate matter using novel sensing technologies with two types of autonomous sensor platforms (AQMesh and PAM);
(2) assess local air quality heterogeneity;
(3) identify outdoor emission sources;
(4) test the impact of clean biogas cooking technologies;
(5) assess self-reported health outcomes; and
(6) initiate cooperation with DAC research institutions.

This report covers activities, data gathered, impact, reflections on the process, and plans and approaches for further funding and dissemination of information.

2. Team

Our team comprised a number of partner organisations:

- Department of Chemistry, University of Cambridge – air quality expertise
- Cambridge Institute for Sustainability Leadership, University of Cambridge – environmental expertise and leadership
- Biogas International Limited (BIL) – a Nairobi-based social enterprise deploying biogas-based technologies in communities
- Adoyo Community Consultancy – Kisumu-based organisation facilitating community engagement in Kenya with local knowledge, translation and logistics services
- Dunga Beach Management Unit (DBMU) - Dunga-based community mobilisation and security
- Centre of Development Studies (CDS), University of Cambridge – international development expertise.

3. Materials and methods

3.1 Study location and overview

Dunga Beach is located on the shores of Lake Victoria, near Kisumu, the third largest city in Kenya, in a predominantly Luo community (the fourth largest ethnic group in Kenya) (Figure 1). The area has a tropical climate with significant year-round rainfall, two rainy seasons and no major dry season.

[6] DeSouza, P. et al. (2017) A Nairobi experiment in using low cost air quality monitors, Clean Air Journal 27 (2) available here

Figure 1: Dunga settlement in western Kenya

The main sources of cooking fuels are: wood (brought from Kisumu and the surrounding area, or gathered locally), charcoal (bought usually from Ugandan supplies offloaded in the Dunga Beach port), and papyrus gathered from a neighbouring wetland. These are burned outdoors on basic ‘three stone’ open fires, or on charcoal stoves called *jikos* (indoor/outdoor depending on weather/time of day) (Figure 2). Kerosene and LPG (gas) are also used by some households.

Figure 2: Traditional cooking stoves used in Dunga: charcoal jikos (outside and inside) and three stone stoves used with firewood and papyrus

As part of CISL’s existing research programme funded by AstraZeneca, domestic-scale biodigesters (and associated cooking stoves burning the biogas which they produce) have been introduced to 50 households in a pilot project implemented by Biogas International Limited (BIL). The technology consists of a flexible digester unit located outside the household, fed with cow-dung, household organic waste and shredded water hyacinth collected from the lake shore (hyacinth is an invasive weed having a disastrous economic effect on lakes and waterways across Africa). Biogas produced within the digester is simply piped into the household where it is connected to a double-ring stove and ready to burn (Figure 3). Further details of the wider project and ongoing M&E are available here.

Figure 3: Flexible biogas digester and clean cooking stove (photo: ©Natasha Grist and Alexandra Winkels)

3.2 Project methodology

3.2.1 Overview

The overall approach taken was a comparative analysis using empirical investigation in a real life context with multiple sources of evidence. Full ethical clearance was obtained from the University of Cambridge and Maseno University, the Kenyan university affiliated with the project and permitting hub for Kenya's National Commission for Science, Technology and Innovation (NACOSTI) which granted a research permit for the duration of the study once full research ethical clearance was obtained from Maseno. All staff members working with the community (Department of Chemistry and Adoyo Community Consultancy) participated in an ethical briefing from a CISL facilitating staff member prior to visiting the community.

3.2.2 Participant sample

This research was designed as a 'case-control study'. A sample of biogas-using households ('case') and non-biogas households ('control') was selected, and indoor air pollution levels were measured in order to understand differences between those using biogas stoves and those using traditional cooking fuels. There is potential for bias and confounding in this method, especially when implemented in a real life context.[7] To minimise this, the team used the same methods for both case and control in order to maintain other variables as similar as possible. We held discussions with local partners and researchers familiar with the site before and during the study. This had two benefits. Firstly, it meant that potential monitoring sites could be identified and verified before our arrival, and necessary additional equipment discussed and ordered in advance to ensure smooth workflow. Secondly, in discussing with local partners, we briefed and shared understandings of the project's aims and goals, which they then used, along with an introductory document produced and translated into Luo language, in order to approach and discuss with community members and potential recipient households. Unusual-looking technologies and research tests can evoke curiosity and concern in many communities, so it is very important to allow sufficient time for acclimatisation, explanation and dialogue. On arrival, the Cambridge team met and discussed remaining questions with householders to discuss their participation.

[7] Kopek, J. A. and J.M. Esdaile (1990) Bias in case-control studies: a review. Jl. Epidemiol Community Health, 44 (3), pp. 179-186. Available here.

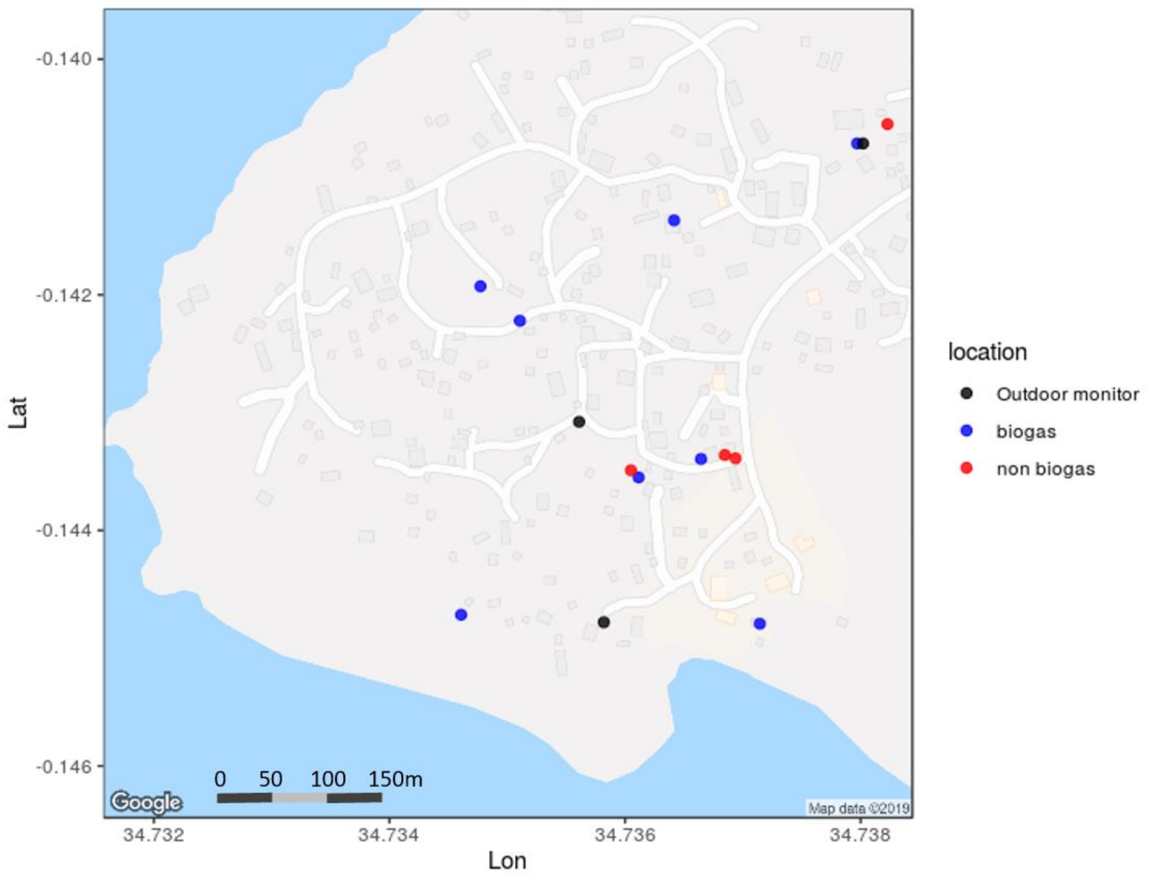


Figure 4: Spatial distribution of selected households and outdoor sites in Dunga

A total of 12 households were selected for detailed indoor air pollution measurement, split between four 'control' households (traditional cooking fuels) and eight 'case' households (biogas technology). The distribution of the households is shown in Figure 4. Of the eight case households, some had adopted biogas as their sole fuel source, whilst others combined biogas with traditional fuels for cooking.

The criteria for participation in the study were:

- availability of mains electricity in the home (to charge the monitoring equipment);
- broad similarity of type and structure between control and case households (see Section 4.1);
- safety and security of scientific equipment for the duration of the study;
- person responsible for cooking able to complete a daily worksheet summarising fuel use for each meal (see Section 3.2.3); and
- interest and willingness of household to participate in the study.

Potential households were identified by a local facilitator, Maurice Misodhi, a representative of the Dunga Beach Management Unit (DBMU). Discussions with the facilitator were led by Adoyo Community Consultancy staff initially, prior to the Cambridge team's arrival, and later directly with the Cambridge team. After agreement, the selected households were offered a small donation to towards incurred electricity costs, added directly as a token to their electricity pre-payment system. In addition, they were offered a small cash payment for their time in participating in the study, completing daily worksheets, and ensuring the security of the equipment.

3.2.3 Daily pen-and-paper diaries and semi-structured household interviews

Participants were asked to keep a diary of the methods, fuels and timing of their cooking activities to allow the team to draw associations with frequency, magnitude and duration of pollution exposures (see

Annex 1). Short verbal interviews were also undertaken to collect information on the socio-economic characteristics of households, building characteristics and self-reported health (see Annex 2). Interviews were carried out in the Luo language with records taken in English. The use of semi-structured questionnaires enabled the collection of quantitative data, while providing the flexibility to investigate responses in more detail.

3.2.4 On-site observations of residential buildings

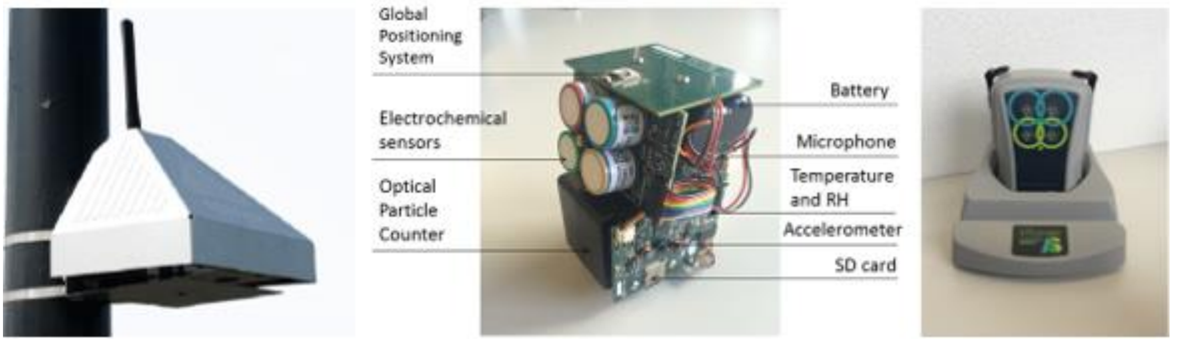
Building characteristics are known to affect indoor air quality. Observations about buildings were therefore carried out throughout the fieldwork period, including location and spatial patterns, construction characteristics, ventilation strategies and architectural designs using written notes, photographs, architectural plans and drawings of the microenvironments of the surrounding area (eg to note outdoor sources of pollution).

3.2.5 Outdoor and indoor air pollution monitoring of targeted air pollutants

A growing evidence base highlights how short-term and long-term exposure to gaseous pollutants and particulate matter is associated with a range of cardio-respiratory health outcomes.[8] Taking into account the limited research infrastructure available to quantify air pollution levels in peri-urban Kenya,[9] this study employed novel sensing technologies that offer an affordable, achievable and validated alternative. Specifically, gaseous pollutants (carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2) and ozone (O_3)) were measured with electrochemical sensors, whilst particulate matter (PM_1, $PM_{2.5}$ and PM_{10}) was measured with Optical Particle Counters (OPC). Gaseous and particulate pollutants were measured indoors and outdoors simultaneously with two types of commercially available autonomous platforms of multiple sensors (Figure 5): a unit suitable for outdoor deployments (AQMesh) and a compact and lightweight personal air quality monitor (PAM) suitable for indoor and personal exposure assessments.

Prior to their deployment, the sensor platforms were co-located next to certified reference instruments in the UK (Department of Chemistry, University of Cambridge) to characterise their performance. At the end of the deployment, the six PAMs were co-located with an AQMesh in the research site for additional quality assurance and quality control of the measurements.

Equipment was shipped via a reputable international courier, but was delayed in customs beyond expected timeframes, posing a risk to the execution of the project. Project staff were required to change the timings of their visit to Kenya at short notice, and then reduce the amount of time for Nairobi-based follow up during the fieldwork period. In addition, unexpectedly high customs costs were invoiced without prior agreement with Cambridge University staff.



[8] Samet, J. M., Zeger, S. L., Dominici, F., Curriero, F., Coursac, I., Dockery, D. W., ... & Zanobetti, A. (2000). The national morbidity, mortality, and air pollution study. Res Rep Health Eff Inst, 94(pt 2), 5-79. http://doi.wiley.com/10.1111/nyas.12720

[9] https://www.theelephant.info/features/2018/07/05/every-breath-you-take-who-is-monitoring-air-quality-in-kenya/

Figure 5: AQMesh external monitor(left); and personal air quality monitor (PAM) (inside showing sensors exposed (middle) and with external cover(right))

Figure 6: (a) First AQMesh in place; (b) AQMesh construction, including solar panels to be independent of irregular mains electricity; and (c) Household PAM in situ, placed by researchers at optimum location in household, with electricity supply ©CISL/Department of Chemistry 2019

<u>Outdoor air pollution measurements</u>

Outdoor air pollution levels were measured continuously for two months (28 May-31 July 2019) with three AQMeshes deployed at strategic locations around the settlement (Figure 4) to understand the spatial and temporal variation of diverse emission sources subject to meteorological factors. The AQMesh has been previously deployed in international projects.[10] The low power demand of novel sensing deployments makes them suitable for use in settings with limited power supply. Local technicians erected metal poles and attached the units at 3m height with a shading device, powered by a battery charged by a solar panel (Figure 6) to circumvent an unreliable local power supply. However, this mode of operation unexpectedly affected the gain and baselines of PM readings, especially PM_{10} and to lesser extent $PM_{2.5}$, as a consequence of the noisy and ultimately lower-than-desired power delivered by the solar panels affecting the intensity of the internal lasers inside the sensors, and hence the operation of its optical particle counters (OPC). This was corrected as soon as the sensors were

[10] Carruthers D.J., Stidworthy A., Clarke D., Dicks J., Jones R., Leslie I., Popoola O., Seaton M. (2019) Urban emission inventory optimisation using sensor data, an urban air quality model and inversion techniques. International Journal of Environment and Pollution. *In press*

connected to mains power. Preliminary results presented in this report (Section 4.2) were post-processed to eliminate erroneous measurements. Measurements were taken in 15-min intervals and sent automatically to a secure server in Cambridge for analysis.

Indoor air pollution measurements

The PAM used in this study has previously been deployed with two large cardio-pulmonary cohorts in China (AIRLESS - Theme 3 APHH project)[11] and in the UK (COPE)[12], as well as in a number of smaller international pilot projects. It is almost completely silent and can operate for around 18-24 hours under battery power or continuously if mains connected. Data are uploaded through GPRS to a secure server in Cambridge. A detailed description of the PAM and the validation of sensor performance in indoor environments is available.[13]

In this study, indoor air pollution levels were measured continuously in 12 households using six PAMs from 27 May to 13 June 2019. PAMs were deployed in the selected households for one week, recording at one minute intervals before being moved to the next household. The rechargeable batteries contained within the PAMs ensured continuous recording in the event of power outages in the local area. The PAMs were left in their charging base-stations for the duration of the deployment so that no input was required by householders.

3.2.6 Data analysis

User friendly, bespoke software has been developed by the Department of Chemistry to automate the management and post-processing of the large volume of raw data collected with the AQMesh and PAM network. Data post-processing was performed in R[14] software. Air pollution measurements, daily diaries and questionnaire responses were held in a relational database management system in SQL to provide complex query capabilities and to maintain relationships between the different components of the data.

3.3 Principal stakeholder discussions and outreach

During the course of the study, we contacted research institutions, local and national government offices, and relevant NGOs and multilateral institutions interested in the health and environmental impacts of air quality.

	Who	Broad role and potential	Detail
1	**Dr Nelson Otieno**	Kisumu/National health company/ wider funder	AZ Medical Adviser and manager of multi-country programmes with oversight of Dunga Beach programme
2	**Dr Benson Nyambega**	Research, affiliation	Maseno University ethics adviser and current Director of Research, Publications and Innovation; background biologist; setting up cancer research centre now; partnership lead for future approaches with Maseno
3	**Osawa William Otta & Dan Marunga**	Kenya government policy influence	Head of Kenya Bioenergy Policy, Kenya Ministry of Energy; met with Jake Reynolds Feb 2019 in Nairobi; interested in this project and outcomes
4	**Dr Dickens Onyango**	County Government policy influence	Kisumu County Director of Health; interested in health impacts and air quality; visited Dunga site 31/5/2019

[11] Shi, Z. et. al. (2018) Introduction to Special Issue: In-depth study of air pollution sources and processes within Beijing and its surrounding region (APHH-Beijing), Atmos. Chem. Phys. Discuss., 19, 1–62, https://doi.org/10.5194/acp-2018-922 .
[12] Moore, E., Chatzidiakou, L., Jones, R.L., Smeeth, L., Beevers, S., Kelly, F.J., K Quint, J., Barratt, B (2016): Linking e-health records, patient-reported symptoms and environmental exposure data to characterise and model COPD exacerbations: protocol for the COPE study, BMJ Open, 6 doi.org/10.1136/bmjopen-2016-011330.
[13] Chatzidiakou, L., Krause, A., Popoola, O. A. M., Di Antonio, A., Kellaway, M., Han, Y., … Jones, R. L. (2019). Characterising low-cost sensors in highly portable platforms to quantify personal exposure in diverse environments. *Atmospheric Measurement Techniques Discussions*, 1–19. https://doi.org/10.5194/amt-2019-158
[14] R Development Core Team: R: (2019). A language and environment for statistical computing. Version 3.6.1 https://cran.r-project.org/doc/manuals/r-release/fullrefman.pdf.

5	**Johnson Charles Apuko**	Research	Environmental Chemist, Maseno University Worked on Air Quality previously. Interested in utilising equipment.
6	**Walter Akeyo, Absa Sedah**	Research	Meteorologist and environmental scientist specialists from Maseno University; visited Dunga 31/5/2019 for discussion, exploring possibilities and capacity building with CU chemistry staff on air quality and biogas discussion with Dom Wanjihia, CEO of BIL
7	**Prof. Charles Obonyo**	Research Partnership Kenya and Kisumu County	Chief Research Officer, Centre for Global Health Research, Kenya Medical Research Institute; interested in partnering in further funded work on adolescent health potentially or other areas
8	**Dr Pauline Andango**	Communication, dissemination	Lecturer, School of Public Health and Community Development, Maseno University; interested in sharing results of air quality study if possible with follow up visit
9	**Dr Henry Neufeldt, Dr David Guimerra**	Research, dissemination	World Agroforestry Centre bioenergy; strong Kisumu environmental link; interested in results
10	**Africa Biogas Partnership Programme / SNV** **Kenya Biogas Programme**	NGO, dissemination, partnership	Bert van Nieuwenhuizen, Chief Technical Adviser, SNV; Kevin Kinusu, Kenya program manager; Jean-Mark Sika ABPP Program Trust Manager; Veril Ayieko, KBP (implementer/Dunga area evaluator); interested in all scientific research around biogas and health impacts
11	**UNEP Sean Khan**	Multilateral influence, research, dissemination, future partnership	Rod Jones contact; discussed July 2019; linked with Nairobi air quality health studies
12	**University of Nairobi Air Quality**	Research, dissemination, future partnership?	Jake Reynolds and John Pharoah to contact / visit September 2019 after discussion with Sean Khan
13	**Clean Cooking Alliance**	NGO, research, dissemination	Astri Sorenson. Natasha Grist and John Pharoah contacted. Moi Uni and Berkeley Uni AQ research in Kenya to start on cooking methods and personal exposure soon– CCA will share details

4. Preliminary results

4.1 Setting

The team's observations suggest that Dunga, an unplanned settlement originating in the late 1950s, has developed in a manner that is broadly representative of many sub-Saharan settlements: clusters of dispersed vernacular houses freestanding around communal open spaces. These open spaces form a 'courtyard' configuration that offers relatively high population densities, privacy and protected outdoor living space, as well as social interaction in the neighbourhood.[15] Due to its unplanned status, further buildings are continually being constructed to meet the demand for accommodation in the area.[16]

[15] Steyn, G. (2005). African courtyard architecture: typology, art, science and relevance. *Acta Structilia: Journal for the Physical and Development Sciences*, *12*(2), 106-129.
[16] Grist, N., Winkels, A. and J. Reynolds (2018) Baseline Study: Dunga Beach Biogas Community and Household Pilot. CISL. https://www.cisl.cam.ac.uk/business-action/inclusive-development/pdfs/biogas-community-baseline-study-external.pdf

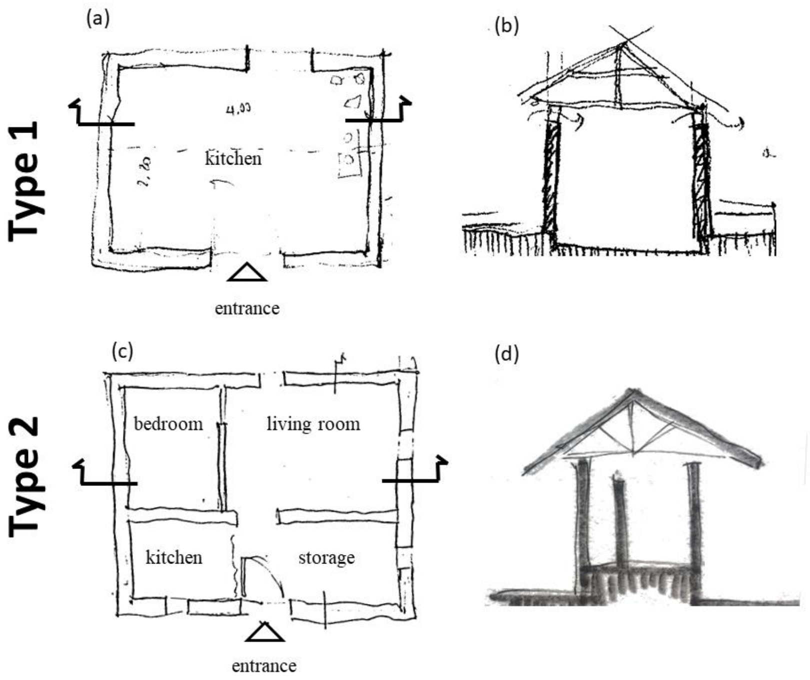


*Figure 7: Classification of housing types in Dunga. **Type 1:** the 'rooms' used by a family for sleeping, cooking and socialising are located in several buildings and also in spaces between buildings. The kitchens are independent single rooms that may also be used as a bedroom for an elderly relative or children. **Type 2:** The space for sleeping and cooking for the family are in the same building. The internal walls offer gaps at the top to allow air to flow freely and light to enter interiors.*

The houses were classified into two categories depending on the placement of the kitchen (Figure 7). All houses were single-storey buildings without internal toilets or chimneys. They were constructed using locally sourced materials with thick stone walls that may or may not be rendered with cement. The majority of houses had cement floors with only one house finished with packed earth. Wooden shutters were fairly common, with and without glazing. The roofs of the buildings were constructed with wooden beams holding metal sheets of corrugated iron in ridged or sloped elevations.

4.2 Effect of outdoor air pollution and cooking technology on household air pollution

Fieldwork in Kenya yielded a comprehensive database of field measurements consisting of 18,000 observations of multiple outdoor air pollutants (data capture rate >90 per cent, ie actual observations/theoretical observations x 100), more than 140,000 observations of indoor air pollution levels (data capture rate >95 per cent), 252 diary entries on household cooking practices, and a 100 per cent response rate to household questionnaire interviews.

Given the challenging timeframe for data processing, it has only been possible to present a preliminary, indicative analysis here. A fuller analysis will be presented in an academic journal article prepared during September – December 2019. Example journals where similar studies have been published include ACP (preferred) IF: 5.6; Enery Policy IF: 4.0; Science of the Total Environment; and Environ. Sci. Technol.

Data from two households in close proximity (both Type 2, Figure 7) are presented as representative examples (Figure 8, Figure 9), both of which participated in the study during the same week. One household (the 'case') had adopted biogas for cooking while the second household (the 'control') used traditional cooking fuel (indoor charcoal and outdoor firewood). **Preliminarily analysis focused on one gaseous species (carbon monoxide, CO) as a proxy of combustion and particulate matter of aerodynamic diameter < 250nm ($PM_{2.5}$).** Outdoor air pollution levels (ie the regional background) were collected via the AQMesh monitor located at the beach (Figure 4, further from the households).

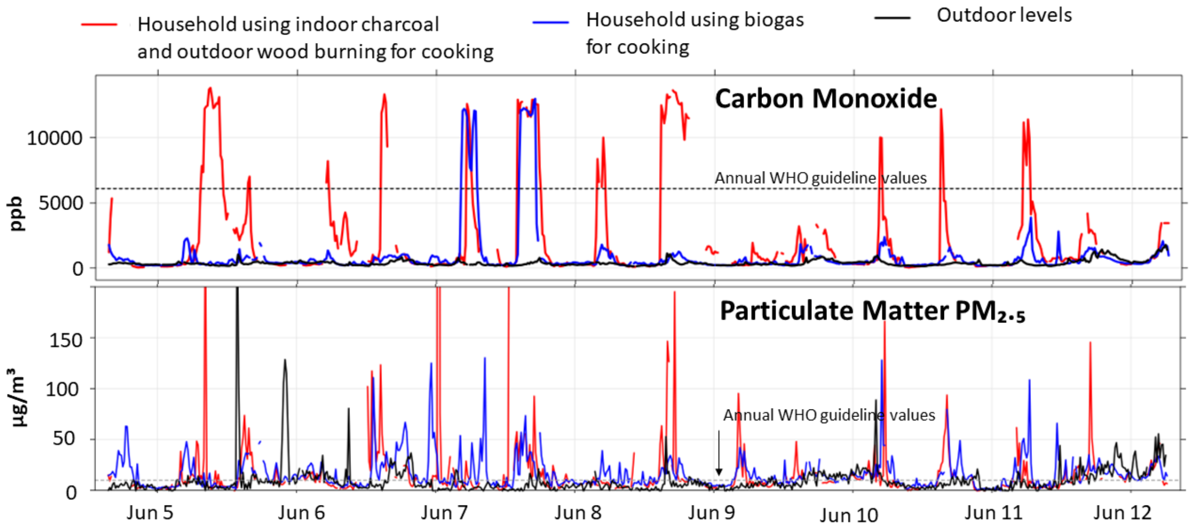


Figure 8: Time series of carbon monoxide and particulate matter in control and case households (red, blue) and outdoors (black) during the period June 5-13, 2019. Time resolution is 15 minutes. Annual WHO guideline values are indicated with dashed lines.

<u>Effect of outdoor air pollution levels on indoor exposure</u>

The time series in Figure 8 shows that indoor levels broadly follow outdoor levels for both gaseous pollutants and particulate matter highlighting the influence of outdoor air pollution to personal exposure. Strong local outdoor sources in the immediate vicinity of the households may elevate indoor levels for extended time periods (e.g. 7th June 2019).

<u>Effect of indoor sources on indoor exposure</u>

An important finding of this work is that air pollution levels recorded indoors are consistently higher than outdoor levels and often exceeded WHO guideline values (Figure 8). Distinct periodic peaks in indoor levels were primarily caused by cooking events. These findings validate the urgent need to tackle indoor air pollution sources to improve public health.

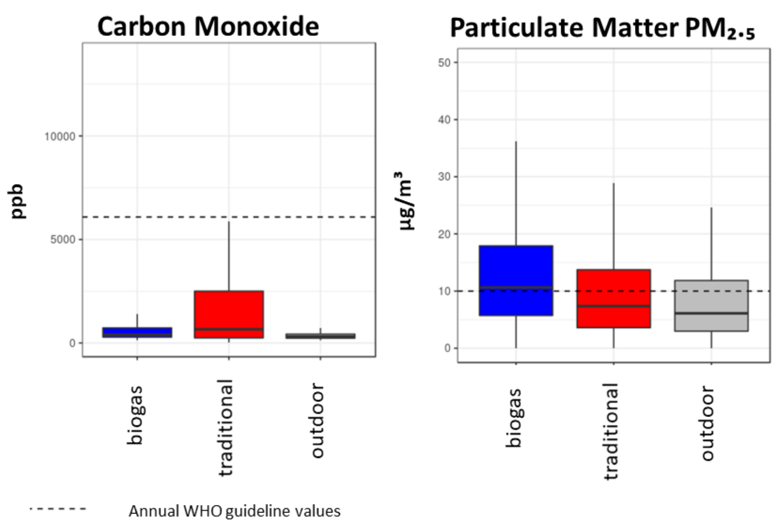


Figure 9: Boxplots of indoor gaseous and particulate matter pollution levels in biogas (case) and traditionally fuelled household (control) shown against (external AQMesh) outdoor measurements.

Effect of cooking fuel on indoor exposure

Carbon monoxide levels were significantly higher in the control household using an indoor charcoal stove (jiko) compared to the biogas household, as might be expected (Figure 8, Figure 9). This is an important finding given the effects of the gases studied on health outcomes.

However, the mean difference between recorded indoor levels of particulate matter ($PM_{2.5}$) was not statistically significantly different between the two households. One possible explanation is that, apart from differences in the cooking fuels, particles in this size range are primarily generated from the cooking of ingredients themselves.[17] Maximum exposure events (Figure 8) were recorded in the household that used traditional cooking methods, and such events may be important triggers for acute health responses. It should be noted that our PM sensors are based on optical methods and measure a specific size range of particles (fine and coarse PM), which is only one component of pollution exposure.

Limitations of current methodological approach

There are certain performance caveats with the low-cost sensors used in this study. Firstly, a limitation of all optical PM sensors, low-cost or reference, is that they cannot measure small particles below a critical size threshold, and it is therefore likely that the mass estimations presented here are underestimated. A more detailed investigation that includes ultra-fine particles, chemical composition and black carbon might be necessary to highlight differences in exposure, but that approach would require further resources.

Secondly, the toxicity of particles is also likely to depend on their chemical composition. Most national networks measure total mass only, and measuring particle chemical composition is currently largely the domain of research. There is a clear need to develop techniques allowing routine PM composition measurements, both for the regulatory networks and for applications such as personal monitoring.

Mains electricity in households allowed continuous ongoing measurement. While it was beyond the scope of this ‘proof-of-concept’ study to manage a larger, more representative sample of households in the community, it should be noted that potentially the most vulnerable families may not have access to mains electricity.

5. Impact

5.1 Impact and SDGs

Through the provision of academically rigorous findings, the study sheds light on international efforts to deliver the UN Sustainable Development Goals (SDGs) which Kenya, among 193 nations, supports. In particular:

SDG 3 – Good health and wellbeing: ensure healthy lives and promote well-being for all at all ages

The study directly sheds light on the delivery of Target 3.9 by revealing the benefits of achieving a ‘clean fuel switch’ to biogas in biomass burning communities:

- Target 3.9: By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination
- Indicator 3.9.1 Mortality rate attributed to household and ambient air pollution.

[17] Abdullahi, K. L., Delgado-Saborit, J.M. and R. M. Harrison (2013) Emissions and indoor concentrations of particulate matter and its specific chemical components from cooking: a review. Atmos, Env. 71, pp 260-294 https://research.birmingham.ac.uk/portal/files/10603660/Emissions_and_Indoor_Concentrations_PostPrint.pdf

SDG 7 – Affordable and clean energy: promoting sustainable energy for healthy homes and lives

The study explores the potential of clean, sustainable cooking energy, produced affordably by households themselves, to create immediate environmental, health, economic, gender and food security benefits, and indirect job creation.

SDG 1 – No poverty: prioritising the health needs of the poor
Biogas energy offers improved access and control over economic resources, reduced energy expenditure, job creation through scalable community scale biogas SMEs, access to saleable bio-slurry and biogas-linked service provision for income generation.

The project sought several specific impacts, with the following results:

5.2 Capacity building, UK

Staff from CISL worked closely with two post-doctoral researchers and a PhD student from the Department of Chemistry, building cross-departmental institutional knowledge and capacity. This was the first visit of two Chemistry department staff to Africa, facilitated by a CISL staff member with significant experience in East Africa and supported by Adoyo Community Consultancy and Biogas International Limited on the ground in Kisumu.

5.3 Capacity building and partnership (Kenya)

The project team made a considered effort to affiliate with Maseno University, allowing it to engage with academic colleagues in Maseno's Environmental Science Department and, briefly, its Department of Public Health. The Cambridge team hosted a visit to the research site for Maseno colleagues, and is currently exploring opportunities for further collaboration.

The team hosted a member of staff from AstraZeneca, Dr Nelson Otieno, who accompanied the engagement with Maseno, establishing common interests on pollution-linked health concerns.

Biogas International staff were involved throughout the study from a technical perspective, putting in place the necessary infrastructure for the monitoring equipment. This work was led by the CEO, Dominic Wanjihia, and a local staff member, Daniel Odhiambo, who supported all aspects of equipment installation, troubleshooting, and with interviewing households. The monitoring equipment was new to the Biogas International team, and there was significant interest in its operation.

Adoyo Community Consultancy's staff members Akoth Omburah and Peter Awinyi received full ethical briefings and project briefings and conducted interviews with households as translators alongside the Cambridge team.

5.4 Interdisciplinary and collaborative research (UK)

A close partnership between CISL, Centre of Development Studies and Department of Chemistry has laid foundations for further partnership work and project development.

5.5 Generating impact from research in and beyond the sectors (DAC and UK)

We envisage CISL using the final report and a short briefing created from this to share with government, business and financial institutions under direction from Dr Jake Reynolds. A number of research and public institutions in Kenya may be interested in these initial findings given the novel technology used. We will follow up over the next six months of the wider project (August to December 2019) with WHO, UNEP, the Clean Cooking Alliance, and the University of Nairobi in addition to our existing stakeholders identified that include Kenya government.

6. Future prospects

6.1 Future expected benefits and impact on Kenya

The team aspires to conceptualising a longer-term research-to-impact programme over the next six months, spanning: (a) two years modelling air quality challenges in different community forms (eg Kenyan urban, peri-urban, rural agricultural, rural pastoral and riverine) as a function of pollution sources; and (b) a further three years assessing the potential of prioritised, strategic interventions in Kenya and DAC countries generally based on the models created. It is hoped any resulting programme will be conducted jointly with local research institutions in the reciprocal manner pioneered by the Cambridge-Africa Programme. The aim will be to build a joint capability with Cambridge which can act as a platform for future research programming and mutual capacity building. If successful, the approach could be expanded to other communities and DAC regions requiring solutions.

6.2 Future work and dissemination

Community feedback

- September 2019: PI and Project Manager will visit Dunga to provide overview results in a meeting of the Dunga biodigester community. The 'control' (non-biogas) households will also be invited to this, or will be visited separately to discuss the results (best approach to be decided in discussion with community facilitators).

Policy outreach and influence

- October 2019: dissemination of final project report to principal stakeholders described in Section 3.3; follow up discussions and continued communication.
- October 2019 develop case study/blog on CISL's research website to amplify messages to public policy, corporate and financial institution network.
- Conference presentations: possible attendance of 2nd World Conference on Global Health and Air Pollution; national presentations dependent on further funding for travel (e.g. Clean Cooking Alliance November 5-7 2019, Nairobi).

Academic outputs and outreach

- Sept-Dec 2019: drafting journal article for publication by end 2020. Further calibration and analysis of results required to produce publication.

Working paper/journal article titled: *'Quantifying the impact of clean fuel switch on indoor air pollution in peri-urban community in Kenya.'*

- October 2019: share final report and discuss with stakeholders including Maseno University and Nairobi University, and Kenya Medical Research Institute.
- March 2020: share results in University of Cambridge seminar on Dunga biogas project.

Using the relationships developed through this project we plan to scan for and consider potential funding applications for air quality and health-related research through GCRF, WHO, UN institutions and UK research bodies (eg Medical Research Council) over the coming 12 months.

7. Conclusions and further opportunities

There is mounting evidence of a causal link between exposure to air pollution and health outcomes. However, due to current limitations in cost, maintenance and availability of instrumentation, most large-scale health studies have focused on developed countries and have relied upon low spatial and temporal resolution, generally using outdoor air quality data as metrics of exposure. This severely limits causal inferences in epidemiological research worldwide. In capturing personal pollution exposure of the population during daily life, emerging low-cost sensing technologies offer a potential ‘paradigm shift’ in addressing this critical shortcoming.

Within the tight timeframe of this study, the team not only shipped monitoring equipment to Kenya, obtained research affiliations, approvals and permits, developed links with a number of key institutions and stakeholders, and built infrastructure within the Dunga community, but also undertook successful primary research. In designing initiatives of this kind in future, we would recommend a minimum operating duration of nine months, preferably 12 months, in order to undertake pre-research preparations in a more realistic manner.

The team noted a significant lack of reliable air quality data in Kenya, and believe that Cambridge is well placed to respond to this deficit in cooperation with in-country partners. At present only one Reference Unit (air quality monitoring) station exists in Kenya which, although mobile, is very limited in data-generation capacity. Several small projects produce area-based or topic-based air quality data, but data concerning personal exposure, place-specific, county level and country level data are lacking, limiting the ability to inform strategies for tackling NCDs arising from poor air quality.

Our preliminary assessment of alternative cooking practices reported on two air pollutants in two households (case and control). Indoor levels of air pollution in both households were higher than outdoor pollution and, between the households, levels of carbon monoxide levels were higher, and statistically significantly different in the household cooking with traditional fuels. Particulate matter levels were also higher in the household using traditional cooking methods, but without a statistically significant difference.

These preliminary findings are purely indicative, and will be supplemented by a full analysis in the coming months. The initial data indicate that innovative, biogas-based cooking technologies can potentially reduce indoor gaseous pollutants significantly (below WHO guidelines). As such they have potential to improve the long-term health outcomes of susceptible subgroups of the population, such as the elderly, young children and women spending a significant amount of time indoors. Our corollary assessment of health impacts on households before and after installation of biogas cooking demonstrates perceived health improvements in many households in respiratory conditions caused by smoke.[18]

Owing to their small size, silent operation and low power consumption, PAMs of the kind used in this study enable the collection of data from challenging, under-researched locations with significant implications for future epidemiological research. Since the monitors are portable and can be carried around by individuals as they go about their daily activities, this study could be greatly expanded on the basis of this initial ‘proof-of-concept’ project.

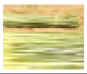
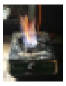
As shown by the high data collection rates, air quality measurement technologies were easily accepted by the local community, albeit within a wider study at the site which generated trust over the preceding 12 months. The present study benefitted from significant technical support from the Kenyan technology company, Biogas International Limited, that was active at the site for the duration of the study, ensuring that monitors continued to operate correctly (the AQMeshes in particular needed periodic attention to power issues) and to move and remove PAMs to storage when not required.

There is substantial interest in Kenya in the monitoring technologies used in this study, including their application to further research in clean cooking practices, and also in air quality measurement generally at county and national levels in Kenya owing to the very limited data currently available. The team proposes to follow up these contacts further with a view to design a larger project with national and international partners. There is a significant opportunity for capacity building in partnership with a national university and multilateral institutions focusing on indoor air quality and health, including UNEP and WHO.

[18] Evaluation of the main Dunga biogas project, report in preparation, contact John Pharoah for further details.

Annex 1: Daily forms for completion by households (Luo)

Households made recordings of the type of cooking stove and fuel they used for the preparation of each meal over a continuous period of seven days whilst a PAM was installed in their kitchen monitoring air quality. In addition, households specified (blue shaded area) whether they cooked inside or outside. This form was produced in the local language, Luo, for ease of completion by households.

NYINGI: PAM:		ODIECHIENG' 1			ODIECHIENG' 2			ODIECHIENG' 3			ODIECHIENG' 4			ODIECHIENG' 5			ODIECHIENG' 6			ODIECHIENG' 7		
		OKINYI	ODIECHIENG'	ODHIAMBO	OKINYI	ODIECHIENG'	ODHIAMBO	OKINYI	ODIECHIENG'	ODHIAMBO	OKINYI	ODIECHIENG'	ODHIAMBO	OKINYI	ODIECHIENG'	ODHIAMBO	OKINYI	ODIECHIENG'	ODHIAMBO	OKINYI	ODIECHIENG'	ODHIAMBO
KENDO MAR RYIEN  	Ei ot																					
	Oko mar ot																					
KENDO MAR OHUNDO  	Ei ot																					
	Oko mar ot																					
 MACH MAR BIOGAS	Ei ot																					
	Oko mar ot																					
 GAS (LPG)	Ei ot																					
	Oko mar ot																					
 STOFF MAR MAFUTA	Ei ot																					
	Oko mar ot																					
 JIKO	Ei ot																					
	Oko mar ot																					

Annex 2: Household interview questionnaire (English)

The following questions were asked to all participating households:

Dunga Beach Air Quality Questionnaire v1

CONFIDENTIAL

Project information sheet ☐ *Consent form* ☐

Interview Number ____________________

Date ____________________

Interviewer(s) ____________________

GPS ____________________

Phone no. ____________________

PAM no ____________________

1. *Respondent background*

1.1 Name ________________________________ 1.2 Age __________ 1.3 Gender F / M

1.4 Married ☐ Widowed ☐ Separated ☐ Single ☐ 1.5 Name of spouse ____________________

1.6 Female headed / Male headed 1.7 How many people stay at this household? ______

1.8 Adults # _____ 1.9 under 18s # _____ 1.10 Dependents # ____

1.11 How many adults and children are present during the day in the household?

1.12 How long have you lived in this community? All your life ☐ *OR* Year you arrived ______________

1.13 What is your total household income per month? *(circle)*

< 5,000 KSh 5,000 - 15,000 KSh 15,000 - 50,000 KSh Over 50,000 KSh

2. Household plan

2.1 Area (m2)

2.2 Year of construction

2.3 Sketch of house plan and placement of the PAM (orientation) (mark kitchen area, any chimneys and window, and any permanent location of 3 stone fire outside the house

3. House characteristics

3.1 Type of house: Wattle & Mud ☐ *Rendered W&M* ☐ *Brick and durable flooring* ☐ *Iron walls* ☐

3.2 *Bathroom (washing facilities/toilet) inside the house: Yes* ☐ *No* ☐

*Short description of bathroom facilities*______________________________________

3.3 Structure of roof: *Flat* ☐ *Sloped* ☐

3.4 Material of roof: *Corrugated iron* ☐ Other _______________________

3.5 Type of floor covering: *Packed earth* ☐ *Concrete* ☐ Other ___________

3.6 Windows. *Brief description (glazed window panes / window frames with solid panel/ open hole:*

____

3.7 Is there a chimney present in the house? *Yes* ☐ *No* ☐

3.8 Can the air flow freely across the house (cross-ventilation)?

3.9 If there is an internal kitchen, do you isolate it from the main living space during cooking activities?

3.10 If there is a kitchen in a separate building, how is it ventilated?

3.11 Heating (if any) ___________________________________

3.12 Do you have electricity? Y/ N

4. Fuel and water uses

	Quantity e.g. 1 bale	Frequency e.g per day/ week/ month/	Costs per unit (KSh)	Total (KSh)	Source	Time spent/ collecting/ preparing	Who is responsible?
5.1 Wood							
5.2 Charcoal							
5.3 Papyrus							
5.4 Paraffin/Kerosene							
5.5 Other fuel source ….							
5.6 Water for household use *(Source: tap, distance to Lake)*							

5. Cooking activity

5.1 What cooking facilities do you have at the moment? 3 stone ☐ Firewood Jiko ☐ Charcoal Jiko ☐

LPG ☐ Biogas ☐ Other _______________________________

5.2 Cooking is done mostly … inside ☐ outside ☐ (notes)____

5.3 How many people do you usually cook for?

5.4 Cooking time record (usually)

Meals cooked	3 stone	Jiko	LPG	Other	Biogas
(record which food)	*Cooking time*				
5.5 Breakfast:					
5.6 Lunch:					
5.7 Dinner:					
5.8 Supper:					
5.9 For selling:					
5.10 Special meals (e.g. nyoyo):					
5.11 Other ...					

6. Health information

6.1 Have you experienced any issues in relation to cooking with firewood, charcoal or papyrus? Y / N

6.2 What are these issues?____

____

6.3 Are you a smoker? *Yes* ☐ *No* ☐

6.3.1 If yes, how many cigarettes do you smoke per day? __________

6.4 How many people smoke indoors in the household?

6.4.1 If you replied yes, how many cigarettes do they smoke per day? __________

6.5 Has anyone in the household suffered from health problems in the last **3 months? *Who?***

Problems with breathing (asthma) .... ☐ ____________________
Respiratory (lung) infection or bronchitis.......................... ☐ ____________________
Heart disease .... ☐ ____________________
High blood pressure.. ☐ ____________________
Dizziness or headache .... ☐ ____________________
Eye irritation/soreness .... ☐ ____________________
Fatigue .... ☐ ____________________
Other issues .... ☐ ____________________
Other issues.. ☐ ____________________
Other issues .... ☐ ____________________

6.6 Has anyone in your household been to a clinic with any of these problems in **last 3 months**? Y/N
6.6.1 (details)____
6.7 Do you think that cooking with biogas has changed or will change any of these problems? Y/N
6.7.1 In what way? ____
6.8 How much do you think you have spent on health related issues in last 3 months? KSh_________
6.9 Do you have health insurance (NHIF)? ______________________________