Frontiers | Frontiers in Public Health

TYPE Original Research
PUBLISHED 17 October 2023
DOI 10.3389/fpubh.2023.1241977

Check for updates

OPEN ACCESS

EDITED BY
Ghulam Mujtaba Kayani,
Hubei University of Economics, China

REVIEWED BY
Masoume Taherian,
Ahvaz Jundishapur University of Medical Sciences, Iran
Michael Poteser,
Medical University of Vienna, Austria
Sasan Faridi,
Tehran University of Medical Sciences, Iran
Dusan Jandacka,
University of Žilina, Slovakia

*CORRESPONDENCE
Habtamu Demelash Enyew
✉ habtdem@dtu.edu.et

RECEIVED 18 June 2023
ACCEPTED 20 September 2023
PUBLISHED 17 October 2023

CITATION
Enyew HD, Hailu AB and Mereta ST (2023) Kitchen fine particulate matter ($PM_{2.5}$) concentrations from biomass fuel use in rural households of Northwest Ethiopia.
Front. Public Health 11:1241977.
doi: 10.3389/fpubh.2023.1241977

Kitchen fine particulate matter ($PM_{2.5}$) concentrations from biomass fuel use in rural households of Northwest Ethiopia

Habtamu Demelash Enyew[1]*, Abebe Beyene Hailu[2] and Seid Tiku Mereta[2]

[1]Department of Public Health, College of Health Sciences, Debre Tabor University, Gondar, Ethiopia, [2]Department of Environmental Health Science and Technology, Institution of Health, Jimma University, Jimma, Ethiopia

Background: Combustion of solid biomass fuels using traditional stoves which is the daily routine for 3 billion people emits various air pollutants including fine particulate matter which is one of the widely recognized risk factors for various cardiorespiratory and other health problems. But, there is only limited evidences of kitchen $PM_{2.5}$ concentrations in rural Ethiopia.

Objective: This study is aimed to estimate the 24-h average kitchen area concentrations of $PM_{2.5}$ and to identify associated factors in rural households of northwest Ethiopia.

Method: The average kitchen area $PM_{2.5}$ concentrations were measured using a low-cost light-scattering Particle and Temperature Sensor Plus (PATS+) for a 24-h sampling period. Data from the PATS+ was downloaded in electronic form for further analysis. Other characteristics were collected using face-to-face interviews. Independent sample t-test and one-way analysis of variance were used to test differences in $PM_{2.5}$ concentrations between and among various characteristics, respectively.

Result: Mixed fuels were the most common cooking biomass fuel. The 24-h average kitchen $PM_{2.5}$ concentrations was estimated to be 405 $\mu g/m^3$, ranging from 52 to 965 $\mu g/m^3$. The average concentrations were 639 vs. 336 $\mu g/m^3$ ($p < 0.001$) in the thatched and corrugated iron sheet roof kitchens, respectively. The average concentration was also higher among mixed fuel users at 493 vs. 347 $\mu g/m^3$ ($p = 0.042$) compared with firewood users and 493 vs. 233 $\mu g/m^3$ ($p = 0.007$) as compared with crop residue fuel users. Statistically significant differences were also observed across starter fuel types 613 vs. 343 $\mu g/m^3$ ($p = 0.016$) for kerosene vs. dried leaves and Injera baking events 523 vs. 343 $\mu g/m^3$ ($p < 0.001$) for baked vs. not baked events.

Conclusion: The average kitchen $PM_{2.5}$ concentrations in the study area exceeded the world health organization indoor air quality guideline value of 15 $\mu g/m^3$ which can put pregnant women at greater risk and contribute to poor pregnancy outcomes. Thatched roof kitchen, mixed cooking fuel, kerosene fire starter, and Injera baking events were positively associated with high-level average kitchen $PM_{2.5}$ concentration. Simple cost-effective interventions like the use of chimney-fitted improved stoves and sensitizing women about factors that aggravate kitchen $PM_{2.5}$ concentrations could reduce kitchen $PM_{2.5}$ levels in the future.

KEYWORDS
biomass fuel, kitchen concentration, fine particle, cooking, Ethiopia

Introduction

Every day, nearly 3 billion people rely on solid biomass fuels (wood, dung, plant leaves, and charcoal) to cook their foods and to provide heat and light (1–3). Burning of these solid biomass fuels with open fires or inefficient stoves results in large amounts of health-damaging pollutants including a multitude of complex particulate matter and carbon monoxide (4–6) that exceed world health organization (WHO) air quality guidelines (24-h mean $PM_{2.5}$ concentrations of 15 μg/m^3) (7). Based on WHO report, in regions where solid biomass fuels are widely used, average levels of $PM_{2.5}$ were very high in kitchens 972 μg/m^3 and for personal exposure of women 267 μg/m^3 (8). In Africa, especially in the east, west, central, and southern parts of the continent, an estimated three-fourths of the population relies on solid biomass fuels for cooking and is exposed to high concentrations of harmful pollutants at home every day (3, 9).

In Ethiopia, more than 95% of the population used solid biomass fuels for cooking and were exposed to kitchen smoke which is typical for low-income countries (10, 11). Evidences from rural Ethiopia showed that women, girls, and children at early age were exposed to extremely high levels of $PM_{2.5}$ (12–14). Previous studies also reported 24-h average particulate matter concentrations of 818 ug/m^3 in slum areas of Addis Ababa, 1,297 ug/m^3 in three regions (Amhara, Oromia, and South Nation Nationalities and People) of Ethiopia, 772 μg/m^3 in Wolaita Sodo town and 410 ug/m^3 in Butajira town (13–16) all exceeded 24-h WHO safety level (17). As previously reported, these differences in concentrations may be due to differences in fuel and kitchen types, measuring devices, sampling seasons, and cooking patterns within households (13, 18–20).

Epidemiological studies are also increasingly showing that exposure to high levels of indoor air pollution from biomass fuel use kills millions and is a major contributor to global climate change (4–6). Household air pollution (HAP) contributed to more than 3.2 million annual premature deaths and 91.5 million disability-adjusted life years (DALYs) worldwide with a clear geographical variation where the majority of the burden is found in southeast Asia and sub-Saharan Africa (21–23). In 2019, air pollution was responsible for 1.1 million deaths across Africa, with more than half of those fatalities associated with household pollutants (24). Pneumonia and stroke are the leading causes of premature death due to HAP (3, 22, 23). About 400,000 children under 5 years old die each year as a result of HAP, primarily in sub-Saharan Africa and Asia (25).

In addition to detrimental cardiovascular effects, growing evidence shows potential perinatal risks associated with solid biomass burning (26–28). Adverse pregnancy outcomes such as low birth weight (LBW), pre-term birth (PTB), intrauterine growth restriction, and post-neonatal infant mortality are associated with biomass fuel smoke exposure (29). Fetuses are the most vulnerable stage to air pollution due to susceptibility at early ages (30, 31). In 2019, more than 100,000 deaths and 11.3 million DALYs related to preterm birth worldwide (66% in western sub-Saharan Africa and south Asia) were caused by excess $PM_{2.5}$, of which nearly two-thirds of them were attributable to household particulate matters $PM_{2.5}$ (32).

According to the local burden of disease estimate in Ethiopia, exposure to HAP from solid biomass fuel use was the second highest risk factor for child pneumonia deaths next to child malnutrition (33). The available local epidemiological studies have reported strong correlations between elevated $PM_{2.5}$ levels and acute respiratory infections (ARIs) among under-five children (16, 34–36). In Adama (southeast Ethiopia), HAP causes premature death and a significant number of DALYs due to biomass fuel use among women (37). Other existing evidences in Ethiopia revealed that the prevalence of acute respiratory infection including pneumonia among under-five children in households using solid biomass fuel remains high, ranging from 8 to 30 percent (34, 38–40).

Research on kitchen area concentration of particulate matter is limited in Ethiopia. Even the available evidences reported different results due to differences in the technologies used in the measurements, the sampling period, the study area (urban vs. rural), the season of measurements (dry vs. wet), the fuel and kitchen types, housing conditions, and other characteristics. Therefore, measuring local kitchen $PM_{2.5}$ concentrations and understanding different factors that influence kitchen particle concentration can inform measures to maximize the effectiveness of various interventions.

Methods and materials

Study setting

This study was conducted in a low-income rural community of the south Gondar zone, northwest Ethiopia as part of the ongoing stove intervention study. Pregnant women were recruited from six kebeles (the smallest administrative unit) of the Guna–Tana integrated field research and development center catchment area. The field research center was established in 2013 by Debre Tabor University to integrate education, research, and community services. It is located 650 km away from the capital city of Ethiopia, Addis Ababa, toward northwest Ethiopia and 105 km far away from the capital city of Amhara regional state, Bahir Dar. Solid biomass fuel is exclusively a household energy source for cooking with traditional three-stone stoves in the study area. Kebeles in the two ecological zones (cold and temperate) were included to represent a diversity of characteristics expected to influence kitchen concentration of particulate matter including altitude, cooking practices, fuel types, and socioeconomic conditions. Tobacco smoking is uncommon and vehicle emission is almost negligible in the study community.

Study design and population

A cross-sectional data was analyzed using the baseline measurements from an ongoing improved stove randomized controlled

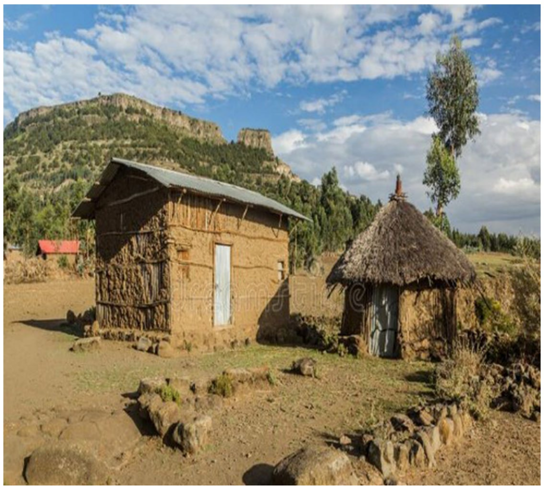

FIGURE 1
Small thatched roof kitchen near the main house.

FIGURE 2
Small corrugated iron sheet roof kitchen near the main house.

field trial study[1] to estimate $PM_{2.5}$ concentrations in kitchens of pregnant women cooking with solid biomass fuel in traditional stoves. The study participants who fulfilled the eligibility criteria were randomly selected and recruited from households in the stove trial project. To be eligible and participate in this study, a pregnant woman must meet the following inclusion criteria: Aged 18–38 years, being the primary cook of the household, in her first or second-trimester gestation (gestational age ≤ 24 weeks), exclusively using the traditional biomass-fueled stove or locally modified mud stove and having enclosed cooking area separated from or attached to the main house. But, pregnant women who had the plan to move permanently outside the study area in the next 12 months and who are engaged in local alcohol production activities were excluded from the study.

1 https://pactr.samrc.ac.za/; Identifier: ACTR202111534227089.

Sample size

The number of households with eligible pregnant women for kitchen $PM_{2.5}$ concentration measurement was determined based on standard conventional power calculations in the HAP intervention studies (41). These standard conventions include achieving a statistical power of 0.80, a value of p of 5% in two-tailed tests, and detecting a 64% HAP reduction due to an improved stove from a previous study (14). But, a reliable Ethiopia-based estimate of the coefficient of variation in HAP reduction was not available before our study to compute the minimum sample size. Therefore, a conservative COV estimate of 0.7 (41) was used which gave a minimum sample size of 43 households in each arm (a total of 86 households with pregnant women). Hence, all the baseline data collected from the upcoming stove trail study were analyzed for 86 randomly selected households.

Variable definitions and measurements

Kitchen

In this study, the kitchen is used to indicate all enclosed cooking spaces separated from or attached to the main house in rural households.

Kitchen types

There were two main kitchen types included in this study. The first one is a small thatched-roof kitchen near the main house. This type of kitchen had low-lying ceilings and very tightly enclosed walls resulting in the accumulation of dense biomass smoke during meal cooking due to the lack of an outlet at the highest part of the roof (Figure 1). The second kitchen is the small congrugated iron sheet(CIS) roof-enclosed kitchen with outlets between the wall and the roof for smoke removal (Figure 2).

$PM_{2.5}$ concentrations

It is the daily average concentrations of $PM_{2.5}$ calculated for the 24-h sampling period. Continuous $PM_{2.5}$ measurements were done using PATS+ following standard protocol. In this study, the device logged particle concentration with a logging interval of 1 min.

Biomass fuel

Any plant or animal matter which when burned provide heat or light. The type of cooking fuel was re-categorized into three classes; (a) firewood (b) cow dung (c) agricultural residue and (d) mixed fuels (using two or more biomass fuels together).

Primary biomass fuel

It is the first fuel choice that is usually cheap and easily available in villages. It's the primary practical option for rural households.

Family size

The total number of individuals permanently living in the household was assessed by recording all individuals (male, female, under-five children) and further categorized as (a) less than five individuals and (b) greater than or equal to five individuals. This classification was based on the average household size in Ethiopia reported by the Ethiopian Demography and health survey of 2016 (10).

Data collection procedures

Survey

All relevant baseline data were collected as part of an ongoing randomized controlled trial study. Face-to-face interviews using structured and pretested questionnaires and observational checklists were conducted by trained first-degree environmental health professionals in the local language (Amharic). The key data were collected on economic status (using the list of assets owned by the households), housing characteristics (floor, wall, roof, number of rooms, windows, and doors), kitchen characteristics (size, presence of windows, and location), fuel types, frequency of cooking, and frequency of Injera baking. Injera is the staple food in Ethiopia which is a flatbread-like pancake prepared from a tiny grain called Teff. Baking Injera is very energy-intensive to cook which uses approximately 50% of the energy consumed in the household (42). We also collected updated information on fuels used and the time activity pattern of the day during the particle measurement phase.

Particulate matter ($PM_{2.5}$) measurements

In this study, kitchen $PM_{2.5}$ concentrations were measured in 86 households using Particle and Temperature Sensor Plus (PATS+) which is a light-scattering particle sensor developed by Berkeley Air Monitoring Group, California. PATS+ is quite popular in this field as it is easy to transport and required less place to install. It had an internal power supply for 80 h of continuous measurement after being completely charged and provided data in a minute interval of time (43, 44). The device had a lower particulate matter detection limit of 10 μg/m³ and an upper particulate matter detection limit of 50,000 μg/m³ with a logging particle concentration interval of 1 min. Previous field validation tests have shown that PATS+ relates well to gravimetric $PM_{2.5}$ estimates in laboratory settings ($R^2 = 0.97$) and in rural biomass-using households ($R^2 = 0.74$) (43).

PATS+ was calibrated using gravimetric filters co-located in a previous study conducted in Ethiopia. Based on the regression result, an adjustment factor was estimated to be 0.8065 (14). But, for this particular study, it was not possible to calibrate the instrument specifically for local particulate matter due to the harsh sampling environments. Instead, we conducted side-by-side inter-comparison tests between PATS+ and DylosDC1700 air monitor devices in a real setting in 11 kitchens following standardized experimental procedures. The result confirmed good data comparability across PATS+ devices (Pearson correlation coefficients: 0.75 to 0.86).

A 24-h continuous kitchen air monitoring was carried out covering all Ethiopian main meals of the day (breakfast, lunch, and dinner) during the study period. Then, for each household, average concentrations were calculated as the means of these minute-by-minute average concentrations for each household with data on a sufficient number of hours (more than 20 h). In each household, monitoring for $PM_{2.5}$ started in the morning at around 8:30 am. We used the morning to the morning as starting and ending points of a sampling day. A total of 4 PATS+ were rotated through households during this study.

Instrument placement in the kitchens

The air monitoring devices were placed in the main kitchen at least 1 m away from the edge of the stove (to prevent from damaging as the devices cannot tolerate extreme temperatures and to represent the general cooking area), at a height of 1.5 m above the floor (the approximate breathing height of standing women), 1.5 m away from doors, windows, and other openings horizontally (to minimize ambient air entering the room) (45), and at a safe location to minimize the risk of interrupting normal household activities or being disturbed (Figure 3). The air monitors were attached to a wall or suspended from the ceiling and run for 24 h to consider households' typical daily cooking activities. In addition to measuring mean $PM_{2.5}$ concentrations, the PATS+ monitors also measured humidity and temperature.

Data quality

Field workers were trained in the use of the sampling equipment (PATS+ and Dylos DC1700), and a detailed manual with pictorial aids developed by the Berkeley air monitoring group (46) was used to assist them. They instructed to follow the standard operating procedures for installing indoor air pollution instruments in a home (45) in gathering kitchen air samples. To ensure that each 24-h period was representative (capturing a typical number of cooking events), measurements of $PM_{2.5}$ concentrations were removed from analysis when the total sampling time was shorter than 20 h.

In a previous study, PATS+ has been validated against gravimetric samples in Ethiopian settings, with the resulting strong linear

FIGURE 3
Placement position of particulate matter monitoring devices in the kitchen area.

correlation ($r^2 > 0.80$) (14). We have also conducted side-by-side inter-comparison tests between PATS+ and DylosDC1700 air monitor devices in a real setting in 11 kitchens following standardized experimental procedures which yield comparable data across PATS+ devices (Pearson correlation coefficients: 0.75 to 0.86). All PATS+ were zeroed in a plastic bag for 10 min before and after deployment in the kitchens. Though readings of optical air monitors are significantly affected by relative humidity levels usually at >80%, the relative humidity recorded in this study area ranged from 53 to 61% and would be unlikely to affect readings by more than 5% as reported from previous literature (47).

Data analysis

Data from the PATS+ air monitoring devices were downloaded in electronic form using the Platform for Integrated Cook Stove Assessment (PICA) software to the computer with CSV format Excel spreadsheets and text files. Paper-based data on the socioeconomics and demographic characteristics including housing conditions, kitchen types, fuel types, and cooking behavior were entered into SPSS software. Before formal statistical analyzes, simple tabulations and diagrams were constructed to gain a good understanding of the data and to identify gross outliers. Then, descriptive statistics including frequencies and percentages for categorical variables, and mean and standard deviations for continuous variables were calculated and presented using tables and graphs. In addition, we examined the pick hours at which the pollutant concentration in the kitchen measures high.

One-way analysis of variance (ANOVA) within 95% limits of a confidence interval, and value of p <0.05 was used to test differences in $PM_{2.5}$ concentrations among different characteristics with multiple levels. Tukey's Honest Significant Difference (HSD) test was done following ANOVA, to assess the significance of differences between pairs of groups. An independent sample t-test was used to check for differences in $PM_{2.5}$ concentrations between two different characteristics at a significant level of 5%. Data were analyzed using the statistical package for social science (SPSS) version 24.0 software and Microsoft Excel for better graphical visuals.

Ethical approval

This study was approved by the institutional review boards of Jimma University with ethical clearance provided (Ref No: IHRPGD/538/2021) to conduct the study. Information about the purpose of the study and potential study outcomes were provided to all participants. All participants were asked to give consent for participation before the commencing of the data collection. As a significant proportion of this population was illiterate, verbal informed consent was received from all participating households. Official letters of cooperation were given to the south Gondar zone health department and respective district health offices and permission to conduct the study was obtained. The right of the respondent to withdraw from the interview or not to participate was respected. During air pollution monitoring sessions, field staff received permission from participants to place air pollution monitoring devices in their kitchens. Devices chosen for pollution have no risk for participants.

Results

Household characteristics

In this study, a total of 86 households (HHs) with eligible pregnant women were approached for kitchen $PM_{2.5}$ concentration measurement. However, air monitoring data from 3 HHs were discarded due to the following reasons; (a) in one HH, an air monitoring device (PATS+) was taken from the kitchen to the main house to prevent it from theft, (b) in another HH, an air monitoring device was covered with the cloth to prevent it from damaging by children and (c) data from the third HH was discarded due to short sampling period (18 h).

All participants were Amhara by ethnicity, Orthodox Christian, and most of them were married. They were living on an earthen floor, wood/mud wall, and corrugated iron sheet (CIS) roof house which is typical in the study area. The mean age of the respondents was 28.7 (SD ± 5.34) years. In this study, there were an average of 4.5 (SD ±1.4) individuals permanently living in the household.

Kitchen characteristics

All households included in this study had a one-roomed separate kitchen with earthen floors and without windows. Nearly, three-fourths of participants had congregated iron sheet (CIS) roofed kitchens 64 (76.7%) and the rest 19 (23.3%) cooked in thatched roofed kitchens near the main house. When cooking, the kitchen doors of all participants' kitchens opened partially or completely. The thatched roof kitchens have no sufficient opening to vent out cooking smoke, making pregnant women more vulnerable. Whereas the kitchens with CIS roofs, though there were no formal ventilations, there were openings between the wall and the ceiling which provided informal ventilation and reduces smoke exposure.

Cooking practices

All participants lived in households where cooking was regularly practiced. Mixed fuels (mainly wood with dung) were the most common fuels used by 34 (40.7%) of the respondents followed by firewood where 27 (32.6%) of the interviewed pregnant women used to cook their food. Nearly three-fourths of the participants 62 (74.7%) used additional fuel to start the kitchen fire, from whom 22 (35.5%) used dried plant leaves and 19(30.6%) used agricultural straws. All participants were baking Injera at least twice per week and other meals daily (average cooking time = 2.8 (SD 0.92) hours/ day) for an average of 5 (SD 1.4) individuals during the study period (Table 1).

Kitchen $PM_{2.5}$ concentration

The average daily sampling time per household was 22.7 h with a range of 21 to 24 h. Because, some of the participating women faced

TABLE 1 Cooking related characteristics and distribution of kitchen $PM_{2.5}$ concentration in rural households of north-west Ethiopia (*n* = 83).

Characteristics	Number	Mean (SD) of $PM_{2.5}$ (ug/m^3)
Age group, in years		
18–24	19	481 [155]
25–31	35	435 [205]
32–38	28	321 [253]
Kitchen roof material		
Corrugated metal roof	64	336 [182]
Thatched roof	19	639 [181]
Types of fuel used during the study period		
Wood	28	358 [190]
Dung	14	414 [204]
Crop residues	9	231 [167]
Mixed fuels	32	493 [233]
Baking *Ijera* during the measurement period		
Yes	29	523 [209]
No	54	343 [202]
Family size		
≥ 5 individuals	42	427 [229]
<5 individuals	41	384 [212]
Number of meals cooked per day		
Twice	10	377 [160]
Three times	28	392 [211]
Four and more times	45	420[240]
Kitchen size		
< 15m^3	27	485 [255]
≥15 m^3	56	367 [193]
Use another fuel to start the fire		
Yes	62	407 [223]
No	20	402 [222]
Types of fuel used to start the fire (*n* = 62)		
Leaves	22	343 [190]
Straw	19	372 [245]
Paper	13	443 [182]
Kerosene	8	613 [224]
Number of meals cooked per day		
One meal	10	377 [160]
Two meals	28	392 [211]
Three and more meals	45	420 [240]
Opening between the kitchen wall and roof		
Yes	15	316 [226]
No	67	429 [215]

unexpected social issues like funerals, health problems, and other family issues that enforced them to go far away from their residences. In this case, they have to lock their kitchen and the installed air monitors have to be uninstalled. Since we planned to consider measurements undertaken for more than 20 h, we excluded one measurement due to the short sampling period (18 h). The average temperature was 20.4°C, while the average humidity was 57% for the cooking area.

The average 24-h kitchen area $PM_{2.5}$ concentrations were estimated to be 405 μg/m^3 (SD 221 μg/m^3) ranging from 52 to 965 μg/m^3 and the median concentrations were less than the mean at 383 μg/m^3. The continuous $PM_{2.5}$ concentration profile consistently showed slight diurnal peaks reflecting morning and evening cooking periods and was lowest overnight when the stove was likely off (Figure 4).

$PM_{2.5}$ concentrations by kitchen characteristics

The presence of an enclosed kitchen was one of the criteria for the HHs to be included in the kitchen area $PM_{2.5}$ concentration measurement. The average $PM_{2.5}$ concentrations was highest in the kitchen with a thatched roof (639 μg/m^3) with daily average concentration ranging from 309 to 965 μg/m^3 as compared with CIS roofed kitchen at an average concentration of 337 μg/m^3 with a range from 52 to 671 μg/m^3 (Figure 5).

The difference in average $PM_{2.5}$ concentrations is mainly due to a lack of outlet between the wall and the roof in the thatched roof kitchen where cooking smoke is trapped. Because the thatched roof kitchens had low-lying ceilings and very tightly enclosed walls resulting in the accumulation of dense biomass smoke during meal cooking. While the CIS roofed kitchen had many outlets at the highest part of the roof which served as smoke removal.

$PM_{2.5}$ concentrations by fuel types

In this study, the average $PM_{2.5}$ concentrations vary with different biomass fuel types used to cook the meal. Burning of mixed biomass fuel in the kitchen produces the highest average $PM_{2.5}$ concentrations. In the kitchens where mixed fuel was used, the average $PM_{2.5}$ concentrations were estimated to be 493 μg/m^3 with a median of 527 μg/m^3. The corresponding average concentration in kitchens with cow dung fuel was estimated to be 414 μg/m^3. For firewood cooking fuel, the average particle concentration was 358 μg/m^3 with a median of 344 μg/m^3 and the least particle concentration was recorded among agricultural residue users at the $PM_{2.5}$ concentrations of 231 μg/m^3 (Figure 6).

In addition to cooking fuel, the use of additional starter fuel to initiate the wood fire affects the concentration of particles in the kitchen. Accordingly, in the kitchen where kerosene was used to start the fire, the average $PM_{2.5}$ concentrations was 493 μg/m^3 followed by 414 μg/m^3 among straw/grass starter fuel users (Figure 7).

Determinants of daily average kitchen concentrations of $PM_{2.5}$

In addition to graphical visualization of raw relationships between different factors and average particle concentration, the model-based analysis provides a quantitative confirmation of important findings.

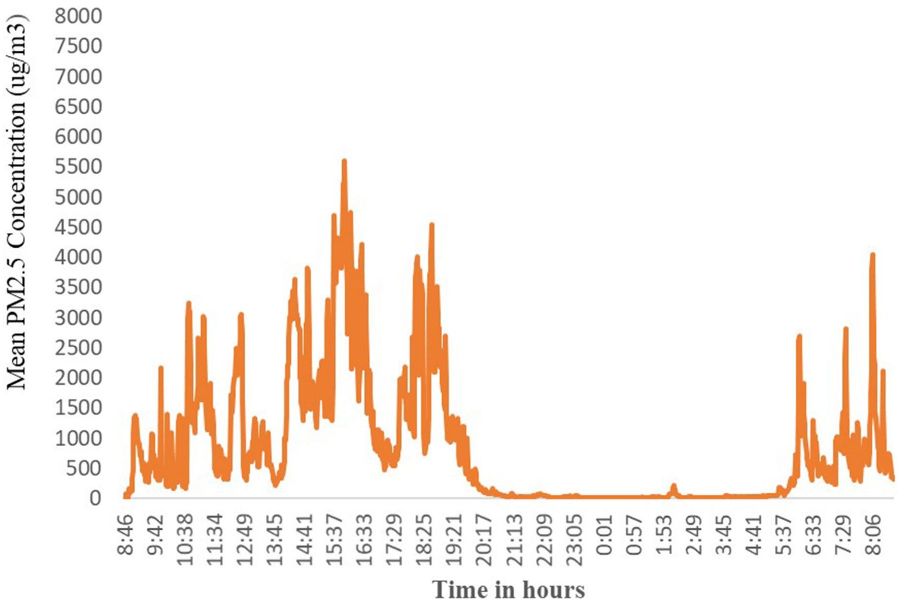

FIGURE 4
The distribution of kitchen area hourly average concentrations of $PM_{2.5}$ (μg/m³) by the time of day.

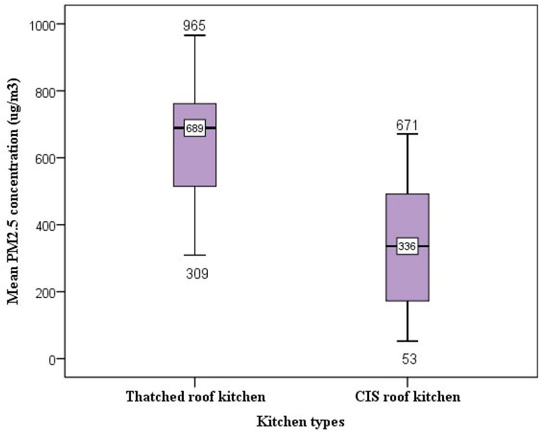

FIGURE 5
Box and whisker plots of 24- h kitchen $PM_{2.5}$ concentrations by kitchen roof type. The ends of the box are at quartiles, so that the length of the box is the interquartile range (IQR). The median is marked by a line within the box. The two whiskers outside the box extend to the smallest and largest observations.

As a result, we used the one-way analysis of variance (ANOVA) test to determine whether there is a significant difference in the mean concentration of $PM_{2.5}$ by each of, the fuel types used to cook, fuel types used to start the fire, number of meals cooked per day and other variables with more than two groups.

An independent sampling t-test was also used to compare the average concentration of two different groups and check for significant differences between these average concentrations. All significance values of Levene's test/statistics based on a comparison of the average concentration were greater than 0.05 indicating the requirement of homogeneity of variance has been met and the ANOVA and independent sample t-tests can be considered to be robust.

Accordingly, a statistically significant difference was observed in average $PM_{2.5}$ concentrations between the thatched roof and CIS roof kitchens. The results indicated that cooking in a thatched roof kitchen emitted on average 639 μg/m³ (SD = 181) $PM_{2.5}$ concentrations, compared with cooking in a CIS roofed kitchen which emitted an average concentration of 336 μg/m³ (SD = 182) $PM_{2.5.}$ This difference was statistically significant at 0.05 level ($t = 6.37$, $p < 0.001$). Using eta-square to examine the effect size, about 33.4% of the variation of $PM_{2.5}$ concentrations could be explained by kitchen roof types.

Similarly, in the kitchen where *Injera* was baked the average concentration of $PM_{2.5}$ was recorded to be 523 μg/m³ (SD = 209), compared with the kitchen where *Injera* was not baked which emitted an average of 343 μg/m³ (SD = 202) $PM_{2.5.}$ This difference was statistically significant at the 0.05 level ($t = 3.81$, $p < 0.001$). Based on the eta-square effect size estimate, only 15.2% of the variation could be explained by Injera baking events.

Regardless of the kitchen type, the result of one-way ANOVA showed a significant difference between fuel types used during the air monitoring period (firewood, cow dung, crop residue, and mixed fuel) and the average concentration of $PM_{2.5}$ ($F = 4.46$, $p = 0.006$). A Tukey *post hoc* test showed that burning of mixed biomass fuel (mean = 493 ug/m³, SD = 233 ug/m³) emitted significantly high average $PM_{2.5}$ concentrations than using both firewood (mean = 347 ug/m³, SD = 189 ug/m³) and agricultural residues (mean = 232 ug/m³, SD = 167 ug/m³). But there is no significant difference in average kitchen $PM_{2.5}$ concentrations among firewood, cow dung, and crop residue users.

Similarly, a statistically significant difference was observed between the types of fuel used to start the fire (dried leaves, straw/grass, and kerosene) and the average concentration of $PM_{2.5}$ ($F = 3.48$, $p = 0.021$). Accordingly, a Tukey *post hoc* pairwise comparison test showed that the use of kerosene to start the fire (mean = 613 ug/m³, SD = 224 ug/m³) has significantly higher average $PM_{2.5}$ concentrations than using dried plant leaves (mean = 343 ug/m³, SD = 190 ug/m³), straw/grass (mean = 372 ug/m³, SD = 245 ug/m³) and papers

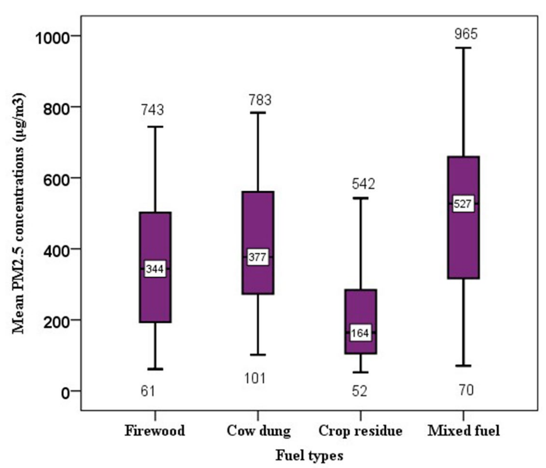

FIGURE 6
Box and whisker plots of 24- h kitchen $PM_{2.5}$ concentrations by types of cooking fuel used during sampling period. The whole boxes represent the interquartile range; numbers on the horizontal line inside the box indicate median. The top and bottom whiskers are minimum and maximum values, respectively.

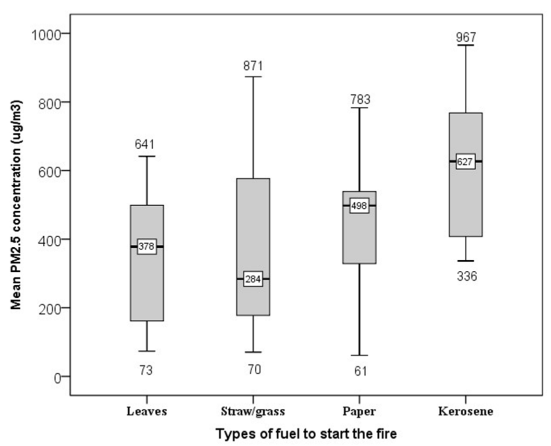

FIGURE 7
Box plot presenting the 24-h Kitchen area $PM_{2.5}$ concentrations using different fuel types to start the fire in the kitchen. The whole boxes represent the interquartile range; numbers on the horizontal line inside the box indicate median. The top and bottom whiskers are minimum and maximum values, respectively.

(mean = 443 ug/m^3, SD = 182 ug/m^3) to initiate the fire in the kitchen. Although 24-h average $PM_{2.5}$ concentrations at different meal cooking frequencies and the presence of openings between the kitchen wall and roof differed, the pairwise comparison indicated that it is not statistically significant ($p > 0.05$; Table 2).

Discussion

In the study area, solid biomass fuels are often used with inefficient and poorly vented cook stoves that result in a high concentration of toxic pollutants (13, 48, 49). In this study, mixed fuels (mainly firewood with cow dung) were the main type of fuel used for cooking.

TABLE 2 Cooking practices and kitchen characteristics associated with average $PM_{2.5}$ concentrations in rural households of north-west Ethiopia.

Characteristics	Average $PM_{2.5}$ difference (ug/m^3)	95% CI	*p*-value	Eta square
Kitchen types				
Thatched roof	Reference	–		33.4%
CIS roof	303	[260, 344]	<0.001	
Fuel types used				
Mixed fuel	Reference	–		14.5%
Firewood	146	[4, 288]	0.042	
Cow dung	63	[−107, 233]	0.766	
Crop residues	261	[56, 466]	0.007	
Fuel types used to start the fire				
Kerosene	Reference	–	–	15.3%
Dried leaves	269	[38, 501]	0.016	
Straw/grass	240	[5, 477]	0.044	
Papers	170	[−81, 422]	0.289	
Injera was baked				
Yes	Reference	–		15.2%
No	180	[86, 273]	<0.001	
Number of meals cooked per day				
One meal	Reference	–		
Two meals	−15	[−211, 181]	0.982	
Three and above meals	−43	[−229, 143]	0.846	
Opening between the wall and roof				
Yes	Reference	–		
No	−113	[−237,10]	0.072	

Similar studies reported biomass fuel as the main domestic energy source for rural Ethiopia (11, 50, 51). The study on fuel consumption patterns in India also revealed that the majority of households used solid biomass fuel (predominantly cow dung and wood) for cooking (52). However, this study's findings are different from results reported in Uganda and Kenya where charcoal and firewood only were reported to be the most commonly used cooking fuels, respectively (53, 54). These differences in fuel preference could be due to accessibility, types of a meal cooked, the design of used stoves, local temperature, and other behavioral and environmental factors.

In this study, the 24-h average kitchen area $PM_{2.5}$ concentration was estimated to be 405 µg/m^3 which is 27 times higher than the safety limit of 15 µg/m^3 recommended by the WHO 24-h mean air quality guideline and five times higher than the most flexible interim WHO target (IT-I) of 75 µg/m^3 (7) indicating the severity of kitchen area $PM_{2.5}$ levels in study rural households.

This estimated 24-h average kitchen area concentration of $PM_{2.5}$ was comparable to what is observed from the results of other kitchen air pollution monitoring studies in Ethiopia. Studies conducted in southern Ethiopia using similar (13) and different (15) air monitor devices in the kitchen have reported comparable results of 410 μg/m³ and 413 μg/m³, respectively. Another published review report in Ethiopia also revealed 24-h average $PM_{2.5}$ concentration of 477 μg/m³ (55). Another measurement of $PM_{2.5}$ during a single Injera baking event in Northwest Ethiopia reported an average $PM_{2.5}$ concentration of 855 μg/m³ (56).

Nearly similar results were reported from studies conducted in India where a 24-h average concentration of 468 μg/m³ was reported (57) and in Nepal with a 48-h average concentration of 417 ug/m³ (58). A relatively higher concentration was reported in Pakistan where the average $PM_{2.5}$ concentration was 531 μg/m³ (59) and in four states in India, 24-h average kitchen $PM_{2.5}$ concentrations of 600 μg/m³ were reported (60). The differences in kitchen particle concentration suggest possible differences in local cooking practices, types of a meal cooked, and fuel types used. These high concentrations of $PM_{2.5}$ as reported both from this study and previously conducted research in the kitchens might be due to the inefficient burning of biomass fuels and inefficient dispersion of particles in the kitchen area.

Because of the differences in kitchen design, the kitchen area concentration of $PM_{2.5}$ also varies (61). Based on the independent sampling t-test, we found higher kitchen $PM_{2.5}$ concentrations in households with thatched roof kitchens compared to households with metal sheet roofed kitchens. This result is similar to research reports conducted in Nepal and Peru where having metal sheet roof kitchens showed some association with decreased $PM_{2.5}$ concentrations compared to roofs made of thatched/grass/straw (62, 63). Research results from Punjab in India also revealed that the concentration of $PM_{2.5}$ varies across different kitchen types (52). As was also evidenced by another study, having a thatched roof was positively associated with increased 24-h PM concentrations (64). The possible reason might be due to better and faster dilution and dispersion of the pollutant taking place in different openings (in the case of metal sheet roofed kitchens) as compared to the confined kitchen (most thatched/grass roofed kitchens).

In this study, we also found that kitchen $PM_{2.5}$ concentrations varied with different fuel types used for cooking. Hence, burning of mixed biomass fuels (mainly firewood with cow dung) emitted average higher $PM_{2.5}$ concentrations than using firewood or agricultural residues only. A similar study on the effect of the fuel type used for cooking in the household showed that women who cooked with dung cake had the highest exposures compared with those who cooked with crop residues and firewood, respectively, in Ethiopia (12). Similarly, the maximum $PM_{2.5}$ emissions were reported from the burning of dung cakes followed by agricultural residues and mixed fuel (wood and dung) uses in India (52). Another study in Nepal reported that biomass fuel was the most significant source of $PM_{2.5}$ followed by kerosene (62). But, in Uganda, women who used crop residues had higher exposures to $PM_{2.5}$ compared to those using wood (12). Because, many characteristics, including heating value, moisture content, chemical composition, and the size and density of the fuel, affect the amount of particles released and these characteristics can vary from fuel to fuel (65).

It is also common practice to use additional fuel to start the wood fire in the kitchen. Dried plant leaves, paper, kerosene, and straw/grass were commonly used wood fire starter fuels in the study area. We also found high $PM_{2.5}$ levels variability by starter fuel type. In the kitchen where kerosene was used to start the wood fire, the average $PM_{2.5}$ concentrations were higher followed by straw/grass users. It is also evidenced that rural Indian women commonly used kerosene to start a fire in the kitchen (66). Though the epidemiological evidence is limited in this regard, paper, plastics, or kerosene are used to start the fire because they have low ignition temperatures which help to catch fire immediately and help the wood or the dung to reach its required ignition temperature.

Recognizing the public health impact of HAP from biomass fuel use and considering the use of biomass fuels in developing countries is likely to remain stable in the near future, WHO suggested several practical interventions for a clean cooking transition before widespread affordable access to electricity (67–69). The introduction of locally acceptable improved stoves, improved housing and ventilation design (replacing thatched roof kitchen with CIS roofed kitchen), and education and awareness-raising to support necessary changes in cultural habits related to cooking are some of the strategies for reducing exposure to household air pollution (17, 56, 70). There is an evidence that a chimney-fitted improved stove reduced wood smoke exposures and was associated with reduced low birth weight occurrence (71). But the most effective way to improve indoor air quality is the use of cleaner fuels, such as biogas, ethanol, and liquefied petroleum gas (9, 17, 72) and electric, wind, and solar are the cleanest option for health (1, 67, 73) however, transition to these fuels is not yet feasible for low-income countries.

Conclusion

Rural households in the study area entirely depend on biomass fuel with traditional three-stone stoves for cooking which emits high levels of particulate matter that exceeded WHO guideline values. The reported kitchen $PM_{2.5}$ concentrations in this study are sufficiently high to be a cause for public health concerns. Since the average $PM_{2.5}$ concentrations were found to be highest in the thatched roof kitchens, replacing the kitchen's roof with CIS to ensure that it allows air exchange during cooking times may be of benefit. Types of cooking fuel, types of fuel used for igniting the cooking fuel, and Injera baking events are also significantly associated with higher $PM_{2.5}$ concentrations. Simple cost-effective interventions like the use of chimney-fitted improved stoves could also reduce kitchen $PM_{2.5}$ levels in the future. This study may be used as a starting point for intervention studies employing quantification of $PM_{2.5}$ levels and other parameters that has to be considered in reducing the $PM_{2.5}$ levels. Our findings also highlight the need to create awareness of the effects of HAP exposure and to identify best practices for reducing exposure in the kitchen to reduce pollution levels.

Potential limitations

Though seasonal variations were reported in previous studies with high concentrations recorded during the cold season (19, 62), the presence of this variation was not captured in this study. The PATS+ measures fine particles at concentrations ranging from 10 to 50,000 ug/m³ and performed well when tested against a gravimetric standard. Due to the harsh sampling environment, we were unable to validate our continuous monitoring against the gravimetric analysis of samples collected in parallel. Therefore, the absolute values of the $PM_{2.5}$ measurements may not be fully accurate and should be interpreted with caution. Although households were randomly selected for air monitoring from those participating in the stove trail study, the latter were recruited based on inclusion criteria which may exclude relevant households. Finally, we did not measure ambient air pollution and therefore cannot account for the proportion of concentration from ambient $PM_{2.5}$ sources.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the institutional review boards of Jimma University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

HE and AH: conceptualization, designing of the methodology, recruitment, training of supervisors, and data collectors. SM and AH: formal data analysis, interpreting the result, writing draft manuscript, and editing. All authors contributed to the article and approved the submitted version.

Funding

This study was supported by Jimma University and Debre Tabor University. This research was also funded in part by a grant from SEAL awards, the nature conservancy foundation.

Acknowledgments

We would like to thank Debre Tabor University, Jimma University, and SEAL Awards, nature conservancy foundation for financial support. We also would like to thank the South Gondar Zone health department and respective district health offices for their cooperation to commence this study. Special thanks go to Gaia clean energy Association, Ethiopia for providing HAP monitoring devices (PATS+) and GEOHealth for Research and Training for Eastern Africa supported by NIH Fogarty International Center, NIEHS, CDC/NIOSH, and the Stockholm Environmental Institute, Kenya for the Daylos DC1700 to use for the $PM_{2.5}$ measurements. We are also grateful to the data collectors and supervisors for maintaining data quality.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

1. WHO. *Opportunities for transition to clean household energy: Application of the household energy assessment rapid tool (HEART)*. Ghana: WHO (2018).

2. WHO. *The energy access situation in developing countries. World Health Organization and the United Nations development Programme*. New York: WHO (2009).

3. Wright CY, Mathee A, Piketh S, Langerman K, Makonese T, Bulani S, et al. Global statement on air pollution and health: opportunities for Africa. *Ann Glob Health*. (2019) 85:144. doi: 10.5334/aogh.2667

4. Ranathunga N, Perera P, Nandasena S, Sathiakumar N, Kasturiratne A, Wickremasinghe R. Effect of household air pollution due to solid fuel combustion on childhood respiratory diseases in a semi urban population in Sri Lanka. *BMC Pediatr*. (2019) 19:1–12. doi: 10.1186/s12887-019-1674-5

5. Rosenthal J, Quinn A, Grieshop AP, Pillarisetti A, Glass RI. Clean cooking and the SDGs: integrated analytical approaches to guide energy interventions for health and environment goals. *Energy Sustain Dev*. (2018) 42:152–9. doi: 10.1016/j.esd.2017.11.003

6. Walker ES, Clark ML, Young BN, Rajkumar S, Benka-Coker ML, Bachand AM, et al. Exposure to household air pollution from biomass cookstoves and self-reported symptoms among women in rural Honduras. *Int J Environ Health Res*. (2020) 30:160–73. doi: 10.1080/09603123.2019.1579304

7. WHO. *WHO global air quality guidelines: Particulate matter (PM2. 5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide: Executive summary*. Geneva: WHO (2021).

8. Bryden KM, Bruce N, Peck M. *WHO indoor air quality guidelines: Household fuel combustion*. Geneva: World Health Organization (2015).

9. Health Effects Institute. *The state of air quality and health impacts in Africa. A report from the state of global air initiative*. Boston, MA: Health Effects Institute (2020).

10. Ethiopia and Calverton. *Ethiopia demographic and health survey, Addis Ababa*. Maryland, USA: Ethiopia and Calverton (2016).

11. Mondal MAH, Bryan E, Ringler C, Mekonnen D, Rosegrant M. Ethiopian energy status and demand scenarios: prospects to improve energy efficiency and mitigate GHG emissions. *Energy*. (2018) 149:161–72. doi: 10.1016/j.energy.2018.02.067

12. Okello G, Devereux G, Semple S. Women and girls in resource poor countries experience much greater exposure to household air pollutants than men: results from Uganda and Ethiopia. *Environ Int*. (2018) 119:429–37. doi: 10.1016/j.envint.2018.07.002

13. Tamire M, Kumie A, Addissie A, Ayalew M, Boman J, Skovbjerg S, et al. High levels of fine particulate matter (Pm2. 5) concentrations from burning solid fuels in rural households of Butajira, Ethiopia. *Int J Environ Res Public Health*. (2021) 18:6942. doi: 10.3390/ijerph18136942

14. Bluffstone R, LaFave D, Mekonnen A, Dissanayake S, Beyene AD, Gebreegziabher Z, et al. *Do improved biomass Cookstoves reduce PM2. 5 concentrations? If so, for whom? Empirical evidence from rural Ethiopia. If so, for Whom? Empirical Evidence from Rural Ethiopia*. World Bank Policy Research Working Paper No. 8930 (2019).

15. Admasie A, Kumie A, Worku A, Tsehayu W. Household fine particulate matter (PM 2.5) concentrations from cooking fuels: the case in an urban setting, Wolaita Sodo, Ethiopia. *Air Qual Atmos Health*. (2019) 12:755–63. doi: 10.1007/s11869-019-00700-0

16. Sanbata H, Asfaw A, Kumie A. Association of biomass fuel use with acute respiratory infections among under-five children in a slum urban of Addis Ababa, Ethiopia. *BMC Public Health*. (2014) 14:1–8. doi: 10.1186/1471-2458-14-1122

17. Carvalho H. New WHO global air quality guidelines: more pressure on nations to reduce air pollution levels. *Lancet Planet Health*. (2021) 5:e760–1. doi: 10.1016/S2542-5196(21)00287-4

18. Benka-Coker ML, Peel JL, Volckens J, Good N, Bilsback KR, L'Orange C, et al. Kitchen concentrations of fine particulate matter and particle number concentration in households using biomass cookstoves in rural Honduras. *Environ Pollut*. (2020) 258:113697. doi: 10.1016/j.envpol.2019.113697

19. Chan KH, Xia X, Ho KF, Guo Y, Kurmi OP, Du H, et al. Regional and seasonal variations in household and personal exposures to air pollution in one urban and two rural Chinese communities: a pilot study to collect time-resolved data using static and wearable devices. *Environ Int*. (2021) 146:106217. doi: 10.1016/j.envint.2020.106217

20. Coffey ER, Pfotenhauer D, Mukherjee A, Agao D, Moro A, Dalaba M, et al. Kitchen area air quality measurements in northern Ghana: evaluating the performance of a low-cost particulate sensor within a household energy study. *Atmos*. (2019) 10:400. doi: 10.3390/atmos10070400

21. HEI. *State of global air 2019: A special report on global exposure to air pollution and its disease burden*. Boston, MA, USA: Health Effects Institute (2019).

22. Murray CJ, Aravkin AY, Zheng P, Abbafati C, Abbas KM, Abbasi-Kangevari M. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. *Lancet*. (2020) 396:1223–49. doi: 10.1016/S0140-6736(20)30752-2

23. Keel J, Walker K, Pant P. Air pollution and its impacts on health in Africa-insights from the state of global air 2020. *Clean Air J*. (2020) 30:1–2. doi: 10.17159/caj/2020/30/2.9270

24. Fisher S, Bellinger DC, Cropper ML, Kumar P, Binagwaho A, Koudenoukpo JB, et al. Air pollution and development in Africa: impacts on health, the economy, and human capital. *Lancet Planet Health*. (2021) 5:e681–8. doi: 10.1016/S2542-5196(21)00201-1

25. Mock CN, Smith KR, Kobusingye O, Nugent R, Abdalla S, Ahuja RB, et al. *Injury prevention and environmental health: Key messages from disease control priorities*. (2018).

26. Lee KK, Bing R, Kiang J, Bashir S, Spath N, Stelzle D, et al. Adverse health effects associated with household air pollution: a systematic review, meta-analysis, and burden estimation study. *Lancet Glob Health*. (2020) 8:e1427–34. doi: 10.1016/S2214-109X(20)30343-0

27. Tipre M, Wickremesinghe R, Nandasena S, Kasturiratne A, Larson R, Meleth S, et al. Prenatal exposure to household air pollution and adverse birth outcomes among newborns in Sri Lanka. *bioRxiv*. (2018):461632. doi: 10.1101/461632

28. Weber E, Adu-Bonsaffoh K, Vermeulen R, Klipstein-Grobusch K, Grobbee DE, Browne JL, et al. Household fuel use and adverse pregnancy outcomes in a Ghanaian cohort study. *Reprod Health*. (2020) 17:1–8. doi: 10.1186/s12978-020-0878-3

29. Palma A, Petrunyk I, Vuri D. *Air pollution during pregnancy and birth outcomes in Italy*. CEIS Working Paper No. 464, (2019).

30. Mulenga D, Nyirenda HT, Chileshe-Chibangula M, Mwila P, Siziya S. Pregnancy outcomes associated with chronic indoor air pollution-related maternal respiratory III health in Ndola and Masaiti, Zambia. *Intern Med*. (2018) 8:2. doi: 10.4172/2165-8048.1000269

31. Olsson D. *Adverse effects of exposure to air pollutants during fetal development and early life: With focus on pre-eclampsia, preterm delivery, and childhood asthma*. Sweden: Umeå Universitet (2014).

32. Liu X-X, Fan SJ, Luo YN, Hu LX, Li CC, Zhang YD, et al. Global, regional, and national burden of preterm birth attributable to ambient and household PM2. 5 from 1990 to 2019: worsening or improving? *Sci Total Environ*. 871:161975. doi: 10.1016/j.scitotenv.2023.161975

33. Reiner RC, Welgan CA, Casey DC, Troeger CE, Baumann MM, Nguyen QAP, et al. Identifying residual hotspots and mapping lower respiratory infection morbidity and mortality in African children from 2000 to 2017. *Nat Microbiol*. (2019) 4:2310–8. doi: 10.1038/s41564-019-0562-y

34. Adane MM, Alene GD, Mereta ST, Wanyonyi KL. Prevalence and risk factors of acute lower respiratory infection among children living in biomass fuel using households: a community-based cross-sectional study in Northwest Ethiopia. *BMC Public Health*. (2020) 20:1–13. doi: 10.1186/s12889-020-08515-w

35. Admasie A, Kumie A, Worku A. Children under five from houses of unclean fuel sources and poorly ventilated houses have higher odds of suffering from acute respiratory infection in Wolaita-Sodo, southern Ethiopia: a case-control study. *J Environ Public Health*. (2018) 2018:1–9. doi: 10.1155/2018/9320603

36. Tefera W, Asfaw A, Gilliland F, Worku A, Wondimagegn M, Kumie A, et al. Indoor and outdoor air pollution-related health problem in Ethiopia: review of related literature. *Ethiop J Health Dev*. (2016) 30:5–16.

37. Balidemaj F, Isaxon C, Abera A, Malmqvist E. Indoor air pollution exposure of women in Adama, Ethiopia, and assessment of disease burden attributable to risk factor. *Int J Environ Res Public Health*. (2021) 18:9859. doi: 10.3390/ijerph18189859

38. Desalegn B, Suleiman H, Asfaw A. Household fuel use and acute respiratory infections among younger children: an exposure assessment in Shebedino Wereda, southern Ethiopia. *Afr J Health Sci*. (2011) 18:31–6.

39. Geberetsadik A, Worku A, Berhane Y. Factors associated with acute respiratory infection in children under the age of 5 years: evidence from the 2011 Ethiopia demographic and health survey. *Pediatr Health Med Ther*. (2015) 6:9.

40. Tsegay T, Biyadgie W. Association of indoor air pollution and other risk factors with acute respiratory infections among children in Sheka zone, south West Ethiopia. *J Harmon Res Med Health Sci*. (2018) 5:1. doi: 10.30876/JOHR.5.1.2018.1-9

41. Edwards R, Hubbard A, Khalakdina A, Pennise D, Smith KR. Design considerations for field studies of changes in indoor air pollution due to improved stoves. *Energy Sustain Dev*. (2007) 11:71–81. doi: 10.1016/S0973-0826(08)60401-9

42. Asmamaw FGAY. Epidemiology of burn injury among children's attended felege hiwot referral hospital in Bahir Dar town, Amhara regional state, Ethiopia, 2017. *J Pediatr Neonatal Care*. (2020) 10:21–7. doi: 10.15406/jpnc.2020.10.00408

43. Group WBW. *Transparent climate and health metrics: An open data dashboard and wireless platform for Cookstove monitoring, in Nexleaf analytics*. (2017).

44. Ajay Pillarisetti TA, Ruiz-Mercado I, Edwards R, Chowdhury Z, Charity Garland L, Drew Hill ID, et al. Small, smart, fast, and cheap: microchip-based sensors to estimate air pollution exposures in rural households. *Sensors*. (2017) 17:1879. doi: 10.3390/s17081879

45. Indoor APT. *Installing indoor air pollution instruments in a home version 5.1*. (2005).

46. Group BAM. *Platform for integrated Cookstove assessment (PICA): Particle and temperature sensor (PATS+) and software specifications*. (2016).

47. Wang Z, Calderón L, Patton AP, Sorensen Allacci MA, Senick J, Wener R, et al. Comparison of real-time instruments and gravimetric method when measuring particulate matter in a residential building. *J Air Waste Manage Assoc*. (2016) 66:1109–20. doi: 10.1080/10962247.2016.1201022

48. Benti NE, Gurmesa GS, Argaw T, Aneseyee AB, Gunta S, Kassahun GB, et al. The current status, challenges and prospects of using biomass energy in Ethiopia. *Biotechnol Biofuels*. (2021) 14:1–24. doi: 10.1186/s13068-021-02060-3

49. Kanno GG, Anbesse AT, Shaka MF, Legesse MT, Andarge SD. Investigating the effect of biomass fuel use and kitchen location on maternal report of birth size: A cross-sectional analysis of 2016 Ethiopian demographic health survey data. *medRxiv*. (2020) 2020:20197871. doi: 10.1016/j.puhip.2021.100211

50. Gebreegziabher Z, Beyene AD, Bluffstone R, Martinsson P, Mekonnen A, Toman MA. Fuel savings, cooking time and user satisfaction with improved biomass cookstoves: evidence from controlled cooking tests in Ethiopia. *Resour Energy Econ*. (2018) 52:173–85. doi: 10.1016/j.reseneeco.2018.01.006

51. Geissler S, Hagauer D, Horst A, Krause M, Sutcliffe P. *Biomass energy strategy Ethiopia*. AMBERO Consulting Gesellschaft mbH Immanuel-Kant-Str, No. 41. p. 61476. (2013).

52. Sidhu MK, Ravindra K, Mor S, John S. Household air pollution from various types of rural kitchens and its exposure assessment. *Sci Total Environ*. (2017) 586:419–29. doi: 10.1016/j.scitotenv.2017.01.051

53. Kansiime WK, Mugambe RK, Atusingwize E, Wafula ST, Nsereko V, Ssekamatte T, et al. Use of biomass fuels predicts indoor particulate matter and carbon monoxide concentrations; evidence from an informal urban settlement in Fort Portal city, Uganda. *BMC Public Health*. (2022) 22:1723. doi: 10.1186/s12889-022-14015-w

54. Musyoka D, Muindi K. A descriptive assessment of household air pollution in rural kitchens in Kenya. *Atmos*. (2022) 13:2115. doi: 10.3390/atmos13122115

55. Asefa EM, Mergia MT. Human exposure to indoor air pollution in Ethiopian households. *Heliyon*. (2022) 8:e11528. doi: 10.1016/j.heliyon.2022.e11528

56. Adane MM, Alene GD, Mereta ST. Biomass-fuelled improved cookstove intervention to prevent household air pollution in Northwest Ethiopia: a cluster randomized controlled trial. *Environ Health Prev Med*. (2021) 26:1–15. doi: 10.1186/s12199-020-00923-z

57. Mukhopadhyay R, Sambandam S, Pillarisetti A, Jack D, Mukhopadhyay K, Balakrishnan K, et al. Cooking practices, air quality, and the acceptability of advanced cookstoves in Haryana, India: an exploratory study to inform large-scale interventions. *Glob Health Action*. (2012) 5:19016–3. doi: 10.3402/gha.v5i0.19016

58. Bartington S, Bakolis I, Devakumar D, Kurmi OP, Gulliver J, Chaube G, et al. Patterns of domestic exposure to carbon monoxide and particulate matter in households using biomass fuel in Janakpur, Nepal. *Environ Pollut*. (2017) 220:38–45. doi: 10.1016/j.envpol.2016.08.074

59. Fatmi Z, Ntani G, Coggon D. Levels and determinants of fine particulate matter and carbon monoxide in kitchens using biomass and non-biomass fuel for cooking. *Int J Environ Res Public Health*. (2020) 17:1287. doi: 10.3390/ijerph17041287

60. Balakrishnan K, Ghosh S, Ganguli B, Sambandam S, Bruce N, Barnes DF, et al. State and national household concentrations of PM2. 5 from solid cookfuel use: results from measurements and modeling in India for estimation of the global burden of disease. *Environ Health*. (2013) 12:1–14. doi: 10.1186/1476-069X-12-77

61. Nayek S, Padhy PK. Daily personal exposure of women cooks to respirable particulate matters during cooking with solid bio-fuels in a rural community of West Bengal, India. *Aerosol Air Qual Res*. (2017) 17:245–52. doi: 10.4209/aaqr.2016.01.0028

62. Pokhrel AK, Bates MN, Acharya J, Valentiner-Branth P, Chandyo RK, Shrestha PS, et al. PM2. 5 in household kitchens of Bhaktapur, Nepal, using four different cooking fuels. *Atmos Environ*. (2015) 113:159–68. doi: 10.1016/j.atmosenv.2015.04.060

63. Fandiño-del-Rio M, Kephart JL, Williams KN, Moulton LH, Steenland K, Checkley W, et al. Household air pollution exposure and associations with household characteristics among biomass cookstove users in Puno. *Peru Environ Res*. (2020) 191:110028. doi: 10.1016/j.envres.2020.110028

64. Pollard SL, Williams D'AL, Breysse PN, Baron PA, Grajeda LM, Gilman RH, et al. A cross-sectional study of determinants of indoor environmental exposures in households with and without chronic exposure to biomass fuel smoke. *Environ Health*. (2014) 13:1–12. doi: 10.1186/1476-069X-13-21

65. McClure CD, Lim CY, Hagan DH, Kroll JH, Cappa CD. Biomass-burning-derived particles from a wide variety of fuels–part 1: properties of primary particles. *Atmos Chem Phys*. (2020) 20:1531–47. doi: 10.5194/acp-20-1531-2020

66. Lam NL, Smith KR, Gauthier A, Bates MN. Kerosene: a review of household uses and their hazards in low-and middle-income countries. *J Toxicol Environ Health Part B*. (2012) 15:396–432. doi: 10.1080/10937404.2012.710134

67. WHO. *Burning opportunity: Clean household energy for health, sustainable development, and wellbeing of women and children*. Geneva: WHO (2016).

68. WHO. *Burden of disease from household air pollution for 2012. 2014*. Geneva: WHO (2016).

69. WHO. *WHO housing and health guidelines*. Geneva: WHO (2018).

70. Edelstein M, Pitchforth E, Asres G, Silverman M, Kulkarni N. Awareness of health effects of cooking smoke among women in the Gondar region of Ethiopia: a pilot survey. *BMC Int Health Hum Rights*. (2008) 8:1–7. doi: 10.1186/1472-698X-8-10

71. Thompson LM, Bruce N, Eskenazi B, Diaz A, Pope D, Smith KR. Impact of reduced maternal exposures to wood smoke from an introduced chimney stove on newborn birth weight in rural Guatemala. *Environ Health Perspect*. (2011) 119:1489–94. doi: 10.1289/ehp.1002928

72. GACC. *Global Alliance for clean Cookstoves: 2017 Progress report*. (2017).

73. Goodwin NJ, O'Farrell SE, Jagoe K, Rouse J, Roma E, Biran A, et al. Use of behavior change techniques in clean cooking interventions: a review of the evidence and scorecard of effectiveness. *J Health Commun*. (2015) 20:43–54. doi: 10.1080/10810730.2014.1002958