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Low correlation between household carbon monoxide and particulate matter concentrations from biomass-related pollution in three resource-poor settings

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Abstract

Household air pollution from the burning of biomass fuels is recognized as the third greatest contributor to the global burden of disease. Incomplete combustion of biomass fuels releases a

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complex mixture of carbon monoxide (CO), particulate matter (PM) and other toxins into the household environment. Some investigators have used indoor CO concentrations as a reliable surrogate of indoor PM concentrations; however, the assumption that indoor CO concentration is a reasonable proxy of indoor PM concentration has been a subject of controversy. We sought to describe the relationship between indoor PM_{2.5} and CO concentrations in 128 households across three resource-poor settings in Peru, Nepal, and Kenya. We simultaneously collected minute-to-minute PM_{2.5} and CO concentrations within a meter of the open-fire stove for approximately 24 hours using the EasyLog-USB-CO data logger (Lascar Electronics, Erie, PA) and the personal DataRAM-1000 (Thermo Fisher Scientific Inc., Waltham, MA), respectively. We also collected information regarding household construction characteristics, and cooking practices of the primary cook. Average 24-hour indoor PM_{2.5} and CO concentrations ranged between 615 and 1440 µg/m³, and between 8.9 and 34.5 ppm, respectively. Minute-to-minute indoor PM_{2.5} concentrations were in a safe range (< 25 µg/m³) between 17% and 65% of the time, and exceeded 1000 µg/m³ between 8% and 21% of the time, whereas indoor CO concentrations were in a safe range (<7 ppm) between 46% and 79% of the time and exceeded 50 ppm between 4%, and 20% of the time. Overall correlations between indoor PM_{2.5} and CO concentrations were low to moderate (Spearman rho between 0.59 and 0.83). There was also poor agreement and evidence of proportional bias between observed indoor PM_{2.5} concentrations vs. those estimated based on indoor CO concentrations, with greater discordance at lower concentrations. Our analysis does not support the notion that indoor CO concentration is a surrogate marker for indoor PM_{2.5} concentration across all settings. Both are important markers of household air pollution with different health and environmental implications and should therefore be independently measured.

INTRODUCTION

Biomass fuels, which include wood, charcoal, dung, and crop waste, are the source of domestic energy for an estimated 40% of the world population (1). Households without access to improved stove technologies burn biomass fuels in unventilated, open-fire stoves for cooking, heating, and other domestic chores (2, 3). When cooking indoors, incomplete combustion of biomass fuels releases a complex mixture of inhalable particulate matter (PM), carbon monoxide (CO), polycyclic aromatic hydrocarbons, and other toxins into the household environment (1). Associations between multiple negative health outcomes and household air pollution have been established in both children and adults (4–7). Consequently, household air pollution is now recognized as the third greatest contributor to global disease burden (8).

Assessment of gravimetric PM in field conditions is difficult, because the equipment required to perform an accurate measurement is expensive; it requires pre- and post-weighing of filters that collect PM using ultra-sensitive scales (9); and, filter clogging is common during prolonged measurements of biomass fuel smoke. On the other hand, CO is relatively easy to assess using inexpensive real-time monitors. Results from previous studies have shown strong correlations between indoor CO and PM concentrations (10,11). Therefore, some investigators have proposed using CO concentrations as a reliable surrogate of PM concentrations since devices to measure CO are cheaper, highly reproducible, and easier to use and deploy in field settings. The assumption that CO is a reasonable proxy of

PM, however, is controversial, as new evidence suggests that PM emissions have high intra-household variability and that PM concentrations vary widely for a given CO concentration (12–15).

In this analysis, we sought to assess the relationship between 24-hour average household PM_{2.5} and CO concentrations in three resource poor-settings in Africa, Asia and South America; and, describe household characteristics associated with indoor air quality. Finally we explored the variability of indoor PM_{2.5} and CO concentrations by setting.

METHODS

Study sites

This study was conducted in three rural, resource-poor regions of Peru, Nepal and Kenya as previously described (16): the Vinchos district in Ayacucho, Peru, comprised of steep, rocky hills at an altitude range of 3,000 to 4,000 meters; the Sarlahi District in southwestern Nepal at 200 meters above sea level in a flat, densely population region; and the Ndanai sub-location of the Uasin Gishu district located in western Kenya at an elevation of 2,300 to 2,500 meters in an sloping, heavily forested area.

Study design

We evaluated baseline (pre-intervention) pollutant concentration data collected as part of multi-center field intervention trial of two types of improved cookstoves. Detailed information regarding the multi-center field intervention trial has been published elsewhere (16). Specifically, we summarized baseline indoor environmental exposures in households of women using an open-fire stove. The study was conducted according to uniform procedures and protocols at each location (16); however, the season of enrollment varied by study setting. We collected information on potential influencing factors to biomass fuel exposure.

Recruitment and consent

Following a census of the study areas, eligible women were randomly selected for participation. We aimed to enroll 138 women into the trial (i.e., a total of 46 women per site) with the expectation that we would have at least 120 (i.e., 40 women per site) who completed an entire year of follow-up. All participants provided verbal informed consent after our research team read the entire informed consent document to them and any questions were answered. Informed consents were verbal because of high illiteracy rates. This study was approved by the Institutional Review Boards of Universidad Peruana Cayetano Heredia (Lima, Peru), Johns Hopkins Bloomberg School of Public Health (Baltimore, USA), Asociación Benéfica PRISMA (Lima, Peru), Moi University (Eldoret, Kenya), Institute of Medicine at Tribhuvan University (Kathmandu, Nepal) and Lifespan/The Miriam Hospital (Providence, USA).

Pollutant exposure assessments

Indoor PM_{2.5} and CO concentrations were simultaneously assessed every minute for a 24-hour period and placed approximately 1.5 meters off the floor and within one meter of the cooking fire to best capture the exposure to individuals who were cooking. and. We

measured nephelometric PM with the personal DataRAM-1000AN (pDR-1000) (Thermo Fisher Scientific Inc., Waltham, MA). Empirical evidence suggests that the pDR-1000 detects particles in the size range of 0.3 to 2 μm more efficiently than those of 2 to 10 μm (17, 18). Moreover, Quintana et al reported a high degree of correlation between the PM determined by the pDR-1000 and $\text{PM}_{2.5}$ (i.e., 2.5 μm or smaller in size) measurements (19). Real-time measurements had to be conducted for at least 18 hours to be included in our analysis. Temperature and relative humidity were also measured every minute using a HOBO Data Logger (Onset Corp., Bourne MA). Relative humidity data was used to adjust nephelometric PM concentrations as previously described (20). Nephelometric PM concentrations were converted to $\text{PM}_{2.5}$ gravimetric-equivalent concentrations using a previously validated equation (13). The EasyLog-USB-CO data logger (Lascar Electronics, Erie, PA) captured direct-reading CO emission concentrations. We defined indoor PM concentrations $< 25 \mu\text{g}/\text{m}^3$ and indoor CO concentrations $< 7 \text{ ppm}$ as safe per international recommendations (21).

Biostatistical methods

Primary objectives of this analysis were to explore the relationship between indoor $\text{PM}_{2.5}$ and CO concentrations, and identify household factors associated with each of these exposures. To characterize the inter-relationship between indoor $\text{PM}_{2.5}$ and CO concentrations, we calculated Spearman correlation coefficients. We also constructed a linear regression model for indoor $\text{PM}_{2.5}$ concentrations as a function of a natural cubic spline of indoor CO concentrations, indicators for site, and an interaction between the elements of the natural cubic spline of indoor CO concentrations and site. We used this model to obtain an expected value for indoor $\text{PM}_{2.5}$ concentrations for a given indoor CO concentrations, and measured agreement between observed and expected indoor $\text{PM}_{2.5}$ concentrations using the Bland-Altman method (22).

To determine factors linked to household air quality, we constructed multivariable linear regression models of indoor $\text{PM}_{2.5}$ or CO concentrations as a function of socioeconomic status (household income, assets, education of primary cook, and number of people living per household), household construction material (walls and roof), degree of ventilation in kitchen (number of open windows and number of door openings), use of alternative fuels (kerosene or LPG), number of people for whom the primary cook prepares meals, and number of families that cook in the same kitchen. We log transformed $\text{PM}_{2.5}$ concentrations because the distribution was right-skewed. All data analyses were conducted with STATA 11.0 (StataCorp., College Station, TX) and R (www.r-project.org).

RESULTS

Household characteristics

We enrolled 137 participants (99% of target enrollment goal), and 128 (93% of enrolled) completed trial activities. We compared household volume, construction characteristics, and socioeconomic status among study participants in Table 1. Household characteristics were heterogeneous between settings. For example, household roofs in Kenya were mainly made of tin, whereas those in Peru were mainly made of thatch and those in Nepal were mainly

made of tiles. In all countries, wall construction was comprised of more than one material including mud, bamboo, or wood. Kitchen dimensions were similar across settings. Households in Nepal had more open windows than did those in Peru and Kenya.

Household air pollutant concentrations

We summarized household air pollution concentrations from burning biomass fuels according to cooking history in Table 2. Specifically, we did not find differences across settings in the number of years that the women had been cooking, the age at which they first started cooking, frequency of cooking sessions in a day, or the average duration of a cooking session. In contrast, availability of a second cookstove varied across settings: LPG stoves were more common in Peru, whereas kerosene stoves were more common in Kenya.

Household air pollution and cooking behavior

We found several differences in the minute-to-minute distributions of 24-hour indoor $PM_{2.5}$ concentrations across the three settings (Figure 1). First, indoor $PM_{2.5}$ concentrations were in a safe range ($<25 \mu g/m^3$) for 65%, 17%, and 40% of the time in Peru, Nepal, and Kenya, respectively. Second, high $PM_{2.5}$ concentrations were common: on average, indoor PM concentrations exceeded $1000 \mu g/m^3$ for 9%, 8%, and 21% of the time in Peru, Nepal, and Kenya, respectively. Third, after analyzing cooking behaviors with regard of time of day, participants in Peru most commonly cooked at 5AM and 4PM and 7AM and 6PM in Nepal, which coincided with peaks concentrations seen in Figure 1. In contrast, women in Kenya commonly cooked at 6AM, 12PM, and 6PM, which coincided with peak concentrations throughout the day. Furthermore, these peaks also reflected the mode of cooking frequency, since women in Peru and Nepal cooked most commonly twice per day, whereas women in Kenya cooked three times per day.

We display the minute-to-minute distributions of 24-hour CO concentrations in Figure 2, which also mirrored the above described cooking behaviors. Indoor CO concentrations were in a safe range (<7 ppm) for 64%, 79%, and 46% of the time in Peru, Nepal, and Kenya, respectively. High concentrations were also variable across settings: indoor CO concentrations exceeded 50 ppm for 7%, 4%, and 20% of the time in Peru, Nepal, and Kenya, respectively. In Figure 3, we compared time-weighted averages of household air pollution concentrations across settings. Mean 24-hour indoor $PM_{2.5}$ and CO concentrations were in similar in range between Peru and Nepal, and considerably higher in Kenya (all $p<0.001$).

Correlation between indoor carbon monoxide and particulate matter concentrations Overall correlations for the relationship between indoor $PM_{2.5}$ and CO concentrations for the entire range of data in Peru and Nepal were in the low range (Figure 4). Although the concentrations of both household air pollutants in Kenya were higher, the overall correlation was in the moderate range. Indoor $PM_{2.5}$ concentrations were differentially more variable across the range of indoor CO concentrations (i.e., a heteroskedastic relationship). Specifically, we found that there was overall poor agreement and evidence of a proportional bias between expected indoor $PM_{2.5}$ concentrations when using a prediction model based on indoor CO concentrations and observed indoor $PM_{2.5}$ concentrations across all settings

(Figure 5). In fact, the difference in observed vs. expected values could range anywhere between $417 \mu\text{g}/\text{m}^3$ to $4137 \mu\text{g}/\text{m}^3$ across settings, and this difference varied by levels of observed indoor $\text{PM}_{2.5}$ concentrations. There was a positive slope between the average of observed vs. expected indoor $\text{PM}_{2.5}$ concentrations and the difference between observed and expected indoor $\text{PM}_{2.5}$ concentrations ($p < 0.001$). Specifically, discordance between observed vs. expected indoor $\text{PM}_{2.5}$ concentrations was greatest at low concentrations across settings.

Household characteristics associated with indoor pollutant concentrations

We present single variable and multivariable analysis for the relationship between household factors and either indoor $\text{PM}_{2.5}$ concentrations or CO concentrations. In single variable analyses, household volume, having two or more open windows, and having mud walls were associated with lower indoor $\text{PM}_{2.5}$ concentrations (Table 3). In multivariable analyses, however, only having 2 open windows remained as a significant factor associated with indoor $\text{PM}_{2.5}$ concentrations. In single variable analyses, having mud walls was the only household factor associated with lower indoor CO concentrations, but was not important in multivariable analyses (Table 4).

DISCUSSION

In this study, we found very high levels of indoor air pollution in all three of the resource-poor rural settings of Peru, Kenya, and Nepal were exposed to high levels of household air pollution on a daily basis. Measured indoor $\text{PM}_{2.5}$ and CO concentrations were several-fold times higher than the proposed 24-hour World Health Organization safe air quality standards of $25 \mu\text{g}/\text{m}^3$ and 7 ppm, respectively (21). The duration of extreme environmental exposures during a 24-hour period was also high across the three settings; however, we encountered marked heterogeneity between and within each setting which was most likely explained by differences in cooking frequency and behavior. Furthermore, given that our results showed a heteroskedastic relationship between minute-to-minute indoor $\text{PM}_{2.5}$ and CO concentrations, we do not support using indoor CO concentrations as a surrogate marker for indoor $\text{PM}_{2.5}$ concentrations. The relationship between indoor $\text{PM}_{2.5}$ and CO concentrations may also vary by setting, and both pollutants should be measured independently.

Our results are comparable to findings reported in previous investigations. In Pollard et al, we suggested that although 24 hour indoor CO concentrations were positively and significantly correlated with $\text{PM}_{2.5}$ concentrations in rural households from Peru: high intra-household variability and wide prediction ranges could potentially affect indoor CO effectiveness as an appropriate surrogate for actual $\text{PM}_{2.5}$ exposure (13). Gu et al also reported significant variation of ultrafine particulate matter concentrations across different environments and activities (14). A study from Burkina Faso found a weak correlation (Spearman $\rho = 0.22$) between PM_{10} and personal CO concentrations among households (15). Naeher et al reported that the association between CO and $\text{PM}_{2.5}$ disappeared at low household air pollution concentrations in households with gas stoves (23). In our current study, while discordance between indoor $\text{PM}_{2.5}$ and CO concentrations was high at low concentrations, the correlation was stronger at higher pollutant concentrations and in specific

settings. These variations may be explained by the types of stoves or fuels used. While we advocate measuring both pollutant concentrations independently, measuring indoor PM_{2.5} concentrations in a subset of household augmented by measuring indoor CO concentrations in larger set of households may be a reasonable monitoring strategy in some settings.

However, there is still ongoing debate as to whether indoor CO concentrations should be used as a surrogate for indoor PM_{2.5} concentrations. Given the low cost and high inter-device reproducibility, multiple studies have opted to use household CO concentration as a proxy for household PM_{2.5} concentration (9). For example, the RESPIRE trial used continuous 48-hour CO concentrations as an indicator of household air pollution exposure in children and nonsmoking women (24). Likewise, the ongoing CAPS study, a cluster randomized controlled trial of improved cookstoves as a strategy to reduce childhood pneumonia in Malawi, was originally designed to measure 48-hour indoor CO as their primary method to assess the impact of the intervention on household air pollution (25). Yet, a recent longitudinal analysis of women in rural Guatemala also found a strong correlation between indoor PM_{2.5} and CO concentrations in a setting with a single prevailing source of combustion (26). Nevertheless, the authors emphasized that their results may not be generalizable to households with multiple sources of air pollution or with different demographic profiles or migration behavior. The complex relationship between indoor PM_{2.5} and CO concentrations has different possible explanations (9, 26). These include significant temporal and spatial variation of both pollutants within households, and differences in behavior and biomass fuel emissions within households. Besides having different environmental properties, health risks from exposure to high CO and PM_{2.5} concentrations also differ. For example, exposure to high CO concentrations has been associated with myocardial ischemia, visual impairment, reduced working and learning capacity (27), whereas exposure to high PM_{2.5} concentrations has been linked to multiple respiratory conditions, cancer, and tuberculosis (5, 6).

The averages of 24-h indoor (kitchen) PM_{2.5} and CO concentrations measured across our study settings were consistent in range with other studies (15, 28, 29). A recent study conducted in Burkina Faso recorded comparable averages of 24-h PM₁₀ concentrations of 2537 µg/m³ and 24-h CO concentrations of 16.9 ppm (15). In our study, we found that not only was the overall quantity of air pollutants high during an average day of exposure, but we also found a prolonged duration of hazardous concentrations. In our study, this was especially worrisome in Kenya where higher indoor PM (>1000µg/m³) persisted on average for more than six hours during a 24-hour monitoring period. Such extreme high levels of both CO and PM encountered in Kenyan households are possibly explained by cooking frequency, fire smoldering throughout the day, and lower numbers of open doors and windows in the kitchen for ventilation. Other studies have suggested that kitchen ventilation is a cost-effective alternative to reduce household air pollution and that, from a public health perspective, increasing ventilation may be a low cost intervention to reduce household air pollution (30). However, natural ventilation might be only feasible in settings with temperate climates and might not be applicable at high altitude or non-tropical settings (31). Neither living conditions nor socioeconomic status were clearly linked to household air pollutant concentrations. It is still sensible to infer that poverty and lack of education has an effect on biomass fuel smoke exposure as socioeconomic status restricts access to proper ventilation

and fuels. While household construction material across the three studied settings were diverse, we did not find that the types of walls or roofs were associated with household air pollution levels. These findings are consistent with those of McCracken et al who suggested that kitchen measures were poor markers of personal exposure to household air pollution (11).

Our study has some potential shortcomings. First, we studied a small sample size within each setting, which may limit generalizability of our study findings. Second, given that emission may be affected by weather (9), we did not collect repeated measures of 24-hour indoor CO and PM concentrations within the same household to understand seasonal variability in household air pollution. Third, household air pollution measurements were collected during a single 24-hour period, it is possible that a single 24-hour measurement may not be representative of actual household exposure levels. Longer periods of monitoring (48–72 hours) or repeated measurements on different days are likely to be more representative of the true degree of household air pollution exposure. We found it challenging to record more 24 hours across all of our settings because of the lack of access to a continuous source of electricity at participating households during the monitoring period. While we did not collect indoor pollutant concentrations on a specific day of the week across households, we avoided family gatherings, festivals, and weekends to obtain an indoor pollutant concentration profile of a typical day. Fourth, there appeared to be important differences in household ventilation across settings. While we used number of opened doors and windows, we did not directly measure the degree of ventilation (31). Fifth, we recorded kitchen pollutant concentrations instead of personal exposures. Nonetheless, an important strength of our study is that we implemented a uniform, standardized study procedure across settings for collection of household and participant characteristics and environmental exposure assessment. A standardized approach to data collection has allowed us to make both within and across setting comparisons of household characteristics, household air pollution concentrations, and their inter-relationships.

CONCLUSIONS

In our study, household members in our three resource-poor settings were exposed to high concentrations of indoor biomass fuel smoke. The main variable associated with higher 24-hour indoor PM_{2.5} concentration was the number of window openings (i.e., a proxy for ventilation), and suggests that better ventilation is a low-cost intervention that may reduce household air pollution. The relationship between indoor PM_{2.5} and CO concentrations was weak especially at low indoor CO concentrations, and our data do not support the use of indoor CO concentration as a surrogate marker for indoor PM_{2.5} concentrations across all settings. Both are important markers of household air pollution with different health and environmental implications and should therefore be independently measured. While discordance between indoor PM_{2.5} and CO concentrations was high at low concentrations, the correlation became stronger at higher pollutant concentrations and in specific settings. While we advocate measuring both pollutant concentrations independently, measuring indoor PM_{2.5} concentrations in a subset of household augmented by measuring indoor CO concentrations in larger set of households may be a reasonable monitoring strategy in some settings.

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Highlights

- We summarized indoor $PM_{2.5}$ and CO concentrations across three resource-poor settings.
- Overall correlations between indoor $PM_{2.5}$ and CO were low to moderate.
- Agreement between observed indoor $PM_{2.5}$ vs. those estimated based on indoor CO was poor.
- Indoor CO is not an adequate surrogate marker for indoor $PM_{2.5}$ across all settings.

Figure 1. Minute-to-minute distribution of 24-hour $PM_{2.5}$ concentrations stratified by hour of the day and setting.

Figure 2. Minute-to-minute distribution of 24-hour carbon monoxide concentrations stratified by hour of the day and setting.

Figure 3. Boxplots of 24-hour indoor carbon monoxide and PM_{2.5} concentrations across the three settings.

Figure 4. Scatterplot of minute-to-minute 24-hour indoor log-scaled PM_{2.5} and CO concentrations stratified by setting. The solid red line represents a smooth spline of the relationship between CO and PM concentrations, and the dashed red lines are a 2 standard error band.

Figure 5. Bland-Altman plots of observed vs. expected indoor log-PM_{2.5} concentrations stratified by setting. Indoor log-PM_{2.5} concentrations were obtained from a regression model based on indoor CO concentrations. The horizontal broken red lines represent a zero difference and ± 2 SDs.

Table 1

Household characteristics in study participants from three resource limited rural settings.

	Overall	Peru	Nepal	Kenya	p-value
Sample size	128	41	44	43	
Roof material, n (%)					
Thatch roof	31 (24)	21 (51)	3 (7)	7 (16)	<0.001
Tin roof	56 (44)	20 (49)	0 (0)	36 (85)	<0.001
Tile roof	22 (17)	0 (0)	22 (50)	0 (0)	<0.001
Abode used as primary wall material, n (%)	38 (29)	38 (93)	40 (91)	43 (100)	0.14
Household characteristics, mean (SD)					
Volume in m ³	28.1 (16.1)	27.1 (12.4)	25.6 (17.2)	31.7 (17.7)	0.2
Windows open in kitchen	2.37 (1.5)	1.3 (1.3)	3.7 (1.6)	1.3 (0.6)	<0.001
Rooms per house	3.7 (1.6)	3.5 (1.5)	4.3 (1.9)	3.2 (1.2)	0.003
Number of rooms exclusively used as bedrooms	1.9 (1.2)	2.2 (1.4)	1.4 (1.1)	2 (1.1)	0.01
Socioeconomic status, mean (SD) or n (%)					
Monthly household income <100 USD	8 (6)	39 (95)	27 (61)	3 (7%)	<0.001
Improved water facilities	88 (69)	39 (89)	44 (100)	5 (12)	<0.001
6 or fewer years of education	80 (63)	38 (93)	40 (91)	2 (5)	<0.001
Improved sanitation facilities	31 (24)	22 (54)	6 (14)	13 (30)	<0.001
Number of assets per households	3.2 (1.8)	2.8 (1.5)	3 (2.0)	3.9 (1.6)	0.01

Table 2
Biomass fuel smoke exposure in women from three resource limited rural settings

	Overall	Peru	Nepal	Kenya	p-value
Sample size	128	41	44	43	
Cooking history, mean (SD)					
Years cooking	23.9 (7.7)	24.2 (7.8)	24.7 (7.4)	23(8.1)	0.58
Age first started cooking	12.28 (2.69)	11.31 (2.37)	12.95 (2.18)	12.51 (3.2)	0.01
Times per day cooked, mode	2	2	2	3	
Total time cooking in hours	3.5 (1.2)	3.7 (1.2)	3.4 (1)	3.2 (1.3)	0.08
Secondary Cookstove Use, n (%)					
LPG	17 (13.3)	8 (19.5)	4(9.1)	5 (11.6)	0.35
Kerosene	11 (8.6)	0	1 (2.3)	10 (23.3)	<0.001
Indoor pollutant concentrations, mean (SD)					
PM in µg/m ³	904 (1086)	615 (651)	650 (959)	1440 (1333)	<0.001
CO in ppm	19.0 (23.1)	14.1(13.4)	8.9 (8)	34.5 (31.1)	<0.001

TABLE 3

Association between household characteristics and log-transformed 24-hour indoor PM_{2.5} concentrations.

	Single variable		Multivariable	
	Coefficient (95% CI)	p-value	Coefficient (95% CI)	p-value
Being poor	0.06 (−0.38 to 0.50)	0.78	−0.18 (−0.72 to 0.37)	0.52
Low education	0.20 (−0.38 to 0.79)	0.49	0.11 (−0.57 to 0.79)	0.75
Household volume	−0.01 (−0.02 to 0.00)	0.07	−0.00 (−0.01 to 0.01)	0.71
Mud walls	−0.84 (−1.49 to −0.19)	0.01	0.16 (−0.88 to 1.20)	0.76
Thatch roof vs. other	−0.05 (−0.44 to 0.34)	0.78	0.57 (−0.54 to 1.68)	0.31
Tin roof vs. other	0.08 (−0.35 to 0.50)	0.72	0.58 (−0.61 to 1.77)	0.33
At least 2 windows (vs. fewer)	−0.56 (−0.92 to −0.19)	0.003	−0.49 (−0.90 to −0.07)	0.02
Total number of assets (per asset)	−0.01 (−0.10 to 0.07)	0.75	−0.03 (−0.15 to 0.09)	0.61
Five or more sleep in same house (vs. fewer)	−0.14 (−0.46 to 0.19)	0.42	−0.11 (−0.49 to 0.27)	0.56
Two or more families cook in same kitchen (vs. fewer)	−0.33 (−0.92 to 0.25)	0.26	−0.22 (−0.81 to 0.37)	0.46
Having 1 open door	0.42 (−0.06 to 0.91)	0.09	−0.57 (−0.11 to 1.24)	0.10
Cooks for more than 6 people	0.19 (−0.32 to 0.71)	0.45	0.34 (−0.23 to 0.92)	0.23
Ever use kerosene gas stove	−0.36 (−0.93 to 0.22)	0.22	−0.25 (−0.84 to 0.35)	0.41
Ever use LPG gas stove	−0.14 (−0.59 to 0.30)	0.52	0.04 (−0.50 to 0.57)	0.89

Table 4

Association between household characteristics and log-transformed 24-hour indoor CO concentrations.

Covariate	Single variable		Multivariable	
	Coefficient	p-value	Coefficient (95% CI)	p-value
Being poor	2.34 (−8.25 to 12.93)	0.66	3.67 (−11.17 to 18.51)	0.62
Low education	1.73 (−12.56 to 16.01)	0.81	−0.48 (−18.97 to 18)	0.96
Household volume	−0.03 (−0.30 to 0.24)	0.83	0.07 (−0.26 to 0.39)	0.68
Mud walls	−18.71 (−34.64 to −2.78)	0.02	5.46 (−22.99 to 33.92)	0.7
Thatch roof vs. other	1.37 (−8.11 to 10.85)	0.78	9.07 (−21.22 to 39.36)	0.55
Tin roof vs. other	−0.56 (−10.83 to 9.71)	0.91	6.52 (−26 to 39.04)	0.69
At least 2 windows (vs. fewer)	−3.34 (−12.30 to 5.61)	0.46	−4.14 (−15.4 to 7.11)	0.47
Total number of assets (per asset)	−0.03 (−2.18 to 2.13)	0.98	−0.60 (−3.88 to 2.68)	0.72
Five or more sleep in same house (vs. fewer)	−0.27 (−8.28 to 7.74)	0.95	−1.78 (−12.07 to 8.5)	0.73
Two or more families cook in same kitchen (vs. fewer)	−13.16 (−27.33 to 1.01)	0.07	−13.11 (−29.24 to 3.01)	0.11
Having 1 open door	−0.71 (−12.72 to 11.31)	0.91	5.33 (−13.08 to 23.75)	0.57
Cooks for more than 6 people	8.24 (−4.13 to 20.62)	0.19	10.28 (−5.33 to 25.9)	0.19
Ever use kerosene gas stove	−5.59 (−19.57 to 8.39)	0.43	−6.29 (−22.49 to 9.92)	0.44
Ever use LPG gas stove	1.04 (−9.78 to 11.87)	0.85	3.90 (−23.61 to 46.02)	0.6