Reduced Indoor Air Pollution but Increased Cooking Time and Fuelwood Consumption of Improved Local Cookstoves in Asuogyaman, Ghana: Implications for Appropriate Stove Design

S. K. Mawusi[1], D. Nukpezah[1*], P. Awudor[1], J. C. Oppong[1], A. B. Asare-Ansah[2], and T. Y. Annang[1]

[1] *Institute for Environment and Sanitation Studies, University of Ghana, P. O. Box LG 209, Legon - Accra.*

[2] *Centre for Remote Sensing and Geographic Information Services, University of Ghana, Legon - Accra.*

*Corresponding Author: *dnukpezah@ug.edu.gh*

Abstract

The intense wood extraction and use in traditional stone fires (TSF) for cooking in the Asuogyaman district in Ghana are associated with deforestation and indoor air pollution (IAP). Therefore, efforts have been made by the volta river authority (VRA) to provide improved local cookstoves christened "climate-smart stoves" to inhabitants of this region. However, these improved cookstoves (ICS) were designed to hold two cooking pots concurrently, contrary to the typical traditional cooking practice of using one pot in the Asuogyaman District. Although this may impact the performance of ICS compared to TSF in terms of reducing cooking time, fuel use and IAP, to date, limited information exists about this impact. This field study evaluated the performance of ICS relative to TSF using the controlled cooking test (CCT) protocol. The CCT involved 10 ICS and 10 TSF households. The test results show that the indoor CO and $PM_{2.5}$ concentrations were 5.470 ± 4.668, and 0.451 ± 0.328 mg/m^3, respectively, for ICS and 13.485 ± 10.925, and 0.867 ± 0.839 mg/m^3 for TSF. Compared to TSF, ICS increased cooking time and fuel use by 78% and 46%, respectively. The findings reveal that aside from efficiency, it is essential to prioritize traditional cooking practices and users' needs when designing improved cookstoves. In conclusion, we assert that ICS contributes significantly to reducing respiratory health issues thus making it ideal for cooking among rural folks. To reduce cooking time and fuel use for ICS however, we recommend that the stove be redesigned in terms of the material used for its construction and the number of pot- holes.

Keywords: Improved Cookstove; Indoor Air Pollution; Deforestation; Respiratory Health; Controlled Cooking Test

Introduction

Burning solid fuels such as wood, crop residues, and animal dung in traditional stone fires (TSF) for cooking and heating is ubiquitous among more than 3 billion people worldwide (Champion et al., 2020). Over 77% of Ghanaian households rely heavily on solid fuels, especially in rural areas (Nazif-Muñoz et al., 2020; Weber et al., 2020), for household energy. It has caused many health and deforestation problems (Carrión et al., 2021; Rosenthal et al., 2018). Most rural Ghana residents are exposed to significant indoor air pollutants from wood and charcoal burning through their regular household tasks (Nazif-Muñoz et al., 2020). In Ghana, indoor air pollution (IAP) accounts for 502,000 disability-adjusted life years (DALYs) and 2.2 per cent of the national burden of disease related to solid fuel consumption (Armah et al., 2015). The WHO also estimates that exposure to IAP accounts for the death of about 16,600 people every year, a disproportionate part of which are women and children between 1 – 4 years (Weber et al., 2020). However, there has been significant interest over the years in finding effective interventions to alleviate the detrimental health and climate impacts of solid fuel use (Barr et al., 2020; Bonjour et al., 2013; de la Sota et al., 2018; Ezzati & Kammen, 2002; Fandiño-Del-Rio et al., 2020; Johnson et al., 2020; Quansah et al., 2017; Rehfuess et al., 2014). Proposed measures to reduce IAP from cooking and heating with solid fuels have comprised changes using improved cookstoves and cleaner fuels, changes to the living environment (e.g., improved ventilation), and changes to user behavior such as observing proper stove/fuel combinations (Del Rio et al., 2020; Li et al., 2022; Pande et al., 2018). Of these, improved cookstoves, especially those with chimneys, have resulted in most reductions in IAP (Huang et al., 2021; Kumar et al., 2021). Improved cookstoves can achieve health and climate change mitigation benefits by reducing incomplete solid fuel combustion (Champion & Grieshop, 2019).

Over the years, the government of Ghana has shown its commitment to easing the health and environmental implications of solid fuel use in Ghana, particularly in rural areas (Carrión et al., 2021). One example is that in 2014, the Ghana Ministry of Energy provided over 20,000 liquified petroleum gas (LPG) stoves through the rural liquified petroleum gas (LPG) programme (Asante et al., 2018). This intervention is said to help reduce deforestation and IAP from solid fuels in households.

The Asuogyaman District, a riparian area in the eastern region of Ghana, forms part of the communities in the Volta Lake basin where the Akosombo dam is located (Ghansah et al., 2016). The dam is the largest hydroelectricity power source in Ghana for domestic and industrial activities (Obahoundje & Diedhiou, 2022). It extends to neighbouring West African countries, including Togo and Benin (Eshun & Amoako-Tuffour, 2016). Past reports (Gordon et al., 2017; GSS, 2021) show that all the rural households - about 80% of the population - cook indoors with wood on TSF. The district's intense reliance on wood for household energy is linked with high indoor air pollution and acute respiratory tract infections (Ampofo et al., 2016; Gordon et al., 2017). Also, this considerable wood consumption rate has proliferated rapid deforestation, evapotranspiration, and silt build-up in the Akosombo hydroelectric dam leading to significant disruption in the generation of hydropower (Obahoundje et al., 2021). The volta river authority (VRA) in 2016 implemented a cookstove intervention program to provide households in the Asuogyaman district with improved local cookstoves (christened as climate-smart stoves) (Gordon et al., 2017; VRA, 2018). The improved local cookstove was envisaged to reduce the rate of forest exploitation and degradation, protect the water in the Akosombo dam for sustained electricity production and reduce high IAP in homes.

Due to its socio-economic benefits, the improved cookstoves (ICS) was surmised to potentially replace the traditional stone fire (TSF) in the Asuogyaman district, thus possibly reducing cooking-related time and wood use (Bilsback et al., 2018). In addition to cutting down on cooking time and fuel use, improved cookstoves can help rural households reduce the detrimental health effects of IAP (Tran et al., 2020). However, the ICS was designed to hold two cooking pots concurrently, contrary to the widespread traditional cooking practice of using one cooking pot in the Asuogyaman District (Gordon et al., 2017). Previous evidence suggests that the performance of cookstoves (i.e., reducing IAP, fuel use and cooking time) is affected when cookstove designs (such as the number of pot-holes) do not meet traditional cooking demands (Del Rio et al., 2020; Rhodes et al., 2014). For example, cooking with one pot on a two-pot-hole stove causes loss of cooking heat to the surroundings through the unused pot-hole (Hafner et al., 2018). This ICS attribute may influence its performance such as increasing fuel consumption and cooking time as well as possible abandonment, especially when there is stove stacking (Jewitt et al., 2020). Also, substantial health benefits from ICS use can only be realized when TSF is replaced (Buthelezi et al., 2019). However, little empirical research has been done to understand how the number of pot-holes of these improved cookstoves influences IAP, cooking time and fuel use compared with traditional stone fires.

Therefore, there is the need to evaluate the performance of ICS with two pot-holes relative to TSF. The present field study assessed the fuel consumption and cooking time savings by these improved cookstoves with two pot-holes and traditional stone fires to fill this gap. It further measured emission reductions of carbon monoxide (CO) and particulate matter of aerodynamic size ≤ 2.5µm ($PM_{2.5}$) by ICS relative to TSF using the controlled cooking test (CCT) protocol. The outcome of the study provides information about the performance of ICS and its ability to reduce IAP in households compared with traditional stone fires. The paper aims to inform policymaking and influence stove design that considers the socio-cultural context such as cooking culture and habit during future cookstove intervention programs.

Materials and methods

Study area

The Asuogyaman district, as shown in Fig.1, is located between latitudes 6º 34º N and 6º 10º N and longitudes 0º 1º W and 0º14E. It stands 120 meters above sea level and covers 1,507 square kilometres, constituting 5.7% of the total land area of the Eastern Region of Ghana (Mawusi, 2019). The district shares borders with Afram Plains South District, the Upper and Lower Manya districts, Kpando, North Dayi, Ho and the North Tongu Districts of the Volta Region. The Volta River passes through such ridges to create a canyon where the Akosombo dam is located (GSS, 2014).

The stoves tested in this study, ICS and TSF, are shown in Fig.2. The traditional stone fire comprises three irregularly shaped stones placed on the ground to support a cooking utensil over an open fire. The ICS is a built-in-place chimney stove made of clay, sand and water and can hold two cooking pots. It has two holes; the first hole fits a large pot and the second hole fits a small pot. It has an extended inner firepit for front-loading of wood, a thick wall of 220 mm reinforced with iron rods to support the combustion chamber, and a gap of 300mm between the base of the pot to the floor of the firepit. *Acacia nilotica* was used in this field study because it is the predominant fuel for cooking in the study area. Wood was purchased from local sellers

Fig. 1 A Map of Asuogyaman district in Ghana

Fig. 2 (A) Improved cookstove with two holes (B) Traditional stone fire

and stored under sheds a week before the field measurement. This was done to save time and labour in carrying wood to the various test communities. The thick wood was cut into 100.52± 25.76 x 8.66 ± 3.31 cm (L×D) and used in both cookstoves. Wood moisture was measured with a Voltcraft FM-300 (Conrad Electronics SE, Hirschau), and an average of 20.95% (dry basis) was used.

Ethical consideration

Ethical clearance for this study was obtained from the Ethics Committee for Basic and Applied Science (ECBAS), University of Ghana, to ensure the protection of the health and rights of study participants. The purpose of the study was carefully explained to participants. Participants were assured of confidentiality and were at liberty to withdraw from the study at any point if they felt uncomfortable.

Survey

An initial face-to-face survey was conducted in September 2018 in twelve communities in the Asuogyaman district namely Surveyline, Kudikope, Ampanawu, Old Apaaso, Nyameben, Adjena Dornor, Dodi Asantekrom, Mapakadan, Klegekorpe, Abume, Kokonte Kpedzi and Labolabo Tornu. Households that used ICS were selected using purposive sampling, while those that used TSF were determined using snowball sampling. Information on socio-demographic variables, ICS and TSF, self-reported health consequences of stove use, and user perception of ICS and TSF were gathered using structured questionnaires and open-ended questions. Before administering, the questionnaires were piloted in the study area to ensure the content was easily understood by study participants and elicited appropriate responses. Information gathered from the survey were used to determine the standard, quantity and type of food often cooked by participants. For this study, only household cooking tasks were performed.

Testing protocol

The Controlled Cooking Test (CCT) designed by Bailis (2007) was used to test the cookstoves in kitchens in this field study. This test assesses the fuel and cooking time savings of an improved cookstove relative to a traditional one and provides a true reflection of in-home stove use (Arora & Jain, 2016). A CCT involves a chef cooking a selected standardized meal three times on a traditional cookstove and improved cookstove. Twenty (20) cookstoves comprising 10 ICS and 10 TSF from Adjena Dornu, Kokonte Kpedzi, Mpakadan and Surveyline were selected for the CCT. This was because the ICS in these villages were the only ones functioning during the field test.

The test was conducted in homes with participants who volunteered. Users of the various stoves were asked to operate them as they usually did during cooking. Kitchens in the study area are built from mud, roofed with aluminium sheets and had little ventilation. Each chef received a pre-weighed bundle of wood before starting the cooking task. The field investigators ensured that the fuel was enough to perform the cooking task. For this study, females in households who participated were made to cook "Banku" because it is the staple meal eaten in the study area. "Banku" is made from boiling a mixture of fermented cassava and corn dough until a thick paste is formed, which is often accompanied by a sauce. The quantity of ingredients used represented the amount of food cooked to meet the demand of a 5-person household, which approximates the average household size in rural communities of the Asuogyaman district (GSS, 2014). The time used during cooking was measured by starting a timer at the ignition of the fuel; the timer was stopped when cooking was finished. For each test, pollutant measurements were started immediately after the stove was ignited and stopped once the food was cooked. A detailed description of the CCT is shown in Mawusi (2019).

Key stove performance indicators

Aside from emissions reduction, specific wood consumption and time spent to cook were used as key stove performance indicators. The calculation of these indicators followed the method used by Bailis (2007), and are shown in the equations below. Specific wood consumption (SC), (equation (4)) is shown as the grams of equivalent dry wood consumed per total weight of food cooked in kilograms (equation (1)). The time spent in cooking is calculated in equation 5:

$$\text{Total weight of food cooked (kg)},\ (w_f) = \sum_{j=1}^{3}(Pj_f - P_j) \quad (1)$$

Where:

J = Index for each empty cooking pot used (up to 3)

Pj_f = weight of pot after cooking

$$\text{Weight of char left after cooking (g)},\ (\Delta C_c) = C_c - k \quad (2)$$

With C_c and k as the weight of char container and charcoal (g), and weight of char container (g), respectively.

$$\text{Equivalent dry wood consumed (g)}, (f_d) = (f_f - f_i) * \{1 - (1.2 * m)\} - 1.5 * \Delta C_c \quad (3)$$

Where f_f " is the final weight of wood (g), f_i is the initial weight of fuelwood (g), m is wood moisture content (% wet basis), and ΔC_c represents the weight of char left after cooking (g).

$$\text{Specific wood consumption (SC)} \left(\frac{g}{kg}\right) = \frac{f_d}{w_f} \quad (4)$$

With f_d and w_f refer to equivalent dry wood consumed (g) and the total weight of food cooked (kg), respectively.

$$\text{Total cooking time (mins)} (\Delta t) = t_f - t_i \quad (5)$$

t_f and t_i are the final and initial cooking times, respectively.

Measurement of indoor air pollution

Indoor concentrations of CO were logged every minute using a high-temporal resolution Aeroqual series 500 portable gas monitor with an appropriate sensor head (Aeroqual Limited, Auckland, New Zealand), and $PM_{2.5}$ with Haz-dust Environmental Particulate Air Monitor (EPAM-7500). Pollutant monitors also logged data on kitchen temperature and relative humidity during cooking. Indoor pollutant monitors were placed 1.5m above the floor and 1.0m in a horizontal distance from stoves to estimate the breathing zone of a woman cooking in a kitchen, as done in other studies (Kephart et al., 2020). Measurement of gaseous pollutants was not affected by outside airflow because kitchens in the study area are usually constructed as stand-alone structures with little ventilation.

Statistical Analysis

The data collected were carefully examined to ensure accuracy. Results are presented using descriptive statistical techniques after processing it using the Statistical Package for Social Sciences (SPSS), version 25.0. A student's t-test was done to test statistically significant differences between measured parameters at a 5% significance level. The data distribution in this study is represented as arithmetic mean ± standard deviation.

Results and discussion

Indoor air concentrations of CO and $PM_{2.5}$

The concentrations of CO and $PM_{2.5}$ measured in this field study are shown in Fig. 3. The overall mean of CO in households that use ICS and TSF was 5.470 ± 4.668 mg/m^3 and 13.485 ± 10.925 mg/m^3, respectively. The improved cookstove showed a 47% reduction in $PM_{2.5}$ concentrations compared to traditional stone fires. The difference between the concentrations of CO and $PM_{2.5}$ for the different stoves in this study was statistically significant ($p < 0.05$). Improved cookstoves efficiently reduce high pollutant emissions compared with traditional stoves (Mitchell et al., 2019). The findings from this present study is in line with Baqir et al. (2019), where improved chulha stoves reduced 51% of CO emissions relative to the traditional chulha stoves. Singh et al. (2012), also made a similar discovery when newly designed improved local cookstoves were tested using CCT in Nepal. Particulate matter ($PM_{2.5}$) concentrations in this present study conform with Pennise et al. (2009), who found a 26% reduction in $PM_{2.5}$ after introducing an improved wood cookstove in Accra, Ghana. Jagger et al. (2017), after investigating air pollutant concentrations of improved wood-burning cookstoves in Malawi, also found that improved wood stoves reduced 20 – 50% more CO and $PM_{2.5}$ than traditional stone fires. Improved cookstoves can effectively reduce household air pollution and improve health. This corroborates the finding of Mawusi (2019), where the number of hospital-reported respiratory tract infection (RTI) cases reduced by 25% a year after the introduction of ICS in Asuogyaman District. But prior to the ICS intervention, RTI was prevalent among the people of Asuogyaman District (Mawusi, 2019). As reported by this present field study, reducing pollutants by ICS makes it ideal for cooking among rural folks. Therefore, providing improved cookstoves on a large scale could help address the adverse human health consequences of wood use (Saini et al., 2020; Thakur et al., 2019).

Fuel use

The results in Fig. 4 show that the average specific wood consumption in ICS was 46% more than TSF, which was statistically significant ($p < 0.05$). Dresen et al. (2014), found that the injera improved local cookstove designed as a single-pothole saved 40% more wood than TSF during a CCT in Ethiopia. Improved cookstoves with two pot-holes were found to reduce wood consumption by about 24% compared to traditional stone fires in Tanzania (Hafner et al., 2020). However, this present field study shows a 46% increase in wood consumption in climate-smart stoves. Besides, the standard deviations show a wide variation in wood consumption for both stoves, especially the ICS. The more variable

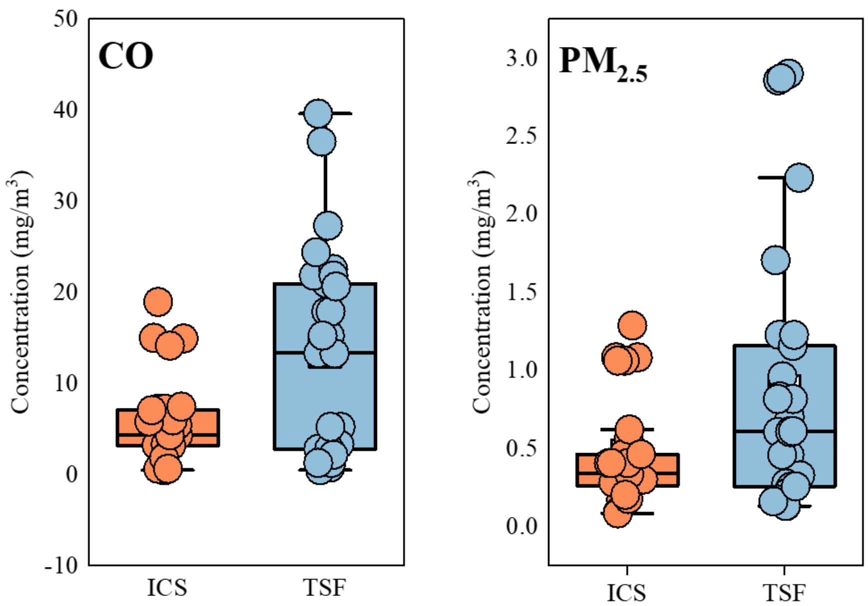

Fig. 3 Box and whisker plots for indoor CO and $PM_{2.5}$ for the different stoves (The central line and white squares show the median and mean, respectively)

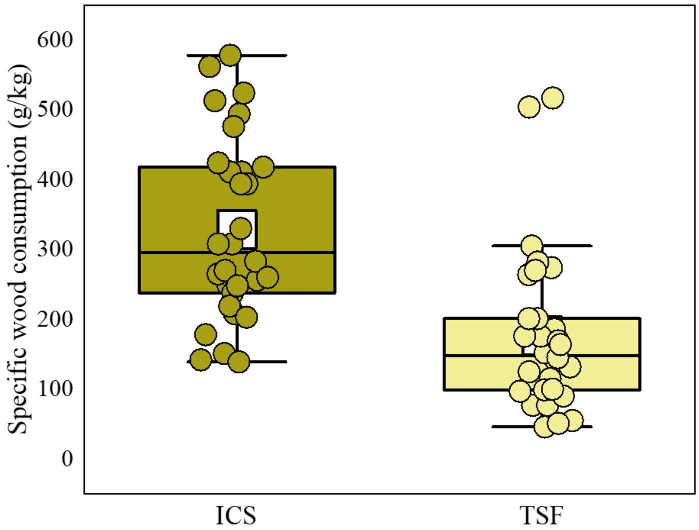

Fig. 4 Box and whisker plots showing the specific wood consumption for the different stoves (The central line and white squares indicate the median and mean, respectively)

use of wood in the climate-smart stove could be due to a lack of training, varying fueling of cookstoves and the cooks' skill. Training informs improved cookstove users about the tasks that cause massive pollutant emissions and fuel use, and this can help users know how to operate their stoves properly (Chagunda et al., 2017). High fuel consumption in the ICS designed with two-potholes suggests its inefficiency and the need to improve the design to suit the cooking culture of the Asuogyamang community. The difference in specific fuel consumption amongst different stoves could be ascribed to differences in design (Mamuye et al., 2018; Shen et al., 2021) and the material from which they were made (Pande et al., 2018). The design of the stoves and the material from which they are made are the essential variables that affect stove performance (Yayeh et al., 2021).

In addition to the number of pot-holes, improved cookstoves without well-designed combustion chambers can consume more fuel than their traditional counterparts (Bilsback et al., 2018; Johnson et al., 2019; MacCarty et al., 2010). This may partly account for the finding in this study. Though ICS is a two-pot stove, residents usually cook food using one pot-hole. Thus, the heat required to cook is lost to the surroundings through the unused pot-hole, increasing fuel consumption (Hafner et al., 2018). Also, user behaviour has been shown to influence the performance of stoves (Li et al., 2020; Shrestha et al., 2021). Users of TSF in this present study proved to be very skilled at tending the fire while cooking and thus maximized fuel energy use. The difference in fire tending habits of stove users affects fuel use during cooking (Moses & MacCarty, 2019; Ventrella & MacCarty, 2019), which could explain this study's finding. There is a need for community-cooking demonstrations to ensure climate-smart stoves' correct and consistent use. These demonstrations will help stove users observe the process of loading, lighting, and cooking on the ICS and ask questions about the novelty of the cookstove (Del Rio et al., 2020). This will enhance fuel use and energy efficiency. The results of this present study suggest that designing double pot-holes ICS for use in communities with a cultural practice of cooking one meal at a time, would defeat some of the intended benefits of ICS since unsustainable harvesting of wood for cooking can cause local environmental impacts such as forest degradation (Bzugu et al., 2019).

Cooking time

The average cooking times of the different stoves are shown in Fig. 5. The range of cooking times for ICS and TSF was 17 – 73 mins. and 11 – 32 mins., respectively, with a mean and standard deviation of 37.300 ± 13.914 mins.

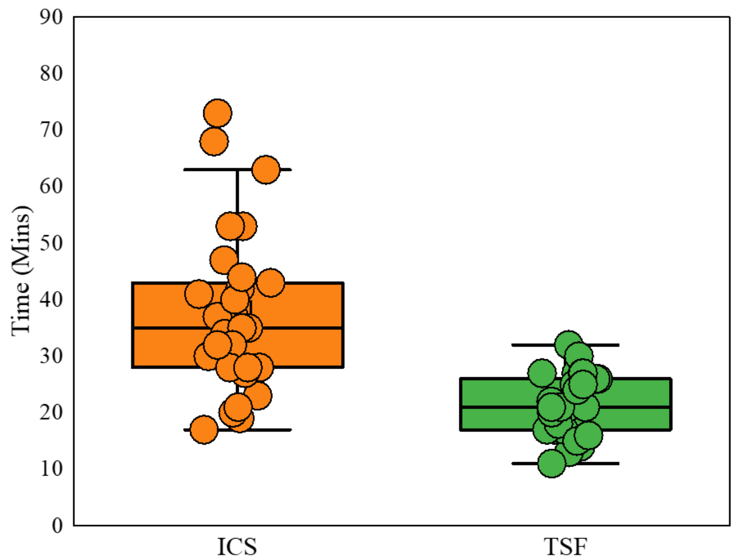

Fig. 5 Box and whisker plots showing the cooking times for the different stoves (The central line and white squares indicate the median and mean, respectively)

and 20.933 ± 5.420 mins., respectively. A statistically significant difference was found between the mean cooking times ($p<0.05$). Improved cookstoves are adept at saving cooking time in households (Jeuland et al., 2015; Manoa et al., 2017; Prah et al., 2021). However, this field test shows that ICS users spent 44% more time cooking than TSF users. This finding does not conform with CSIR (2017) results, where climate-smart stoves used 5% less cooking time than traditional stone fires.

In other studies, consistent with the findings of this present field test, traditional stone fire and improved stove users spent 17- and 22-minutes cooking, respectively (Adkins et al., 2010). Improved cookstoves do not consistently outperform traditional stone fires (Hafner et al., 2020). Traditional stone fires could perform better than improved cookstoves on some metrics such as cooking time (Jetter & Kariher, 2009; Obi et al., 2019; Ochieng et al., 2013). In their study, Hafner et al. (2020) reported that traditional fire stoves outperform improved cookstoves when cooking tasks are done with one pot, as was the case in this present study. TSF boiled water and finished cooking faster, in some cases even significantly faster, than an improved cookstove across all types of fuels tested (Grimsby et al., 2016; Medina et al., 2017). According to Zube (2010), traditional stone fires can be unexpectedly efficient if used cautiously. Users of TSF have the leeway to keep the cooking pot in proximity to the fire, thereby increasing radiative heat transfer (Zube, 2010). Also, the non-existence of any close material avoids the loss of heat meant to make the pot hot. The popularity of the traditional stone fires as inefficient is mainly due to the loss of radiative energy from the fire to the environs during use. Another flaw with TSF is the absence of a restricted current pathway for the fire vapours causing too much integration of cooler air from the surroundings (Ballard-Tremeer & Jawurek, 1996; Kees & Feldmann, 2011).

Improved cookstoves are beneficial compared with traditional cookstoves. But they can be inefficient if not properly designed (Samal et al., 2019; Thompson et al., 2019). Enclosed combustion chambers in improved cookstoves engulf the fire, limit the quantity of fuel fed into the stove, reduce fuel use, and speed up cooking. By restricting the inflow of surrounding air, improved cookstove users can use stoves at an ideal air-to-fuel ratio while increasing heat transfer to cooking pots (Kshirsagar & Kalamkar, 2014; Tryner et al., 2014). Aside from the longer ignition time for the ICS, it was observed that experienced cooks operating the traditional stone fires developed various skills to save cooking time, which was not observed while using the climate-smart stove. And this apart from the number of pot-holes for ICS account for the observed results in the present study. Based on these findings, it is suggested that households use TSF for one-pot meals and ICS when meals with more than one pot are cooked, e.g. when preparing lunch or dinner. Therefore, stove stacking and usage of stoves for different purposes is recommended for cooking efficiently.

Implications and limitations

This study provided valuable information about the performance of double pot-hole climate-smart stoves relative to traditional stone fires in the Asuogyaman district of Ghana. It served as a basis for appraising the improved cookstove intervention program undertaken by the volta river authority. ICS significantly reduced indoor air pollutants during in-home use but consumed more wood and took longer to cook meals largely due to radiative heat emanating from the unused pot-hole. Aside from emission reductions, it is essential to prioritize traditional cooking practices and users' needs when designing improved cookstoves. It could be better if ICS is designed with one pot-hole to suit the domestic cooking needs of the users and reduce cooking time and fuel use associated with the loss of cooking heat to the environs. It is not generally true that improved cookstoves can reduce cooking time and fuel use. But it is contingent on the design and the ability to satisfy traditional cooking needs.

The factors that limited the scope of this study are duly acknowledged. The study was limited to 20 cookstoves because they were the only functional stoves in the community at the time of the study. Larger sample size would have reduced possible errors associated with the sampling. Future studies where functional stoves are available should consider increasing the sample size of the cookstoves.

Conclusion

The following conclusions were reached based on the study's findings:

- The ICS efficiently reduces CO and $PM_{2.5}$ emissions that emanate from cooking with wood in households.
- Improved cookstoves with two pot-holes were inefficient in reducing wood consumption during cooking compared with TSF.
- Traditional stone fires were more efficient in saving cooking time than the improved cookstoves with two pot-holes.

The findings reveal that a second look should be taken at the engineering of ICS in terms of the material used for its construction, the number of pot-holes and venting since these have been shown to affect fuel use in stoves. Thus, the ICS design should consider the cooking practice of the Asuogyaman district. The stoves could also be used in well-ventilated structures to reduce indoor air pollutants further. Due to the emissions reduction potential of ICS, efforts should be made by the VRA to supply them to all households in the Asuogyaman District. Adoption and sustained use could be ensured by incentivizing users.

References

Adkins, E., Tyler, E., Wang, J., Siriri, D., & Modi, V. (2010). Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. *Energy for Sustainable Development*, **14(3)**, 172-185.

Ampofo, S., Sackey, I., & Ampadu, B. (2016). The nexus of population change, agricultural expansion, landscape fragmentation in the Volta gorge area, Ghana. *Ethiopian Journal of Environmental Studies and Management*, **9(4)**, 412-429.

Armah, F. A., Odoi, J. O., & Luginaah, I. (2015). Indoor air pollution and health in Ghana: Self-reported exposure to unprocessed solid fuel smoke. *EcoHealth*, **12(2)**, 227-243.

Arora, P., & Jain, S. (2016). A review of chronological development in cookstove assessment methods: Challenges and way forward. *Renewable & Sustainable Energy Reviews*, **55**, 203-220. doi:10.1016/j.rser.2015.10.142

Asante, K. P., Afari-Asiedu, S., Abdulai, M. A., Dalaba, M. A., Carrión, D., Dickinson,

K. L., Abeka, A.N., Sarpong, K. & Jack, D. W. (2018). Ghana's rural liquefied petroleum gas program scale up: A case study. *Energy for Sustainable Development*, **46**, 94-102.

Bailis, R. (2007). Controlled Cooking Test (CCT), Version 2.0; Household Energy and Health Programme, Shell Foundation; August 2004. *Berkeley, California: the University of California-Berkeley*. . Retrieved from http://www.pciaonline.org/files/CCT_Version_2.0_0. pdf (accessed 2013 Oct 14).

Ballard-Tremeer, G., & Jawurek, H. (1996). Comparison of five rural, wood-burning cooking devices: efficiencies and emissions. *biomass and bioenergy*, **11(5)**, 419-430.

Baqir, M., Bharti, S., Kothari, R., & Singh, R. (2019). Assessment of an energy-efficient metal chulha for solid biomass fuel and evaluation of its performance. *International Journal of Environmental Science and Technology*, **16(11)**, 6773-6784.

Barr, D. B., Puttaswamy, N., Jaacks, L. M., Steenland, K., Rajkumar, S., Gupton, S., Ryan, P.B., Balakrishnan, K., Peel, J.L., Checkley, W., & Clasen, T. (2020). Design and rationale of the biomarker center of the household air pollution intervention network (HAPIN) trial. *Environmental health perspectives*, **128(4)**, 047010.

Bilsback, K. R., Eilenberg, S. R., Good, N., Heck, L., Johnson, M., Kodros, J. K., Kodros, J.K., Lipsky, E.M., L'Orange, C., Pierce, J.R., Robinson, A.L., Subramanian, R., Tryner, J., Wilson, A., & Volckens, J. (2018). The Firepower Sweep Test: A novel approach to cookstove laboratory testing. *Indoor air*, **28(6)**, 936-949.

Bonjour, S., Adair-Rohani, H., Wolf, J., Bruce, N. G., Mehta, S., Prüss-Ustün, A., Lahiff, M., Rehfuess, E.A., Mishra, V., & Smith, K. R. (2013). Solid fuel use for household cooking: country and regional estimates for 1980–2010. *Environmental health perspectives*, **121(7)**, 784-790.

Buthelezi, S. A., Kapwata, T., Wernecke, B., Webster, C., Mathee, A., & Wright, C. Y. (2019). Household fuel use for heating and cooking and respiratory health in a low-income, South African coastal community. *International journal of environmental research and public health*, **16(4)**, 550.

Bzugu, P., Egbeadumah, M., Aliyu, A., & Ibrahim, A. (2019). Deforestation Adaptation Strategies Among Farmers in Nigeria. *Journal of Land and Rural Studies*, **7(1)**, 57-70.

Carrión, D., Prah, R., Tawiah, T., Agyei, O., Twumasi, M., Mujtaba, M., Jack, D & Asante, K. P. (2021). Enhancing LPG Adoption in Ghana (ELAG): A trial testing policy-relevant interventions to increase sustained use of clean fuels. *Sustainability*, **13(4)**, 2213.

Chagunda, M. F., Kamunda, C., Mlatho, J., Mikeka, C., & Palamuleni, L. (2017). Performance assessment of an improved cook stove (Esperanza) in a typical domestic setting: implications for energy saving. *Energy, Sustainability and Society*, **7(1)**, 1-9.

Champion, W. M., & Grieshop, A. P. (2019). Pellet-fed gasifier stoves approach gas-stove like performance during in-home use in Rwanda. *Environmental science & technology*, **53(11)**, 6570-6579.

Champion, W. M., Warren, S. H., Kooter, I. M., Preston, W., Krantz, Q. T., DeMarini, D. M., & Jetter, J. J. (2020). Mutagenicity- and pollutant-emission factors of pellet-fueled gasifier cookstoves: Comparison with other combustion sources. *Science of The Total Environment*, **739**, 139488.

Council for Scientific and Industrial Research (CSIR). (2017). Performance Test Evaluation of Improved Biomass (Woodfuel) Cookstove.

de la Sota, C., Lumbreras, J., Pérez, N., Ealo, M., Kane, M., Youm, I., & Viana, M. (2018). Indoor air pollution from biomass cookstoves in rural Senegal. *Energy for Sustainable Development*, **43**, 224-234.

Del Rio, D. D. F., Lambe, F., Roe, J., Matin, N., Makuch, K. E., & Osborne, M. (2020). Do we need better behaved cooks? Reviewing behavioural change strategies for improving the sustainability and effectiveness of cookstove programs. *Energy Research &*

Social Science, **70**, 101788.

Dresen, E., DeVries, B., Herold, M., Verchot, L., & Müller, R. (2014). Fuelwood savings and carbon emission reductions by the use of improved cooking stoves in an Afromontane Forest, Ethiopia. *Land*, **3(3)**, 1137-1157.

Eshun, M. E., & Amoako-Tuffour, J. (2016). A review of the trends in Ghana's power sector. *Energy, Sustainability and Society*, **6(1)**, 9. doi:10.1186/s13705-016-0075-y

Ezzati, M., & Kammen, D. M. (2002). The health impacts of exposure to indoor air pollution from solid fuels in developing countries: knowledge, gaps, and data needs. *Environmental health perspectives*, **110(11)**, 1057-1068.

Fandiño-Del-Rio, M., Kephart, J. L., Williams, K. N., Moulton, L. H., Steenland, K., Checkley, W., & Koehler, K. (2020). Household air pollution exposure and associations with household characteristics among biomass cookstove users in Puno, Peru. *Environmental research*, **191**, 110028.

Ghansah, B., Asare, Y. M., Tchao, E. T., & Forkuo, E. K. (2016). Mapping the spatial changes in Lake Volta using multitemporal remote sensing approach. *Lakes & Reservoirs: Research & Management*, **21(3)**, 206-215.

Gordon, C., Nukpezah, D., Tweneboah-Lawson, E., Ofori, B., Yirenya-Tawiah, D., Pabi, O., Ayivor, J.S., Koranteng, S., Darko, D., & Mensah, A. (2017). West Africa: Water Resources Vulnerability Using a Multidimensional Approach: Case Study of Volta Basin. *Climate vulnerability: understanding and addressing threats to essential resources*, pp. 283e309. https://doi.org/10.1016/B978-0-12-384703-4.00518-9.

Grimsby, L. K., Rajabu, H. M., & Treiber, M. U. (2016). Multiple biomass fuels and improved cook stoves from Tanzania assessed with the Water Boiling Test. *Sustainable Energy Technologies and Assessments*, **14**, 63-73. doi:https://doi.org/10.1016/j.seta.2016.01.004

Ghana Statistical Service (GSS). (2014). 2010 Population & Housing Census - District Analytical Report for Asuogyaman District. Retrieved from Retrieved from http://www.statsghana.gov.gh/docfiles/2010_District_Report/Eastern/ASUOGYAMAN.pdf

Ghana Statistical Service (GSS). (2021). 2021 Population and Housing Census: Provisional Results Press Release. Retrieved from https://statsghana.gov.gh/gssmain/storage/img/infobank/2021%20PHC%20Provisional%20Results%20Press%20Release.pdf

Hafner, J., Uckert, G., Graef, F., Hoffmann, H., Kimaro, A., Sererya, O., & Sieber, S. (2018). A quantitative performance assessment of improved cooking stoves and traditional three-stone-fire stoves using a two-pot test design in Chamwino, Dodoma, Tanzania. *Environmental Research Letters*, **13(2)**, 025002.

Hafner, J. M., Uckert, G., Hoffmann, H. K., Rosenstock, T. S., Sieber, S., & Kimaro, A. A. (2020). Efficiency of Three-Stone Fire and Improved Cooking Stoves using on-farm and off-farm fuels in semi-arid Tanzania. *Energy for Sustainable Development*, **59**, 199-207. doi:https://doi.org/10.1016/j.esd.2020.10.012

Huang, S., Guo, C., Qie, R., Han, M., Wu, X., Zhang, Y., Yang, X., Feng, Y., Li, Y., Wu, Y., & Wu, Y. (2021). Solid fuel use and cardiovascular events: A systematic review and meta-analysis of observational studies. *Indoor air*, **31(6)**, 1722-1732.

Jagger, P., Pedit, J., Bittner, A., Hamrick, L., Phwandapwhanda, T., & Jumbe, C. (2017). Fuel efficiency and air pollutant concentrations of wood-burning improved cookstoves in Malawi: implications for scaling-up cookstove programs. *Energy for Sustainable Development*, **41**, 112-120.

Jetter, J. J., & Kariher, P. (2009). Solid-fuel household cook stoves: Characterization of performance and emissions. *biomass and bioenergy*, **33(2)**, 294-305.

Jeuland, M., Bhojvaid, V., Kar, A., Lewis, J., Patange, O., Pattanayak, S.K., Ramanathan, N., Rehman, I.H., Soo, J.T., & Ramanathan, V. (2015). Preferences for improved cook stoves: Evidence from rural villages in north India. *Energy Economics*,

52, 287-298.

Jewitt, S., Atagher, P., & Clifford, M. (2020). "We cannot stop cooking": Stove stacking, seasonality and the risky practices of household cookstove transitions in Nigeria. *Energy Research & Social Science*, **61**, 101340.

Johnson, M. A., Garland, C. R., Jagoe, K., Edwards, R., Ndemere, J., Weyant, C., Patel, A., Kithinji, J., Wasirwa, E., &Nguyen, T. (2019). In-home emissions performance of cookstoves in Asia and Africa. *Atmosphere*, **10(5)**, 290.

Johnson, M. A., Steenland, K., Piedrahita, R., Clark, M. L., Pillarisetti, A., Balakrishnan, K., Peel, J.L., Naeher, L.P., Liao, J., & Wilson, D. (2020). Air pollutant exposure and stove use assessment methods for the household air pollution intervention network (HAPIN) trial. *Environmental health perspectives*, **128(4)**, 047009.

Kees, M., & Feldmann, L. (2011). The role of donor organizations in promoting energy efficient cook stoves. *Energy Policy*, **39(12)**, 7595-7599.

Kephart, J. L., Fandiño-Del-Rio, M., Williams, K. N., Malpartida, G., Steenland, K., Naeher, L. P., Gonzales, G.F., Chiang, M., Checkley, W., & Koehler, K. (2020). Nitrogen dioxide exposures from biomass cookstoves in the Peruvian Andes. *Indoor air*, **30(4)**, 735-744.

Kshirsagar, M. P., & Kalamkar, V. R. (2014). A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design. *Renewable and Sustainable Energy Reviews*, **30**, 580-603.

Kumar, N., Phillip, E., Cooper, H., Davis, M., Langevin, J., Clifford, M., & Stanistreet, D. (2021). Do improved biomass cookstove interventions improve indoor air quality and blood pressure? A systematic review and meta-analysis. *Environmental Pollution,* **290**, 117997.

Li, C., Ye, K., Mawusi, S., Zhang, W., Xu, Y., Xu, J., Zhou, W., Li, J., Jiao, M., Shrestha, P., Pang, R., Hussein, R., Xue, C., & Liu, G. (2020). A 24-h real-time emissions assessment of 41 uncontrolled household raw coal combustion stoves in four provinces of Northern China. *Atmospheric Environment*, **235**, 117588.

Li, C., Ye, K., Zhang, W., Xu, Y., Xu, J., Li, J., Mawusi, S.K, Shrestha, P., Xue, C., & Liu, G. (2022). User behavior, influence factors, and impacts on real-world pollutant emissions from the household heating stoves in rural China. *Science of The Total Environment*, 153718.

MacCarty, N., Still, D., & Ogle, D. (2010). Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. *Energy for Sustainable Development*, **14(3)**, 161-171.

Mamuye, F., Lemma, B., & Woldeamanuel, T. (2018). Emissions and fuel use performance of two improved stoves and determinants of their adoption in Dodola, southeastern Ethiopia. *Sustainable Environment Research*, **28(1)**, 32-38. doi:https://doi.org/10.1016/j.serj.2017.09.003

Manoa, D. O., Oloo, T., & Kasaine, S. (2017). The Efficiency of the Energy Saving Stoves in Amboseli Ecosystem-Analysis of Time, Energy and Carbon Emissions Savings. *Open Journal of Energy Efficiency*, **6(03)**, 87.

Mawusi, S. K. (2019). Impact of Climate-Smart Stoves on Household Air Pollution in Asuogyaman District, Eastern Region, Ghana. (Masters Dissertation). University of Ghana,

Medina, P., Berrueta, V., Martínez, M., Ruiz, V., Edwards, R., & Masera, O. (2017). Comparative performance of five Mexican plancha-type cookstoves using water boiling tests. *Development Engineering*, **2**, 20-28.

Mitchell, E.J.S., Ting, Y., Allan, J., Lea-Langton, A., Spracklen, D., McFiggans, G., Coe, E., Routledge, M.N., Williams, A., & Jones, J. M. (2019). Pollutant emissions from improved cookstoves of the type used in sub-Saharan Africa. *Combustion Science and Technology*.

Moses, N. D., & MacCarty, N. A. (2019). What makes a cookstove usable? Trials of a usability testing protocol in Uganda, Guatemala, and the United States. *Energy*

Research & Social Science, **52**, 221-235.

Nazif-Muñoz, J. I., Spengler, J. D., Arku, R. E., & Oulhote, Y. (2020). Solid fuel use and early child development disparities in Ghana: analyses by gender and urbanicity. *Journal of exposure science & environmental epidemiology*, **30(4)**, 698-706.

Obahoundje, S., & Diedhiou, A. (2022). Potential impacts of climate, land use and land cover changes on hydropower generation in West Africa: a review. *Environmental Research Letters*.

Obahoundje, S., Youan Ta, M., Diedhiou, A., Amoussou, E., & Kouadio, K. (2021). Sensitivity of Hydropower Generation to Changes in Climate and Land Use in the Mono Basin (West Africa) using CORDEX Dataset and WEAP Model. *Environmental Processes*, **8(3)**, 1073-1097.

Obi, O. F., Okechukwu, M. E., & Okongwu, K. C. (2019). Energy and exergy efficiencies of four biomass cookstoves using wood chips. *Biofuels*.

Ochieng, C. A., Tonne, C., & Vardoulakis, S. (2013). A comparison of fuel use between a low cost, improved wood stove and traditional three-stone stove in rural Kenya. *biomass and bioenergy*, **58**, 258-266.

Pande, R. R., Kalamkar, V. R., & Kshirsagar, M. (2018). Making the popular clean: improving the traditional multipot biomass cookstove in Maharashtra, India. *Environment, Development and Sustainability*, **21(3)**, 1391-1410.

Pennise, D., Brant, S., Agbeve, S. M., Quaye, W., Mengesha, F., Tadele, W., & Wofchuck, T. (2009). Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. *Energy for Sustainable Development*, **13(2)**, 71-76.

Prah, R. K. D., Carrion, D., Oppong, F. B., Tawiah, T., Mujtaba, M. N., Gyaase, S., Kwarteng, A., Ae-Ngibise. K.A., Agyei, O., & Twumasi, M. (2021). Time Use Implication of Clean Cookstoves in Rural Settings in Ghana: A Time Use Study. *International journal of environmental research and public health*, **18(1)**, 166.

Quansah, R., Semple, S., Ochieng, C. A., Juvekar, S., Armah, F. A., Luginaah, I., & Emina, J. (2017). Effectiveness of interventions to reduce household air pollution and/or improve health in homes using solid fuel in low-and-middle income countries: A systematic review and meta-analysis. *Environment international*, **103**, 73-90.

Rehfuess, E. A., Puzzolo, E., Stanistreet, D., Pope, D., & Bruce, N. G. (2014). Enablers and barriers to large-scale uptake of improved solid fuel stoves: a systematic review. *Environmental health perspectives*, **122(2)**, 120-130.

Rhodes, E. L., Dreibelbis, R., Klasen, E., Naithani, N., Baliddawa, J., Menya, D., Khatry, S., Levy, S., Tielsch, J.M., & Miranda, J. J. (2014). Behavioral attitudes and preferences in cooking practices with traditional open-fire stoves in Peru, Nepal, and Kenya: implications for improved cookstove interventions. *International journal of environmental research and public health*, **11(10)**, 10310-10326.

Rosenthal, J., Quinn, A., Grieshop, A. P., Pillarisetti, A., & Glass, R. I. (2018). Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals. *Energy for Sustainable Development*, **42**, 152-159.

Saini, J., Dutta, M., & Marques, G. (2020). A comprehensive review on indoor air quality monitoring systems for enhanced public health. *Sustainable Environment Research*, **30(1)**, 1-12.

Samal, C., Mishra, P. C., Mukherjee, S., & Das, D. (2019). Evolution of high performance and low emission biomass cookstoves-an overview. Paper presented at the AIP Conference Proceedings.

Shen, H., Luo, Z., Xiong, R., Liu, X., Zhang, L., Li, Y., Du, W., Chen, Y., Cheng, H., Shen, G., & Tao, S. (2021). A critical review of pollutant emission factors from fuel combustion in home stoves. *Environment international*, **157**, 106841.

Shrestha, P., Zhang, W., Mawusi, S. K., Li, J., Xu, J., Li, C., Xue, C., & Liu, G. (2021). In-use emissions and usage trend of pellet heating stoves in rural Yangxin, Shandong Province. **Environmental Pollution**, **280**, 116955.

Singh, A., Tuladhar, B., Bajracharya, K., & Pillarisetti, A. (2012). Assessment of effectiveness of improved cook stoves in reducing indoor air pollution and improving health in Nepal. *Energy for Sustainable Development*, **16(4)**, 406-414.

Thakur, M., van Schayck, C., & Boudewijns, E. (2019). Improved cookstoves in low-resource settings: a spur to successful implementation strategies. *NPJ primary care respiratory medicine*, **29(1)**, 1-3.

Thompson, R. J., Li, J., Weyant, C. L., Edwards, R., Lan, Q., Rothman, N., Hu, W., Dang, J., Dang, A., Smith, K. R., & Bond, T.C. (2019). Field emission measurements of solid fuel stoves in Yunnan, China demonstrate dominant causes of uncertainty in household emission inventories. *Environmental science & technology*, **53(6)**, 3323-3330.

Tran, V. V., Park, D., & Lee, Y.-C. (2020). Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality. *International journal of environmental research and public health*, **17(8)**, 2927.

Tryner, J., Willson, B. D., & Marchese, A. J. (2014). The effects of fuel type and stove design on emissions and efficiency of natural-draft semi-gasifier biomass cookstoves. *Energy for Sustainable Development*, **23**, 99-109.

Ventrella, J., & MacCarty, N. (2019). Monitoring impacts of clean cookstoves and fuels with the Fuel Use Electronic Logger (FUEL): Results of pilot testing. *Energy for Sustainable Development*, **52**, 82-95.

Volta River Authority (VRA). (2018). VRA News for Second Quarter 2018. Retrieved from Retrieved from https://www.vra.com/resources/newsletters/2018/VRA%20NEWS%20Second%20Quarter%202018.pdf.

Weber, E., Adu-Bonsaffoh, K., Vermeulen, R., Klipstein-Grobusch, K., Grobbee, D. E., Browne, J. L., & Downward, G. S. (2020). Household fuel use and adverse pregnancy outcomes in a Ghanaian cohort study. *Reproductive health*, **17(1)**, 1-8.

Yayeh, T., Guadie, A., & Gatew, S. (2021). Adoption and fuel use efficiency of mirt stove in Dilla district, southern Ethiopia. *Cleaner Engineering and Technology*, **4**, 100207. doi:https://doi.org/10.1016/j.clet.2021.100207

Zube, D. J. (2010). Heat transfer efficiency of biomass cookstoves. (Doctoral Dissertation). Colorado State University, Fort Collins, Colorado.