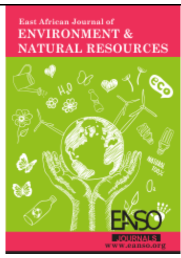
East African Journal of Environment and Natural Resources, Volume 7, Issue 2, 2024
Article DOI: https://doi.org/10.37284/eajenr.7.2.2558



East African Journal of Environment and Natural Resources
eajenr.eanso.org
Volume 7, Issue 2, 2024
Print ISSN: 2707-4234 | Online ISSN: 2707-4242
Title DOI: https://doi.org/10.37284/2707-4242

EAST AFRICAN NATURE & SCIENCE ORGANIZATION

Original Article

Cooking Emissions and Health Effects among Households in Dodoma City, Tanzania

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Article DOI: https://doi.org/10.37284/eajenr.7.2.2558

Date Published:

27 December 2024

Keywords:

Carbon Monoxide, Cooking Energy, Health Effects, Household Air Pollution, and Particulate Matter.

ABSTRACT

Background and objective: The biomass for cooking in Tanzania carries significant health implications and leads to adverse environmental issues such as deforestation. Despite these concerns, there is a lack of information about the nature and extent of cooking emissions within the country. To address this gap, a study was conducted to evaluate cooking emissions and health effects among households in Dodoma City, Tanzania. **Methods:** A descriptive cross-sectional study was conducted using multistage cluster random sampling, 285 households located in the peri-urban of the study area were selected to participate in the study. A combination of questionnaires, observational checklists, and sampling devices (Aeroqual™ S500 for Carbon Monoxide and Temptop® PMD351 for Particulate Matters) were employed for data collection, adhering to established protocols. Collected data were entered into an Excel spreadsheet and analyzed using STATA 17 software. **Results:** Out of 285 participants, 74.7% predominantly use charcoal for cooking, with 68.4% having outdoor kitchen setups. Statistically significant differences in pollutant concentrations were observed across various fuel types, with firewood emitting higher levels of particulate matter and carbon monoxide. Carbon monoxide concentrations during cooking were higher than WHO guidelines for firewood, charcoal-gas, and charcoal. Additionally, a positive correlation between pollutant concentrations was noted. Lung problems 17.8% followed by eye irritation 15.7% were highly mentioned by those who claimed to know the health effects associated with cooking emissions. **Conclusion:** Charcoal and firewood remain the primary cooking fuels in the study area despite their significant negative impacts. Our findings highlight a lack of awareness among community members regarding the health effects of biomass cooking emissions and insufficient guidance on constructing healthy kitchens. To address this, local government authorities should enforce building standards, and raise health awareness among community members.

Article DOI: https://doi.org/10.37284/eajenr.7.2.2558

Also, the engagement of both the public and private sectors is of great importance to ensure affordable access to modern fuels and improved stoves. These measures are essential for promoting healthier cooking practices and mitigating the adverse effects on households.

APA CITATION

Mkunda, M. Y., Anna, G., Ngowi, A. V., Bachwenkizi, J., Anicetus, H. E. & Sichazwe, K. S. (2024). Cooking Emissions and Health Effects among Households in Dodoma City, Tanzania. *East African Journal of Environment and Natural Resources*, *7*(2), 117-137. https://doi.org/10.37284/eajenr.7.2.2558.

CHICAGO CITATION

Mkunda, Mwanini Yakobo, Godson Anna, Aiwerasia Vera Ngowi, Jovine Bachwenkizi, Honest Emanuel Anicetus and Kunda Sichele Sichazwe. 2024. "Cooking Emissions and Health Effects among Households in Dodoma City, Tanzania". *East African Journal of Environment and Natural Resources* 7 (2), 117-137. https://doi.org/10.37284/eajenr.7.2.2558

HARVARD CITATION

Mkunda, M. Y., Anna, G., Ngowi, A. V., Bachwenkizi, J., Anicetus, H. E. & Sichazwe, K. S. (2024) "Cooking Emissions and Health Effects among Households in Dodoma City, Tanzania", *East African Journal of Environment and Natural Resources*, 7 (2), pp. 117-137. doi: 10.37284/eajenr.7.2.2558.

IEEE CITATION

M. Y., Mkunda, G., Anna, A. V., Ngowi, J., Bachwenkizi, H. E., Anicetus & K. S., Sichazwe "Cooking Emissions and Health Effects among Households in Dodoma City, Tanzania", *EAJENR*, vol. 7, no. 2, pp. 117-137, Dec. 2024. doi: 10.37284/eajenr.7.2.2404

MLA CITATION

Mkunda, Mwanini Yakobo, Godson Anna, Aiwerasia Vera Ngowi, Jovine Bachwenkizi, Honest Emanuel Anicetus & Kunda Sichele Sichazwe. "Cooking Emissions and Health Effects among Households in Dodoma City, Tanzania". *East African Journal of Environment and Natural Resources*, Vol. 7, no. 2, Dec 2024, pp. 117-137, doi:10.37284/eajenr.7.2.2558.

INTRODUCTION

Approximately 99% of the global population breathes polluted air that surpasses the air quality guidelines set by the World Health Organization (World Health Organization, 2024). Air pollutants are categorized based on the nature of emission, including gaseous pollutants (such as gases and vapours), suspended particulate matter (PM) (comprising mists, fumes, and smoke), and polycyclic aromatic hydrocarbons (Manisalidis et al., 2020). However, pollutants of major public health concern include particulate matter, Carbon monoxide, Sulfur dioxide, Nitrogen dioxide, and ground-level Ozone(World Health Organization, 2024). These pollutants are generated as a result of either natural processes or anthropogenic activities including biomass use for energy. It is estimated that 2.9 million premature deaths occur annually worldwide as a result of household air pollutants released while using biomass for cooking (Carter et al., 2017).

About half of the world's population and around 95% of the population (Khoshnevis Yazdi & Khanalizadeh, 2017) in developing countries still depend on biomass and coal as a source of energy for cooking and heating. Also, there has been an increase in biomass use for energy particularly in low-income households (Khoshnevis Yazdi & Khanalizadeh, 2017). The use of firewood and charcoal as a source of energy for cooking is common in the United Republic of Tanzania (Hafner et al., 2020). Country reports (The United Republic of Tanzania, 2017) show that 71% of households use firewood as the source of energy for cooking, followed by charcoal 37.0%, liquefied petroleum gas 7.2 % and kerosene 5.0 %. However, firewood is the most common fuel in rural while charcoal and other fuels are commonly used by the majority of households in urban and peri-urban(The United Republic of Tanzania, 2017). Apart from the adverse environmental problems attributed to air pollution like greenhouse gas emissions, deforestation, and erosion that result from biomass use, the emissions released during cooking sessions

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has also health implications(Woolley et al., 2022). When inhaled, the pollutants are known to cause various diseases including lower respiratory infections (LRI) such as pneumonia, chronic obstructive pulmonary disease (COPD); cardiovascular disease, and cancers (Manisalidis et al., 2020; Puzzolo et al., 2024; Qiu et al., 2023; Simkovich et al., 2019).

Efforts have been undertaken globally to address the existing household air pollution problem, including the adoption of stove interventions such as modern stoves equipped with chimneys and enhancing building ventilation. Furthermore, progress has been made towards transitioning away from polluting fuels such as firewood, charcoal, and coal to cleaner alternatives like Electricity, Liquified Petroleum Gas (LPG), and Natural gas. These initiatives align with the objectives of the United Nations Sustainable Goal 7, which seeks to ensure access to clean energy by 2030(*Energy - United Nations Sustainable Development*, n.d.).

In Tanzania, according to the Global Burden of Disease Survey, there was a significant increase in premature deaths due to household air pollution from 22,729 in 2013 to 33,070 in 2019 (Roy, 2016; The United Republic of Tanzania, 2019). Despite this burden, in Tanzania like other developing countries information is scarce about the nature and levels of household air pollutants and associated health risks. Therefore, this study aimed to assess cooking emissions levels and associated health effects among households in Dodoma City, Tanzania. Findings from this study improve the evidence base for implementing public health initiatives regarding energy use for cooking among households.

MATERIALS AND METHODS

Study area and design

A descriptive cross-sectional study was conducted in Dodoma City, the City covers 2,769 km^2 with a population of 765,179 (The United Republic of Tanzania, 2022). It is located at *latitude 6°10'19.96"S and longitude 35°44'22.09" E.* Administratively, the city has four divisions which are Kikombo, Hombolo, Dodoma and Zuzu which are further subdivided into forty-one wards. (Figure 1) shows a map of the study area.

Sampling procedures

A multistage cluster random sampling was employed for this study. Hombolo, Kikombo, and Zuzu divisions were purposively selected for data collection. These divisions are located at the peripherals of the city, the selection of peri-urban areas relies on the fact that households in peri-urban use different kinds of sources of cooking energy of interest in this study (The United Republic of Tanzania, 2017). Five wards were randomly selected from selected divisions, two from the Hombolo division i.e Hombolo Bwawani (households 5,332), Makutupora (households 5,472); two from Zuzu division i.e Nala (households 3,407), Mbabala (households 4,385); and one ward from Kikombo division i.e Mtumba (households 4,249). Moreover, one Street (Mtaa) (the lower administrative unit in the town setting) was randomly selected from each selected ward. From overall selected streets a total of 285 households were randomly selected to participate in this study.

Within this sample, 15 households were monitored for levels of PM (Particulate Matter) and CO (Carbon Monoxide). Among these households, four exclusively used firewood, six utilized charcoals, and three relied on gas as their primary fuel source. Additionally, two households employed a combination of charcoal and gas for their cooking needs. The distribution of the households sampled for cooking emissions considered that charcoal was predominantly used followed by firewood and gas in a study area.

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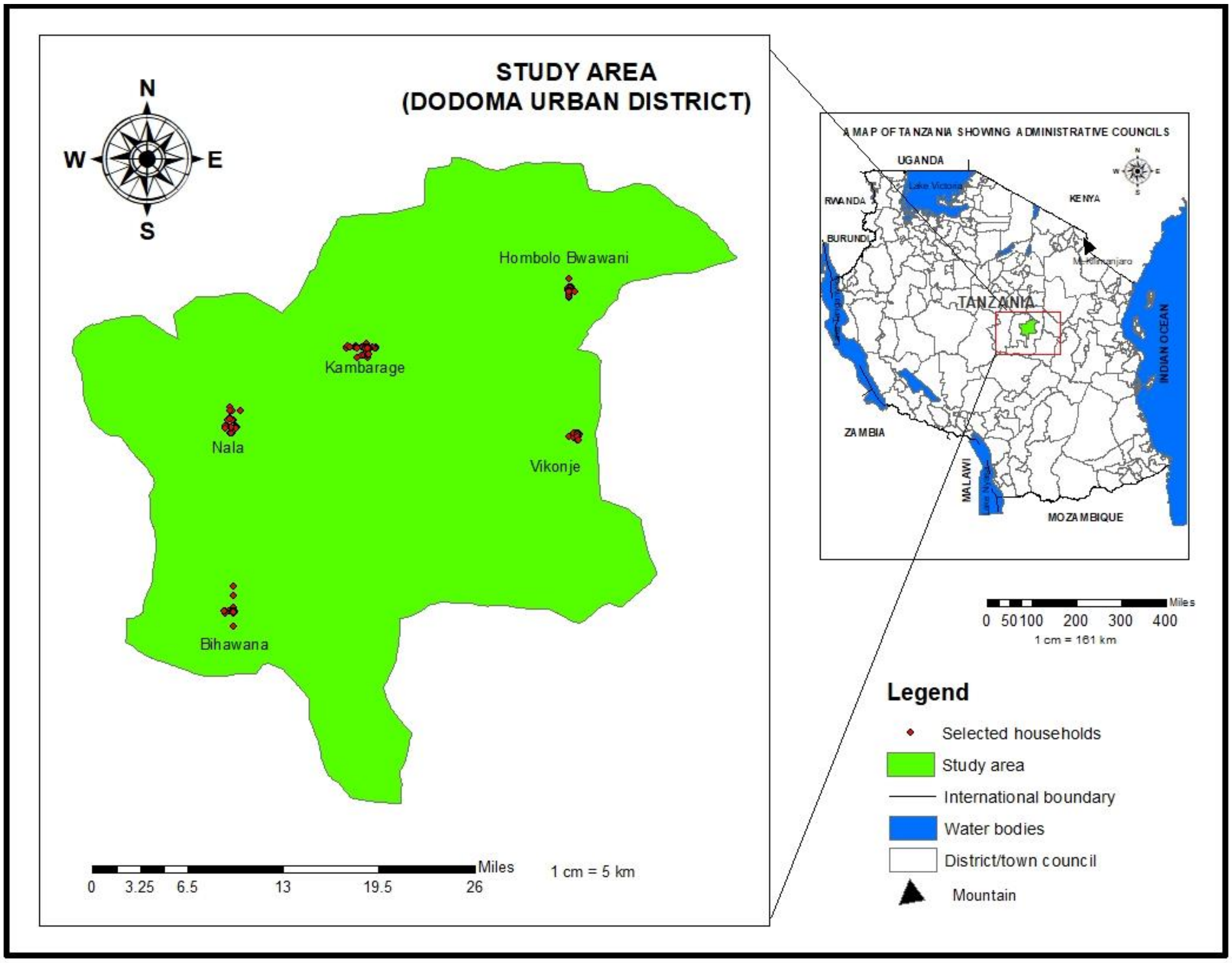
Figure 1. A map showing a study area



Data collection tools and procedures

A detailed questionnaire and observational checklists were used to collect information about perceived health effects and other parameters potentially relevant to indoor air pollution. The questionnaire was divided into three major sections which were socio-demographic characteristics, accessibility of cooking fuel and cooking practices, health problems associated with cooking emissions and exposure management.

The administered questionnaire was translated into the Swahili language to enhance the understanding of the respondents. The questionnaire was pre-tested and corrections were made for clarity. Those corrections included rephrasing and changing the flow of some questions.

We used Temptop® PMD351 made by Elitech Technology Inc., United States (Temptop, 2021) and Aeroqual™ series 500 made by Aeroqual Limited, New Zealand for monitoring of PM and CO respectively. Both devices are handheld portable and real-time air quality monitoring devices have been used in previous studies (Kumar et al., 2022a; Mohammed, 2023; Remington et al., 2022). The Temptop® PMD351 device has five channels for simultaneous detection of PM_{10}, $PM_{2.5}$, $PM_{4.0}$, $PM_{1.0}$, and TSP (Total suspended particles) mass concentration. Also, the Temptop® PMD351 sensor uses light scattering (optical sensor) to measure the particle number and size distribution of materials suspended in the air. Aeroqual™ series 500 can measure up to 30 pollutants(AEROQUAL, 2022) by using different sensors but as per our objectives, only the CO sensor head was employed.

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Both devices were manufacturer-calibrated prior to their use. Also, during operation, the Temptop® PMD351 device was Zero calibrated on a weekly basis using a standard filter. Temperature and relative humidity are the important meteorological parameters that influence the detection of pollutants by using Low-cost sensors like Aeroqual S500 and Temptop® PMD351(Crilley et al., 2018; Wang et al., 2021). In this regard, the temperature and relative humidity were monitored along with pollutants. Particulate matter data is generally required to be corrected for the hygroscopic growth of particles at the RH higher than 85%(Crilley et al., 2018; Jayaratne et al., 2018). We did not apply any corrections since our data were within the acceptable RH range. A tape measure was used to measure kitchen room dimensions which determined the ventilation of the room and concentration of emissions.

Ethical clearance with IRB no. UI/EC/23/0255 was obtained before study from the University of Ibadan. This study was also ethically certified by the Tanzanian National Institute of Medical Research (NIMR). Moreover, before data collection, the local government authorities of the study area were well informed.

Exposure assessment

The monitoring of emissions was conducted in the cooking places which were classified as indoor kitchens with/without partitions, outdoor enclosed kitchens, outdoor semi-enclosed kitchens, and open-air kitchens. As illustrated in supplemental materials Figure S2, an indoor kitchen with no partition was a type of kitchen whereby cooking practices took place in one of the living rooms. The indoor kitchen with partition was the type of kitchen in which the stove/ cooking activities took place in a specially allocated room within the main house. The outdoor enclosed kitchen was the one where the kitchen room was located outside the main house and with an enclosed structure. The outdoor semi-enclosed kitchen was the type of kitchen located outdoors with semi-enclosed structure for instance one/two sides wall with/without roof materials.

The monitoring activity took place between August 12, 2023, and October 16, 2023. A total of 15 households were monitored, with each household being observed for four days. Measurements were done during the preparation of lunch and dinner of which the devices were allowed to run 15 minutes before and after preparations of the food. During sampling, instruments were placed 3 inches apart at the average adult breathing height of 150 cm and 150cm away from the cook/stove (Chowdhury et al., 2012; Kumar et al., 2022a). The logging of data in both devices was at a rate of one minute however, the average concentration in each type of fuel sampled was calculated to compare it with WHO global air quality guidelines. Consent to monitor was usually obtained from a head of household the previous day and the cooking times were determined at the beginning of the day to facilitate scheduling of the monitoring. Also, sampling records were taken about the type of fuel that was used at the time, cooking style, type of food that was prepared, number of kitchen occupants, total time spent in the kitchen, observed health symptoms, and management of smoke. Figure 2 shows the positioning of air quality samplers in a study field.

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Figure 2. Positioning of air quality sampler

Statistical analysis

Each household involved in the study received a unique identification number. Questionnaire responses were recorded and entered into an Excel spreadsheet. Air quality monitor and spirometer data were retrieved via USB connections and manufacturer software. Analysis was performed using STATA version 17. Descriptive statistics and graphical representations were used to summarize data, with continuous variables presented as both mean and standard deviation or median and interquartile range (IQR). Inferential statistics included the Kruskal-Wallis's test, Wilcoxon signed-rank test, and Spearman rank correlation were used to test for the association. The selection of these tests was due to the data structure of our study which involved not normally distributed data, continuous and categorical variables.

RESULTS

Demographic characteristics

As shown in Table 1, the majority of the household heads were in the age group of 15-62 years old while the least group represented by those with 94 years old and above was only 0.35%. Also, more than half of all heads of households were male and married. Around half of selected households had at least one under-five-year-old child with a mean age of 2.4 years ±1.199. It was found that around half of all respondents had attained primary education level while only 14.9% had attained secondary school and above. 82.1% of respondents were self-employed and the average household's monthly income for the majority was below 300,000 Tanzanian shillings.

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Table 1. Demographic characteristics of the respondents

Demographic variables		Frequency	Percent	Cumulative percent
Age of household's head	15- 30	48	16.84	16.84
	31- 46	89	31.22	48.06
	47- 62	79	27.74	75.80
	63- 78	45	15.78	91.58
	79- 94	23	8.07	99.65
	94+	1	0.35	100.00
	Total	**285**	**100.00**	
Sex of household's head	Female	97	34.04	34.04
	Male	188	65.96	100.00
	Total	**285**	**100.00**	
Marital status	Single (Never married)	17	5.92	5.92
	Cohabiting	2	0.70	6.62
	Married	184	64.81	71.43
	Separated	20	6.97	78.40
	Divorced	6	2.09	80.49
	Widowed	56	19.51	100.00
	Total	**285**	**100.00**	
Presence of <5years children	Yes	146	50.87	50.87
	No	138	49.13	100.00
	Total	**285**	**100.00**	
The education level of respondents	No formal education	62	21.60	21.60
	Incomplete primary school	28	10.10	31.7
	Complete primary school	152	53.31	85.01
	Complete secondary school (Form four)	34	11.85	96.86
	Incomplete secondary school	1	0.35	97.21
	More than secondary school	8	2.79	100.00
	Total	**285**	**100.00**	
Occupation of respondents	Self-employed	234	82.1	82.1
	Employed	29	10.1	92.2
	Not working	19	7.8	100.00
	Total	**285**	**100.00**	
Average income per month (TSH)	≤300000	212	74.4	74.4
	310000-500000	32	11.2	85.6
	510000-700000	22	7.7	93.3
	710000-900000	4	1.4	94.7
	910000+	3	1.1	95.8
	No response	12	4.2	100.00
	Total	**285**	**100.00**	

Fuel use patterns

Regarding fuel use, as shown in Table 2, the majority of respondents were using charcoal for cooking but none of the respondents depended on kerosene/animal waste. Also, most of the respondents had an energy mix with charcoal playing a big role. Only less than one per cent of respondents accessed the cooking energy through

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charity (being brought by relatives) but the majority of them used to access it through either buying from vendors or fetching directly from the nearby forests and the fetching time ranged between 40 minutes to 8 hours. Supplemental materials Figure S1 shows the storage of fetched firewood in the household. The monthly household's income influenced primary cooking energy (P-value=0.0001), respondents spent per meal on average 560, 600, and 400 Tanzania shillings for buying charcoal, firewood and gas respectively. About 60.98% of respondents had electricity as the source of energy for lighting while the least group 2.787% used kerosene. Other sources were solar, flashlights on their mobile phones and normal flush light torches.

Table *2*. Household's Sources of Cooking Energy

Sources of cooking energy		Frequency	Per cent	C.Percent
Primary cooking energy	Charcoal	85	29.83	29.83
	Firewood	164	57.54	87.37
	Gas	36	12.63	100
	Total	**285**	**100**	
Secondary Cooking energy	Charcoal	128	44.9	44.9
	Crops residue (Maize corn)	7	2.5	47.4
	Electricity	2	0.7	48.1
	Firewood	31	10.9	59
	Gas	56	19.6	78.6
	None	61	21.4	100
	Total	**285**	**100**	

Cooking practices

In our study, the kitchens for the large group about 68.4% were located outdoors in either an enclosed room, semi-enclosed structures, or open-air as shown in supplementary materials table S1. About 55.3% of kitchens had their walls constructed using mud while few were made up of grass/leaves/cloths. Also, about 97.8% of kitchens had their roof materials made of metal sheets. All the kitchens in this study were using natural ventilation. Also, 88.3% of enclosed kitchens had at least one window while the remaining had none. Table 3 stipulates the kitchen's dimensions. Figure 3 shows the field pictures of kitchen and stove designs. The traditional three-stone stoves were common among firewood users. Charcoal stoves were commonly made of either round metal barriers or metal casing with inner ceramic liners. Gas users had either two plate stoves or one plate stove commonly placed on a table or the floor.

Table 3: Household's Kitchen dimensions

Variable	Door's area(m^2)	Window's area(m^2)	Volume(m^3)
Median	1.394	0.404	19.55
IQR	0.479	1.05	21.80
Minimum	0.509	0	2.7
Maximum	3.57	2.88	175.5

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Figure 3: Field picture showing Kitchen's and stove's design

A. Outdoor enclosed kitchen (Roof= Metal sheet Wall=Mud) B. Charcoal stoves C. Gas cylinder and stove on a table J. The use of plastics during fire ignition
D. Outdoor semi enclosed kitchen (Roof= Canvas fabric Wall=Textiles) E. Outdoor semi enclosed kitchen (Roof=Metal sheets Wall= Woods and fabrics)
F. Three stones Firewood Stove G. Outdoor enclosed kitchen (Roof =Mud Wall= Mud) H. Two plate gas stove (On table) and Gas cylinder

The cooking activities in about 98.25% of the households were conducted by females. Also, as stipulated in Figure 4, the number of kitchen occupants during cooking was reported to reach up to 4 people. The majority were frequently using the steaming method and the remaining were using the frying method. Ugali (stiff porridge) and rice were the common foods prepared. Cooking of ugali for instance involves boiling water, adding maize/millet flour, and mashing the solid mix until it is well cooked. Moreover, the preparation of stew involved both frying for a few minutes and steaming. The number of meals prepared per day ranged between 1 to 3 also, the meal preparation time ranged between 15 minutes to 180 minutes. The cooking activity started with lighting of the stove of which the use of small pieces of wood, grasses/leaves and plastics to help the process was common among firewood and charcoal users. After the cooking session was done the heating of water for bathing was common among households, particularly during the preparation of dinner.

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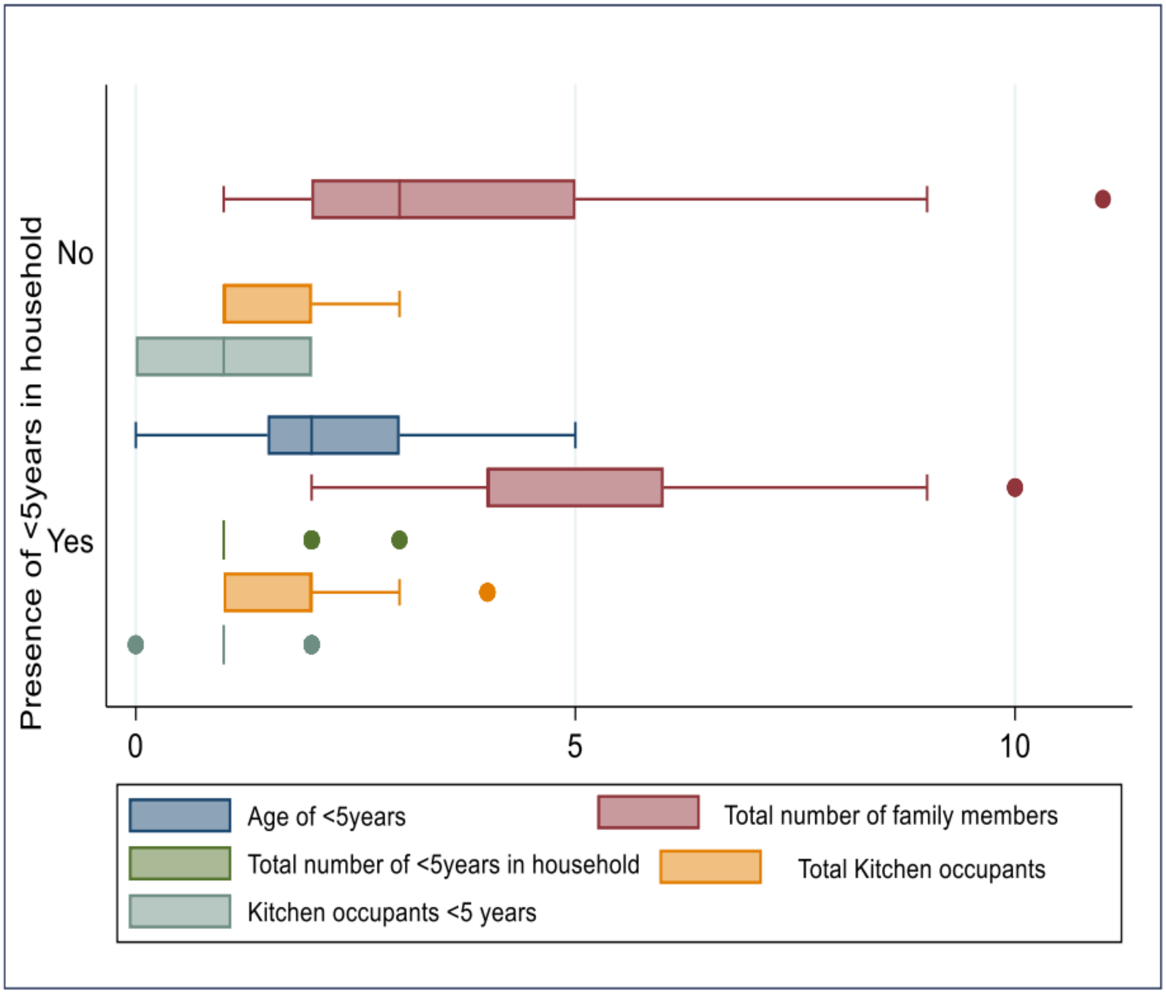
Figure 4: Family size and kitchen occupants during cooking session



Health Effects of Exposure to Household Air Pollutants

In this study, participants were asked if they thought that the cooking fuel emissions had any health effects. The majority 71.93% knew that there were health effects, 18.95% didn't know and 9.12% said there was no health effect. Health effects mentioned by those who knew included Chest pain 7.7%, eye irritation 15.7%, lung problems 17.8%, Chest tightness 0.7%, coughing 11.5%, headache 2.8%, shortness of breath 2.1%, watery eyes 0.7%, Sneezing 0.3%, Suffocation 1.4%, TB 0.7%, Nose Irritation 0.35%, Blood and body water loss 0.35%, and Liver problems 0.35%.

As it's shown in Figure 5 Watery eyes, coughing and headache were signs commonly experienced by users of both firewood and charcoal. On the other hand, gas users reported no health symptoms during cooking sessions. As stipulated in Table 4 below firewood users reported more health symptoms than users of other fuels in the last 12 months. 68% of all wheezing cases experienced wheezing/whistling when they did not have a cold/flu, also the majority had shortness of breath when the wheezing noise was present. Moreover, the majority of those who had ever experienced an attack of shortness of breath, the attack came on during the daytime when at rest. The coughing cases were commonly reported among the main household's cooks and children while in few were other members of the

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family. Among all coughing cases, only around 30% had coughing accompanied by rapid breathing. Apart from, the main household cook other family members particularly children were reported to have this health.

Figure 5: Perceived health symptoms during cooking sessions among firewood users and Charcoal users

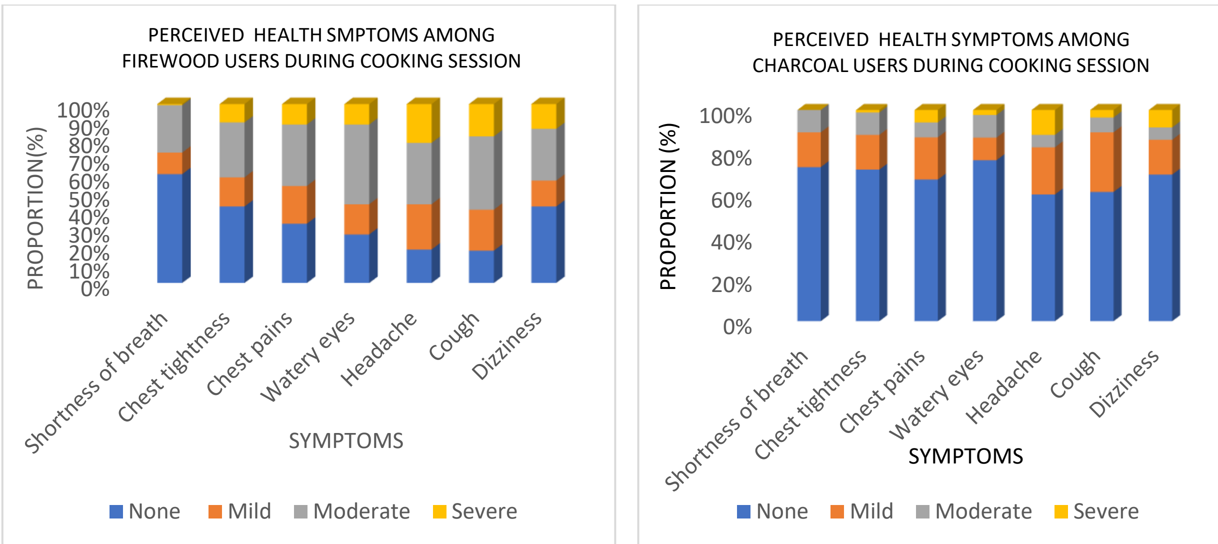

Table 4: Perceived health symptoms in the last 12 months

Variables		Primary cooking energy			Total
		Charcoal	**Firewood**	**Gas**	
Wheezing or whistling in the chest	No	70 (82.4)	118 (72.0)	32 (88.9)	219 (76.8)
	Yes	15 (17.6)	46 (28.0)	4 (11.1)	66 (23.2)
	Total	**85**	**164**	**36**	**285**
Ever woken up with a feeling of tightness in your chest	No	64 (75.3)	111 (67.7)	33 (91.7)	209 (73.3)
	Yes	21 (24.7)	53 (32.3)	3 (8.3)	77 (26.7)
	Total	**85**	**164**	**36**	**285**
Attack of shortness of breath	No	60 (70.6)	91 (55.5)	30 (83.3)	181 (63.5)
	Yes	25 (29.4)	73 (44.5)	6 (16.7)	104 (36.5)
	Total	**85**	**164**	**36**	**285**
At least one family member had coughing problems	No	27 (31.8)	46 (28.0)	25 (69.4)	98 (34.4)
	Yes	58 (68.2)	118 (72.0)	11 (30.6)	187 (65.6)
	Total	**85**	**164**	**36**	**285**
Usually bring up any phlegm from your chest first thing in the morning	No	60 (70.6)	96 (58.5)	31 (86.1)	**187** (65.6)
	Yes	25 (29.4)	68 (41.5)	5 (13.9)	**98** (34.4)
	Total	**85**	**164**	**36**	**285**

Pollutant concentration and their variability

Results show that the median temperature was 28.6°C (P-value < 0.05) while the average relative humidity was 40.6% (P-value > 0.05). During the sampling of pollutants, the average cooking time per type of fuel was 46 minutes for firewood, 54 minutes for charcoal, 38 minutes for gas, and 48 minutes for the kitchen which used gas and charcoal simultaneously.

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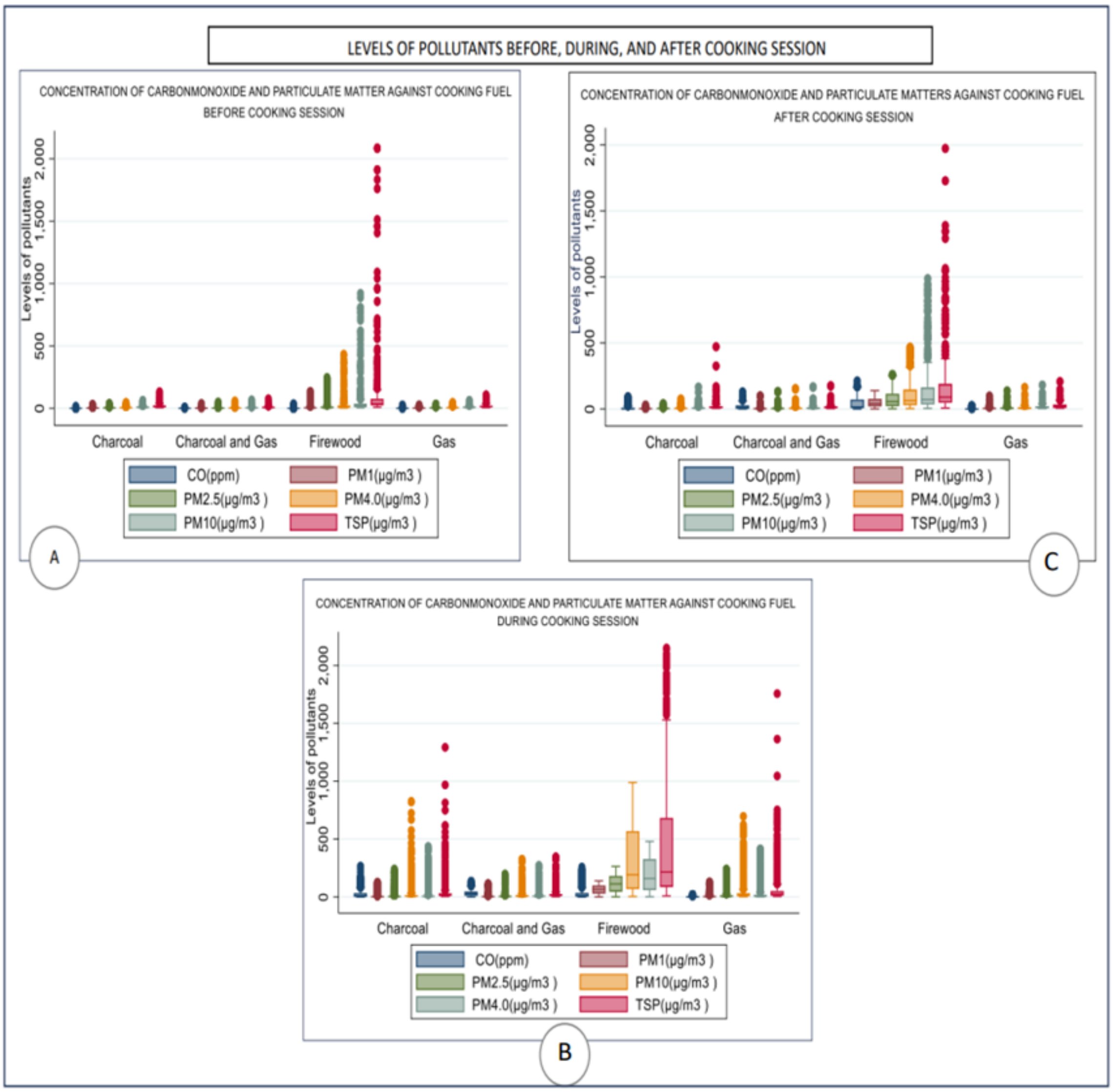
There was a statistically significant difference in the concentration of pollutants among different types of fuel (Kruskal-Wallis rank test P-value=0.0001). Moreover, as stipulated in Figure 6, the concentrations were significantly higher (Wilcoxon sign rank test P-Values <0.05) during the cooking session and dropped after the session. When the cooking session was going on, firewood had the highest average concentration of CO about 36.04527ppm while gas had the lowest average concentration of 2.666853ppm. Moreover, firewood had the highest median concentration of TSP, PM_{10}, PM_4, $PM_{2.5}$, and PM_1 about 115.3 µg/m^3 (379.9), 192.5 µg/m^3 (496.8), 159.8 µg/m^3 (265.8), 113.2 µg/m^3 (133.4), and 65.4 µg/m^3 (65.8) respectively.

Figure *6*: Pollutant levels (A) before (B) during and (C) after the cooking session



Furthermore, the peak concentrations of PM across all types of fuels and kitchens were found to be in the order of $PM_1 < PM_{2.5} < PM_4 < PM_4 < PM_{10} < TSP$. The maximum levels of pollutants were relatively low in the outdoor open-air kitchen. Moreover, there was a positive correlation between concentrations among pollutants, and temperature but a negative correlation between particulate

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matter and relative humidity as shown in Supplemental materials (Figure S3) and (Table S2).

Other potential sources of exposure to air pollutants were also determined. It was found that about 12.98% of all respondents reported having at least one member of the family who is a cigarette smoker. Also, 37.89% of all respondents reported the burning of coils/tabs for repelling mosquitoes. Additionally, about 30.18% of all respondents had open-fire trash burning near the house.

DISCUSSION

In this cross-sectional study, we observed significant differences in pollutant concentrations across various fuel types, with firewood emitting higher levels of particulate matter and carbon monoxide. Carbon monoxide concentrations during cooking were higher for firewood, compared to WHO daily average limits. Health effects mentioned by those who knew included lung problems followed by eye irritation.

Fuels use patterns

The study findings revealed diverse fuel usage patterns, aligning with prior reports. Urban households primarily consumed charcoal (79%), followed by firewood (28%) and LPG (20%) (Ishengoma & Igangula, 2021). Similar trends were observed in Rwanda(Woolley et al., 2022) where 75% of participants favoured charcoal. Notably, no respondents in this study relied on kerosene or animal waste, diverging from Nigerian findings (Mbanya & Sridhar, 2017) where kerosene ranked second after firewood. National policies favouring cleaner fuels have led to a decline in kerosene usage(Doggart et al., 2020) from 42% in 2001 to 3% in 2018. Despite abundant firewood access initially, urban expansion has led to scarcity, prompting the use of less preferred, smokier species like *Mapululu*. This parallels findings in Nepal (Dahal & Parajuli, 2020) and Kenya (Jung & Huxham, 2018a) where various tree species were utilized for firewood. Escalating biomass scarcity forces low-income households to resort to high-polluting alternatives like plastics, exacerbating health risks. Significant time investments in firewood collection pose economic and social burdens, particularly for women and children. Some households supplement income by selling firewood, complicating efforts to transition to alternative fuels. Cooking energy selection hinges on financial capacity, accessibility, and food type with concerns about LPG safety and refill costs inhibiting its widespread adoption. Respondents favoured firewood due to its accessibility, affordability, quick cooking, and flavour enhancement, consistent with findings in Nepal. Despite increased electricity access (64.8%), electric stove usage remains negligible (<1%) due to high operational costs, reinforcing the persistence of fuel stacking patterns.

In fuel stacking patterns households keep on using traditional fuels along with modern fuels despite of availability of modern types of cooking energy and avoid complete transformation to modern fuels(van der Kroon et al., 2013). This was also observed in Dar es Salaam (Alananga & Igangula, 2022) where it was acknowledged that modern fuels are more efficient and cleaner but households kept on using a combination of both due to price reasons. National Energy Policy of 2015(The United Republic of Tanzania, 2015) point out that in order to achieve the country’s desired socio-economic development, modern energy services play a crucial role. Also, the National Clean Cooking Strategy of 2024-2034(The United Republic of Tanzania, 2024) calls for different stakeholders both in the public and private sector get engaged in ensuring easy access to modern sources of cooking energy.

Cooking practices

Cooking practices and kitchen conditions were also investigated altogether have a significant contribution to emission levels. Similarly to what was observed in Rwanda(Woolley et al., 2022), the majority had outdoor kitchens. The use of outdoor open-air or semi-enclosed kitchens poses a risk of shifting the cooking activity from outside to inside, particularly during unfavourable weather

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conditions. Altogether the habit of cooking indoors in a living room increases the chance of other family members apart from the main cook getting exposed to the emissions. A study conducted in China(Zhang & Smith, 2007) pointed out that room layout/house structure can significantly affect temporal and spatial distributions of pollutant concentrations within a household. Moreover, the decision to cook inside the main house made by the majority of charcoal and gas users in this study is casually influenced by the relatively low smoke level produced by these kinds of fuels compared to firewood. However, the absence of smoke doesn't mean that there are no other invisible emissions emitted from the fuel hence it is important to keep on maintaining the ventilation of the room. The use of natural ventilation as the only option in this study differs from the observation (Kumar et al., 2022b) made in twelve global cities in which mechanical ventilation was found in some home kitchens. The absence of modern firewood stoves in this study might be influenced by the low coverage of Improved cooking stove projects in a region implemented by several development partners within the country. The great variation in dimensions of the kitchen among households observed among participants of this study is evidence of lacking of proper guidelines on designing of kitchen and its location.

In this study females either mother/wife, elder daughter, or household maid were highly engaged in the cooking activities. This is because traditionally in developing countries cooking is exclusively done by women and it occupies up to 50% of women's daily duties compared to other family members(Bwenge, 2011). Also, apart from the main household's cooks, others may accompany him/her during cooking sessions. The reasons for the occupancy of non-cook were waiting for food, nursing, visitation, and helping with cooking activities. This implies that non-cooks get exposed to the emissions, hence promoting clean cooking in the household not only saves the main cook but also other members of the family.

Health Effects of Exposure to Household Air Pollutants

Results show that most of the mentioned effects are short-term, which means that respondents had low knowledge of other effects like heart diseases, stroke, stillbirth etc. as suggested in other studies (Kumar et al., 2022b). Those who said no health effects had a concern that they had been using biomass for their whole life and thought that not being hospitalized/ having serious symptoms during cooking sessions meant that biomass use was safe. This establishes a need for community health awareness of the long-term effects of biomass emissions as other studies suggest the significant role of cumulative exposure on associated health impacts (Kumar et al., 2022b). The symptoms experienced by participants of this study are supported by similar symptoms reported in Nigeria (N. Mbanya & K. C. Sridhar, 2017) and Bagamoyo (Kilabuko et al., 2007).

As it is already mentioned that women are highly engaged in cooking activities, it is important to integrate clean cooking awareness into maternal health programs. Also, strengthening health education about clean cooking during community workshops.

Pollutant concentration and their variability

Supported by (Balakrishnan et al., 2013) in India, pollutant levels in our study varied across types of cooking fuel. The concentration of CO emitted by firewood is similar to what was observed in Nepal (Sapkota et al., 2010) and Kenya (Jung & Huxham, 2018b). According to (World Health Organization, 2021) the CO daily permissible limit is 7 mg/m^3. In our study, the average concentration of carbon monoxide among firewood, Charcoal-gas, and Charcoal during cooking sessions was above the WHO daily average. However, the concentration of gas was below the WHO limits.

As already shown, in the study, it was found that firewood emitted a relatively high concentration of PM_{10} which is similar to(N. Mbanya & K. C.

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Sridhar, 2017) in Ibadan whereby Wood users were exposed to significantly higher levels of PM_{10} during the cooking time (1640 µg/m^3) than charcoal users (1159µg/m^3) and users of modern fuels (LPG and electricity) (300µg/m^3). (Kilabuko et al., 2007) Bagamoyo showed that firewood had experienced the episodic peak concentration of PM_{10} which varied from 3200 to 10000µg/m^3. These levels were very high compared to the findings of this study because the measurement was taken in rural settings and the dimensions of the kitchens and fuel use practices might differ from the peri-urban settings of this study. The peak concentration of PM2.5 emitted by firewood was not similar to what was reported by (Sapkota et al., 2010) in Nepal whereby the concentration of $PM_{2.5}$ among firewood users was up to 850 µg/ m^3. These differences in concentrations might be attributed to differences in the wood species used in these studies. In another study (Kumar et al., 2022b) which involved global cities the peak concentration of $PM_{2.5}$ was high among charcoal (200 µg/m^3) followed by gas users (150 µg/m^3) which is similar to the findings of this study.

(World Health Organization, 2021) recommends permissible level of 25 µg/m^3 and 50 µg/m^3 as a daily average for $PM_{2.5}$ and PM_{10} respectively. While Gas and charcoal emitted the concentrations of PM_{10} and $PM_{2.5}$ which were below WHO daily exposure average limit, the firewood emitted the concentration which was almost 4 and 5 times higher respectively. However, during frying/ when there was pollution from the outdoor environment the peak concentrations in households using LPG and charcoal were above the standards. This is also supported by (Kumar et al., 2022b) which showed that the cooking method and type of food prepared influence the amount of particulates released in the air. For instance, grilling, deep or shallow frying, stir-frying, roasting, and charbroiling vary in levels of emission of particulate matter(Apte & Salvi, 2016). Additionally, the type of food prepared for instance the meat, the type of oil used for cooking, and the amount of fat in the meat also influence the levels of the emissions.

Having gas as a second leading after firewood with higher peak concentrations of TSP and PM_1 in the study is not similar to (Tiwari et al., 2013), the tests revealed the order of poor air quality being high in firewood and least in the LPG. This is because compared to experimental studies performed under controlled conditions, other conditions like the contribution of outdoor air conditions to indoor air quality in field studies might lead to poor air quality even when relatively cleaner fuels are used. Additionally, the fact that other sources of exposure to pollutants were mentioned apart from household cooking fuel use, means that any intervention which focuses on clean cooking could reduce the burden of exposure to pollutants.

The findings from this study provide a baseline and reveal opportunities to reduce exposure to in-kitchen air pollution. The study area has given an important mixture of data which might be applicable in both urban and rural areas.

In this study, the small sample size for in-kitchen air quality monitoring is the main limitation and this was because of limited available resources in terms of time and devices to capture a large number of households. However, to make sure that the objectives of this study were met, households were purposively selected by critical considerations of factors that affect the levels of pollutants to be monitored to get findings from households with varying characteristics.

CONCLUSION

The results of this study reveal that firewood (utilized in three-stone fires) and charcoal remain the predominant sources of cooking energy in the study area, despite their significant adverse environmental, social, and health consequences. Moreover, the study highlights a concerning lack of awareness regarding the detrimental effects of biomass cooking emissions, coupled with a dearth of guidance on constructing safe and healthy kitchen environments.

Therefore, responsible local government authorities prioritize the enforcement of building standards including improved ventilation design. It is important for both the public and private sectors to support the National Clean Cooking Strategy (2024-2034) to enhance access to modern fuel alternatives and improved cook stoves including subsidizing the services. Community health education efforts should be intensified regarding the short- and long-term impacts of cooking emissions. This includes the integration of clean cooking awareness in maternal health programs. These measures are essential for promoting healthier cooking practices, mitigating environmental degradation, and safeguarding public well-being in the study area and beyond. Moreover, further investigations are recommended for personal exposure to cooking emissions as well as lung function tests among the main household cooks across sources of cooking energy.

AUTHORS CONTRIBUTION

M.Y. Mkunda helped in the design of the study, collection and analysis of data, creation of study reports and writing of manuscript. G. Anna, and A.V. Ngowi research advisors, reviewing and editing the manuscript. J. Bachwenkizi participated in the data collection process, reviewing and editing the manuscript. Honest Emanuel Anicetus participated in data collection. Ms. Kunda Sichele Sikazwe participated in data collection.

ACKNOWLEDGEMENTS

The authors wish to thank the Tanzania Ministry of Health, Tanzania Industrial Development Organization (TIRDO), and the Local government authority of the study area for the support and cooperation which was given leading to the accomplishment of this work. Funding for this research was provided by the African Union Commission through the Pan African University Life and Earth Sciences Institute (Including Health and Agriculture), Ibadan, Nigeria.

ABBREVIATIONS

CO	Carbon monoxide
PM_1	Particulate matter of less than 1 µm in mean aerodynamic diameter
$PM_{2.5}$	Particulate matter of less than 2.5 µm in mean aerodynamic diameter
PM_4	Particulate matter of less than 4 µm in mean aerodynamic diameter
PM_{10}	Particulate matter of less than 10 µm in mean aerodynamic diameter
TSP	Total Suspended Particles
WHO	World Health Organization
<	Less than
%	Per cent

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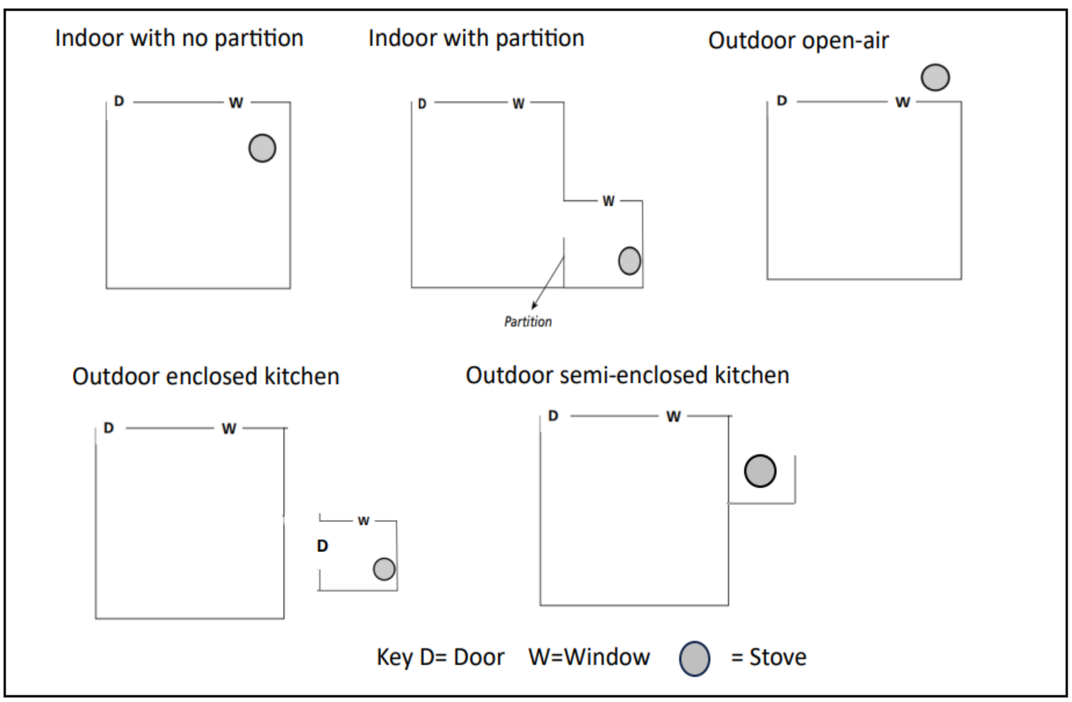
Article DOI: https://doi.org/10.37284/eajenr.7.2.2558

Supplemental figure

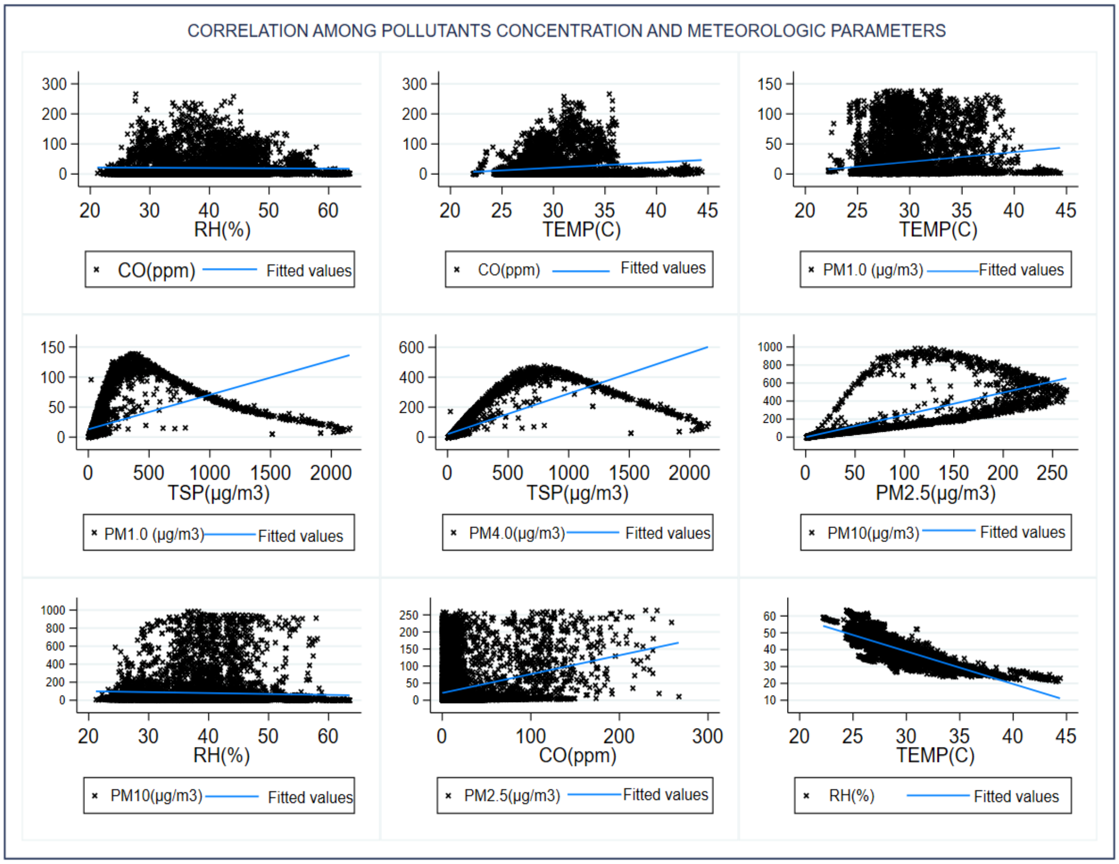
Figure S1. Storage of fetched firewood in the household

Figure S2. Sketch diagram showing the location of the kitchen



East African Journal of Environment and Natural Resources, Volume 7, Issue 2, 2024
Article DOI: https://doi.org/10.37284/eajenr.7.2.2558

Figure S3. Correlation among pollutant concentrations, temperature and relative humidity



Supplemental tables

Table S1 Location of kitchen among households and types of fuel used

Location of kitchen	Primary cooking energy			
	Charcoal	Firewood	Gas	Total
Indoor kitchen with no partition	27	22	17	**66**
Indoor kitchen with partition	14	0	11	**25**
Outdoor semi-enclosed kitchen	10	48	1	**59**
Outdoor enclosed kitchen	23	57	7	**87**
Outdoor open-air kitchen	11	37	0	**48**
Total	**85**	**164**	**36**	**285**

Table S2. Spearman rank correlation coefficients among pollutant concentrations and meteorologic parameters

Variables	CO (ppm)	PM_1 (µg/m^3)	$PM_{2.5}$ (µg/m^3)	PM_4 (µg/m^3)	PM_{10} (µg/m^3)	RH (%)	TEMP (°C)
CO (ppm)						0.0619	0.1568
PM_1(µg/m^3)	0.2835					-0.1842	0.1666
$PM_{2.5}$(µg/m^3)	0.2833	0.9937				-0.1816	0.1591
PM_4(µg/m^3)	0.2788	0.9790	0.9948			-0.1828	0.1548
PM_{10}(µg/m^3)	0.2689	0.9513	0.9763	0.9920		-0.1897	0.1530
TSP(µg/m^3)	0.2419	0.9034	0.9365	0.9623	0.9869	-0.2060	0.1553
TEMP (°C)						-0.8321	

