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A Simplified Model for Estimating Household Air Pollution in Challenging Contexts: A Case Study from Ghana

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Abstract: Almost three billion people rely primarily on inefficient and polluting cooking systems worldwide. Household air pollution is a direct consequence of this practice, and it is annually associated with millions of premature deaths and diseases, mainly in low- and lower-middle-income countries. The use of improved cookstoves often represents an appropriate solution to reduce such health risks. However, in the distribution of such units, it can be necessary to prioritize the beneficiaries. Thus, in this study, we conducted field research involving five rural villages in the Northern part of Ghana, where using three-stone fires or rural stoves was common. Concentrations of $PM_{2.5}$, PM_{10}, and carbon monoxide (CO) were measured indoors and outdoors. Considering each field mission lasted less than 24 h, assumptions were made so as to calculate the average pollutant concentrations in 24 h through a new, simplified equation that combined efficiency and cost-savings by shortening field assessments. The obtained values were compared with international guidelines. The results showed that $PM_{2.5}$ and PM_{10} limits were overstepped in two villages, which should thus be prioritized. However, further research will be necessary to strengthen and validate our proposed equation, which must be seen as a starting point.

Keywords: HAP; rural communities; developing countries; simplified model

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1. Introduction

Almost three billion people worldwide rely primarily on inefficient and polluting cooking systems [1]. Household air pollution (HAP) is a direct consequence of this practice. Every year, almost 4 million people die prematurely from illnesses related to HAP from inefficient cooking practices using polluting stoves [2]. Such deaths mainly occur in low- and lower-middle-income countries [3]. Furthermore, ambient (i.e., outdoor) air pollution has been estimated to cause 4.2 million premature deaths globally per year in cities and rural areas [4]. According to the WHO [4], about 90% of such early deaths occur in low- and middle-income countries.

The health risks associated with air exposure to particulate matter (PM), carbon monoxide (CO), and other substances have been studied over the years by the WHO, which has developed guidelines for both indoor and outdoor environments [5,6]. Lee, Spath et al. [7] have recently conducted a systematic review and meta-analysis to investigate the relationship between short-term exposure to carbon monoxide and myocardial infarction, demonstrating a higher risk of myocardial infarction per mg/m^3 increase in ambient carbon monoxide concentration. Besides, Han et al. [8] have studied long-term exposure to $PM_{2.5}$ and the risk of developing chronic obstructive pulmonary disease in the elderly, finding a significant association. In further research, Lee, Bing et al. [9] have noted that the burden of cardiorespiratory, paediatric, and maternal diseases associated with HAP has declined worldwide. However, it is still high in the world's poorest regions. Recent research has also focused on the association between air pollution and COVID-19 mortality or morbidity. A study [10] has found that higher historical $PM_{2.5}$ exposures were positively associated with higher county-level COVID-19 mortality rates in the United States. A study [11] has found that, in the Lombardy region (Italy), the mean annual concentrations of $PM_{2.5}$ and PM_{10} were associated with increased COVID-19 incidence rates. Marquès et al. [12] have found similar results concerning long-term exposure to PM_{10} and COVID-19 severity and mortality in Spain. Consequently, air pollution can cause many threats, and appropriate interventions are needed to reduce it, both outdoors and indoors.

Most of the health risks associated with traditional and polluting cookstoves are concentrated in low- and middle-income countries, including Ghana. Specifically, as reported by some authors [13–15] and witnessed during our field assessment, most people cook using traditional and polluting stoves in rural Ghana. The use of such stoves is associated with many diseases that can also affect children, causing respiratory morbidity [16], adverse foetal growth outcomes [17], and even death due to acute lower respiratory infections [18].

However, many factors can influence the air emissions associated with polluting cooking systems, such as the type of cookstove and its conditions, the environmental characteristics of the area, and the kind of fuel burned [19,20]. Besides, in isolated settlements, many managing issues can affect the research activities, such as difficulties for operators in finding safe and comfortable places to sleep and staff shortages [21]. Such problems may hinder the chances of conducting long and detailed field assessments. Therefore, short missions can represent the best way to combine efficiency and cost-savings, reaching a high number of people that could be beneficiaries of additional interventions.

In rural contexts, the distribution of improved cookstoves has often represented the most appropriate solution to reduce such health risks. For instance, Grajeda et al. [22] have proven the effectiveness of gas and chimney biomass stoves for reducing HAP in Guatemala. Van Gemert et al. [23] have shown the health benefits of improved cookstoves in rural communities of Uganda, Vietnam, and Kyrgyzstan. De la Sota et al. [24] have demonstrated that, in Senegal, improved cookstoves have contributed to a reduction of total fine and ultrafine particles and carbon monoxide. Furthermore, the WHO has provided air-emission guidelines, considering both short-term and long-term exposure effects [5,6]. Unfortunately, despite enhanced air quality, achieving the WHO's standards is not always guaranteed, even when improved cookstoves are implemented [23]. Furthermore, in rural contexts, long-term-exposure threshold limits can be more challenging to evaluate. Thus, although advanced air air-quality models have been developed [25,26], in some cases, simplified methodologies that estimate the average air quality in 24 h can be more practical.

Thus, the scope of our research was to identify a model that could allow for prioritizing interventions based on fast field missions. Indeed, our work was conducted in the context of an international cooperation project for local development [27] in which improved cookstoves will be distributed over the years. However, it has to be considered that step-by-step interventions often characterize development projects. Therefore, it is crucial to identify the households that are the most exposed to high levels of air pollution (in indoor or even in semi-indoor spaces) that will be, for example, the first recipients of improved cookstoves. Our previous, preliminary work [28] encouraged us to develop our approach further, and from that point, we have developed the present manuscript. The research is based on a field assessment carried out in Northern Ghana, involving five rural villages. The exposure to $PM_{2.5}$, PM_{10}, and CO was measured. Then, a simplified equation was developed and used to compare the obtained values with international guidelines. However, it must be highlighted that the study represents a preliminary screening and not a long-term analysis. Indeed, the proposed model will need further validation during future field assessments in the same or similar locations. We hope that other researchers will contribute to validating and improving the model.

2. Materials and Methods

2.1. Study Area

Ghana is a country located in West Africa with a population of more than 30 million inhabitants [29]. According to the World Bank [30], it is a lower-middle-income country.

The savannah zone, in which the rural villages were assessed, is the least economically developed area, and it is characterized by reduced rainfall and infertile lands [31]. Furthermore, the continued use of wood among solid fuels for cookstoves in the region contributes to deforestation and the diffusion of arid lands [14].

The use of three-stone fires or traditional and polluting cookstoves is widespread in rural areas of Ghana, as witnessed during the field mission conducted in November 2019 in the northern part of the country in the five villages, as shown in Figure 1. The villages were located in the following districts: Zabzugu (village A), Nanumba South (village B), Kpandai (village C), Mion (village D), and East Mamprusi (village E). The villages were involved in this research since they were beneficiaries of an international cooperation project led by Cooperazione Internazionale Sud Sud (CISS) NGO [27]. Many environmental and livelihood activities were conceived. Our institution, CeTamb (University of Brescia), was the partner organization in charge of the environmental field assessment, as discussed below.

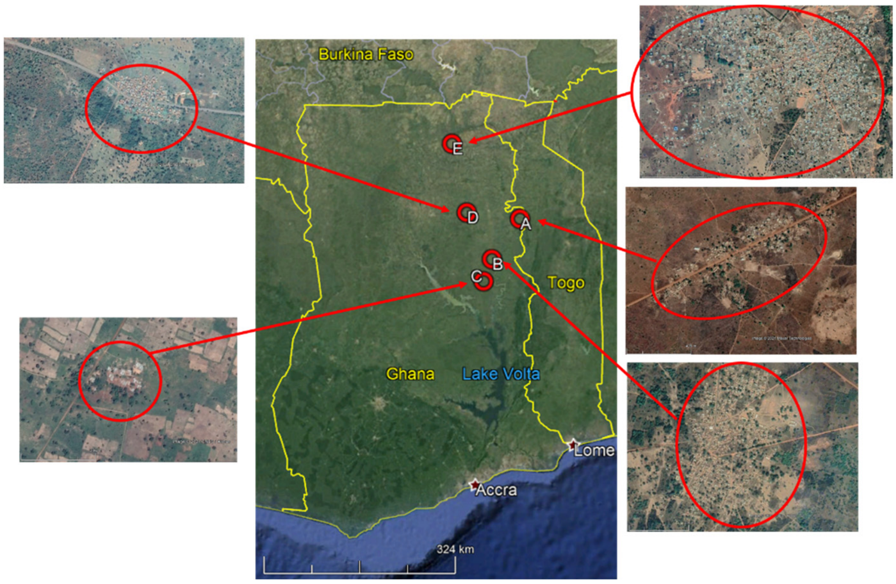

Figure 1. Physical map of Ghana with the location of the five villages investigated (from Google Earth Pro on desktop).

Northern Ghana experiences a dry season from November to May and a wet from June to October [32]. Consequently, the field mission occurred during the dry season.

2.2. Study Design

The concentrations of $PM_{2.5}$, PM_{10}, and CO in the air were measured. Measurements were taken near indoor kitchens, internal courtyards, and outdoors. Outdoors, the concentrations were investigated both close to rural stoves and in other areas of each village, away from where the inhabitants were cooking. Close to cookstoves, the measurements were taken where people were cooking at a height of approximately 1 m from ground level and between 0.5 and 1.0 m from any cookstove they were using. The position of this last measurement corresponded to the breathing zone of the people who were cooking.

A portable device was employed to measure the concentrations of $PM_{2.5}$ and PM_{10} in the air (Trotec International, particle measuring device BQ20, measurement interval 0–2000 μg/m^3, resolution 1 μg/m^3, detector type: scattered light measurement). Carbon monoxide (CO) was measured using a different device (CO-910 Carbon Monoxide, measurement interval 0–1000 ppm, resolution 1 ppm, sensor: stabilized electrochemical gas-specific). However, it must be highlighted that such devices can be considered low-cost compared to very advanced and expensive ones. Furthermore, in the given context, it was impossible to carry out any calibration or comparison with a gravimetric sampler using a standardized procedure. Thus, the probability exists that some measurements could be approximate. However, other research has recently used these devices (Trotec International BQ20) for air measurements [33,34]. Every field mission in each village lasted between 1 and 3 h because of the bad quality of most roads and the distance from the headquarters, located in Tamale (the Northern Region's capital). Besides, it was not possible to spend the night in the villages. Consequently, each air quality measurement lasted between 15 and 60 min.

However, even during the shortest missions, crucial information was collected. Indeed, each field assessment allowed us to understand people's habits better. Such information was used in developing the equation discussed below.

The obtained values were compared with international guidelines [5,6,35]. Concerning PM, according to the WHO, there is no evidence of a difference in the hazardous nature of PM from indoor sources compared with those from outdoor sources [5]. As a consequence, the WHO [6] reference values for outdoors were also considered for the indoor areas. The guideline values, as a mean in 24 h, are 25 $\mu g/m^3$ and 50 $\mu g/m^3$ for $PM_{2.5}$ and PM_{10}, respectively [6].

Concerning CO, threshold limit values for acute exposure, i.e., short-term intervals, exist. In particular, the WHO [5] provides CO guidelines for 15 and 60 min of indoor exposure, giving limit values of 100 mg/m^3 and 35 mg/m^3, respectively. The United States Environmental Protection Agency (US EPA) [35] provides CO guidelines for 60 min of outdoor exposure, assigning 35 ppm. It can be noted that the WHO and the EPA refer to indoor and outdoor short-term exposure, respectively. However, the threshold limit is practically the same; indeed, although distinct units of measurement were used (i.e., mg/m^3 and ppm, respectively), the conversion factor at 25 °C is close to 1 [5]. However, chronic CO exposure appears to be different from acute exposure, and the limit in terms of the arithmetic mean concentration in 24 h equal to 7 mg/m^3 is also given by the WHO [5].

As anticipated, a challenge was that the threshold limits related to long-term exposure were given in terms of mean value in 24 h, while the on-field measurements lasted no more than 1 h. As a consequence, an equation was created based on the following assumptions:

- People, mainly women, who cooked for 3 h per meal, and 2 meals per day, were considered;
- The trend of air emissions was the same for both meals, and the temporal trend was defined and confirmed by taking as a reference previous publications that analysed case studies from Ghana [13–15];
- Measurements taken far from smoke were considered to define $PM_{2.5}$, PM_{10}, and CO concentrations during non-cooking times.

The first assumption was based on information collected during the field missions (observations and questions posed to local communities). The data are available upon request to the authors. In particular, women cooked from 2 to 5 h per meal, depending on the food and the number of people.

Concerning the second assumption, it must be considered that the concentrations were measured during the second daily meal, which usually generates a higher level of pollutants [14,15]. Consequently, it represents a conservative assumption.

The last assumption was made possible using measurements taken in other areas of each village, away from where inhabitants were cooking. More precisely, such measures were taken at least 30 m from any human activity.

The proposed, simplified equation that was used to estimate PM average concentration in 24 h is:

$$PM_{av,\,24} = (PM_{av,\,meas} \times h_{cook} + PM_{clean} \times h_{no\ cook})/t \quad (1)$$

with:

- $PM_{av,\,24}$ = PM concentration as an average in 24 h;
- $PM_{av,\,meas}$ = average PM concentration measured in a given time (60 or 30 min for the case study);
- h_{cook} = time of cooking per day, equal to 6 or 12, if 60 or 30 min are considered for the calculation of the average PM concentration, respectively;

- PM_{clean} = PM concentration measured far away from smoke or during non-cooking times;
- $h_{no\ cook}$ = time without cooking per day, equal to 18 or 36 h, if 60 or 30 min are considered for the calculation of the average PM concentration, respectively;
- t = 24 or 48, if 60 or 30 min are considered for calculating the average PM concentration, respectively.

Equation (1) was also used for the average concentration of CO in 24 h.

As anticipated and shown in Table 1, we conducted measurements close to each stove within a time interval of 15–60 min. For example, in village A, we measured $PM_{2.5}$ concentrations at 16:07, 16:14, and 16:22 (total time interval: 15 min).

Table 1. Concentrations of $PM_{2.5}$, PM_{10}, and CO as measured in the five villages.

Location	Observations	Time	$PM_{2.5}$ [µg/m^3]	PM_{10} [µg/m^3]	CO [ppm] (SD)
Village A	Indoor, close to rural stoves	16:07	87	164	16 (0.0)
		16:14	46	93	21 (1.4)
		16:22	64	107	12 (2.8)
Village B	Courtyard, close to rural stoves	12:47	98	140	8 (1.4)
		12:53	316	514	7 (0.0)
		12:59	61	89	11 (2.8)
		13:05	87	146	10 (0.0)
		13:11	163	268	8 (1.4)
		13:47	93	134	3 (1.4)
Village B	Semi-enclosed space, close to rural stoves	12:50	193	323	15 (4.2)
		12:56	1323	2000 [a]	22 (0.0)
		13:02	385	645	18 (2.8)
		13:08	624	1047	12 (1.4)
		13:14	231	391	4 (1.4)
		13:50	70	102	4 (0.0)
Village C	Outdoors, close to rural stoves	12:33	34	55	10 (2.8)
		12:39	29	51	4 (1.4)
		12:45	23	43	3 (0.0)
		12:51	25	45	3 (0.0)
		12:57	28	51	3 (1.4)
		12:59	37	69	8 (1.4)
		13:03	31	52	3 (0.0)
Village D	Outdoors, close to rural stoves	13:55	15	28	4 (1.4)
		14:05	56	99	19 (2.8)
		14:15	17	35	2 (1.4)
		14:25	15	29	1 (0.0)
Village E	Semi-enclosed space, close to rural stoves	16:00	417	685	25 (1.4)
		16:03	375	618	22 (1.4)
		16:08	1490	2000 [a]	25 (4.2)
		16:13	96	164	8 (1.4)
		16:18	144	238	14 (1.4)
		16:23	253	406	19 (1.4)
		16:28	299	481	18 (1.4)
		16:30	289	465	12 (0.0)

[a] 2000 µg/m^3 was the maximum detectable limit.

Unfortunately, it was impossible to use Equation (1) for village A due to the available measurement's short timeframe (15 min). However, with the appropriate proportions, the equation can also be used for other time durations, even 15 min, although an unduly short duration could reduce the accuracy.

Besides, technical documents [36,37] from local offices allowed us to collect and analyse some epidemiological information at the district level. Such documents were collected with the help of the local staff of CISS NGO.

3. Results and Discussion

3.1. $PM_{2.5}$, PM_{10}, and CO Results

Table 1 summarizes the concentrations of $PM_{2.5}$, PM_{10}, and CO measured in all five villages. It has to be noted that, when possible, especially in courtyards, people cooked while placing themselves in such a way as to avoid or reduce their inhalation of smoke. Therefore, the exposure could often be lower, and the following assumptions represent a conservative approach that aims to guarantee a higher level of safety for the people.

It is important to consider that the device for measuring PM automatically gave the average value after 1 min. Conversely, the device for measuring CO gave an instant value; as a consequence, we reported a 1-minute mean value after taking 2 measures per minute. Therefore, in Table 1, the standard deviation (SD) associated with CO is shown in brackets.

3.2. Comparison with International Guidelines

In all five villages, the average CO concentration in 15 min or 60 min was always measured at a level below the limit mentioned for short (acute) exposure [5,35].

As anticipated, it was impossible to use Equation (1) for village A due to the measurement's short duration (15 min). In villages B-E, the average concentrations of $PM_{2.5}$, PM_{10}, and CO in time intervals of 30 or 60 min were calculated as a mean of the respective values of Table 1. The results are summarized in Table 2. Samples observations number (N) and standard deviation (SD) are reported in brackets.

Table 2. Average concentrations of $PM_{2.5}$, PM_{10}, and CO.

Location	Further Notes	Time Interval [Minutes]	$PM_{2.5}$ [μg/m^3] (N; SD)	PM_{10} [μg/m^3] (N; SD)	CO [ppm] (N; SD)
Village B	Courtyard, close to rural stoves	60	136 (6; 94.3)	215 (6: 158.1)	8 (6; 2.8)
Village B	Semi-enclosed space, close to rural stoves	60	471 (6; 458.8)	751 (6; 691.8)	13 (6; 7.4)
Village B	Far away from smoke	-	23 (8; 2.7)	43 (8; 5.4)	2 (8; 0.6)
Village C	Outdoors, close to rural stoves	30	30 (7; 4.9)	52 (7; 8.5)	5 (7; 2.9)
Village C	Far away from smoke	-	21 (3; 0.6)	39 (3; 0.6)	2 (3; 0.0)
Village D	Outdoors, close to rural stoves	30	26 (4; 20.2)	48 (4; 34.3)	7 (4; 8.4)
Village D	Far away from smoke	-	18 (4; 1.5)	34 (4; 4.2)	3 (4; 0.6)
Village E	Semi-enclosed space, close to rural stoves	30	420 (8; 445.3)	632 (8; 579.5)	18 (8; 6.2)
Village E	Far away from smoke	-	15 (3; 5.0)	28 (3; 8.0)	2 (3; 0.6)

The values of Table 2 were crucial for the implementation of Equation (1), the results of which are shown in Table 3. In villages B-E, the 24-h average value was calculated both for particulate matter and for CO. For example, the $PM_{2.5}$ average value in village C was obtained from Equation (1) as follows:

$$PM_{av,\,24} = \{(30\ [\mu/m^3] \times 12\ [h] + 21\ [\mu/m^3] \times 36\ [h]\}/48\ [h]$$

Table 3. Concentrations of $PM_{2.5}$, PM_{10}, and CO as an average in 24 h, as calculated with Equation (1).

Location	Further Notes	Concentration Using Equation (1)			Threshold Limits by WHO [5,6]		
		$PM_{2.5}$ [$\mu g/m^3$]	PM_{10} [$\mu g/m^3$]	CO [ppm]	$PM_{2.5}$ [$\mu g/m^3$]	PM_{10} [$\mu g/m^3$]	CO [ppm]
Village B	Courtyard, close to rural stoves	51	86	4	25	50	7
Village B	Semi-enclosed space, close to rural stoves	135	220	5			
Village C	Outdoors, close to rural stoves	23	43	3			
Village D	Outdoors, close to rural stoves	20	37	4			
Village E	Semi-enclosed space, close to rural stoves	116	179	6			

Indeed, in village C, a time interval of 30 min was used; consequently, the corresponding coefficients mentioned in Equation (1) were taken.

It can be noted that measurements in villages B and E went far beyond the limits for $PM_{2.5}$ and PM_{10}, while villages C and D did not exceed the limits by a little. CO limit concentrations were never exceeded, but the value was almost reached in village E.

The trend of particulate matter emissions was not very different from that of similar contexts in Ghana [14].

3.3. Health Outcome Considerations

It has to be highlighted that, concerning PM, we followed a conceptual approximation. Indeed, different contaminants can be within the PM, causing various health risk levels [38]. However, in many recent studies [22,23], the health assessment has been based on $PM_{2.5}$ and PM_{10}, in addition to other substances.

As anticipated, the documentation collected in Ghana during the field mission in November 2019 allowed the identification of helpful elements. In particular, in addition to malaria (endemic in Ghana) [39], respiratory infections and diarrhoea were the most common diseases in the districts where it was possible to obtain information, namely East Mamprusi [36] and Zabzugu [37].

The results from this study confirmed that rural cookstoves, even in courtyards and semi-enclosed spaces, may represent a health risk among rural village inhabitants. Indeed, in two villages out of five, i.e., villages B and E, the estimated emissions of $PM_{2.5}$ and PM_{10} exceeded the WHO's limits.

In addition, the health information available for village E [36] was consistent with our results; indeed, respiratory infections were among the most common diseases in the East Mamprusi District. Similarly, a study conducted among rural communities in Mexico [40] found that respiratory diseases occurred about twice as frequently in the rural population compared to that of urban areas, despite vehicular pollution and smoking frequency being greater in urban populations. Therefore, the authors identified two potential factors: cooking with solid fuels and the open burning of waste. The Ghanaian villages involved in our study had similar characteristics.

Furthermore, our analysis is supported by the findings from a systematic review and meta-analysis in which acute respiratory infections and chronic bronchitis were significantly associated with using biomass fuels in rural areas [41].

3.4. Relevance of the Equation

It has to be highlighted that Equation (1) has some approximations. As discussed above, many factors can influence the level of air pollution that affects a specific household, for example, the fuel used by each family and the type of cookstove. However, such differences can represent the equation's advantage because it could overcome the challenge of monitoring many households in less time.

The results may permit identifying the most affected villages or households in terms of HAP. As anticipated, it could represent a crucial point; indeed, in international cooperation projects similar to ours, the prioritization of interventions is often strategic for many reasons. For instance, the project could envisage a gradual distribution of resources or funds; therefore, it would be necessary to identify beneficiaries of higher priority. However, our results will need to be integrated with further specific analyses and interventions. Indeed, in many cases, women and children are the most exposed and vulnerable. Furthermore, systematic behaviour change campaigns can be crucial [42] and should accompany appropriate technology distribution.

Equation (1) can also be used in international development cooperation projects and field research where operators must conduct many field assessments in several villages. In particular, it can be crucial when operators can hardly spend more than 24 h in the same place or if they do not have adequate instrumentation to compensate for their absence. For instance, Smith et al. [43] conducted a randomized controlled trial to evaluate the effect of reduction in HAP in children in Guatemala. However, infant 48-h carbon monoxide measurements were used for exposure-response analysis, and it is not always possible to access such instrumentation. In addition, Fullerton et al. [44] surveyed HAP in rural and urban areas of Malawi, but the duration of each measurement was, on average, around 20 h. Besides, Ni et al. [45] investigated the seasonal variations in the outdoor, indoor, and personal air pollution exposures of women using wood stoves on the Tibetan Plateau. However, the authors measured the 48-h personal exposure of women to $PM_{2.5}$ and CO. Such procedures could not easily be carried out in our case study.

Therefore, an approach based on the simplified equation proposed here can represent a good compromise in challenging contexts in the case of lack of resources or time, or if it is necessary to prioritize some beneficiaries. However, Equation (1) should be validated and improved in future research. Indeed, as anticipated, the daily trend of emissions on which we have based our model references previous studies carried out in rural Ghana by other researchers [13–15]. At the same time, given the current uncertainty level, we followed a conservative approach. However, in the future, some more-accurate values should be identified, for example, using a coefficient to evaluate the different concentrations of pollutants in the two main daily meals.

4. Conclusions

As discussed, disseminating improved cookstoves in rural villages of low- and middle-income countries represents a global challenge that can improve millions of people's quality of life [46].

Unfortunately, many people still use traditional and polluting cookstoves and suffer from many related diseases. In this context, the current research was conducted, and a new, simplified equation was developed to easily compare the obtained values with international guidelines. Indeed, the equation can be helpful in similar situations. For example, the equation can be crucial when rapid field assessments are required. Such a procedure can allow for prioritizing activities toward the most vulnerable and affected villages or households, especially when a lack of economic or material resources characterizes a project.

Equation (1) will need to be validated and improved in future missions and in similar contexts. Average values obtained by more extended measurements through 24-h monitoring, and involving more households, will be necessary. Consequently, one of the next steps should consist of conducting validation activities that have been hindered by the COVID-19 pandemic [47] and the other reasons discussed in the manuscript. We also hope for improvements from additional case studies and contributions from other researchers. Indeed, we think our work represents a good starting point. It could be handy in challenging situations.

However, constraints that affected the present research need to be considered in future validation and improvements of the equation. For example, the seasonal and diurnal variation in background concentrations of PM and CO can be considerable. Furthermore, the possible influence of other air pollution sources should be considered, both outdoors and indoors. Besides, stoves burning charcoal, wood, or other fuels can have different emissions profiles, and when possible, that should be taken into account. Improving this equation and its reliability could contribute to the development of dependable field activities that are both fast and cheap. The equation could also be employed in future missions to calculate the 24-h average air emissions from improved cookstoves, comparing the values before and after their implementation.

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