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Implications of Traditional Cooking on Air Quality and Female Health: An In-Depth Analysis of Particulate Matter, Carbon Monoxide, and Carbon Dioxide Exposure in a Rural Community

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Abstract: Indoor air pollution, particularly in rural communities, is a significant health determinant, primarily due to the prevalence of traditional cooking practices. The WHO estimates 4.3 million annual deaths related to household air pollution. This study quantifies indoor pollutants and assesses health impacts and perceptions regarding traditional cooking. Using Extech air quality monitoring equipment, the study measured particulate matter (PM), carbon monoxide (CO), and carbon dioxide (CO_2) in 48 rural homes. A survey of 39 women gathered insights on their use of wood for cooking and perceptions of air quality. This dual approach analyzed both environmental and social dimensions. Findings showed fine particulate matter (0.3, 0.5, 1.0, and 2.5 µm) exceeded safety limits by threefold, while coarser particulates (5.0 and 10 µm) were concerning but less immediate. CO levels were mostly acceptable, but high concentrations posed risks. CO_2 levels indicated good ventilation. Survey responses highlighted reliance on wood and poor air quality perceptions demonstrating little awareness of health risks. Common symptoms included eye discomfort, respiratory issues, and headaches. The study emphasizes the need for interventions to reduce exposure to indoor pollutants and increase awareness of health risks to encourage cleaner cooking practices in rural communities.

Keywords: traditional cooking; indoor pollution; rural communities; woman exposure; health impact

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1. Introduction

Indoor air quality significantly impacts human health, especially in rural areas where traditional cooking methods often involve burning biomass. These methods depend mostly on biomass fuels like wood, dung, and agricultural residues, chosen for their availability and low cost [1–4].

The typical technology used in rural traditional cooking is the three-stone fire. This setup uses three stones arranged in a triangle to hold a cooking pot above an open flame. In some places, simple stoves made from clay or metal are used. This practice is a key component of indoor air pollution, contributing significantly to the concentration of PM, CO, and CO_2 in the domestic environment [5,6].

Particulate matter is a complex mixture of extremely small particles and liquid droplets suspended in the air. When inhaled, these particles can penetrate deep into the respiratory system, causing significant health problems [7–11]. It has been established that exposure to PM, particularly fine particles with a diameter of 2.5 µm or less ($PM_{2.5}$), is associated with respiratory diseases, cardiovascular diseases, and premature death [12–14].

CO is a colorless, odorless, and tasteless gas that is slightly less dense than air. It is toxic to hemoglobic animals when encountered in concentrations above about 35 ppm. In indoor environments, exposure to high levels of CO can cause symptoms such as headaches, dizziness, weakness, nausea, vomiting, chest pain, and confusion. In severe cases, it can lead to loss of consciousness and death [15–17].

CO_2, a colorless gas with a density about 60% higher than that of dry air, is naturally present in the Earth's atmosphere as part of the carbon cycle. However, in indoor environments, high levels of CO_2 can cause health problems [18,19]. While it is generally not harmful at low concentrations, exposure to high levels of CO_2 can lead to health problems like the ones described for CO. A large body of literature has investigated the impact of indoor air pollution on health, particularly in developing countries where traditional cooking methods are prevalent [20–26]. However, much of this research has focused on the general population, with less attention given to specific vulnerable groups such as women.

In rural communities, women are particularly at risk from the health effects of indoor air pollution due to their role in cooking and other domestic activities that demand a significant amount of time indoors, often near the source of pollution, such as a traditional cookstove [27,28]. This prolonged exposure to indoor air pollutants can have serious health consequences, impacting millions with respiratory and cardiovascular diseases, acute infections, chronic eye issues, and cancer risk [29].

The World Health Organization identifies indoor air pollution from traditional cooking methods as a major global health hazard, particularly in developing nations. Worldwide, fuelwood use is common in low-income areas where modern energy sources are neither affordable nor accessible.

In sub-Saharan Africa, fuelwood and charcoal are the primary energy sources for cooking and heating. The International Energy Agency (IEA) reports that around 80% of the population in this region relies on traditional biomass, including fuelwood [30]. In countries like Ethiopia, Tanzania, and Nigeria, most rural populations depend on biomass for their daily energy needs. South Asia shows similar patterns; in India, for example, nearly 60% of households use fuelwood or biomass for cooking. This trend is also seen in other countries like Nepal and Bangladesh, where many rural residents rely on fuelwood due to the lack of affordable or accessible alternatives [31].

In Latin America, the use of fuelwood varies by country. For instance, Guatemala and Honduras have high biomass usage rates, with over 50% of the population depending on it. Conversely, more urbanized countries like Mexico, Brazil, and Argentina have lower dependency rates, although rural areas still use it significantly [32,33]. The persistent use of biomass fuels in these regions is driven by socio-economic and environmental factors. Often, the availability and low cost of fuelwood make it a preferred energy source, despite its lower efficiency and higher environmental impact compared to modern energy sources.

Despite the growing evidence of the health risks associated with indoor air pollution, there are still significant gaps in our understanding of this issue. There is a need for more detailed, context-specific research to understand the exposure levels and health impacts of indoor air pollution in different settings, including rural communities where traditional cooking methods are prevalent.

This study aimed to address this gap by investigating the exposure of women in a rural community to PM, CO, and CO_2 due to traditional cooking. The research focused on measuring indoor concentrations of these pollutants and assessing their impact on health, as well as exploring perceptions related to indoor air pollution and health. The findings provide important insights into the health risks associated with indoor air pollution in rural communities and highlight the need for targeted interventions to reduce exposure and improve health outcomes.

2. Materials and Methods

The investigation into the exposure of women to PM, CO, and CO_2 due to traditional cooking was conducted in 48 rural settlements. The homes were randomly selected to represent the typical living and cooking conditions in the community of Agua Caliente. In the community, traditional stoves are typically constructed using locally sourced materials and simple techniques. Usually, a mixture of clay, mud, and sometimes straw or other organic materials is used to build a circular or rectangular base with bricks or stones bonded with mud or clay to form the stove's body and create the combustion chamber. These basic stoves exhibit low combustion efficiency, often converting less than 20% of the wood's energy potential into usable heat. The remainder of the energy is lost as excess heat or through fumes from incomplete combustion, full of particles and gases that impact indoor air quality.

The community of Agua Caliente is located along the shore of Lake Chapala in Jalisco, Mexico, at 20°18′45.35″ N, 102°55′43.07″ W, at an altitude of 1621 m.a.s.l. (Figure 1). The community's total population is 988 individuals, of which 489 are men and 499 are women. The economy of the community is based on the cultivation of corn and agricultural crops such as chayote and beans, as well as local fishing.

Figure 1. The community of Agua Caliente is located along the shore of Lake Chapala, Jalisco, Mexico.

The primary method of data collection was through the measurement of indoor PM, CO, and CO_2 using portable devices sourced from Extech Instruments Corporation, Nashua, New Hampshire, USA; which provide real-time estimations. To measure PM, an Extech VPC-300 particle counter; was used to quantify the number of particles in indoor air. The equipment's measuring principle is based on the fundamentals of the isokinetic principle [34]. This principle ensures that the velocity of the air entering a sampling device is equal to the velocity of the air in the environment being sampled. By maintaining this condition, the sample collected is representative of the actual particle concentration in the environment [35]. The particle counter was capable of detecting particles across a size range of 0.3, 0.5, 1.0, 2.5, 5.0, and 10 µm, thus providing a detailed profile of the particulate matter present in the homes. Simultaneously, indoor CO levels were determined using an Extech CO-10. This instrument has a detection range from 0 to 1000 ppm and a resolution of 1 ppm, offering precise measurements of CO concentrations.

To ensure that the number of particles is measured accurately, it is important to zero the particle count sensor by purging before any determination. After this important step, the measurement conditions of sampling time, mode, cycle, and delay interval of tests are set up [35]. The device was set up to perform five tests of one minute in a cumulative mode, a delay test interval of 3 s, and flow rate of 2.83 L per minute. Inside every settlement, the measurements were repeated twice by hand-holding the instrument at a height of 1.5 m above the ground at a horizontal distance of 1 m from the combustion source. In this way, the total number of particles was quantified in a total time period of ten minutes for a volume of 28.32 L of filtered air.

The measuring campaign was carried out during the dry season and covered the months from February to May, and the time interval from 6:00 a.m. to 18:00 p.m. covered the during and after cooking conditions. Most used fuelwood comes from local trees like huizache (*Vachellia farnesiana*), encino (*Quercus*), and mesquite (*Prosopis juliflora*).

Simultaneously, for a sampling time of 10 min, indoor CO levels were determined using an Extech CO-10. This instrument has a detection range from 0 to 1000 ppm and a resolution of 1 ppm, offering precise measurements of CO concentrations. In addition to PM and CO, the study also measured indoor CO_2 levels. This was achieved using an Extech EA-80, a device with a detection range from 0 to 600 ppm and a resolution of 1 ppm. This allowed for the accurate quantification of CO_2 concentrations within the homes.

To supplement these objective measurements, the study also sought to gather information about the perceptions towards the effects of indoor air quality and health. To this end, 39 adult women were interviewed using a structured questionnaire. The questionnaire was designed to gather specific information about their opinions and perceptions towards the use of wood as the main energy source for cooking and the potential impact on the health of the women. The selection of participants was determined by their willingness to participate in the study, and it was warranted by them signing a written consent letter. Moreover, the perception and opinions of adult women are of great relevance since their exposure to compromised indoor air quality is an important issue in terms of frequency and long-term exposure.

Descriptive statistics were used to summarize the data and provide an overview of the indoor air quality in the homes. Further inferential statistical analysis was carried out to examine the relationship between the use of traditional cooking methods and the indoor air quality. In summary, the methods employed in this study were designed to provide a comprehensive understanding of the exposure of women to PM, CO, and CO_2 due to traditional cooking methods in a rural community. The combination of objective measurements and subjective experiences provided a nuanced perspective on this complex issue.

3. Results

The indoor particulate matter was measured in 48 rural homes using an Extech VPC-300 particle counter. Although the VPC-300 is mainly applied to classify air cleanliness in clean rooms, we used it in this study as a reference tool to value indoor conditions of rural homes that rely on fuelwood as the main energy source for cooking. Table 1 shows reference values for the particle size and qualifying conditions according to ISO guidelines for clean rooms [36].

Table 1. Average numbers of particles in relation to size and indoor conditions according to ISO guidelines for clean rooms [36].

Size of Particle (μm)	Reference Values		
	Good	Caution	Danger
0.3	0–100,000	100,001–250,000	250,001–500,000
0.5	0–35,200	35,201–87,500	87,501–175,000
1.0	0–8320	8321–20,800	20,801–41,600
2.5	0–545	546–1362	1363–2724
5.0	0–193	194–483	484–966
10	0–68	69–170	171–340

3.1. Particulate Matter Distribution

In our study, the average number of ultrafine particles, particularly those with diameters of 0.3 and 0.5 μm, exceeded the upper reference limit for the DANGER category by more than threefold (Table 1). Correspondingly, this compromised condition occurred in 27% and 25% of the 30 and 22 homes, respectively, where quantified particles were classified in the DANGER category (Table 2). A similar pattern was found for fine particles of 1.0 and 2.5 µm where 13 and 20 family units were classified in the DANGER category from which 15% and 19% of them surpassed the upper limits of DANGER, respectively (Table 2).

Table 2. Frequency distributions of qualified indoor conditions in relation to size of particles.

Size of Particle (µm)	Good	Caution	Danger	Row Total
0.3	0	18	30	48
	0.00%	37.5%	62.5%	100%
0.5	6	20	22	48
	12.5%	41.67%	45.83%	100%
1.0	17	18	13	48
	35.42%	37.5%	27.08%	100%
2.5	9	19	20	48
	18.75%	39.58%	41.67%	100%
5.0	11	24	13	48
	22.92%	50%	27.08%	100%
10	10	22	16	48
	20.83%	45.83%	33.33%	100%

The study's findings on ultrafine and fine particle show that they pose significant health risks due to their ability to penetrate deep into the lungs, enter the bloodstream, and distribute to various organs. Their systemic effects are largely mediated through inflammation and oxidative stress, contributing to a wide range of diseases.

In rural environments, the combustion of biomass fuels such as fuelwood generates significant quantities of ultrafine particles [37,38], often surpassing safety thresholds similar to those reported in the current study.

Coarser particles of sizes 5.0 and 10 µm were mostly categorized in the CAUTION category, specifically, 24 and 22 of total households, respectively (Table 2). As a result of their larger size, they are efficiently trapped by the body's respiratory defenses, including the nasal passages and mucociliary clearance system. This limits their penetration into the deeper parts of the lungs and reduces their potential to cause systemic health effects. However, they can still contribute to respiratory irritation and exacerbate conditions like asthma. Their overall health impact is considered less significant compared to smaller particulate matter. Understanding these mechanisms highlights the importance of focusing regulatory efforts on reducing exposure to fine and ultrafine particles, which pose greater health risks.

Concerning GOOD indoor conditions, the particles of 1.0 µm resulted with the highest frequency, and none of the domestic establishments recorded a GOOD indoor qualification for the particles of 0.3 µm; thus, these establishments were the most significant in terms of exposition and health risk (Table 2).

Our findings also highlight the urgent need for interventions aimed at reducing particulate matter exposure, particularly for vulnerable populations such as women in rural communities. Implementing cleaner cooking technologies and improving ventilation could mitigate these health risks, emphasizing the importance of addressing indoor air pollution comprehensively.

3.2. CO Levels

Indoor CO levels were determined using an Extech CO-10. The average values in the 48 homes ranged from 4.25 to 7.85 ppm, which falls within the category of good indoor air quality according to the threshold level of 9 ppm. However, absolute maximum values of

37 ppm and 64 ppm were also recorded as extreme events, which over long-term exposure are important as they classify between the border line of the eight-hour exposition limit and the appearance of CO poisoning symptoms (Table 3).

Table 3. Reference values of CO in relation to indoor air quality [39].

Concentration (ppm)	Condition and Possible Health Effects
0–1	Normal ambient level
9	Threshold of good indoor air quality
50	Limit of eight-hour exposition
200	Mild headache, fatigue, nausea, and dizziness
400	Strong headache, life-threatening after 3 h of exposition
800	Dizziness, nausea, convulsions, death after 2 to 3 h
1600	Nausea occurs within 20 min, death might occur within 1 h
12,800	Death occurs in 2 to 3 min

3.3. CO_2 Levels

Indoor CO_2 levels were measured using an Extech EA-80. The recorded values ranged from 350 ppm to 628 ppm, with a mean value of 437 ppm and a standard deviation of 61.38 ppm. These figures comply with the reference values for good ventilation [40].

CO_2 is primarily a byproduct of human respiration and combustion processes. Indoors, CO_2 levels can quickly rise without adequate ventilation, leading to poor air quality. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends that indoor CO_2 levels not exceed 1000 ppm to ensure good air quality [41]. Ventilation is crucial for diluting indoor pollutants, including CO_2. In environments where PM levels are dangerously high, maintaining good CO_2 ventilation levels is essential for ensuring indoor air quality and protecting public health. By employing a combination of mechanical ventilation, filtration, and real-time monitoring, it is possible to manage both CO_2 and PM levels effectively. This integrated approach is crucial for minimizing health risks and promoting a healthier indoor environment.

3.4. Perception of Indoor Air Quality

Interviews conducted with 39 adult women using fuelwood as the primary energy source for cooking revealed that only 2% utilized liquefied petroleum gas (LP gas) or electricity. Regarding exposure, 46% spend 8–11 h indoors and have continuously been exposed for 21 to 40 years. A significant 53.85% identified indoor air quality as bad but were not conscious about the effects on their health, as only 38.46% identified a direct relationship. The most reported signs and symptoms related to indoor air quality were ocular discomfort, respiratory symptoms, and headaches. However, 46% did not relate any symptoms to indoor air quality (Table 4).

Other studies often report varying levels of awareness about the relationship between the state of the environment and health. For instance, some research indicates that awareness can be influenced by education and socio-economic status, with higher awareness in more educated populations. However, there is often a disconnect between recognizing poor air quality and understanding its health impacts [42,43].

Results from the inferential statistical analysis seeking to evaluate associations among identified symptoms and daily and long-term exposures were not statistically significant, since corresponding p values were larger than 0.05. The chi-square test is particularly useful when dealing with qualitative data such as those resulting from the perception study, where variables are divided into distinct categories rather than measured on a numerical scale. The chi-square test evaluates whether the observed frequencies in each category differ significantly from the frequencies expected under the null hypothesis of independence. Although the test outcomes were not statistically significant, the most remarkable conclusion that can be made from the analyses is that ocular and respiratory symptoms were most frequently associated with a daily exposition of 8–11 h. With respect to long-term exposure, ocular, respiratory, and headache symptoms were most frequently associated with 21–40 years. Finally, ocular and headache symptoms were linked to bad indoor conditions, and ocular effects were directly connected to compromised indoor conditions (Table 4).

Table 4. Distributions of responses about opinions and perception from questionnaire.

	Wood *		**LP Gas**	**Electricity**		**Row Total**
ENERGY SOURCE	37		1	1		39
	94.97%		2.56%	2.56%		100%
DAILY EXPOSURE (Hrs)	4–7		8–11	12–15		
	10		18	11		39
	25.64%		46.15%	28.21%		100%
LONG-TERM EXPOSURE (Yrs)	1–20		21–40	>40		
	12		17	10		39
	30.77%		43.59%	25.64%		100%
INDOOR CONDITION	GOOD		REGULAR	BAD		
	8		10	21		39
	20.51%		25.64%	53.85%		100%
HEALTH THREATENING	YES		NO			
	15		24			39
	38.46%		61.54%			100%
SYMPTOMS	OCULAR	RESPIRATORY	HEADACHE	DIZZINESS	NONE	
	7	7	4	3	18	39
	18%	18%	10%	8%	46%	100%

* Used fuelwood comes from locally available trees like huizache (*Vachellia farnesiana*), encino (*Quercus*), and mesquite (*Prosopis juliflora*).

4. Discussion

This research demonstrates that women in rural communities are exposed to dangerous levels of particulate matter due to traditional cooking methods, despite average carbon monoxide and carbon dioxide levels falling within safe ranges. The study provides the first evidence of such a dichotomy in indoor air quality within rural homes using fuelwood for cooking. This is the first time that the indoor air quality in rural homes of Agua Caliente has been analyzed with such precision, revealing the alarming levels of particulate matter to which women are exposed. Particularly noteworthy is the high concentration of ultrafine (0.3 and 0.5 µm) and fine particles (1.0 and 2.5 µm) that fall within the DANGER category according to reference values to classify air cleanliness in clean rooms.

Fuelwood continues to be a predominant energy source in rural communities due to a complex interplay of environmental, economic, cultural, and infrastructural factors [44]. This multifaceted reliance is underpinned by the accessibility of forest resources and the minimal infrastructure requirements for fuelwood utilization.

In many rural areas, particularly in regions such as sub-Saharan Africa, the proximity of forests and woodlands facilitates the procurement of fuelwood, making it a readily available energy source. The lack of necessity for sophisticated distribution infrastructure, unlike electricity or gas, further entrenches its use, especially in areas where modern energy infrastructure is deficient. From an economic perspective, fuelwood represents a cost-effective energy solution. Its affordability is a significant determinant for rural households where financial constraints limit access to alternative energy sources. The economic calculus often favors fuelwood, as its procurement costs are substantially lower compared to other energy forms. Furthermore, the collection and sale of fuelwood can constitute a vital component of household economies, providing a source of income that is particularly crucial for marginalized groups, including women and children [45].

Cultural and traditional practices also play a pivotal role in sustaining fuelwood usage. Traditional cooking methods, which often utilize wood-fired stoves, are deeply embedded in the culinary practices of many communities. The sensory qualities imparted by wood fires, such as taste and texture, are culturally valued, reinforcing the continued preference for fuelwood. Additionally, social norms and customs contribute to the persistence of fuelwood use, as these practices are interwoven with daily life and community identity [46].

Energy security considerations further underscore the reliance on fuelwood. The use of locally sourced fuelwood enhances energy resilience by reducing dependence on external energy supplies and insulating communities from market volatility. This sense of energy independence is particularly pronounced in rural settings where alternative energy sources are either unreliable or unavailable [47].

Environmental considerations, particularly the perception of fuelwood as a renewable resource, also influence its sustained use. When harvested sustainably, fuelwood can be seen as a viable energy source that mitigates environmental degradation. Sustainable management practices, such as controlled harvesting and reforestation, can alleviate adverse ecological impacts, promoting the perception of fuelwood as an environmentally responsible option [48].

Policy and governance issues significantly impact the availability of alternative energy sources. The absence of comprehensive policy frameworks and insufficient investment in energy infrastructure often result in a lack of viable alternatives to fuelwood. This policy vacuum perpetuates the dependency on traditional energy sources, as governmental support for alternative energy development remains inadequate [49].

Technological barriers further entrench the use of fuelwood. Limited access to modern energy technologies and appliances in rural areas exacerbates the reliance on traditional energy forms. The technological gap, characterized by the unavailability of efficient energy solutions, reinforces the dependence on fuelwood, as communities lack the means to transition to more advanced energy systems [50].

Furthermore, the study's findings underscore the importance of developing and implementing sustainable interventions to reduce particulate matter exposure. Some intervention programs have been implemented to raise awareness about the interconnections between environmental conditions and the health of communities and ecosystems [51]. These programs are crucial in promoting sustainable practices and mitigating the adverse health effects associated with traditional cooking methods [52,53]. One successful example of such interventions is the introduction of improved cookstove programs. These initiatives aim to reduce indoor air pollution by promoting the adoption of stoves that burn fuelwood more efficiently, thereby decreasing the emission of harmful particulates. In several rural communities, these programs have led to significant reductions in respiratory ailments, demonstrating the potential for improved health outcomes when cleaner technologies are adopted [54,55]. Moreover, educational campaigns have been instrumental in increasing awareness about the health impacts of fuelwood combustion. By engaging local communities through workshops and training sessions, these programs empower individuals with the knowledge needed to make informed decisions about energy use. This heightened awareness often translates into behavioral changes that prioritize cleaner and more sustainable energy solutions. Additionally, some intervention programs have successfully integrated local cultural practices and knowledge systems, ensuring that solutions are contextually relevant and more likely to be embraced by the community. By respecting and incorporating indigenous knowledge, these programs foster a sense of ownership and responsibility, enhancing their effectiveness and sustainability.

The burning of biomass fuels, such as wood, generates a large amount of particulate matter. This, coupled with inadequate ventilation in many rural homes, could lead to high concentrations of particulate matter indoors. This result may be further exacerbated by the long hours women spend indoors, increasing their exposure to these pollutants. These results are consistent with previous research highlighting the health risks associated with exposure to particulate matter. However, our study goes further by providing detailed measurements of the number of particles in rural homes, thereby offering a more nuanced understanding of the indoor air pollution problem in these settings.

Interestingly, the average values of carbon monoxide and carbon dioxide in the homes were within the range considered safe for indoor air quality. However, extreme events with maximum values of 37 ppm and 64 ppm for carbon monoxide were recorded, indicating that transient, high-level exposures may occur, potentially posing health risks. Furthermore, the interviews revealed that while more than half of the respondents identified indoor air quality as bad, a significant proportion were not conscious about the effects on their health. This disconnect between perceived air quality and awareness of health impacts underscores the need for education and awareness campaigns alongside interventions to improve indoor air quality. Despite the novelty of this finding, these results may be limited by the relatively small sample size and the specific geographical and cultural context of the study. The indoor air quality and exposure patterns may vary in other rural communities or regions with different cooking practices or housing characteristics. Therefore, while the findings provide important insights into the indoor air pollution problem in rural communities, caution should be exercised in generalizing the results to other settings.

5. Conclusions

This investigation elucidates the critical exposure of women in rural communities to hazardous indoor air pollution, primarily due to the use of biomass fuels such as fuelwood for cooking. Our data indicate that the mean concentrations of fine particulate matter (PM) with aerodynamic diameters of 0.3, 0.5, 1.0, and 2.5 μm significantly exceed the threshold values classified as "DANGER" according to ISO standard to classify air cleanliness in clean rooms. Specifically, particle counts surpass the upper danger limits by more than threefold, affecting 27%, 25%, 15%, and 19% of the households surveyed. Although average carbon monoxide (CO) levels were within permissible limits, acute exposure events reaching concentrations of 37 ppm and 64 ppm were documented as extreme events, which over long-term exposure are important as they classify between the border line of the eight-hour exposition limit and the appearance of CO poisoning symptoms as mild headache, fatigue, nausea, and dizziness.

Carbon dioxide (CO_2) is predominantly generated as a byproduct of both human metabolic processes and combustion activities. In enclosed environments, inadequate ventilation can precipitate a rapid accumulation of CO_2, thereby degrading indoor air quality. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) stipulates that indoor CO_2 concentrations should not exceed 1000 ppm to maintain acceptable air quality standards. Effective ventilation plays a pivotal role in the dilution of indoor pollutants, including CO_2, which is crucial in settings where particulate matter (PM) levels are critically elevated.

In rural communities where fuelwood serves as the principal energy source, the challenge of maintaining optimal indoor air quality is exacerbated. Combustion of biomass fuels releases a complex mixture of pollutants, including PM, CO, and CO_2, necessitating robust ventilation solutions. This is particularly vital in rural dwellings where architectural designs may inherently limit natural ventilation.

To address the challenge of indoor air pollution management, an integrated strategy employing mechanical ventilation, high-efficiency particulate air filtration, and real-time air quality monitoring is recommended. Mechanical ventilation systems, such as heat recovery ventilators or energy recovery ventilators, can provide continuous air exchange while minimizing energy loss.

Real-time monitoring of indoor air quality parameters, including PM, CO, and CO_2 levels, enables timely interventions to maintain safe thresholds. Advanced sensor technologies can provide continuous data, facilitating adaptive management strategies that respond dynamically to fluctuations in pollutant levels. This proactive approach is essential for minimizing health risks associated with prolonged exposure to elevated indoor pollutant concentrations.

These findings are pivotal as they provide quantitative evidence of the air quality challenges confronting women in these rural settings, directly linked to traditional cooking methodologies. The elevated particulate matter concentrations are associated with increased risk for respiratory and cardiovascular pathologies. Despite some awareness of suboptimal air quality, a significant portion of the women lacked understanding of the health consequences, indicating a substantial knowledge deficit that warrants immediate attention.

Future research should prioritize longitudinal cohort studies to meticulously assess the chronic health effects associated with prolonged exposure to elevated PM levels. Such studies could elucidate the incidence and prevalence of respiratory and cardiovascular diseases within these populations and establish causal relationships with indoor air pollution. Additionally, the deployment of biomarkers for exposure and effect, such as exhaled nitric oxide and blood inflammatory markers, could provide deeper insights into the physiological impacts of chronic pollutant exposure. Moreover, there is a pressing need to develop and evaluate intervention strategies aimed at mitigating indoor air pollution. This could encompass the promotion of cleaner cooking technologies, such as improved biomass stoves or liquefied petroleum gas (LPG) alternatives, coupled with enhanced ventilation systems. Public health initiatives should also focus on educational programs to elevate awareness about the health risks associated with indoor air pollution and the advantages of adopting cleaner cooking practices.

In summary, this study emphasizes the urgent need to address indoor air pollution in rural communities that rely on traditional cooking practices. It highlights the importance of incorporating air quality considerations into public health frameworks and policy development to protect the health and well-being of vulnerable populations. Future research and interventions should be strategically designed to systematically address these challenges, ensuring sustainable improvements in both indoor air quality and public health outcomes.

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