Exposure to air pollutants and heat stress among resource-poor women entrepreneurs in small-scale cassava processing

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Abstract

Exposure to air pollutants and heat stress from traditional cooking fires is the leading cause of mortality and morbidity in low- and middle-income countries globally and have an adverse effect on the environment. According to the World Health Organisation, 3.8 million people die annually prematurely from illness related to household air pollution. Families living in poverty are at the highest risk, especially women and children. In this study, exposure to particulate matter ($PM_{2.5}$, and PM_{10}), carbon monoxide (CO) and Nitrogen dioxide (NO_2) were measured among resource-poor women cassava processors. The test locations were chosen in the peri-urban settlements of Abeokuta in the Ogun State of Nigeria, where household women entrepreneurs roast *garri* (granulated cassava) for sale in the local market. The measurements were taken for two types of stoves which are generally existing in the study location. First a rectangular stove (RS) with two operators, and second a circular stove (CS) with one operator, both stoves used wood as fuel. The emissions were compared with a modern mechanical liquified petroleum gas burner based *garri* roaster (GS).

Hours spent per day in front of *garri* stoves ranged from 6 to 12 hours for both stoves, with a frequency of 1 to 3 days of operation per week. It was found that CS operators were spending significantly more time in producing *garri*, which is due to the low capacity of the CS. Average $PM_{2.5}$ concentration for RS and CS were 381 and 273 µg/m^3 respectively, estimated to be 21 and 41 µg/m^3 on an annual mean level basis. Similarly, for PM_{10} the mean concentration levels were 1580 and 594 µg/m^3 for RS and CS, respectively. The annual mean levels for PM_{10} were about 89 µg/m^3 for both types of stoves. CO exposure during *garri* processing was up to five times higher than the recommended concentrations with a four-hour mean of 48 and 50 mg/m^3 for RS and CS stove respectively. NO_2 levels were very low, ~ 0 ppm.

This investigative research concluded that wood-fired small-scale *garri* producers in Nigeria are exposed to very unhealthy levels of PM, CO and thermal stress. The concentrations levels of both PM and CO were exceeding the global as well as Nigerian ambient air quality standard regulations. Along with air pollution, thermal stress was a significant issue, which is known to exacerbate the negative effect of air pollution on the human body.

Keywords *Particulate matter; Carbon monoxide; Heat stress; Food-processing; Firewood stoves*

1. Introduction

Occupational health and safety-related research and prevention in low- and middle-income countries (LMIC) have mostly focused on large scale industries (Ajayi 2017; McCann 1996; Osei Tutu and Anfu 2019). Although being a vital part of the food delivery system, the informal sector such as home-based small-scale cottage food processing industries is consistently neglected by policymakers. A high proportion of these small-scale enterprises generally use solid biomass fuel such as wood, animal dung, charcoal, crop wastes and coal, resulting in exposure to health-damaging particulate matter and greenhouse gases. Examples of such small-scale enterprises can include street food vending, fish smoking, drying, palm oil production and roasting operations in LMIC (Ajayi 2017). As many of these workers are women, they are likely to have with them infants and young children who are exposed to dangerous levels of air pollutants. It is estimated that globally about three billion people are exposed to pollution associated with burning of biomass especially in LMIC, resulting in 2.9 million deaths annually, and significant damage to health, environment and economy

(Simkovich et al. 2019). Although these figures are mostly collected for household air pollution, they may also include many individuals who depend on biomass fuels to earn a living by processing food products at small-scale.

Cassava tuber processing into *garri*, (a fermented and roasted granular cassava staple food product) is an excellent example of small-scale food processing industry in LMIC, which involve a considerable amount of solid biomass fuel burning. It is an important staple in West Africa, where per capita consumption is more than 120 kg per year (Anyanwu et al. 2015; Okafor et al. 1998). The estimate suggests that cassava and its processed products supply about 300 kcal/capita/day in Nigeria of which *garri* is the foremost contributor (Chilaka et al., 2018; FAO, 2018). *Garri* processing and distribution provide livelihoods to millions of farmers, household processors, processing equipment manufacturers, transporters, and traders (Okafor et al., 1998). Some estimate suggests that up to 5 million *garri* processors exist in Nigeria (Anyanwu et al., 2015). Processing is primarily dominated by women at household and cottage industry level. The sheer scale of *garri* production is such, that thousands of tonnes of *garri* are produced at small-scale levels with daily processing capacity as low as 50 to 100 kg.

Although, mechanised *garri* roasting equipment based on diesel and gas burners are developed and various pilot plants have been established in Nigeria, the traditional micro (household) and small processing enterprises are the most common producers of *garri* in rural as well as urban areas (Akinbami and Momodu 2013; Anyanwu et al. 2015; Ceceiski 1995). In these micro and small processing enterprises, solid biomass fuel (mostly wood and crops residues) is the common fuel source (Ifegbesan et al. 2016). The roasting process in *garri* production is an energy-intensive method requiring about 1 kg of wood (~18 MJ) per 4 kg *garri* (Ceceiski, 1995). In Nigeria, more than 66% of the households depend on the solid biomass as fuel (Nigeria Demographic Health Survey, 2013). This figure rises to 80% in rural and peri-urban areas (Dutta et al. 2018; Ifegbesan et al. 2016). The primary reason for the use of these fuels is low cost, availability and inadequate regulatory environment.

Some of the major pollutants which result from incomplete and inefficient combustion of solid biomass are particulate matter (PM) (especially fine particles < 2.5 µm of aerodynamic diameter), carbon monoxide (CO) and oxides of nitrogen (NOx) (Nayek and Padhy 2018). Long term exposure to these pollutants above the safe concentration's levels (Table 1), can cause respiratory problems, low birth weights, lung cancer, ocular ailments, and increased susceptibility to infectious diseases such as tuberculosis (Dutta et al. 2018; Ifegbesan et al. 2016; Obaseki et al. 2017; Olopade et al. 2017). Women and children are at higher risk, as already mentioned, they are the ones involved in the roasting part of *garri* production (Akinbami and Momodu 2013). Moreover, the burning of biomass-based fuel has direct implications for deforestation and climate change.

Fine particles ($\leq PM_{2.5}$) are in particular a cause of concern due to their accumulative nature which can initiate acute lower respiratory infection in young children (< 5 years), and obstructive pulmonary disease, heart diseases, lung cancer and stroke in adults (> 25 years) (Etchie et al. 2017). $PM_{2.5}$ can pass the lungs barrier and enter the bloodstream. In a cross-sectional study, Ofori et al., (2018), found an inherent association of biomass-based fuel pollution with increased blood pressure leading to cardiovascular disorders among rural-dwelling women in southern Nigeria. A clean-stove intervention experiment displayed reduced cardiovascular stress and prothrombotic effects from decreased household air pollution in pregnant women in Ibadan, Nigeria (Olopade et al. 2017). Akinbami and Momodu, (2013) during a survey conducted in Osun State, Nigeria reported that about 73% of the rural women in Nigeria are involved in *garri* and palm oil production using firewood stoves causing health and environment problems. Nigeria ranks 4th after China, India and Pakistan in the list of top 20 countries with the highest annual premature mortality attributed to $PM_{2.5}$ for population < 5 and ≥ 30 years old. Countries like Nigeria are at much higher risk as the natural sources of PM such as dust from the Saharan desert can overwhelm the anthropogenic PM generation (Giannadaki et al. 2016). CO is produced when fuels containing carbon such as wood is burnt with inadequate oxygen to convert all the carbon into carbon dioxide. The major health effects in terms of CO exposure are related to the reduced ability of red blood cells to take up oxygen from the lungs leading to a wide range of symptoms. Moreover, higher levels of CO are also known to contribute to the formation of tropospheric ozone, also known as ground-level ozone. Tropospheric ozone is an air pollutant, which occurs when nitrogen oxides, CO and volatile organic compounds react in the atmosphere in the presence of sunlight. National estimates of exposure to PM and CO and its impact on health and economy is still deficient in developing countries like Nigeria. Such information, typically lacking at the local level is a major hindrance towards employing any mitigation and intervention strategy (Akinbami and Momodu 2013; Etchie et al. 2017). The extent of research and development in the area of personal exposure to household air pollution in SSA (Sub-Saharan Africa) has been extremely limited, where most epidemiological studies have relied on indirect methods and proxies of exposure (Okello et al. 2018).

Along with pollutants mentioned above, another factor which may play a significant role in health is heat stress, particularly in hot and humid climates of tropics (Hyatt et al. 2010). When subjected to heat stress, the human body thermoregulation system attempts to enhance heat loss, this response can sustain a strain on the body, which can cause heat illness (Parson 2003). Environmental studies have proved that extreme heat exposure can increase mortality (Afshari and Shirali 2019; Kakaei et al. 2019). Heat stress is known to cause a range of symptomatic exhaustion such as heat cramps, heat stroke, poor concentration, fatigue, and reduced productivity in terms of loss in production and income (Kjellstrom et al. 2009; Parson 2003). Apart from increase core body temperature, dehydration and inadequate liquid intake is also a major driver of clinical diseases (chronic kidney diseases). A recent review by Kakaei et al., (2019) reveals that research and development on heat stress are rather limited to developed countries, and very little work on this aspect has been done in developing world, especially in SSA. Hence, an attempt was made to calculate the heat stress index for the *garri* processors by recording temperature and humidity surrounding the *garri* processing unit. It is principally important, as most of the *garri* processors are directly exposed to heat from roasting equipment in addition to already hot and humid conditions prevailing in the tropics.

In this study, a series of uninhibited field measurements of $PM_{2.5}$ and PM_{10}, CO and NO_2 were recorded for two types of build-in-place (not movable) *garri* stoves used commonly among resource-poor women entrepreneurs, in peri-urban settlements of Ogun state, Nigeria. The objective was to understand the personal occupational exposure to the women operators, rather than overall pollution emission from burning wood in *garri* stoves. The concentrations of these pollutants were compared with a modern mechanical liquified petroleum gas burner based *garri* roasters and recommendations for reducing the health impact of PM and CO on women and children was looked at. Moreover, an investigation was made if CO measurement using low-cost personal monitors can be a proxy to estimate exposure to $PM_{2.5}$, as some of the previous studies have shown a significant correlation between CO and $PM_{2.5}$ concentrations (McCracken and Smith, 1998; Roden et al., 2009).

Results of this study would assist in understanding more accurate personal exposure levels among the selected group of women and help develop future intervention programs. Also, the aim is to emphasise the role of women in energy policy and research in LMIC.

2. Methodology

2.1. Study area and survey design

The study was conducted during the month of January 2019 (dry season) in the peri-urban areas of Abeokuta city in Nigeria. Abeokuta is the largest city and the state capital of Ogun state in south-western Nigeria. The population of the city and its surroundings is about 450,000. The geography of Abeokuta lies in the fertile country of wooded savannah. Cassava, cotton, maize, palm oil and yams are some of the major crops grown and processed in and around the city. The precise location of the surveyed cites is shown in Figure 1.

Before measurements for PM, CO and NO_2 were conducted a field survey in the form of the personal interviews was carried out among the selected *garri* processors. The personal interviews were based on a semi-structured questionnaire to understand the type of fuel used, structure of the kitchen, daily/weekly *garri* roasting patterns, seasonal changes in patterns and identify if the locations are in proximity of a major source of emissions such as highway and a power plant, which can influence the emissions readings.

A total of 11 resource-poor women entrepreneurs involved in the processing of *garri* for market sale were selected from three different settlements in the peri-urban area of Abeokuta, Nigeria. Previous studies have shown that low socioeconomic status communities tend to have higher exposure to air pollutants (Obaseki et al. 2017; Zhou et al. 2011) due to lack of consistent physical access to clean fuels. The selection was based on the *garri* making facilities which used biomass fuel (wood). The selected processing systems were further divided based on the type of build-in-place stoves they were using (figure 2), namely single operator round pan stove (CS) and a double operator rectangular pan stove (RS). For comparison, reading from a natural gas burner stove (GS) was also recorded.

2.2. Instrumental setup and data collection

The concentrations of particulate matter with an aerodynamic diameter smaller than 2.5 μm ($PM_{2.5}$) and 10 μm (PM_{10}) was measured in $\mu g/m^3$ at one-minute intervals by a particle counter PCE-PCO2 (PCE Instruments GmbH, Deutschland). Apart from PM, temperature and humidity were also recorded with the PCE-PCO2. Real-time CO levels were measured every minute using portable dataloggers EL-USB-CO300 (Lascar Electronics Ltd, UK), with a measurement range of 0-1000 ppm and a resolution of 0.5 ppm, same sensors for CO have been used previously by Okello et al., (2018), and have been found suitable and accurate for the field measurement. NO_2 was measured by Gasman NO_2 (Crowcon, Oxfordshire, UK). The CO concentrations were converted into mg/m^3 by using the conversion factor of 1 ppm = 1.1642 mg/m^3 (EC 2014).

Previous studies show that time-weighted average area concentration of the major pollutants may not reflect the personal exposure accurately (Nayek and Padhy 2018), hence rather than a 24 h exposure period, the personal exposure is better to measure during the cooking period, when women and children are present in the processing area. Hence, measurements were recorded based on the 'breathing zone sampling' method, where static sensor set-up (consisting of $PM_{2.5}$, PM_{10}, CO, NO_2 data logger) placed in such a way (figure 3) that it mimics the sitting position of the processors. The CO sensors were set up in two different configurations, apart from the static sensor set-up, a personal CO data logger (EL-USB-CO300) was provided to the operator to clip onto clothing as close to the face as possible.

During the *garri* processing, it was observed that when the smoke became too thick and intense, the *garri* worker (wearing the CO personal sensor) would lean away from the roaster and if necessary, stand up and temporarily move away. Therefore, the interest was to see how the readings of the static and personal CO sensors differed.

2.3. Data analyses and statistics

Annual personal exposure levels (PE_{Annual}) of *garri* processors were estimated using equation 1 (Harrison et al. 2002; Hwang et al. 2018). C_m and t_m are four hourly mean concentration (for PM and CO (µg/m^3)) and time spent (hours) in the microenvironment (m) respectively. In this study, one microenvironment was considered which is a *garri* processing unit, and t_m is the average time spent at the *garri* processing centre annually.

$$PE_{Annual} = \frac{C_m \times t_m}{h_{Annual}} \quad \dots\dots\dots..(1)$$

$h_{Annual} = number\ of\ hours\ in\ a\ year\ (factor\ value = 8760)$

Thermal heat stress in terms of the temperature-humidity index (referred to as heat index, thereafter) HI_c was calculated using equation 2 (Brooke Anderson et al. 2013; Costanzo et al.

2006). In the absence of a WBGT (Wet Bulb Globe Temperature), the heat index is the best possible heat screen measure (Hyatt et al. 2010).

$$HI_c = (T - 0.55)(1 - \left(0.001 \times \left(\frac{R}{100}\right) \times (T - 14.5)\right) \ldots \ldots \ldots (2)$$

Where, T = Dry bulb temperature in °C

R = Relative humidity in %

Mass concentration of the PM and CO was illustrated by the descriptive statistics like mean, and standard mean error. Data distributions of the pollutants were represented through a Boxplot with whiskers. One-way analysis of variance was conducted for testing the significant differences among samples. A linear regression model was developed to understand if the correlation between CO and $PM_{2.5}$ is high enough to use relatively cheap CO sensor data as a tool to estimate $PM_{2.5}$ concentrations. SigmaPlot 12.0 (Systat Software GmbH, Erkrath, Germany) was used to do all statistical analysis and preparing graphs.

3. Results

3.1. Kitchen arrangement and roasting frequencies

The descriptive information from the *garri* roaster survey questionnaire is summarized in table 2. All the stoves used locally procured wood as fuel to roast *garri*. The majority (70%) of the kitchen arrangements were open from all sides (no sidewalls), hence ventilation can be considered very good for all kitchen arrangement. However, the triangular cone roof lack any passage for the smoke directly from the rooftop. The seasonal patterns in *garri* roasting seemed to not differ drastically, where eight out of eleven respondents did not report any changes in the frequency and duration of *garri* processing. The most common unit used to compare exposure to air pollutants is based on exposure over the time period of one year, hence we estimated the exposure on a yearly basis. On average, each CS operator spent 11.25 hours in a day, with a frequency of 2.25 days per week, accounting for an estimated 1,316 hours of exposure per year. For RS, the exposure per year was 496 hours due to large pan size, which enabled reaching the desired quantities of *garri* produced in less time.

During the survey, it was also observed that young children were accompanying most of the women *garri* processors, putting them at a higher risk of air pollution and heat exposure.

3.2. Particulate matter exposure

The data from the *garri* processing units (figure 4), shows that maximum exposure of PM for both $PM_{2.5}$ and PM_{10} was attributed to the RS, which is probably associated with the size of the stove and amount of wood burning is much higher than the CS. We also compared these values to ambient conditions (place away from any active source of pollution, or when no fuel was burning), and the average values of $PM_{2.5}$ and PM_{10} were 49 and 142 $\mu g/m^3$ respectively. This shows that the ambient PM concentrations are in general also higher than the recommended WHO values (Table 1) in peri-urban environments. We speculate that the higher ambient conditions might be caused by the present weather conditions because the survey was undertaken during the Harmattan. This is a season in the West African subcontinent, which occurs between the end of November and the middle of March. It is characterized by the dry and dusty northeasterly trade wind which blows from the Sahara Desert over West Africa into the Gulf of Guinea. Figure 5 provides a snapshot of the four-hour measurement window for PM and compare it with the recommended WHO values. The PM concentrations which the *garri* processor women and accompanied children are exposed to are significantly higher than the WHO guidelines values. Interim guidelines and standards for environmental pollution control in Nigeria suggests a daily average of 250 $\mu g/m^3$ for particulate matters (does not specify between PM_{10} and $PM_{2.5}$). Hence, observing the mean concentration of PM from *garri* processing in table 3, the levels are way above the Nigerian ambient air quality standards. Under the US-EPA $PM_{2.5}$ air quality index, these levels of PM would be deemed *Very Unhealthy*, triggering serious health effects on the exposed people. The levels of annual mean concentration contribution (Table 3) just from *garri* processing are almost double the WHO recommended value of 10 and 20 μg/m^3 for $PM_{2.5}$ and PM_{10}, respectively.

In our study, PM data is only from static sensors as we did not have access to personal PM sensors, however previous studies (Harrison et al. 2002; Hwang et al. 2018) on the relationship between personal versus static concentration of PM shows a significant correlation (R^2 = 0.80 to 0.90). Hence, we can assume that personal exposure in the case of PM could be in the range of 80 to 90% of the static concentrations in the *garri* processing microenvironment.

3.3. Carbon monoxide exposure

The mean concentrations for 4 hourly measurement period for static sensors was ~50 mg/m^3 for the CS and 48 mg/m^3 for RS. Whereas, the personal data logger (fixed on the processors' clothing) gave a mean measurement of 14 and 28 mg/m^3 respectively. The measurement at the start of the fire and at the end of the roasting process was avoided to get a more realistic understanding of the CO. McCracken and Smith, (1998) found during cooking tests in Guatemala that firewood stoves may show elevated levels of CO in the beginning and end of the cooking process. In the same study, the average CO concentration from open fire stoves was reported to be up to 120.5 mg/m^3 which is close to the concentration recorded in CS arrangement for *garri* roasting. A box plot diagram of CO concentrations for various stove and datalogger settings is presented in figure 6. RS presented a larger range for both sensor settings, with concentration going up to 228 mg/m^3; which could be attributed to the higher amount of wood-burning as the size of the RS is considerably bigger than CS.

Results from one-way analysis of variance and descriptive statistics for CO concentrations are presented in table 4. The personal sensor measurements were significantly lower for CS and RS with p-values < 0.05, however, this effect was not present in the case of GS where concentration from both sensor settings was statistically same. In some previous studies CO levels as a proxy indicator of $PM_{2.5}$ has been investigated, which make sense as CO sensors are low cost, lightweight, have long battery life and can easily be used. McCracken and Smith,

(1998) also reported a high correlation ($r^2 = 0.87$) between suspended particles and CO for an open fire. However, in our research for *garri* roasting measurements, the correlation between PM and CO was poor (figure 7).

3.4. Nitrogen dioxide exposure

The levels of NO_2 for all the measurements were 0 ppm, which shows that burning of biomass-based fuel such as wood does not produce a significant amount of NO_2 gas.

3.5. Thermal stress

The data analysis in figure 8 shows that heat index (HI) which *garri* producers are exposed to during roasting can be considered as hot conditions and can potentially have a detrimental effect on their health. It must be noted that ambient conditions in Nigeria during the dry season (month of January, when the survey was conducted) are relatively hotter, which will have an influence on the HI values as the shaded kitchen only provides protection from direct sunlight and have no other means to alter the temperature and humidity conditions under the shed. These HI values represent the heat stress experienced by the women processors and who are roasting *garri* and others who are accompanying them (for example a young child). The average ambient maximum and minimum temperatures at the study site during the survey period was ranging from 22 - 35 °C. We also found that the processors usually start working between 4 and 10 am in the morning in order to avoid the hottest part of the day.

4. Discussion

4.1 Kitchen arrangement and roasting frequencies

The exposure duration, particularly for CS, was close to previous reports, where annual exposure of up to 1,500 hours was reported at *garri* roasting workstations (Akinbami and Momodu 2013). Previous studies based on time-activity diaries from SSA (Okello et al. 2018) have shown that children aged < 2 years spend close to 90% of the time in the same microenvironment as of their mothers. Okello et al. (2018) also quantified how women and young children are exposed to up to five times higher PM2.5 than counterpart adult male. Akinbami and Momodu, (2013) indicated in their survey among rural Nigerian women, that demand for *garri* for domestic consumption within Nigeria market is high and will continue to dominate in all the regions of the country. Also, the social and cultural factors which forbid women to take part in certain economic activities, leaving them no choice to work in *garri* processing, which is traditionally a women activity. Women also reported a general increase in body temperatures, which was associated with smoke inhalation from roasting pan, leading to fatigue and aches (Akinbami and Momodu 2013). Also, air pollution exposure in younger women is more important as it is associated with adverse pregnancy outcomes such as stillbirth, preterm birth, low birth weight, reduced fetal head circumference and miscarriage (Dutta et al. 2018), putting new-born and young mothers at risk.

4.2 Particulate matter exposure

PM is the most important indicator of air quality, the major component of PM are sulphates, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water (WHO 2018). While PM10 with a diameter of ≤ 10 microns can penetrate deep inside the lungs, the more damaging particles are those with a diameter of ≤ 2 microns, i.e. PM2.5.

Giannadaki et al., (2016) estimated in their sensitivity analysis of PM and annual mortality rates, applying WHO guidelines value of 25 µg/m3, PM2.5 can reduce the mortality rates due to air pollution by 17%. In a similar study from India Etchie et al., (2017) stated that if world attains United States Environmental Protection Agency’s ambient PM2.5 limit of 12 µg/m^3, 1.4 million premature deaths can be avoided worldwide.

From a cross-sectional survey from rural East Africa, Okello et al., (2018) reported mean 24 hours PM2.5 levels of up to 205 µg/m3, and highest among the young and adult female groups and accompanying infants. Majority of the garri processing in Nigeria is done by women, hence, there is likely to be a direct correlation among young children’s exposure and their mother, as young children are expected to spend more time in the same microenvironment as their mother.

Titcombe and Simcik, (2011) reported levels of $PM_{2.5}$ as high as 1574 µg/m^3 from open wood fires in Tanzania from indoor kitchen settings. In the same study, authors compared 'fuel-efficient' wood stoves with traditional practices and found that proper use of improved fuel-efficient stoves can reduce the exposure by more than 90%. Okello et al. (2018), reported much similar exposure in adult females from Ethiopia and Uganda where the $PM_{2.5}$ levels were ranging from 50 to 650 µg/m^3. Nayek and Padhy (2018), reported much higher indoor $PM_{2.5}$ concentrations from rural Indian traditional biomass cooking stoves, with mass concentrations going above 2000 µg/m^3 in the least ventilated kitchens during domestic cooking periods. Van Vliet et al. (2013) reported exposure to fine particles in households using biomass fuel from rural Ghana, where 24-h integrated mean concentrations of $PM_{2.5}$ were 446.8 µg/m^3 from static sensors in the kitchen environment.

4.3 Carbon monoxide exposure

The general global and Nigerian air quality standard regulations (FEPA 1991) suggest that the maximum mean exposure of CO for an eight-hourly period should not exceed more than 10 mg/m3. However, during garri processing the women processor and accompanying children were exposed to the levels which are 2 to 5 times higher.

Previous studies have argued, that in general personal monitoring, which is an individual's exposure pattern in various microenvironments he or she is exposed to, would give lower concentrations than fixed site or static monitoring (Van Vliet et al. 2013). In our case, the reason for lower CO personal exposure is more related to the movement of *garri* stove operators to avoid the heavy smoke and heat influx many times and return to the original position as the smoke diminish. In certain cases (i.e. 24-monitoring) wearing personal sensors can modify the behaviour of the participants, however in our case as the measurements were taken for a 4-hour representative period of *garri* processing, no behaviour modification of the participants was observed.

Although it was obvious from the results that medium and large-scale liquefied petroleum gas-fired mechanical roasters would reduce the exposure to pollutants, however the capital and operating cost of that equipment is out of reach of the majority of resource-poor small-scale *garri* processors. PM sensors are generally expensive, an investigation was made if the CO measurement from low-cost sensors alone would be a suitable proxy for $PM_{2.5}$, however, the correlation was rather weak. We speculate that this can be explained through the reason provided by Roden et al. (2009), who stated that such a correlation is best suited for laboratory measurement but not for field measurements where there are additional factors such as wind speed and direction. Also, it may be the case that the higher correlation in previous studies was for the entire wood burning cycle, as it may significantly differ at different times during the combustion process. Okello et al., (2018) also mentioned in their discussion on PM2.5 and CO, that the correlation between both is rather weak.

4.4 Thermal stress

Thermal stress is still the most neglected occupational hazard in the tropical and subtropical regions (Hyatt et al., 2010) and was included in our study because of the additional heat from the fire along with the high ambient temperature. The heat index (HI) also known as Temperature Humidity Index (THI) is a common measure of thermal stress, which is comparable to the apparent temperature or Wet Bulb Globe Temperature (WBGT) (Brooke Anderson et al. 2013; Hyatt et al. 2010). HI supplies an estimate of the feeling of heat among the human population who are exposed to thermic and hygrometric environments and allows to analyse comfort level. The value of HI above 26.5°C is considered as hot conditions and is far from the comfort zone which lies in about 15 – 20°C HI value (Costanzo et al., 2006). Other references can be made from U.S. National Weather Service Heat Index ($HI=f(T, RH)$), where heat index > 37.778°C is classified as Very Hot conditions. At very hot conditions, the human body starts gaining heat rather than dissipating, which can increase the core body temperature (CBT), and disturb the body heat balance. CBT in humans lies in between 36.5 – 37 °C whereas skin temperature is about 32 °C (Parson 2003). Along with CBT increase, dehydration by sweating is another important factor during working in hot conditions.

Samuel and Adetifa, (2012) reported a mean WBGT of 35°C during garri production among a sample of garri-roasting workstations from Nigeria. Samuel and Adetifa also interviewed the garri processors about their experience of heat stress during garri making, in which 85% of the respondents defined conditions as very hot and damaging to their health. Exposure to such excessive thermal stress is known to cause a multitude of heat-related problems such as heat syncope, exhaustion, cramps, heat shock, heatstroke, fatigue, lack of concentration, and confusion (Kakaei et al. 2019). These symptoms not only result in heart-related disorders and higher risks of work-related accidents but also cause loss of productivity and worker's income (Afshari and Shirali 2019). Some estimate suggests that the loss of productivity can be halved with an increase of 2°C in WBGT (K. R. Smith et al. 2014), hence the economic impact of decreased work capacity can endanger livelihoods. Sahu et al., (2013) opined that work productivity of the workers in the rice field of West Bengal when exposed to thermal stress was significantly reduced, a rise in 1°C WBGT had an impact of ~5% on productivity.

In a recent study on the synergistic effect of high temperature and ambient air quality, it was found that the effects of PM2.5 and PM10 were significantly stronger under high-temperature conditions (Lee et al. 2018). Piver et al. (1999) assessed the impact of combined heat and pollution exposure in the urban environment of Tokyo and concluded that maximum temperature and concentration of pollutants such as NO2, were the most significant heatstroke risk factor. Also, the health risk is known to increase with the extent of physical effort, which is quite relevant to the women garri producers as it was observed that workers continuously stir the granules to avoid loss of quality. Increasing ambient temperatures due to climate change pose an additional threat to workers in tropical and sub-tropical LMIC where seasonal heat is already very high. (Hyatt et al. 2010; Kjellstrom et al. 2009; Sahu et al. 2013). Estimates from Inter-governmental Panel on Climate Change, 2007 suggests that average global temperature will go up by 2 – 4 °C by 2100, moreover, average global temperatures have already risen by 1 °C in 2015 (Afshari and Shirali 2019). Hence, rising temperature due to climate change would result in less work done in non-cooled conditions in hot countries.

5. Conclusion and recommendations

This investigative research determined that wood-fired small-scale garri producers in Nigeria are exposed to very unhealthy levels of PM, CO and thermal stress. Women and young children were at the highest risk. It is important to note that thermal stress is known to exacerbate the effect of airborne pollutants, particularly for pregnant women and children, causing a multiplier negative effect on health. Thus, long term exposure to these levels of air pollutants and heat to women and accompanying young children (particularly less than 5 years) is a significant risk factor towards various acute and chronic respiratory and cardiovascular diseases. A high level of $PM_{2.5}$ and CO during the *garri* roasting process also indicates incomplete combustion of wood fuel in the currently available stoves and roasting apparatus arrangement. Small improvements in the stove design such as providing more air inlets in the combustion chamber and provision of a chimney to carry the fumes away may help improve air quality. There are examples from the previous studies where low-cost energy-efficient wood fuel stoves resulted in significantly lower air pollution and enhanced utilisation of fuel (Ifegbesan et al. 2016; McCracken and Smith 1998; Olopade et al. 2017; Roden et al. 2009). Moreover, it is important to consider social and behavioural factors such as the closeness of young children to mothers while planning and implementing mitigation strategies. Preventive public health education should focus on women, for example informing the workers to drink enough water during roasting spells to avoid at least certain negative effects on their physical health.

Future work should consider collecting data for longer durations, in various socio-economic settings and over different seasons. However, collection of data over extended duration is particularly difficult in rural and peri-urban SSA due to practical problems (e.g. provision of uninterrupted power supply, and convincing people to wear the sensors for longer durations). A comparison of rural, peri-urban and urban settings would also provide good insights into the external contributing factors, for example, it may be the case that in urban settlements of big cities the exposure may be much higher due to pre-existing poor air quality caused by vehicular and industrial emissions. Understanding the physiological responses to heat stain in terms of deep body temperature, heart rate and sweating rate can shed more light on the adverse effects of air pollutants and heat. Along with negative health effect, heat stress and air quality have a significant effect on worker productivity, further investigations in reduced productivity and its effect on livelihoods for low socio-economic communities would be thought-provoking.

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Conflict of Interest and ethical standards

Authors declare there is no conflict of interests. Authors declare that experiments comply University of Greenwich, United Kingdom ethical standards.

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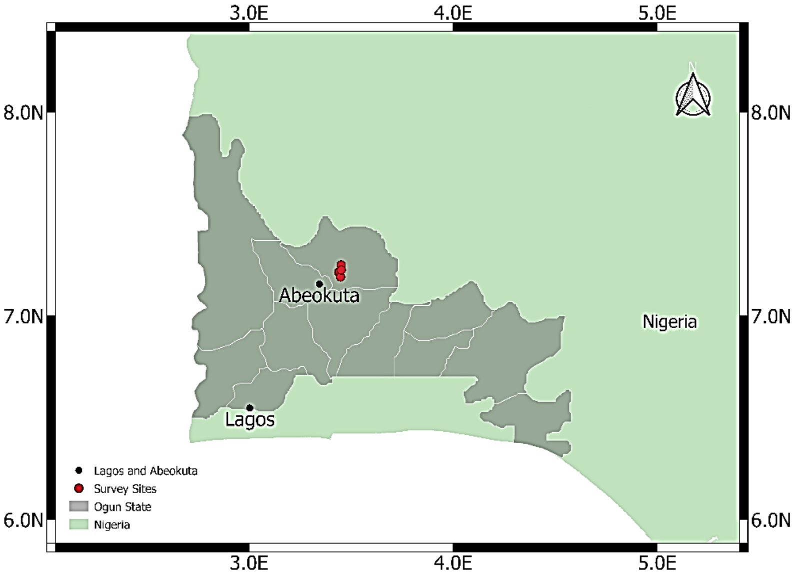

Figure 1: Survey sites.

Rectangular stove (RS) Dimensions: L=127 cm, B= 91 cm, H = 56 cm Material: Clay stove with cast iron pan.

Circular stove (CS) Dimensions: D = 80 cm Material: Clay oven with cast iron pan.

Natural gas burner stove (GS) Dimensions: D = 100 cm Material = Iron stove and steel pan.

Figure 2: Pictorial Illustrations of stoves (Credit: Keith Tomlins).

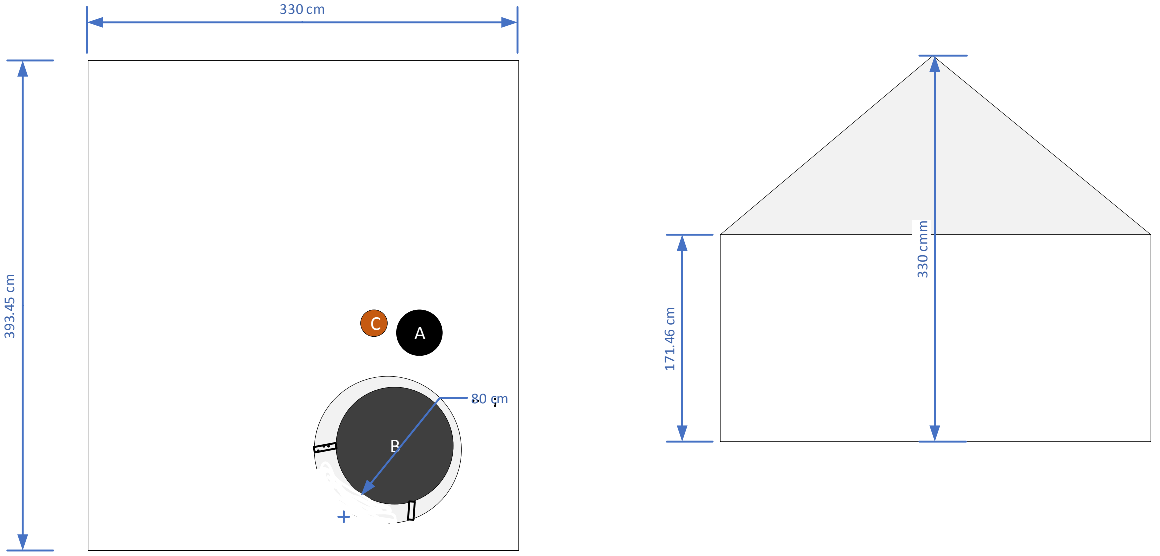

Figure 3: A typical *garri* roasting arrangement for individual roasting circular stove type (left) and transverse section showing height and roof structure of the kitchen (right). *(B-stove, A-Operator, and C-the static sensor setup, dimensions not to scale)*

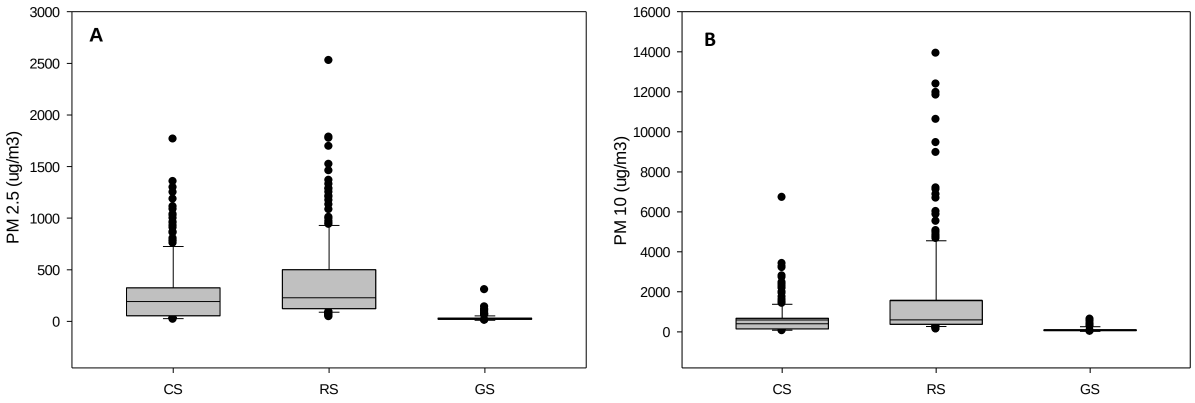

Figure 4: Box Plot of $PM_{2.5}$ (A) and PM_{10} (B) concentrations of the circular stove (CS), rectangular stove (RS), and gas stove (GS).

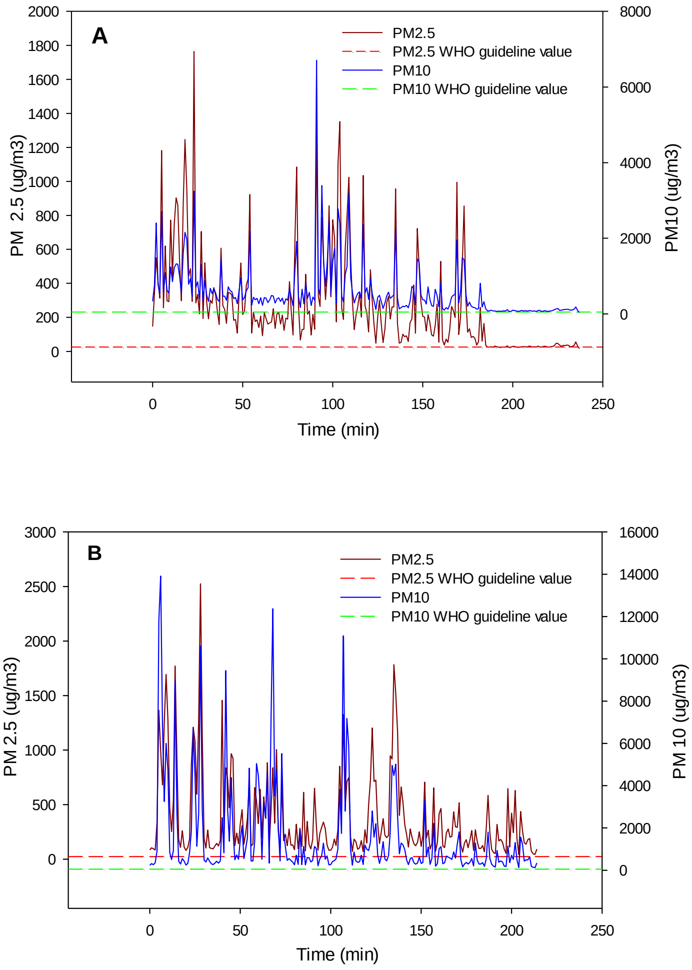

Figure 5: Concentration of $PM_{2.5}$ and PM_{10} during garri processing for circular (A) and rectangular stoves (B). Note: The four hours exposure measurement period. (RS- Rectangular stove, CS-Circular stove).

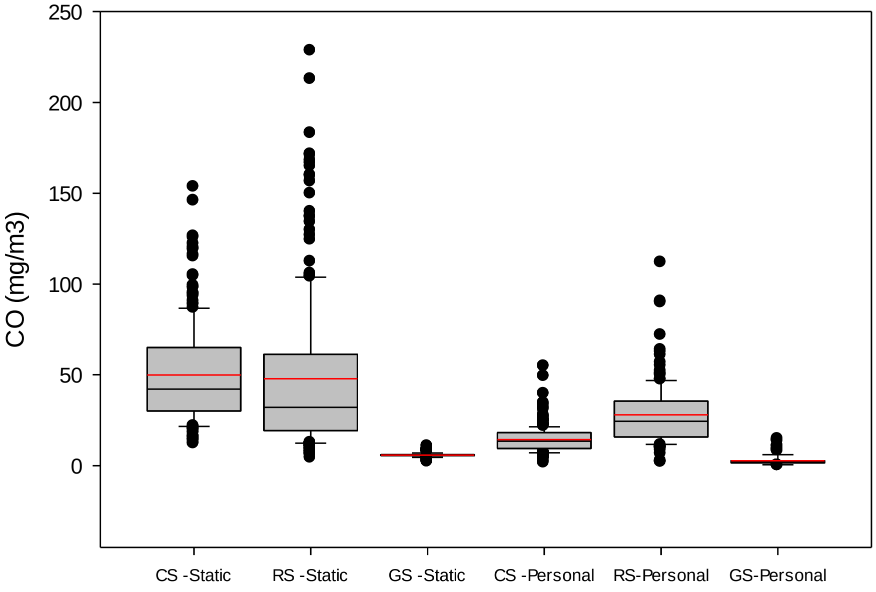

Figure 6: Concentration of CO for static sensor and personal sensors for various stove types. Note: Measurement for a 4-hour period during *garri* roasting. The data is from the static sensor

setup of data logger EL-USB-CO300 (RS- Rectangular stove, CS-Circular stove). The red line represents the mean levels of CO concentrations, and the black line is the median.

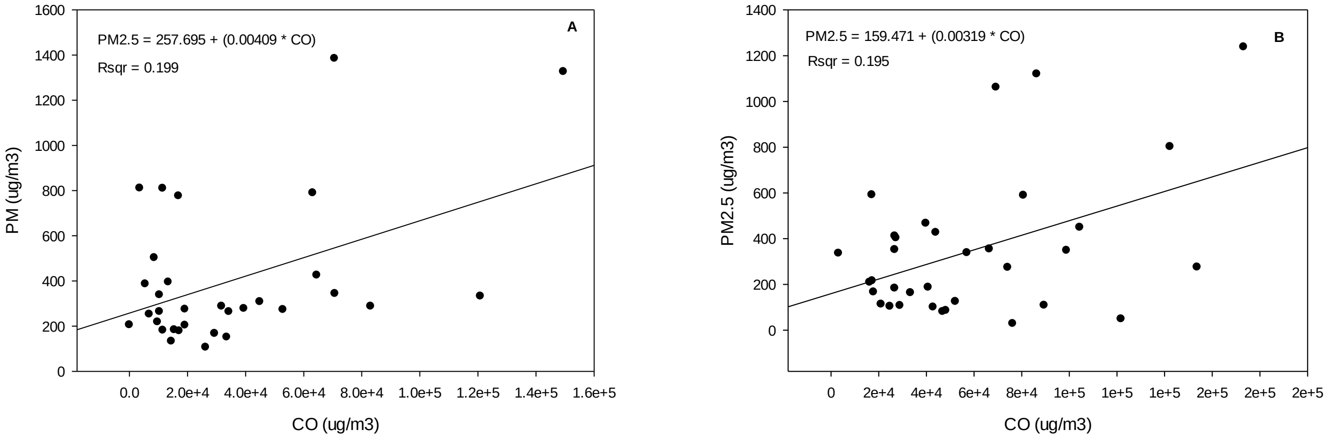

Figure 7: $PM_{2.5}$ concentration regressed against CO concentration for the rectangular stove (A) and circular stove (B). Note: The regression analysis was conducted on half-hourly mean data rather and every minute data.

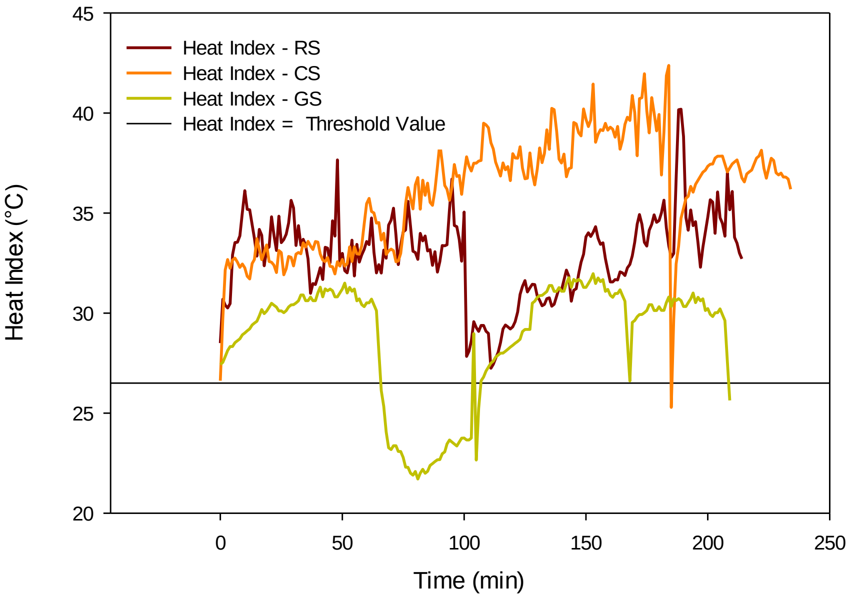

Figure 8: Heat index profile of microclimate (to which the operator and accompanying children would be exposed to) around three types of garri stoves for a period four hours. (RS-Rectangular stove, CS-Circular stove).

Table 1: Ambient air quality guidelines (adapted from Giannadaki et al., 2016).

Pollutant	Guideline values	Guiding authority
Particulate Matter (PM)*		
Fine Particulate Matter ($PM_{2.5}$)	10 µg/m^3 annual mean 25 µg/m^3 24-hours mean	World Health Organisation (WHO)
Coarse Particulate Matter (PM_{10})	20 µg/m^3 annual mean 50 µg/m^3 24-hours mean	
Carbon monoxide (CO)	10 mg/m^3 8-hours mean	European Commission (EU)

*The PM guideline values differ from country to country, for a specific region or country please refer to relevant concentration's values.

Table 2: Descriptive statistics from survey.

Parameter/Stove Type	Rectangular Stove (RS) n=3	Circular Stove (CS) n=8
Mean Length of garri processing shed (cm)	296.66	392.45
Mean breadth of garri processing shed (cm)	273.33	330.00
Mean height of garri processing shed (cm)	179.66	171.46
Mean *garri* roasting duration (h/day)	7.33	11.25
Mean frequency per week (days)	1.3	2.25
Annual exposure days (calculated)*	20.70	54.99
Annual exposure hours (calculated)	496.8	1319.76
Amount of garri production per day (kg)	133.33	100.00
Women operators	4	8.00
Man operators	2	0.00

$*Annual\ exposure\ days = \left[\frac{(Mean\ garri\ raosting\ hours\ per\ day) \times (mean\ frequency\ per\ week)}{24}\right] \times 52.14$

Table 3: Average annual personal exposure contribution of $PM_{2.5}$ and PM_{10}

Stove and Particulate Matter type	Mean concentration during garri processing (C_m) µg/m^3	Std. Error µg/m^3	Hours spent in garri processing per year	Annual mean concentration contribution (PE_{Annual}) (only from *garri* processing)
PM2.5 RS	381.18	26.68	496.8	21.62
PM2.5 CS	273.09	19.05	1319.76	41.14
PM2.5 GS	32.56	3.4	834*	3.10
PM10 RS	1580.23	159.36	496.8	89.62
PM10 CS	594.26	47.79	1319.76	89.53
PM10 GS	107.64	21.27	834*	10.25

*The gas stove was used for about 16 hours per week, accounting for about 834 hours annually.

Table 4: Descriptive statistics for carbon monoxide concentration for different sensor and stove settings.

Stove and sensor settings settings	**Mean concentration during garri processing (C_m) mg/m^3**	**Std. Error mg/m^3**	**25% Percentile**	**75% Percentile**
CO – CS (static sensor)	49.84$^{\mathbf{a}}$	1.75	30.02	65.05
CO – RS (static sensor)	47.81$^{\mathbf{c}}$	2.72	19.26	61.28
CO-GS (static sensor)	5.82$^{\mathbf{e}}$	0.12	5.5	6.0
CO-CS (Personal sensor)	14.31$^{\mathbf{b}}$	0.45	9.40	18.13
CO – RS (Personal sensor)	27.97$^{\mathbf{d}}$	1.33	15.72	35.51
CO-GS (Personal Sensor)	2.64$^{\mathbf{e}}$	0.26	1.5	2.63

Note: CO – Carbon Monoxide, CS-Circular Stove, RS -Rectangular Stove, GS-Gas Stove. The mean concentration value with a different letter in superscript shows the value is significantly different with a P-value < 0.05.