A Section 508–conformant HTML version of this article is available at https://doi.org/10.1289/JHP1049.

Predictors of Personal Exposure to Fine Particulate Matter, Black Carbon, and Carbon Monoxide among Pregnant Women in Rwanda: Baseline Data from the HAPIN Trial

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Background: Exposure to household air pollution from the combustion of solid fuels is a leading risk factor for death and disease in low- and middle-income countries, where cleaner cooking and lighting options are often unavailable. Few studies have measured personal exposure during pregnancy, a sensitive period of development, particularly in Africa.

Objective: We aimed to characterize exposure during early to midpregnancy among women in Rwanda and to assess predictors of personal exposure, including stove and fuel type, cooking behaviors, housing conditions, sociodemographic characteristics, and other potential sources of exposure.

Methods: We assessed 24-h baseline personal exposure data among 798 pregnant women in the Household Air Pollution Intervention Network (HAPIN) trial in Rwanda, including 717 with fine particulate matter ($PM_{2.5}$), 569 with black carbon (BC), and 716 with carbon monoxide (CO) samples. Best subsets regression identified key predictors of personal $PM_{2.5}$, BC, and CO exposure, defined by maximizing adjusted R^2 values and minimizing prediction errors (Mallow's C_P and the Bayesian information criterion).

Results: The 24-h median concentrations at baseline were $88.9\ \mu g/m^3$ [interquartile range (IQR) = 85.0], $10.9\ \mu g/m^3$ (IQR = 7.6), and 1.12 ppm (IQR = 1.9) for $PM_{2.5}$, BC, and CO, respectively. Households using kerosene as a primary lighting source had higher $PM_{2.5}$ levels (median = $116\ \mu g/m^3$, IQR = 107) than those using electricity ($64\ \mu g/m^3$, IQR = 69). Women in households with modified biomass stoves with a chimney had lower median values ($48\ \mu g/m^3$, IQR = 52) for $PM_{2.5}$, compared with those in households using open fires ($113\ \mu g/m^3$, IQR = 74) and other traditional stove types ($155\ \mu g/m^3$, IQR = 43) that yielded the highest values. Consensus models from the best subsets' regression explained 26% of the variation in $PM_{2.5}$, 36% in BC, and 31% in CO concentrations.

Conclusions: Based on a unique and large dataset describing personal exposure among pregnant women in rural Rwanda, lighting and cooking practices described some variability in household $PM_{2.5}$ concentrations, but overall, substantial unexplained variability remained. https://doi.org/10.1289/JHP1049

Introduction

More than 3 million people die prematurely yearly from illnesses attributable to exposure to household air pollution from inefficient cooking using polluting stoves and kerosene.[1,2] In addition, exposure to household air pollution increases the risk of developing noncommunicable diseases, such as lung cancer, chronic obstructive pulmonary disease, ischemic heart disease, and stroke.[3,4] The highest health risks associated with using polluting fuels and technologies are borne by women and children, who are often responsible for household tasks like cooking and collecting firewood.[2]

The combustion of solid fuels emits many air pollutants of health concern, including fine particulate matter ($PM_{2.5}$; inhalable particles with aerodynamic diameters that are $\leq 2.5\ \mu m$),[5] carbon monoxide (CO; an odorless, colorless gas[6]), and black carbon (BC), which together compose a significant portion of the $PM_{2.5}$ contributing to the ongoing climate change problem.[7]

At the household level, various fuel types are used for cooking, including biomass such as wood, agricultural waste, and charcoal. According to the National Survey on Cooking Fuel Energy and Technologies in Households, as of May 2021, 80.4% of homes in Rwanda used firewood for cooking, and 18% used charcoal.[4] Households using crop residues and liquid propane gas (LPG) accounted for 9.5% and 5.6%, respectively.[3] The use of other sources of energy accounted for the remaining 5.9% of households. It is expected that households mix fuel types rather than rely on one fuel exclusively for cooking.[3] Electricity is the main energy source used for lighting by households, according to the Rwanda Energy

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Supplemental Material is available online (https://doi.org/10.1289/JHP1049).
There is no conflict of interest to declare.

Received 21 December 2023; Revised 15 November 2024; Accepted 4 December 2024; Published 10 January 2025.

Group (REG) (47%).[3] Other prevalent sources of energy for lighting are phone flashlights (28%) and solar power (14%).[8]

Another study conducted in Rwanda in 2018 showed that the 24-h mean concentrations of $PM_{2.5}$ and PM ≤ 10 μm in aerodynamic diameter (PM_{10}) were significantly higher in the dry season than in the wet season.[9] Between March and July 2018, results of a later study[5] revealed that the ambient average $PM_{2.5}$ in Kigali was $52\,\mu g/m^3$, significantly higher than World Health Organization (WHO) annual interim target 1 ($35\,\mu g/m^3$).

Understanding predictors of personal exposure to household air pollution and identifying key sources is essential to designing effective interventions to reduce exposures and associated health effects.[10] Given that air pollution has been shown to affect every major organ system,[11] mitigating key sources can help from the exposure side. Studies conducted elsewhere have identified a number of predictors of exposure to household air pollution, including kitchen type and lighting source. For example, a study in Mozambique found that, compared with women who had an open-air kitchen or did not have a kitchen, those who used an enclosed or partially enclosed kitchen had a 61% [95% confidence interval (CI): 17%, 122%] higher BC exposure. Exposure to BC was also higher in women using kerosene as a lighting source.[12] However, these studies focused on a single type of exposure, not a combination of exposures (i.e., $PM_{2.5}$, BC, and CO).

To date, few studies have described important predictors of household air pollution based on measured levels of exposure, including stove type, housing characteristics, cooking behaviors, and other sources of exposure, particularly in sub-Saharan settings. To address this gap in the available evidence, our work explored baseline data among pregnant women from Rwanda from the Household Air Pollution Intervention Network (HAPIN) trial to assess two aims: *a*) to characterize 24-h household air pollution personal exposure of $PM_{2.5}$, BC, and CO; and *b*) using a best subsets modeling approach, to identify key baseline predictors of personal exposure to these three household air pollutants among measured household variables. We hypothesized that a combination of stove, cooking, sociodemographic, and household factors would be predictive of personal household air pollution exposures among pregnant women at the HAPIN trial baseline visit in Rwanda and that stove type and lighting sources would be primary drivers of household air pollution.

Materials and Methods

Study Area and Population

The study was conducted in Kayonza District, one of the seven districts constituting the Eastern Province of the Republic of Rwanda. The district area comprises an estimated $1{,}954\,km^2$.[13] The landscape of the Kayonza District consists of hills and slopes whose altitude varies between 1,400 and 1,600 m.[14] The study region, situated in a wet tropical climate area, alternates between two wet and two dry seasons annually. The annual average rainfall varies between 1,000 and 1,200 mm; March and April typically receive the most precipitation.[15] The recorded annual average temperature lies between 18°C and 26°C. According to the Integrated Household Living Conditions Survey 4 (EICV4), the total population of the Kayonza District is estimated at 375,846 inhabitants, which accounts for 3.1% of the whole population of Rwanda and has a density of $192\,inhabitants/km^2$.[16] Most households in the Kayonza District (94%) use solid biomass fuels for cooking, primarily firewood, charcoal, and crop residues. It is important to note that the fuel types are not always exclusive, and households tend to combine different types of energy for cooking. Cleaner energy types, such as LPG and electricity, are still rarely used consistently in rural areas, such as the study region of this research.[1]

Participant Recruitment and Inclusion/Exclusion Criteria

This study was part of the HAPIN trial that was conducted in international research centers (IRCs) in rural areas of Jalapa, Guatemala; Tamil Nadu, India; Puno, Peru; and Eastern Province, Rwanda[17]; however, our results focus on Rwanda baseline data, which included 798 nonsmoking pregnant women 18 to <35 years of age [confirmed by government-issued identification (ID) whenever possible] who had agreed to participate with informed consent and who cooked primarily with biomass, lived in the Kayonza District, were at 9 to <20 wk gestation at recruitment, and had a pregnancy confirmed by ultrasound.[18] A portable ultrasound [Edge (Edge Ultrasound System), Sonosite/Fujifilm Edge (FUJIFILM SonoSite Inc.)] was used by qualified individuals (who were also additionally certified centrally) in a clinic or home environment to establish eligibility. A potentially eligible pregnant woman was excluded from recruitment if she reported currently smoking cigarettes or other tobacco products, was planning to move permanently outside the study area within the next 12 months, was primarily using a fuel other than biomass, or was likely to primarily use LPG in the near future.

Study Design

This study used a cross-sectional design based on the baseline data from the Rwanda IRC; however, we will briefly describe the entire HAPIN trial to give a fuller picture of the long-term study. Before any intervention, the baseline data represented primarily biomass fuel cooking for all study participants. The HAPIN study is a global multicenter study (ClinicalTrials.gov identifier NCT02944682), evaluating the health effects of an LPG cookstove and fuel intervention in Guatemala, Peru, Rwanda, and India. The HAPIN trial research design has been discussed in greater detail elsewhere.[18] Briefly, 800 pregnant women from homes using biomass fuel were identified and enrolled at each of the four IRCs. The intervention, which included a free 18-month supply of LPG, was randomly assigned to half of the homes. The remaining half, who featured as controls, continued to use biomass-fueled traditional cookstoves. Mothers and children in both control and intervention groups were followed until the child turned 1 y old. The location was specifically chosen to represent a variety of criteria likely to affect intervention results, such as altitude, population density, cooking methods, baseline pollution levels, and sources of pollution other than cooking, to maximize generalizability. In addition, other variables, such as fuel types, habitation characteristics, and socioeconomic situations, that may affect the outcomes of interventions were measured and recorded. In this paper, we report baseline exposure levels and investigate predictors of 24-h personal exposure to $PM_{2.5}$, BC, and CO among pregnant women in Rwanda.

The study protocol was reviewed and approved by institutional review boards or ethics committees at Emory University (00089799), Johns Hopkins University (00007403), Sri Ramachandra Institute of Higher Education and Research (IEC N1/16/JUL/54/49) and the Indian Council of Medical Research–Health Ministry Screening Committee [5/8/4-30/(Env)/Indo-US/2016-NCD-I], Universidad del Valle de Guatemala (146-08-2016/11-2016), Guatemalan Ministry of Health National Ethics Committee (11-2016), Asociacion Benefica PRISMA (CE2981.17), London School of Hygiene and Tropical Medicine (11664-5), Rwandan National Ethics Committee (357/RNEC/2018), and Washington University in St. Louis (201611159). The study has been registered with ClinicalTrials.gov (NCT02944682).

Exposure Measurement

Full details explaining the exposure measures for HAPIN have been published previously.[18,19] In brief, personal exposures of pregnant women were measured with Enhanced MicroPEM

(ECM) manufactured by RTI International for $PM_{2.5}$ before randomization. The ECM was used to collect $PM_{2.5}$ gravimetrically with a filter by drawing air through an impactor attached to a cassette containing 15-mm Teflon filters (PT15-AN-PF02; MTL Corporation). The ECM contained a calibrated mass–flow element, a six-axis accelerometer (to log activity rate and to verify the user complied with wearing the sampler), and measured real-time $PM_{2.5}$ levels with a nephelometer (light-scattering sensor). It also logged temperature, relative humidity, and filter pressure drop. CO was measured by Lascar CO loggers worn in a vest or apron for a 24-h period during the pregnancy. BC was measured on the $PM_{2.5}$ filters collected via the ECM. BC was quantified on the filters using a SootScan Model OT21 transmissometer (Magee Scientific), often used for characterizing BC for personal exposure and emissions studies. The instrument measured the light attenuation through the filter at the 880-nm wavelength, which was then converted into a BC surface deposition.

The women were asked to wear the vest or apron at all times during the full 24-h measurement period except when sleeping, bathing, or conducting other activities for which the equipment could not be safely worn. The vests and aprons secured the ECMs and CO loggers near the breathing zone, an approach similar to those used in other household air pollution exposure studies.[18,20] Compliance was checked via the ECM's accelerometer data to detect motion during normal daily activities, and as part of the survey, participants were also directly asked at the end of each sampling duration about wearing the monitors.

Data Processing and Quality Assurance

Multiple trainings were conducted at each site to standardize and implement the co-developed operating procedures. In collaboration with the data management core, file naming, data uploading, and data quality checking protocols and tools were developed to ensure organization and timely resolution of issues. Exposure instrument data were downloaded on local computers and backed up on the cloud in secure folders. Multiple quality control (QC) steps for each exposure data stream were taken to include only valid household air pollution measures.[17]

Survey Variables

Qualified fieldworkers visited the households at the beginning of the study to conduct baseline surveys and other assessments after recruitment and informed consent. Research assistants conducted interviews and surveys in the participant's native language. The baseline visit included a survey covering a range of topics covering cooking behaviors, household composition, and socioeconomic and demographic information like age in years that was confirmed by national ID card, education that was self-reported and split into no formal education, primary or secondary incomplete, and secondary, college, or university categories. Other self-reported variables included housing characteristics, cooking behaviors, socioeconomic variables, exposure to secondhand tobacco, and dietary diversity. Dietary diversity was measured using the minimum diet diversity (0 to 10) scale adapted from the Food and Agriculture Organization of the United Nations Minimum Diet Diversity for Women (FAO 2016).[32] Variables recorded by field workers included ventilation, electricity, lighting source, fuel type, stove type, and stove location. Material items were selected as useful indicators of socioeconomic status (SES) by other HAPIN investigators to be used across all publications. Because SES and other social determinants of health might influence individual interactions with household exposures, the study included such measures at all study sites. Pregnant women were surveyed by a trained fieldworker or nurse who measured resting blood pressure (model HEM-907XL; Omron) in triplicate and maternal weight (seca 876/874 scales; Seca) and height (seca 213 stadiometer; Seca) in duplicate. Separate questionnaires assessed physical activity, dietary diversity, household food insecurity, and household expenditures. Detailed categories for each variable are shown in Table 1.

Statistical Analysis

Data were cleaned and analyzed using R (version 4.2.2; R Development Core Team) and RStudio (version 4.2.2; RStudio Team), primarily relying on the "tidyverse," "leaps," and "ggplot2" packages. The initial raw dataset included 798 observations of Rwandan pregnant women at baseline (2 women were deemed ineligible after recruitment). For analysis, we included only valid exposure data among pregnant women as identified by the HAPIN Exposure Core, for a total of $N = 717$ $PM_{2.5}$ observations, $N = 569$ BC observations, and $N = 716$ CO observations. Exposures were removed when they did not pass quality assurance (QA) and QC tests. For example, BC was measured on the same type of filter as used for gravimetric $PM_{2.5}$ analysis. Given that any filter data that did not pass QA/QC for gravimetric analysis would not have been valid for BC either, that led to fewer valid BC samples than $PM_{2.5}$ because we also used the light-scattering (nephelometer) data whenever possible to estimate $PM_{2.5}$ in case of an invalid filter. In that case, we would have a $PM_{2.5}$ estimate, but not a valid BC estimate. The second cause for the discrepancy was that any filter that had a >100-μg equivalent deposition of BC was out of the range of the instrument.

Detailed exploratory data analysis was carried out by removing missing or invalid data and assessing frequencies and means [standard deviation (SD), median, minimum–maximum, and 25th and 75th quartiles] of 24-h exposures and all covariates. We provided descriptive summaries in tables and figures (e.g., histograms, box-and-whisker plots) formats. We assessed Spearman correlations of exposure variables and distributions of raw vs. natural log-transformed exposures. After assessing how well the observed and transformed exposure measurements met the assumptions of linear regression, we decided to use the transformed versions. We created a cooking frequency summary variable to simplify the analysis of raw data capturing women's behaviors around the amount of cooking each week, calculated as the product of the number of days she cooked per week and the number of times she cooked per day, to give us a self-reported estimate of the number of times she cooked in a week (i.e., cooking hours per week $=$ cook days/week $\times$ cook hours/day).

We highlighted covariates with variation in responses (e.g., categories of responses included at least 5% of the sample for categorical variables). We assessed covariates' associations with household air pollution exposures in the crude variable (i.e., unadjusted) linear regression models. We explored how these covariates correlated with one another to assess potentially strong correlations. We examined contingency tables for categorical variables to see if any had responses overloaded in just a few cells.

We ran the best subsets of linear regression using the R package "leaps" to identify those measured covariates that might be predictive of natural log-transformed personal $PM_{2.5}$, BC, and CO concentrations using the exhaustive selection algorithm. In categorical responses, the first response category was defined as the reference category; for example, for "no/yes" variables, "no" was the reference, or for "0/1" variables, "0" was the reference category. Variables were included in the best subsets approach if they were associated with an air pollutant in crude univariable models ($p \leq 0.20$), and no variables were forced in or out in the final best subsets' regressions. No limit was set on the number of variables to be maintained in the best model. The "best" model

Table 1. Baseline characteristics of pregnant women at the Household Air Pollution Intervention Network (HAPIN) Rwanda site ($N = 798$).

Variable	Missing	Mean ± SD; minimum–maximum; or *n* (%)
Mother: highest level of education completed	0	
1: no formal education or primary school incomplete		338 (42)
2: primary school complete or secondary school incomplete		318 (40)
3: secondary school complete or vocational or some college or university		142 (18)
Maternal age at baseline (y)	0	27.3 ± 4.4; 18.0–34.9
Mother: occupation outside the home		
Agriculture/farming	0	
Yes		591 (74)
No		207 (26)
Service/commercial	0	
Yes		136 (17)
No		662 (83)
No work outside the home	0	
Yes		59 (7)
No		739 (93)
Other	0	
Yes		62 (8)
No		736 (92)
Mother cooking times (number of times a mother cooks per week)	0	13.0 ± 5.0; 1–49
Electricity as a primary or secondary lighting source (presence of electricity in the home)		
Yes		260 (35)
No		538 (65)
Primary fuel type	2	
Cow dung		0 (0)
Wood		580 (73)
Charcoal		197 (25)
Other		19 (2)
Primary lighting source	2	
Torch (battery)		173 (22)
Kerosene lamp		59 (7)
Solar light		257 (32)
Electricity		226 (28)
Other		81 (10)
Secondary lighting source	5	
None		193 (24.3)
Candles		153 (19.2)
Torch (battery)		127 (16)
Kerosene lamp		35 (4.4)
Other: solar light, electricity, traditional stove		34 (4.3)
Cell phone		251 (31.7)
Primary stove type	61	
Open/3 stone fire, mud/metal chula		329 (41.3)
Biomass stove/plancha with chimney, Imbabura		201 (25.2)
Rondereza		205 (25.7)
Other		2 (0.25)
Primary stove location	2	
In participant's bedroom, room adjacent to bedroom, or separated from bedroom but still inside		69 (8.7)
Outside the house		248 (31.2)
In separate building		479 (60.2)
Mother: smoke tobacco	1	
No		795 (99.7)
Previous smoker		2 (0.2)
Current smoker		0 (0)
Secondhand smoke tobacco (smoke from someone else in the house)	0	
Yes		30 (4)
No		768 (96)
Household construction materials	0	
Floor concrete		
Yes		522 (65)
No		276 (35)
Floor mud	0	
Yes		526 (66)
No		276 (35)
Wall mud	0	
Yes		421 (53)
No		377 (47)
Wall concrete	0	
Yes		188 (24)
No		610 (76)
Wall wood	0	
Yes		263 (33)
No		535 (67)
Wall firebrick	0	
Yes		758 (95)
No		40 (5)
Wall mudbrick	0	
Yes		516 (65)
No		282 (35)
Wall wattle	0	
Yes		750 (94)
No		48 (6)
Household material items owned	0	
Cable TV		
Yes		71 (9)
No		727 (91)
Radio	0	
Yes		449 (56)
No		349 (44)
Cell phone	0	
Yes		631 (79)
No		167 (21)
Watch	0	
Yes		220 (28)
No		578 (72)
Bank account	0	
Yes		232 (29)
No		566 (71)
Curtains or blinds	0	
Yes		339 (42)
No		459 (58)
Maternal dietary diversity (score of 0–10)	1	
Minimum diet diversity <5		689 (86)
Minimum diet diversity ≥5		108 (14)
Food insecurity	20	
None		296 (38)
Mild		221 (28)
Moderate/severe		261 (34)

Note: —, not applicable; SD, standard deviation.

was defined as the one that maximized the adjusted R^2 value and minimized the prediction errors of Mallow's C_P and Bayesian information criterion (BIC).[33] Statistical significance was set at $\alpha = 0.05$.

Results

Participant and Household Characteristics

Table 1 displays the characteristics of the full study sample of the participants and their households. These characteristics ($N = 798$) were similar within each subset sample with valid exposure measures. The mean $\pm$SD age of the participating women was 27.3 ± 4.4 y, and they were all currently nonsmokers (as per

Table 2. Baseline personal exposure to 24-h $PM_{2.5}$, BC, and CO among pregnant women at the HAPIN Rwanda site.

Exposure	N	Mean ± SD ($\mu g/m^3$)	Median	25th percentile	75th percentile	Min	Max
$PM_{2.5}$ ($\mu g/m^3$)	717	111.9 ± 97.8	88.9	54.1	139.08	14.2	1,089.9
BC ($\mu g/m^3$)	569	12.2 ± 8.5	10.9	7.3	14.9	2.7	76.9
CO (ppm)	716	2.5 ± 4.2	1.1	0.51	2.42	0.0	44.4

Note: Exposure data are shown as raw (untransformed) values. BC, black carbon; CO, carbon monoxide; HAPIN, Household Air Pollution Intervention Network; max, maximum; min, minimum; $PM_{2.5}$, particulate matter ≤2.5 μm in aerodynamic diameter (measured in $\mu g/m^3$); SD, standard deviation.

HAPIN study inclusion criteria). Approximately 42% of the women had either no formal education or an incomplete primary school education. Most of the women participated in agricultural (74%) and commercial activities (17%) for employment, with "commercial activities" referring to any income-generating activities other than farming. Almost all participating women used biomass (wood 73%, charcoal 25%) for cooking. Primary sources of lighting were mixed as follows: torch (battery) (22%), electricity (28%), kerosene lamp (7%), solar power (32%), and other (10%). Most (94%) of the walls of the study households were built with wattle, and most floors were constructed of mud (66%). A large percentage (31.2%) of participating women reported that their primary stove was located outside their households, and 60.2% cooked in a separate building (Table 1).

Personal Exposure to Household Air Pollution

Table 2 summarizes baseline exposures of measured pollutants as raw (untransformed) concentrations. The median $PM_{2.5}$ concentration ($n = 717$) was 88.9 $\mu g/m^3$ (IQR = 85.0, range: 14.2–1,089.8 $\mu g/m^3$), the BC median ($n = 569$) was 10.9 $\mu g/m^3$ (IQR = 7.6, range: 2.7–76.9 $\mu g/m^3$), and the CO median ($n = 716$) was 1.1 ppm (IQR = 1.9, range: 0.0–44.4 $\mu g/m^3$) (Table 2). The Spearman correlation coefficients of the raw exposure concentrations were as follows: 0.83 for $PM_{2.5}$ and BC, 0.25 for $PM_{2.5}$ and CO, and 0.11 for BC and CO.

Characterizing Personal Exposures to Air Pollutants

Box plots characterizing personal exposure concentrations and selected household conditions and practices appear in Figure 1. For primary lighting sources, electricity users had the lowest median of $PM_{2.5}$ exposure (63.7 $\mu g/m^3$, IQR = 69.0) compared with those using other sources, and kerosene users had the highest median $PM_{2.5}$ (115.5 $\mu g/m^3$, IQR = 106.6) (Figure 1A). For primary stove type, as expected, participants who used improved biomass stoves with a chimney had the lowest median $PM_{2.5}$ exposure levels (47.5 $\mu g/m^3$, IQR = 52.4) compared with open fire and other traditional stove types, which had median $PM_{2.5}$ exposures ranging from 91.6 to 155 $\mu g/m^3$ (IQRs ranged from 73.8 to 42.8; Figure 1B). For primary fuel type, charcoal users had almost half the median $PM_{2.5}$ exposure levels (47 $\mu g/m^3$, IQR = 51.0) compared with wood fuel users (104 $\mu g/m^3$, IQR = 91.1) (Figure 1C). Numeric data used to generate box plot figures can be found in Tables S3–S5.

Results from Best Subsets Regression Models

Best subsets regression model selections result in a model that maximizes the adjusted R^2 and minimizes the prediction error [as measured by residual sum of squares (RSS), C_P, and BIC] to determine the predictors of exposure. The adjusted R^2 represents the proportion of variation in the outcome that is explained by the predictor variables, where the higher the adjusted R^2, the better the model fit. Tables S1 and S2 display all individual adjusted R^2 values for every variable assessed in the model selection process, even for those not retained in the final consensus models, and final consensus model results.

Table 3 presents the consensus $PM_{2.5}$ model that had an adjusted $R^2 = 0.264$, Mallow's $C_P = 5.813$, and $BIC = -86.486$. The following variables were retained in the final consensus model for $PM_{2.5}$ with their individual adjusted R^2 values and effect estimates respectively shown in parentheses: maternal age (adjusted $R^2 = 0.15$), (−0.01); maternal education (adjusted $R^2 = 0.21$–0.22); employment status (adjusted $R^2 = 0.24$–0.25); material wealth items (i.e., cable TV, watch, bank account; adjusted $R^2 = 0.26$); housing materials (i.e., wood for walls; adjusted $R^2 = 0.26$); primary lighting sources (i.e., kerosene; adjusted $R^2 = 0.26$); solar (adjusted $R^2 = 0.26$); electricity (adjusted $R^2 = 0.26$); secondary lighting source (torch battery and other sources; adjusted $R^2 = 0.26$); stove type (i.e., biomass with chimney, Rondereza; adjusted $R^2 = 0.25$); cooking location (i.e., cooking outside or in a separate building; adjusted $R^2 = 0.25$); and cooking frequency (adjusted $R^2 = 0.25$).

Table S1 highlights the results of the consensus BC model with an adjusted $R^2 = 0.357$, Mallow's $C_P = 2.269$, and $BIC = -146.822$. The variables retained in the final consensus model for BC (adjusted R^2 values) included; maternal age (adjusted $R^2 = 0.21$), food insecurity as a socioeconomic indicator (adjusted $R^2 = 0.28$), maternal education (adjusted $R^2 = 0.33$), employment status (adjusted $R^2 = 0.35$), material wealth items (i.e., cable TV, watch, bank account; adjusted $R^2 = 0.36$), housing materials (i.e., wood and mud for walls; adjusted $R^2 = 0.36$), secondary tobacco exposure (adjusted $R^2 = 0.36$), primary lighting sources (i.e., kerosene; adjusted $R^2 = 0.36$), secondary lighting source (other sources; adjusted $R^2 = 0.35$), fuel types (i.e., charcoal and other; adjusted $R^2 = 0.35$), stove type (i.e., other; adjusted $R^2 = 0.34$), and cooking frequency (days per week; adjusted $R^2 = 0.34$).

The results of the consensus CO model are presented in Table S2 and had an adjusted $R^2 = 0.311$, Mallow's $C_P = 7.1$, and $BIC = -118.551$. The variables retained in the final consensus model for CO (adjusted R^2 values) included employment status (adjusted $R^2 = 0.28$–0.29), material wealth items (i.e., cable TV, bank account; adjusted $R^2 = 0.29$–0.31), housing materials (i.e., mud floor and wall types; adjusted $R^2 = 0.31$), secondary tobacco exposure (0.31), primary lighting sources (i.e., electricity; adjusted $R^2 = 0.31$), secondary lighting source (torch, other sources; adjusted $R^2 = 0.31$), fuel types (i.e., charcoal; adjusted $R^2 = 0.30$), stove type (i.e., Rondereza; adjusted $R^2 = 0.30$), cooking location (i.e., cooking outside or in a separate building; adjusted $R^2 = 0.30$), and cooking frequency (adjusted $R^2 = 0.29$).

Discussion

Overview of Main Findings

Among the factors that influenced the concentration of $PM_{2.5}$, electricity as the primary lighting source at baseline was associated with the lowest median (64 $\mu g/m^3$) $PM_{2.5}$ exposure, and kerosene was associated with the highest exposure concentrations (116 $\mu g/m^3$). For primary stove types, the biomass/improved stove-with-chimney yielded the lowest median (47.5 $\mu g/m^3$) for $PM_{2.5}$, and $PM_{2.5}$ from other stove types, such as open fire, Rondereza, and other biomass stoves, ranged from 92 to 155 $\mu g/m^3$. Participants who cooked outside their rooms had the

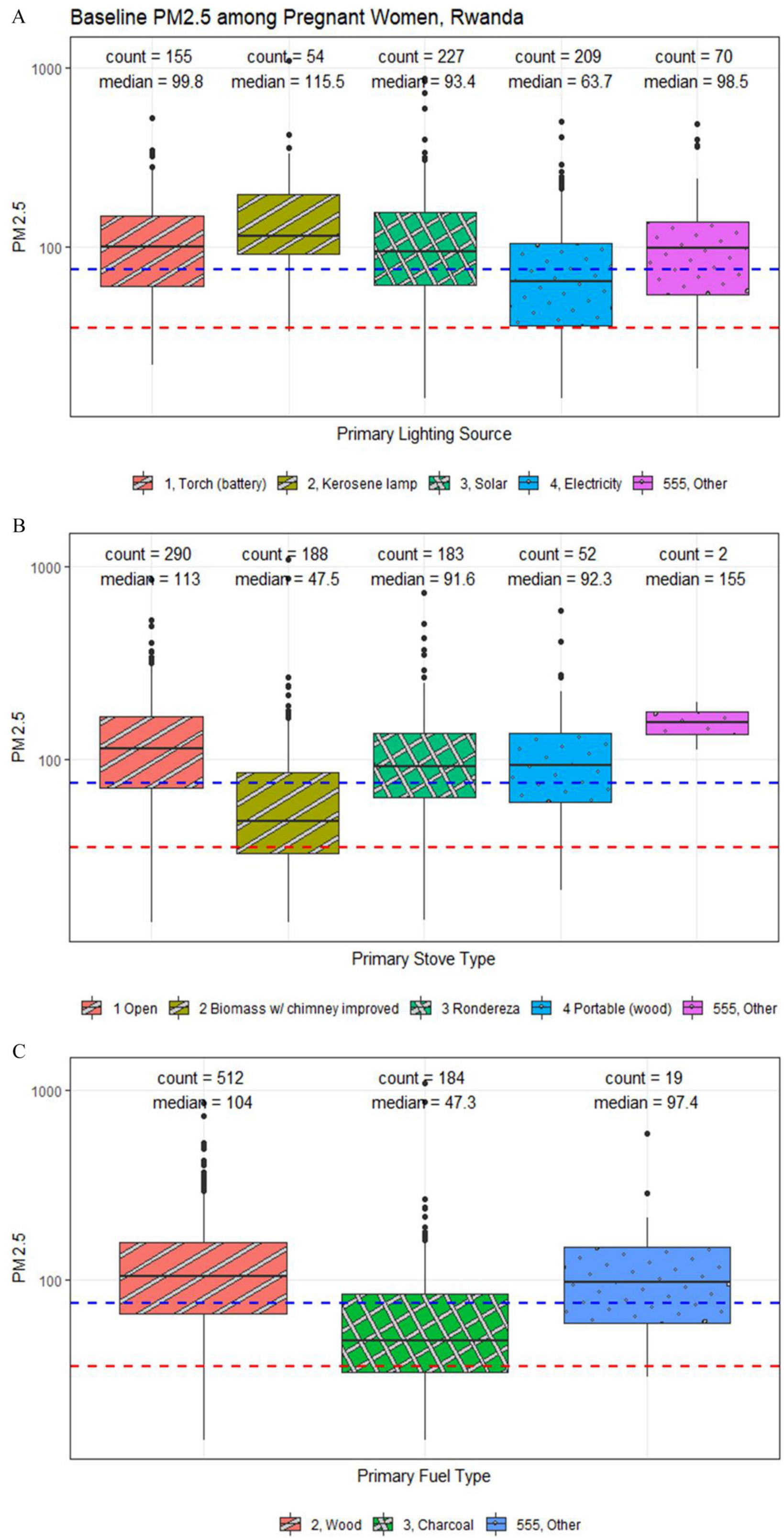

Figure 1. Concentrations of household fine particulate matter ($PM_{2.5}$) in $\mu g/m^3$ by (A) primary lighting source, (B) primary stove type, (C) and primary fuel type based on personal monitoring in women enrolled in the HAPIN trial in Rwanda. Count represents the number of samples. The blue dashed line represents the World Health Organization (WHO) 24-h interim target 1 at 75 $\mu g/m^3$, and the red dashed line is the annual interim target 1 at 35 $\mu g/m^3$. Numeric data can be found in Tables S3–S5. Note: HAPIN, Household Air Pollution Intervention Network.

highest observed $PM_{2.5}$ exposures (102 $\mu g/m^3$). For primary fuel type, charcoal stoves were associated with median $PM_{2.5}$ exposures, about half of those associated with wood fuel stove exposures (47 $\mu g/m^3$ vs. 104 $\mu g/m^3$, respectively). Overall, the lighting sources, stove types, and fuel, which are indicators of SES, housing materials, cooking frequency, and kitchen location,

Table 3. Best subsets regression and model selection for $PM_{2.5}$ exposure among pregnant women at the HAPIN Rwanda site, $n = 717$.

Variable name	R^2 values	Adjusted R^2 values
Maternal age at baseline	0.1517778	0.150
Food insecurity score	0.1885398	0.186
Dietary diversity		
0: minimum diet diversity <5	Ref	Ref
1: minimum diet diversity ≥5	0.204594	0.201
Education		
None, primary incomplete (Ref)	Ref	Ref
Primary/secondary incomplete	0.2168798	0.212
Secondary complete, some college	0.2282409	0.222
Electricity		
No	Ref	Ref
Yes	0.238486	0.231
Occupation: agriculture		
No	Ref	Ref
Yes	0.2473567	0.239
Occupation: commercial		
No	Ref	Ref
Yes	0.2548806	0.245
Occupation: household		
No	Ref	Ref
Yes	0.261321	0.251
Cable TV		
No	Ref	Ref
Yes	0.2671408	0.256
Radio		
No	Ref	Ref
Yes	0.2712954	0.259
Blinds		
No	Ref	Ref
Yes	0.2751215	0.261
Cell phone		
No	Ref	Ref
Yes	0.2774866	0.263
Watch		
No	Ref	Ref
Yes	0.2790741	0.263
Bank account		
No	Ref	Ref
Yes	0.2802177	0.263
Mud floor		
No	Ref	Ref
Yes	0.2816841	0.263
Concrete floor		
No	Ref	Ref
Yes	0.2830152	0.263
Wattle wall		
No	Ref	Ref
Yes	0.2842587	0.264
Mud wall		
No	Ref	Ref
Yes	0.2854504	0.264

Note: Variables retained in the final best subsets consensus models ($n = 19$). Adjusted $R^2 = 0.264$. Mallow's $C_P = 5.813$. BIC $= -86.486$. Adjusted R^2 (or adjusted coefficient of determination) is a modified version of the R^2 statistic that adjusts for the number of predictors in a regression model. It addresses the issue of R^2 potentially misleadingly increasing as more predictors are added to the model even if those predictors do not significantly improve the model's explanatory power. BIC, Bayesian information criterion (a criterion for model selection among a finite set of models; balances the goodness of fit of a model with the complexity of the model, penalizing models that are more complex); HAPIN, Household Air Pollution Intervention Network; MALLOW's Cp, Mallow's *Cp* [pronounced "C-p"; a criterion used in model selection for regression models; particularly useful in the context of selecting among models with different numbers of predictors (variables)]; $PM_{2.5}$, particulate matter ≤2.5 μm in aerodynamic diameter (measured in μg/m^3); R^2, or the coefficient of determination, is a statistical measure representing the proportion of the variance for a dependent variable that is explained by an independent variable or variables in a regression model; Ref, reference.

were retained as important predictors of personal exposure to $PM_{2.5}$, BC, and CO. The consensus model adjusted R^2 values showed the combination of these variables explained between 26%, 36%, and 31% of the observed variation in $PM_{2.5}$, BC, and CO concentrations, respectively.

Personal $PM_{2.5}$ BC, and CO Levels

Most previous studies assessing predictors of personal exposure to $PM_{2.5}$, BC, and CO have been conducted in developed countries in urban areas and have focused on a single type of exposure.[12] In contrast, assessments of directly measured personal exposure to $PM_{2.5}$, BC, and CO are rare in rural or peri-urban settings in low- and middle-income countries, where $PM_{2.5}$, BC, and CO exposures are largely due to household fuel combustion. The daily median $PM_{2.5}$ personal levels we observed in pregnant women from Rwanda (88.9 μg/m^3) were many times higher than those reported in adults and children from European cities (<2.8 μg/m^3), in children from rural Italy (5 μg/m^3),[21] and in women from rural Ghana (9 μg/m^3).[22] Our $PM_{2.5}$, BC, and CO 24-h personal levels were more comparable to levels of personal exposures to $PM_{2.5}$, BC, and CO among pregnant women using biomass at the HAPIN India IRC (75.5 μg/m^3, 9.6 μg/m^3, 0.8 ppm, respectively).[23] They can also be compared with results from other locations within the HAPIN trial that showed that the $PM_{2.5}$ median was 84.9 μg/m^3 for the control arm and 82.7 μg/m^3 for the intervention arm, the median for BC was 11 μg/m^3 for the control arm and 10.6 μg/m^3 for the intervention arm, and the median for CO was 1.2 μg/m^3 for the control arm and 1.3 μg/m^3 for the intervention arm.[24] A study conducted in Rwanda in 2018 showed that outdoor 24-h mean $PM_{2.5}$ and PM_{10} concentrations were significantly higher in the dry season than in the wet season.[25] Another study conducted between March and July 2018 revealed that the ambient average $PM_{2.5}$ in Kigali was 52 μg/m^3, significantly higher than WHO interim target 1 (35 μg/m^3). The $PM_{2.5}$ level in the dry seasons was ∼2 times the $PM_{2.5}$ level during the following wet seasons, whereas the BC level was 40%–60% higher in dry seasons than in wet seasons.[9] The results of both studies were a bit lower than what we observed; however, all study results show that the concentrations of $PM_{2.5}$ and BC are higher than the WHO interim annual target 1, which is in agreement with a study conducted in Peru that found strong associations between household air pollution and rainy seasons.[7] Those studies also measured ambient concentrations, and the instruments used were different from our personal exposure monitoring devices.

Cooking-Related Predictors

Existing literature indicates that relevant determinants of personal exposure to household air pollution from household fuels are the type of cooking fuel, the type of stove, the time spent cooking, and the role of ventilation.[26,27] In our study, personal mean exposures to $PM_{2.5}$, BC, and CO were similarly predicted by this combination of factors, as also were lighting sources and indicators of SES. In contrast to our findings, another study discovered that among pregnant women from metropolitan Tanzania, outside cooking was associated with a 14.5-μg/m^3 lower median $PM_{2.5}$ personal exposure than indoor cooking, and the highest measured personal exposure (i.e., CO) was 25.2 ppm.[28] The inconsistency in definitions of kitchen type; however, complicates comparisons between the different research studies. Our study provides results similar to those of the study of Curto et al.[12] conducted in rural Mozambique, who reported that after the stepwise selection, kerosene-based lighting's partial contribution to the BC mean was 8.2% (adjusted total R^2 of 21.6%) and 7.3% to the BC peak (adjusted total R^2 of 20.1%).[12] It is unclear if partially covered kitchens should be considered indoor or outdoor cooking,[29] or if the absence of a kitchen indicates that cooking is done with community members or in agricultural plots, as has previously been observed in rural Ghana.[22]

Role of Access to Electricity in Reducing Kerosene Utilization

The government of Rwanda put in place an electrification program aimed at connecting households to both grid and off-grid energy sources. Between July 2021 and May 2022, 104,227 households were connected to the grid, and 101,711 households were connected using off-grid options (Standalone Solar Home Systems and Mini-grids), bringing the total number of households linked to the grid up to 1,375,192 from the 1,270,965 connected as of the end of June 2021 and 578,895 households connected to the off-grid network, up from 477,184. The Development Bank of Rwanda (BRD) in 2018 launched nationwide awareness and promotion initiatives for off-grid solar systems in collaboration with REG-Energy Development Corporation Limited and other stakeholders. There were 205,938 more connections made between July 2021 and May 2022, bringing the total number of houses connected to either the grid and off-grid supply up from 1,748,149 connections the year before to 1,954,087. Between July 2021 and May 2022, 376 social and economic productive use areas (PUAs), as opposed to the intended 360 PUAs, received energy connections. These consist of, among other things, shopping malls, coffee shops, milk collection facilities, water pumping stations, schools, and medical facilities. The nationwide electrical grid has built high-voltage transmission lines for regional interconnection and power evacuation, in addition to extending distribution lines across the nation. This provides context for our findings indicating that the percentages of households in Rwanda using kerosene lamps or solar energy for light were 7% and 28%, respectively.[30,31]

Strengths

Key strengths of this study include the collection of directly measured personal 24-h maternal $PM_{2.5}$ valid measures from high-quality monitors with a large sample size ($n = 798$ initial observations). Furthermore, the fact that local, Rwanda-based researchers were responsible for data collection helped minimize any information that was left out, given that data collectors spoke the same language as the participants and understood local norms and values. Last, this baseline analysis came from the HAPIN study, a rigorously designed and implemented study of high-quality data collection and ongoing QA.

Limitations

There was potential for missing important variables to help predict more of the variation in household air pollution concentrations. Ambient air pollution data were not available for analysis that could have added a useful comparison to personal exposures from household air pollution; survey data did not use any variables that could have indicated other sources of air pollution, such as traffic or neighbors.[17] In addition, the study was a cross-sectional analysis, which limited exploring variation by seasons and other time trends. We used baseline data for pregnant women from the HAPIN trial, and future studies should consider the full trial data to include multiple time points, as well as any impacts of the intervention [for example, how participant behavior (e.g., cooking times, fuel types) may have changed during the measurement period].

Conclusions

In Rwanda, where access to clean household energy is scarce for cooking, we found that pregnant women who used cooking stoves with biomass fuels had high levels of personal $PM_{2.5}$, BC, and CO exposure. Although most people have access to electricity for lighting in their households, the small number of participants using kerosene-based lighting had the highest median concentrations. These findings support the necessity of making clean energy sources more widely available to reduce personal household air pollution exposures to levels closer to the WHO air quality guidelines, given that most median values for $PM_{2.5}$ were greater than the WHO interim target 1 annual and 24-h guidelines. This is especially important among this study population of pregnant women, who represent a potentially sensitive period of exposure. Therefore, this can serve as a benchmark for policymakers to develop relevant policies and strategies to address clean energy challenges in Rwanda.

Acknowledgments

We thank R. Chartier, C. Garland, and A. Lovvorn for their input and support in developing the exposure sampling materials and protocols. We are also thankful to the field teams at each of the research centers for their feedback and input.

This study was funded by the National Institutes of Health (NIH cooperative agreement 1UM1HL134590) in collaboration with the Bill & Melinda Gates Foundation [OPP1131279]. A.P. was partially supported by the HERCULES Center P30ES019776.

A multidisciplinary, independent Data and Safety Monitoring Board (DSMB) appointed by the National Heart, Lung, and Blood Institute (NHLBI) monitors the quality of the data and protects the safety of patients enrolled in the HAPIN trial. NHLBI DSMB: N.R. Cook, S. Hecht, C. Karr, K.H. Kavounis, D.-Y. Kim, J. Millum, L.A. Reineck, N. Sathiakumar, P.K. Whelton, and G.G. Weinmann. Program Coordination: G. Rodgers, Bill & Melinda Gates Foundation; C.L. Thompson, National Institute of Environmental Health Science; M.J. Parascandola, National Cancer Institute; D.M. Krotoski, *Eunice Kennedy Shriver* National Institute of Child Health and Human Development; J.P. Rosenthal, Fogarty International Center; C.R. Nierras, NIH Office of Strategic Coordination Common Fund; and A. Punturieri and B.S. Schmetter, NHLBI. The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the NIH, the Department of Health and Human Services, the US Government, or the government of Rwanda.

Deidentified data associated with the paper will be deposited in Emory's Dataverse data repository. A DOI for the data will be created to allow citation with the publication of the paper. Dataverse is widely accessible and provides long-term access to the public and to related research communities.

References

1. IHME (Institute for Health Metrics and Evaluation). 2022. GBD Compare. http://vizhub.healthdata.org/gbd-compare [accessed 11 August 2022].
2. WHO (World Health Organization). 2022. Household air pollution and health. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health [accessed 17 August 2022].
3. Schraufnagel DE, Balmes JR, Cowl CT, De Matteis S, Jung S-H, Mortimer K, et al. 2019. Air pollution and noncommunicable diseases: a review by the Forum of International Respiratory Societies' Environmental Committee, part 2: air pollution and organ systems. Chest 155(2):417–426, PMID: 30419237, https://doi.org/10.1016/j.chest.2018.10.041.
4. Lee B-J, Kim B, Lee K. 2014. Air pollution exposure and cardiovascular disease. Toxicol Res 30(2):71–75, PMID: 25071915, https://doi.org/10.5487/TR.2014.30.2.071.
5. US EPA (US Environmental Protection Agency). 2016. Particulate Matter (PM) Basics. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics [accessed 17 August 2022].
6. City of Oskaloosa, Iowa. 2022. Carbon Monoxide Facts. https://www.oskaloosaiowa.org/DocumentCenter/View/46/Carbon-Monoxide-Facts?bidId= [accessed 17 August 2022].
7. US EPA. 2011. Black carbon research and future strategies: reducing emissions, improving human health, and taking action on climate change. Science in Action. Washington, DC: US EPA. https://www.epa.gov/sites/default/files/2013-12/documents/black-carbon-fact-sheet_0.pdf [accessed 18 July 2022].

8. CFET (Centre For Emerging Technologies). 2021. *National Survey on Cooking Fuel Energy and Technologies in Households, Commercial and Public Institutions in Rwanda*. Kigali, Rwanda: Ministry of Infrastructure Ministry of Finance.
9. Subramanian R, Kagabo AS, Baharane V, Guhirwa S, Sindayigaya C, Malings C. 2020. Air pollution in Kigali, Rwanda: spatial and temporal variability, source contributions, and the impact of car-free Sundays. Clean Air J 30(2), https://doi.org/10.17159/caj/2020/30/2.8023.
10. Tonne C. 2017. A call for epidemiology where the air pollution is. Lancet Planet Health 1(9):e355–e356, PMID: 29851646, https://doi.org/10.1016/S2542-5196(17)30163-8.
11. Thurston GD, Kipen H, Annesi-Maesano I, Balmes J, Brook RD, Cromar K, et al. 2017. A joint ERS/ATS policy statement: what constitutes an adverse health effect of air pollution? An analytical framework. Eur Respir J 49(1):1600419, PMID: 28077473, https://doi.org/10.1183/13993003.00419-2016.
12. Curto A, Donaire-Gonzalez D, Manaca MN, González R, Sacoor C, Rivas I, et al. 2019. Predictors of personal exposure to black carbon among women in southern semi-rural Mozambique. Environ Int 131:104962, PMID: 31301586, https://doi.org/10.1016/j.envint.2019.104962.
13. Republic of Rwanda. 2015. *Fourth Population and Housing Census, Rwanda, 2012. District Profile: Kayonza*. http://statistics.gov.rw/sites/default/files/publications/c1abf91d-acdc-4e61-9ba5-d8ae92b35c1c/RPHC4%20-%20District_Profile_KAYONZA.pdf [accessed 18 July 2022].
14. Republic of Rwanda. 2019. *Kayonza District. Environmental and Social Management Plan (ESMP) for Construction of 100 Classrooms and 140 Latrines under Quality Basic Education for Human Capital Development (QBE-HCD) Project in Kayonza District. Final Report*. https://www.mineduc.gov.rw/fileadmin/user_upload/Mineduc/SPIU_Documents/ESMP/kayonza/KAYONZA_DISTRICT-_ESMP_FOR_CONSTRUCTION_OF_CLASSROOMS_AND_LATRINES_SUB-PROJECTS_UNDER_RWANDA_QBE-HCD_PROJECT.pdf [accessed 18 July 2022].
15. Republic of Rwanda. n.d. *Kayonza District Developpement Plan*. https://www.kayonza.gov.rw/fileadmin/user_upload/kayonza/Inyandiko/Imihigo/2013-2018__DDP_KAYONZA_DISTRICT_FINAL_VERSION.pdf [accessed 18 July 2022].
16. Republic of Rwanda. 2015. *National Institute of Statistics of Rwandan Integrated Household Living Conditions Survey – 2013/14. Main Indicators Report, August 2015*. https://www.statistics.gov.rw/file/4445/download?token=9YG7-2UO [accessed 18 July 2022].
17. Johnson MA, Steenland K, Piedrahita R, Clark ML, Pillarisetti A, Balakrishnan K, et al. 2020. Air pollutant exposure and stove use assessment methods for the Household Air Pollution Intervention Network (HAPIN) trial. Environ Health Perspect 128(4):047009, PMID: 32347764, https://doi.org/10.1289/EHP6422.
18. Clasen T, Checkley W, Peel JL, Balakrishnan K, McCracken JP, Rosa G, et al. 2020. Design and rationale of the HAPIN study: a multicountry randomized controlled trial to assess the effect of liquefied petroleum gas stove and continuous fuel distribution. Environ Health Perspect 128(4):047008, PMID: 32347766, https://doi.org/10.1289/EHP6407.
19. Johnson M, Pillarisetti A, Piedrahita R, Balakrishnan K, Peel JL, Steenland K, et al. 2022. Exposure contrasts of pregnant women during the Household Air Pollution Intervention Network Randomized Controlled trial. Environ Health Perspect 130(9):097005, PMID: 36112539, https://doi.org/10.1289/EHP10295.
20. Bruce N, McCracken J, Albalak R, Schei MA, Smith KR, Lopez V, et al. 2004. Impact of improved stoves, house construction and child location on levels of indoor air pollution exposure in young Guatemalan children. J Expo Anal Environ Epidemiol 14(suppl 1):S26–S33, PMID: 15118742, https://doi.org/10.1038/sj.jea.7500355.
21. Buonanno G, Stabile L, Morawska L, Russi A. 2013. Children exposure assessment to ultrafine particles and black carbon: the role of transport and cooking activities. Atmos Environ 79:53–58, https://doi.org/10.1016/j.atmosenv.2013.06.041.
22. van Vliet D, de Vugt ME, Bakker C, Pijnenburg YAL, Vernooij-Dassen MJFJ, Koopmans RTCM, et al. 2013. Time to diagnosis in young-onset dementia as compared with late-onset dementia. Psychol Med 43(2):423–432, PMID: 22640548, https://doi.org/10.1017/S0033291712001122.
23. Ye W, Thangavel G, Pillarisetti A, Steenland K, Peel JL, Balakrishnan K, et al. 2022. Association between personal exposure to household air pollution and gestational blood pressure among women using solid cooking fuels in rural Tamil Nadu, India. Environ Res 208:112756, PMID: 35065931, https://doi.org/10.1016/j.envres.2022.112756.
24. Ye W, Steenland K, Quinn A, Liao J, Balakrishnan K, Rosa G, et al. 2022. Effects of a liquefied petroleum gas stove intervention on gestational blood pressure: intention-to-treat and exposure-response findings from the Household Air Pollution Intervention Network (HAPIN) trial. Hypertension 79(8):1887–1898, PMID: 35708015, https://doi.org/10.1161/HYPERTENSIONAHA.122.19362.
25. Kalisa E, Nagato EG, Bizuru E, Lee KC, Tang N, Pointing SB, et al. 2018. Characterization and risk assessment of atmospheric $PM_{2.5}$ and PM_{10} particulate-bound PAHs and NPAHs in Rwanda, Central-East Africa. Environ Sci Technol 52(21):12179–12187, PMID: 30351039, https://doi.org/10.1021/acs.est.8b03219.
26. Ezzati M, Henley SJ, Thun MJ, Lopez AD. 2005. Role of smoking in global and regional cardiovascular mortality. Circulation 112(4):489–497, PMID: 16027251, https://doi.org/10.1161/CIRCULATIONAHA.104.521708.
27. Baumgartner J, Schauer JJ, Ezzati M, Lu L, Cheng C, Patz J, et al. 2011. Patterns and predictors of personal exposure to indoor air pollution from biomass combustion among women and children in rural China. Indoor Air 21(6):479–488, PMID: 21692855, https://doi.org/10.1111/j.1600-0668.2011.00730.x.
28. Wylie BJ, Kishashu Y, Matechi E, Zhou Z, Coull B, Abioye AI, et al. 2017. Maternal exposure to carbon monoxide and fine particulate matter during pregnancy in an urban Tanzanian cohort. Indoor Air 27(1):136–146, PMID: 26880607, https://doi.org/10.1111/ina.12289.
29. Brauer M, Saksena S. 2002. Accessible tools for classification of exposure to particles. Chemosphere 49(9):1151–1162, PMID: 12492169, https://doi.org/10.1016/s0045-6535(02)00245-x.
30. Republic of Rwanda. 2022. *Ministry of Infrastructure. Energy Sector. Forward Looking Joint Sector Review Report for FY 2022/23*. https://www.mininfra.gov.rw/index.php?eID=dumpFile&t=f&f=51952&token=ba5d34a4e705b576a0447405d594e6b40151d3db [accessed 3 May 2023].
31. Muyanja D, Allen JG, Vallarino J, Valeri L, Kakuhikire B, Bangsberg DR, et al. 2017. Kerosene lighting contributes to household air pollution in rural Uganda. Indoor Air 27(5):1022–1029, PMID: 28267233, https://doi.org/10.1111/ina.12377.
32. FAO (Food and Agriculture Organization of the United Nations). 2021. Minimum Dietary Diversity for Women. FAO: Rome. https://doi.org/10.4060/cb3434en.
33. Kassambara A. 2018. Regression model accuracy metrics: R-square, AIC, BIC, Cp and more. In: *Machine Learning Essentials. Practical Guide in R*. Scotts Valley, California: CreateSpace Independent Publishing Platform, 60–64.