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Indoor pollution in high-altitude dwellings: An assessment of affecting factors across four Sherpa villages in the Khumbu region, Nepal

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Abstract

Household air pollution (HAP) from biomass fuel smoke is a major health risk, especially in developing countries. The ventilation of buildings and the type of fume discharge could also affect HAP. The present study aims to investigate the impact of stove type and kitchen characteristics on levels of pollutants. In particular, we investigated the potential geometric ventilation of buildings using geometric ventilation index (GVI), the presence of chimneys, the type of fuel and the environmental carbon monoxide level (a marker of indoor pollution) in the households of four Sherpa villages located in a mountain region of Nepal at altitudes between 2500 and 3900 m. We analysed 114 buildings (76 private residences and 38 lodges that accommodate tourists). Lodges had a more effective discharge system and a higher GVI, which had an inverse, significant correlation with indoor CO levels ($r = 0.52$). The level of indoor CO was more than 50% higher in private residences than in lodges. In the univariate analysis, only the absence of a chimney was associated with higher indoor CO (OR 3.4 (CL95%, 1.2–10.0), $p = 0.02$). We conclude that the adoption of chimneys and sealed stoves with exhaust pipes should be the first measure taken to reduce pollutants inside the households of high mountain regions until a switch to clean fuels can be achieved.

Keywords

Indoor pollution, Household air pollution, Carbon monoxide, Geometric ventilation index, Biomass fuel, Mountain area, Developing countries

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Introduction

In the last 15 years, we have seen mounting evidence of the health effects of biomass fuel smoke. Recent studies show that household air pollution (HAP) from biomass fuel smoke is a major health risk, especially in developing countries.[1] HAP is significantly linked to respiratory diseases (acute lower respiratory tract infections among children and chronic obstructive pulmonary disease, asthma and lung cancer among adults); cardiovascular diseases (arteriosclerosis, hypertension, ischemic heart disease and stroke); eye disease (cataracts); and low birth weight and infant mortality.[2–7] In developing countries, solid fuels (wood, animal dung, charcoal, crop wastes and coal) are used for heating and cooking and are often burnt in inefficient and highly polluting stoves, which are often located in places without

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adequate natural ventilation. This is true for many countries, including Nepal, where the burning of open fires is very common in rural villages. A study in the Terai, a plain region in southern Nepal, reported that air pollution in rural households was much higher than the recommendations of the World Health Organization and of the National Ambient Air Quality Standards for Nepal.[8,9] As the adverse health effects of HAP are determined not only by the level of health-damaging pollutants but also by the total duration of exposure, people living in cold mountain regions could suffer the greatest effects, as they are exposed to these pollutants almost 24 hours a day, especially in winter. Moreover, at altitude, water boils at a lower temperature, and therefore, longer boiling and cooking times are expected throughout the year; the reduced oxygen availability at high altitude also affects the incompleteness of combustion, increasing emissions.

There are three main solutions to reduce human exposures to HAP: the use of clean fuels, improvement of natural ventilation in buildings and the use of more advanced stoves, which release little pollution.[10–12] [AQ1] The adoption of clean fuels should be the best option to reduce the direct health risks of HAP, but this is often difficult to achieve due to economic, logistical and sometimes cultural issues.[9–11,13–15] Therefore, a feasible strategy to reduce the health impact of biomass smoke and the risk of chronic diseases remains the improvement of natural ventilation and discharge of fumes. If fuel type remains unchanged, fume discharge systems and natural ventilation in the kitchen, which is affected by both the configuration of the rooms and the layout of the openings, can play a key role in determining HAP.

It follows that a survey performed in villages with different types of housing, in which some households still use traditional open fire stoves while others have installed chimneys or smoke collectors, could provide interesting insights. In Nepal, in the high Himalayan region where ethnic Sherpas live, there are many villages with different types of houses. In fact, there are both lodges to accommodate tourists and traditional houses, some of which have been improved over the years. Traditional Sherpa houses typically have two storeys: the lower level is used to keep livestock and food while the upper level is the living space, usually without divisions among the kitchen, living and sleeping areas.[16] This fact exposes all the inhabitants (not just women and children) to domestic pollution throughout the day because almost all domestic activities are conducted inside this room, often near the stove, especially in winter. The increasing number of trekkers in the last 10–15 years has affected the typology of the houses, and new buildings (lodges) have been constructed to accommodate the tourists.[17] In the lodges, the kitchen is always separated from the living room. At the same time, private residences have also improved, especially with regard to the discharge of fumes. In fact, until 10–15 years ago, in most kitchens the only system of smoke discharge was the opening of windows and doors, and people used open fires. In recent years, the use of chimneys, smoke hoods or sealed stoves has been promoted, with a favourable effect on indoor air quality.[18]

To the best of our knowledge, no research has ever analysed indoor pollution in relation not only to the presence of fume discharge and the type of stove and fuel used but also in relation to the architectural characteristics and the natural ventilation of buildings in a high Nepalese Himalayan region.

The present study investigates the potential geometric ventilation of buildings, the presence of chimneys, the type of fuel, and the environmental and exhaled carbon monoxide levels in the households of four villages located in a high mountain region of Nepal. The specific objective was to investigate the impact of stove type and kitchen characteristics on the level of indoor pollution inside the kitchen of both lodges and residential buildings.

The present study was carried out within the framework of a research project on the effects of household air pollution on respiratory and cardiovascular health, which is the medical division of a project called SHARE – Stations at High Altitude for Research on the Environment.[19]

Methods

The Nepal Academy for Science and Technology (NAST) approved the protocol.

Study setting

The study was conducted between April 2011 and August 2012 in four villages located at different altitudes in the Khumbu in Nepal: Phakding and Pangboche at 2500 m and 3900 m, respectively; and Thamo and Thame, located at 3700 m and 3900 m in a less touristic side valley (Figure 1). All are rural villages settled in a remote area, without roads and car traffic. All goods (and, of course, all scientific instruments) are carried on the shoulders of porters or on the backs of yaks. The villages are within a one- to four-day walk from the small airport at Lukla. In these villages, researchers went from house to house explaining the purpose of the study and seeking permission to take measurements: 80% of the households participated in the study. Only seven households (6%) refused, while the remaining 16 (14%) were not at home.

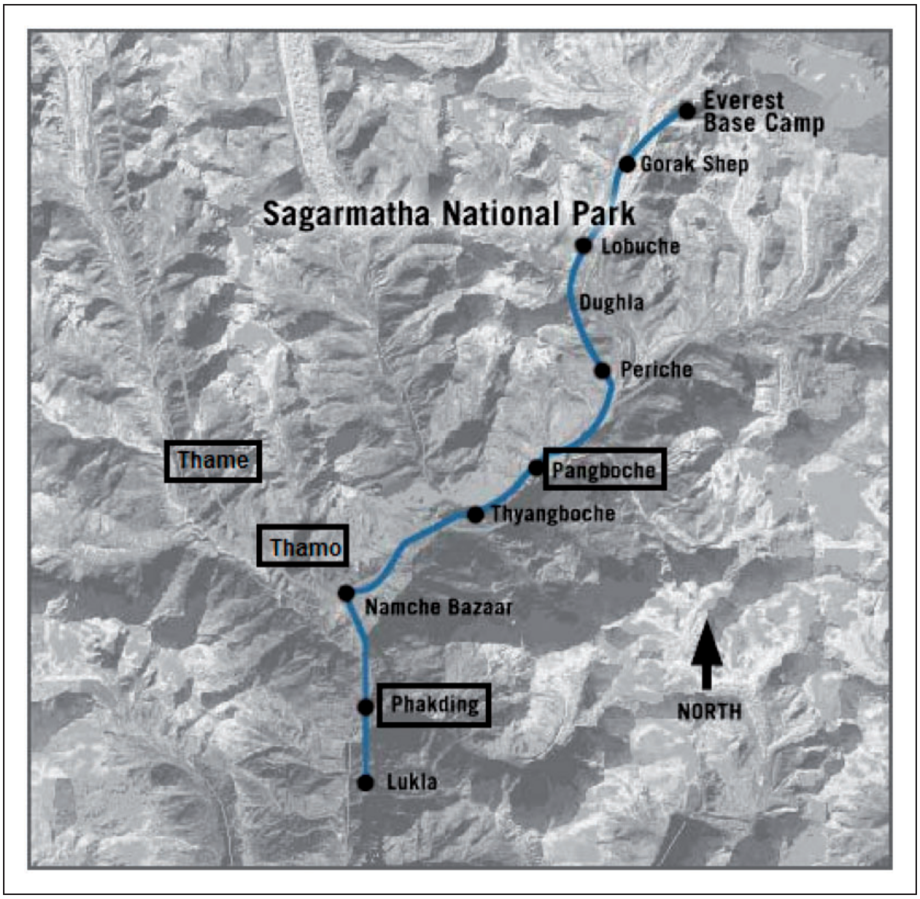

Figure 1. Map of the Khumbu valley: the locations of the study are evidenced with a box.

General data collection and architectural survey

In each household, researchers visited the kitchen and recorded the type of stove and the presence or absence of fume discharge systems, the daily hours during which the stove was lit and the type of fuel and energy sources used. All information was qualitatively assessed through a questionnaire and direct observation.

In addition, an indoor architectural survey was performed. Measurements were taken by metric cord in Thame and by laser diastimeter (LeikaDisto D2) in the other villages. In each kitchen, we measured indoor plan geometry and height, paying attention to the number and size of openings (windows and doors), the presence of ventilation grates and eave spaces and the location of the stove. Measurements were affected by some approximations. In particular, the natural stone walls were assumed to be orthogonal with a constant thickness of 40 cm. Regarding the windows and doors, we measured the real opening in masonry because of the heterogeneity of the frame's structures. Finally, we set an accuracy of ±5 cm.

Household functional classification

We classified the households into two groups according to their function: private residences, where people live and perform domestic activities, and lodges, where tourist services are provided. While the structure of private residences corresponds to the standard described in Sestini and Somigli,[16] in the lodges the kitchen is always separated from the living room. Nevertheless, the owners, the cook and the kitchen staff spend most of their day inside the kitchen.

Indoor and exhaled CO

We measured the environmental carbon monoxide (CO) concentration in established points of the kitchen by means of a digital, fast responding portable CO detector (Lafayette CMM-18 carbon monoxide meter, STC, Bergamo, Italy), equipped with a stabilized electrochemical Gas-specific (CO) sensor. The instrument was factory calibrated and had a measurement resolution of 1 ppm. The calibration was repeated before each research period. In particular, the CO level was measured close to the stove (1.5 m above the ground and 1 m away from the stove horizontally); in front of windows and doors and in the middle of the distance between these points and the stove. The measurement was repeated during a 45- to 60-min stay in the building, and the average of these measurements was used in the analyses. In addition, it was recorded whether the fire/heat source was turned on or off during the measurement.

Exhaled CO was measured from all the inhabitants of the household present at the time of the visit (other medical data are not reported here). Exhaled CO concentration was measured using the piCO + Smokerlyzer® (COSMED, Roma, Italy). Study participants were asked to exhale completely, inhale fully and then hold their breath for 15 s before exhaling rapidly into a disposable mouthpiece. Current smokers were excluded from the present analysis.

Ventilation

We estimated the potential geometric ventilation of the buildings – using the geometric ventilation index (GVI) – as the ratio between the area of openings and the room size (equation 1):

$$GVI = S_{ae}/V_I \quad (1)$$

where S_{ae} is the area of the opening to the outside and V_I is the internal volume. The unit of parameter is m^{-1}. In particular, a higher value of the ventilation index (GVI) corresponds to a better change of air in the room. According to Italian rules, the minimum reference value calculated for residential buildings is $0.046\,m^{-1}$.[20] No such information is available regarding residential ventilation in Nepal.

Statistical analyses

Statistical analyses were performed using the statistical software package NCSS 2008 (NCSS, LLC: Kaysville, Utah, USA). Continuous variables were expressed as the mean ± standard deviation or median (interquartile range) if not normally distributed. Analysis of variance was used to compare the ventilation index, the indoor CO and the exhaled CO in the private houses and lodges in the four villages. Categorical variables were analysed by the chi-square test. The Spearman's rank correlation coefficient was used for the univariate correlation between exhaled and indoor CO and Ventilation Index and indoor CO. The Mann–Whitney test was used to compare the indoor CO in the private houses and lodges.

Multivariable logistic regression analysis was performed, considering increased indoor CO (>5 ppm) as the dependent variable and the type of building, absence of chimney, GVI (>0.046) and use of biomass fuels as independent variables. We set the level of indoor CO to 5 ppm, as this is the limit considered acceptable by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE 62.1-2013).[21,22]

Results

We visited 24 buildings in Thame (in April 2011), 38 in Pangboche and 26 in Phakding (in October 2011), and 26 in Thamo (in August 2012). One hundred fourteen buildings (76 private residences and 38 lodges) were therefore evaluated. Exhaled CO was analysed for 151 participants (79 females and 76 males).

Functional classification

In Thame and in Thamo, 80% of the visited households were private residences and the remaining 20% were lodges. In the other two villages, the ratio between private houses and lodges changed, with 60% private residences and 40% lodges, possibly due to the effect of the higher number of tourists who stay overnight in these villages on their way to Everest Base Camp (Figure 1).

Geometric ventilation index

The GVI was significantly higher in lodges than in private residences ($p < 0.05$). Higher GVIs were found in Pangboche compared to other villages, possibly because of a higher number of lodges compared to private houses in this tourist village (Figure 2).

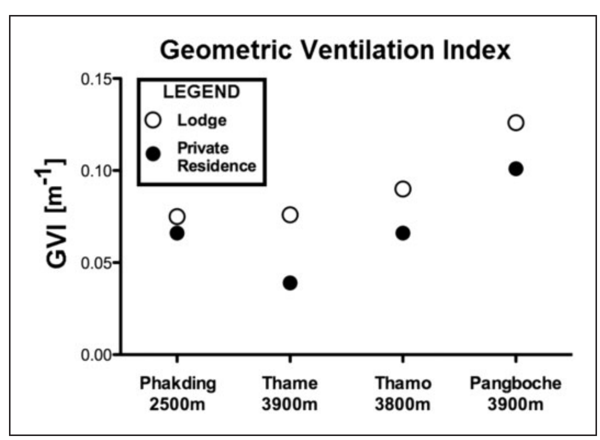

Figure 2. Geometric ventilation index in the four villages. In each village, GVI was significantly higher in lodges than in private residences. All values are significantly different from those measured at Pangboche ($p < 0.05$).

Smoke discharge

The smoke discharge systems are described in Table 1. We classified the buildings into two categories. In particular, we defined the absence of a chimney as the absence of any fume discharge system or as the use of a traditional fire, covered by a hood, without any opening in the roof for fumes to escape. The presence of a chimney was defined as any opening in the roof above the brazier to vent smoke outside the kitchen, also including stoves with sealed chimneys.

In Thamo, both private residences and lodges lacked fume discharge systems. In Thame, 47.4% of private residences had simple or improved discharge systems (hole in wall/roof, 5.3%; and stove and chimney, 42.1%). The remaining 52.6% of the sample had no fume discharge system. The majority of lodges (60%) had an improved discharge system, while the others used the traditional hood with no exit for fumes. At Phakding, the more touristic village at lower altitude, 64.3% of private residences had only a hood without an exit pipe, while an improved discharge system was available in the majority of lodges (60%). At Pangboche, the touristic village at higher altitude, the majority of the private residences had no discharge system, while only 40% of lodges had a stove and chimney system.

Energy sources

As shown in Table 2, in the villages at higher altitude (Pangboche, Thame and Thamo), most households used cow and yak dung briquettes (83.8%, 63% and 69.7%, respectively) while in Phakding wood was the only fuel source. Electricity was available in some buildings (3 in Thame, 15 in Thamo, 6 in Phakding and 4 in Pangboche) but only for a few hours and was mainly used for lighting. Electricity was the main energy source in only 14/114 (12.3%) buildings: 3 private residences in Thamo, 1 in Thame and 10 lodges (6 in Phakding and 4 in Pangboche).

Daily burning hours

The daily burning hours ranged from 3 to 12 in the private residences and from 2 to 11 in the lodges. Specifically, the average was 10 h for both lodges and private residences in Pangboche, and 9 h and 11 h for lodges and private residences, respectively, in Phakding. Data about daily burning hours in Thame and Thamo were missing due to the loss of the load containing the book with these data.

Indoor CO

Due to technical problems, we did not perform this measurement in Thame. Only data from Pangboche, Phakding and Thamo were therefore available. The results showed that when the fire/heat source was turned off, the indoor CO concentration was always below 3 ppm, while when it was turned on, values ranged from 1 to 45 ppm. In more than 50% of residential houses, the level of indoor CO was above the

Table 1. Percentage of the total number of buildings, classified according to the type of fumes discharge.

	Private Residences				Lodges			
Village	None	Hoodwithout exit pipe	Hole in wall/roof	Stove and chimney	None	Hoodwithout exit pipe	Hole in wall/roof	Stove and chimney
Thame	15.8	36.8	5.3	42.1	–	40	–	60
Pangboche	4.8	66.7	9.5	19	6.7	53.3	–	40
Phakding	–	64.3	35.7	–	–	40	–	60
Thamo	35.4	64.6	–	–	–	100	–	–

Table 2. Percentage of the total number of buildings using the different energy sources (not exclusively).

	Private residences				Lodges			
Village	Wood	Dung	Gas	Electricity	Wood	Dung	Gas	Electricity
Thame	96.3	63.0	–	3.7 (1)	100.0	60.0	–	20.0
Pangboche	–	71.4	25.0	3.6	–	83.8	58.0 (2)	3.2 (2)
Phakding	100.0	–	–	–	78.2	–	30.4 (2)	4.3 (4)
Thamo	91.0	69.7	–	69.7 (3)	100.0	60.0	–	100.0

Table 3. Mean level of indoor and exhaled CO in three villages, where the measurement was possible.

Village	(a) Indoor CO median (IQR) (ppm) Private residences	Lodges	(b) Exhaled CO mean ± SD (ppm) All
Pangboche	8.26 (1–28)[a]	4.90 (2–12)	9.6 ± 7.7
Phakding	5.20 (1–9.5)[a]	3.60 (1–6)	9.1 ± 5.3
Thamo	30.28 (11–45)	11[b]	13.0 ± 8.1

[a]Not significant.
[b]One sample only.

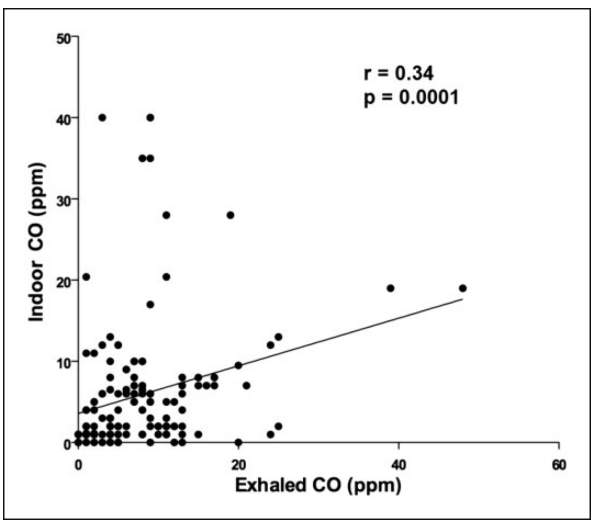

Figure 3. Linear regression between exhaled and indoor CO.

recommended limit (>5 ppm), while in lodges this percentage was lower but still quite considerable. Note that in Thamo, the measurement was possible only in one lodge and was therefore excluded from the comparative analysis (Table 3). [AQ2]

Exhaled CO

Three pieces of data are missing from Pangboche and one from Thamo because of the inability of the subjects to hold the apnea. A total of 151 participants successfully performed this test. Mean exhaled CO was higher than expected for non-smokers,[23] without any significant difference among the three villages (data not reported). The exhaled and indoor CO (Figure 3) were significantly related ($r = 0.34$, $p = 0.0001$), while

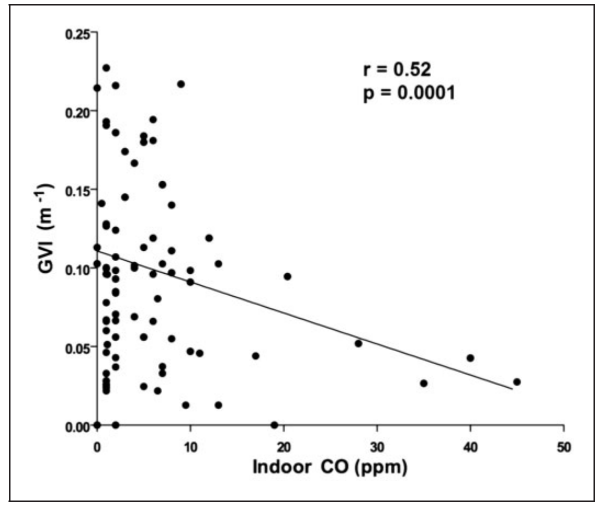

Figure 4. Linear regression between Indoor CO and GVI. A significant negative relationship was found between ventilation of the building and the level of indoor CO.

the indoor CO was inversely associated with the GVI ($r = 0.52$, $p = 0.0001$) (Figure 4).

To better investigate the factors influencing indoor CO, univariate and multivariable logistic regression analyses were performed, using higher indoor CO (>5 ppm) as the dependent variable. In the univariate analysis, only the absence of a chimney was associated with higher indoor CO (OR 3.4 (CL95% 1.2–10.0), $p = 0.02$), while biomass fuel use, private residence and GVI were not significantly associated with higher indoor CO. The multivariable logistic regression analysis that included the above-mentioned variables as independent control variables showed that the absence of a chimney was associated with 5.2-fold increased odds of having higher indoor CO (OR 5.2, CL95% (1.5–17.6), $p = 0.009$). Superimposable results were obtained when the ventilation coefficient was inserted into the model as a continuous variable (OR 5.2, CL95% (1.5–17.8), $p = 0.008$) (Figure 5).

Discussion

The aim of this study was to investigate the effects of different methods of fume discharge, the geometric ventilation of buildings and the type of fuel on carbon monoxide levels inside houses with different household characteristics in the Khumbu, a mountain region in Nepal.

The region was chosen due to the absence of road and car traffic and the very low smoking rate of the Sherpa population, which makes it possible to study the health effects of indoor pollution without other confounding factors. In fact, solid biomass fuel is the major source of domestic energy in this region, used for both cooking and heating.

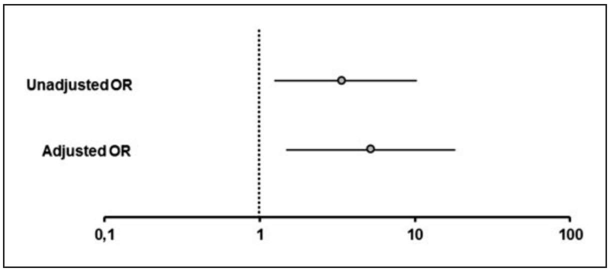

Figure 5. Logistic regression analysis considering indoor CO > 5 ppm as dependent variable and absence of chimney as independent variable.

The main finding of this study is the predominant role of the smoke discharge system (mainly the presence or absence of a chimney) in determining the level of indoor pollution (measured by the mean indoor CO concentration). Natural ventilation did not seem to play an equally significant role even when we found a significant relationship between the level of indoor CO and the GVI. The importance of fume discharge and more advanced cook stoves on pollution levels and health outcomes is supported by interventional studies, such as those already successfully implemented in some regions of Nepal and in other developing countries.[24–26]

However, some conflicting results exist: Pollard et al.,[27] in a cohort of Peruvian households, demonstrated that having a homemade chimney did not reduce environmental exposures significantly. In fact, in this study the levels of 24-h indoor CO were 4.6 ppm and 7.2 ppm in the presence or absence of a chimney, respectively. It is conceivable that in the presence of heavier exposure to indoor pollutants, as reported by Pollard et al.,[27] the presence of a chimney, if not combined with a more advanced stove, is not enough to improve indoor air quality.

We used the measurement of indoor CO as an indirect marker of indoor pollution, as it is a simple and cheap method, and it was shown that the emission factor of CO is similar for dung and wood, while those of particulate, nitrous and sulphur oxides are much higher when using dung.[28,29] We have found a significant, even if weak, correlation between exhaled and environmental CO. The measurement of exhaled CO provides an immediate, non-invasive method of assessing exposure to both smoke and other sources of pollution. Among the Sherpa, the rate of smoking is quite low; in fact, only 4% of participants were smokers and we could easily exclude them from the analysis. As it is known that in a non-smoking population, elevated levels of exhaled CO are likely due to the inhalation of noxious particles,[30] it follows that in non-smoking individuals included in the present analysis, the level of exhaled CO was mainly due to exposure to high levels of carbon monoxide inside the kitchens. It is known that emissions in kitchens can vary from season to season due to changes in moisture content, and this fact could contribute to explaining the higher level of environmental CO measured in Thamo during summer, when the humidity is very high.[31]

Regarding fuel type, in Phakding, we registered a 100% use of wood, while in the other villages wood is used together with dung. This is probably because wood can be easily found at lower altitude[32] and is preferred by the population. In fact, yak and cow dung must be processed for a long time before they can be used as fuel; furthermore, the heating value is higher for wood than for dung.[33] This leads to a higher emission of CO per gram of cooked food when dung is used compared to wood.[34]

We did not find any difference in pollution levels between wood and dung because we measured only the environmental CO as a marker of indoor pollution, and the emission factor for this gas is the same, regardless of the fuel used.[29] The measurement of PM could have given different results. We could not compare the effect of traditional and clean fuels (electricity, gas, kerosene). In fact, clean fuels were used only in a very small sample of buildings, making it difficult to highlight their effect compared to traditional fuels. Our results are therefore different from others reported in the literature, in which it was possible to compare highly polluting fuels with cleaner ones.[13,35]

Ventilation

We investigated the potential geometric ventilation of buildings through the GVI, as it was expected to affect indoor pollutant concentrations. However, outcomes did not completely confirm this hypothesis, even if a correlation between GVI and indoor CO was found (high ventilation, low indoor CO concentration and vice versa) but not confirmed by the multivariable logistic regression. This could be due to the limitations of the methodology (see below) as well as to behavioural practices of occupants. In fact, the windows are usually kept closed, even in summer, thus reducing the effective ventilation and creating a gap between potential and real ventilation. Furthermore, ventilation is affected not only by the geometry of the building and the position and use of the openings but also by other physical parameters such as temperature, weather conditions and time of year. The literature on these phenomena in developed countries is vast and the results generally take into account several affecting parameters.[36] On the other hand, in developing countries, even if the international community appears to be aware of the topic,[10,37] information is very scarce. To the best of our knowledge, no studies in Nepal have taken into account, in any way, the ventilation of buildings.

Private residences and lodges

We were also interested in investigating the difference between private residences and lodges, which have different household characteristics. In general, lodges had better potential geometric ventilation, as GVIs for lodges were mostly higher compared to the other buildings. In addition, the smoke discharge systems were different: in general, private residences had no effective fume discharge systems, while lodges commonly installed some type of fume discharge. Even if the use of fuel was mainly affected by altitude (dung at higher altitudes and wood at lower ones), gas and electricity were mainly used in lodges.

Generally, indoor pollution was greater in private residences compared to lodges. In fact, in private residences, the indoor CO level was higher than recommended. This was not the case for many lodges, probably because of the combined effect of better geometric ventilation and the use of fume discharge systems. However, the comparison between the two did not reach statistical significance, probably due to the scattering of the values.

Limitations

This study was affected by several limitations, in part due to the lack of facilities, which is typical of remote areas in developing countries. The main limitation is the lack of 24-h monitoring of carbon monoxide. In fact, we did not monitor the CO concentration over an extended period, in different weather conditions or in different seasons. However, the measurement performed during this study, which was instantaneous and averaged in the kitchen, can be considered representative of the CO emissions that were of course much higher during the burning period. In addition, Siddiqui et al.[12] showed that in rural Pakistani kitchens (where wood is burned), instantaneous measurements were comparable to the mean of 8-h monitoring. There are still limitations on the measurements in relation to the weather, and we lack data collected in the winter season. Thus, no conclusion can be provided regarding annual variation. Another limitation is the unavoidable approximation of the architectural evaluation. In fact, in many buildings there is a narrow gap between the walls and the ceiling, making it difficult to correctly estimate the ventilation index. In addition, the different materials used for the roofs of buildings (wood, mud or metal sheet roofs) can affect the results, allowing different levels of ventilation in the kitchen through eaves. Finally, our research took into account only the potential geometric ventilation of the buildings, independent of season, time and weather conditions.

Conclusion

The main aim of this study was to investigate the parameters affecting indoor air pollution in high-altitude dwellings in the Khumbu (Nepal). In these villages, the mixing of traditional houses and more innovative tourist homes enabled a comparison between different household characteristics. Our main findings are that the fume discharge system had the strongest impact, while the potential geometric ventilation did not play as significant a role in determining the indoor pollution level. Furthermore, lodges and private residences differed in terms of potential geometric ventilation, fume discharge systems and fuel sources, all of which probably combined to produce different levels of indoor pollution.

Authors' Contribution

Enrico Duo collected data at Thame, Pangboche and Phakding; analysed all data and wrote the manuscript. Rosa Maria Bruno had full access to all the data in the study and contributed substantially to the data analysis. Buddha Basnyat contributed to the study design and revised critically the manuscript. Maniraj Neupane collected data at Thamo and contributed to the manuscript. Luca Pomidori contributed to collect and analyse data at Thame. Ghan Bahadur Thapa collected data in Thamo and Thame and contributed to the analysis. Lorenza Pratali contributed to the study design and data interpretation. Annalisa Cogo is the guarantor of the content of the manuscript, revised manuscript critically and provided final approval of the version to be published. All authors approved the version to be published.

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Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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