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Indoor Air Quality and Ventilation in Tuberculosis-Affected Households: A Cross-Sectional Assessment Using Carbon Monoxide and Carbon Dioxide

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ABSTRACT: Background: Poor ventilation can increase accumulation of re-breathed air and airborne Mycobacterium tuberculosis, while carbon monoxide (CO) reflects combustion-related indoor air pollution. Evidence integrating CO and carbon dioxide (CO₂) at the household level remains limited in TB-affected homes.

Objectives: To assess indoor air quality and ventilation status in TB-affected households using CO and CO₂ measurements, describe housing and ventilation characteristics, and examine associations with household and individual factors.

Methods: A community-based cross-sectional study included 180 households of pulmonary TB patients in urban and rural areas of Puducherry; a structured questionnaire recorded sociodemographic, housing, and household air-quality characteristics. We measured indoor CO and CO₂ using a real-time sensor. We used independent-samples t tests or one-way ANOVA for comparisons, and Pearson correlation for continuous variables.

Results: Mean indoor CO was 1.080 ± 0.155 ppm and mean CO₂ was 588.8 ± 176.6 ppm. No household exceeded the WHO CO values. CO₂ was ≤ 1000 ppm in 93.9% of households. Adequate overall ventilation was reported in 92.8% of households; however, cross-ventilation was present in only 16.7%. Among categorical variables, five were nominally associated with CO and none with CO₂. Income correlated with CO ($r=0.154$, $p=0.039$) and CO₂ ($r=0.226$, $p=0.002$), while number of rooms correlated with CO₂ ($r=0.166$, $p=0.028$).

Conclusion: Most TB-affected households had low CO and CO₂ concentrations, with few CO associations noted. Promoting universal ventilation, directly assessing CO₂, reducing biomass use, and ensuring appropriate fresh-air exchange during air-conditioner use remain relevant household TB-control measures.

1. INTRODUCTION

Tuberculosis (TB) remains a major global public-health problem. The World Health Organization (WHO) estimated that 10.7 million people developed TB and 1.23 million died from the disease in 2024, with India contributing approximately one quarter of the global burden.¹ The WHO South-East Asia Region continues to carry more than one third of the global caseload, making prevention of household and community transmission a continuing priority.²

Transmission of *Mycobacterium tuberculosis* occurs through infectious aerosols, and the probability of transmission is strongly influenced by exposure duration, occupancy and ventilation. A systematic review identified inadequate housing and ventilation as important determinants of pulmonary TB.³ In traditional homes in rural KwaZulu-Natal, opening windows and doors substantially increased air exchange and reduced modelled TB transmission risk.⁴ Recent work from Puducherry similarly showed low air changes per hour under closed conditions and poorer air exchange during air-conditioner use, whereas natural ventilation improved air exchange.⁵

Indoor CO₂ is widely used as a practical indicator of rebreathed air and ventilation adequacy. A South African classroom study identified approximately 1000 ppm as a pragmatic threshold related to TB transmission control,⁶ based on the rebreathed-fraction framework described by Rudnick and Milton.⁷ Carbon monoxide, in contrast, primarily reflects incomplete combustion from fuels, tobacco smoke, traffic and other sources; WHO guidance provides time-based exposure values for CO and addresses household fuel combustion.^{8,9}

Indoor air pollution is also relevant to TB risk. Tobacco smoke, secondhand smoke and biomass-fuel smoke have been associated with TB infection and disease,¹⁰ and a matched case-control study reported increased pulmonary TB odds with secondhand smoke, biomass fuel use, overcrowding and inadequate ventilation.¹¹ Higher personal 24-hour CO exposure has also shown a dose-response association with pulmonary TB among adults living with HIV.¹²

Few South Asian household studies have jointly measured CO and CO₂ alongside detailed structural, ventilation, neighbourhood and behavioural characteristics in TB-affected homes. The present study therefore assessed indoor air quality and ventilation in 180 TB-affected households in Puducherry, compared measurements with accepted benchmarks, and explored household factors associated with measured concentrations.

2. MATERIALS AND METHODS

2.1 Study design and setting

This community-based cross-sectional study was conducted in households of pulmonary TB patients residing in urban and rural Primary Health Centre (PHC) areas of the Puducherry region under the National TB Elimination Programme. Each household was assessed once during household contact/home assessment.

2.2 Study population, sample and recruitment and data collection

The study included 180 households of registered pulmonary TB patients identified from PHC treatment records. Selected using simple random sampling from the cohort of primary cluster-sampled households. Households were visited, and a semi-structured questionnaire was administered, supplemented by direct household observation, capturing sociodemographic characteristics, housing characteristics, and household air-quality practices. Indoor CO and CO₂ concentrations were measured in parts per million (ppm) using a portable real-time air-quality sensor called ATMOS. Candidate explanatory variables included age, sex, education, occupation, income, family structure, smoking and secondhand smoke, house type and construction, number of rooms, ventilation status, cross ventilation, separate kitchen, mechanical ventilation, cooking fuel, air-conditioner use, road/traffic exposures, and other household practices.

2.3 Operational definitions and benchmark classification

CO₂ categories were defined as <1000 ppm (adequate ventilation), and ≥1000 ppm (poor ventilation or inadequate), based on the National Building Code of India (NBC) 2016, Part B specified ventilation criteria¹⁶. The 1000-ppm benchmark is also consistent with TB-related rebreathed-air literature.^{6,7}

Indoor CO was compared descriptively with WHO guideline values of 6 ppm for a 24-hour mean and 9 ppm for an 8-hour mean.⁹ These comparisons were treated as contextual benchmarks rather than direct time-weighted compliance testing.

2.4 Statistical analysis

Continuous variables were summarised using mean $\pm$ standard deviation (SD), median, interquartile range (IQR) and range as applicable. Categorical variables were summarised as frequencies and percentages among valid responses. For categorical predictors with two levels, mean CO and CO₂ were compared using independent-samples t tests; variables with three or more levels were assessed using one-way ANOVA. Continuous predictors were assessed using Pearson correlation coefficients. All tests were two-sided, and $p < 0.05$ was treated as nominally statistically significant. No formal multiplicity correction was applied. Analyses were performed using SPSS version 24.0.

2.5 Ethical considerations

The study was conducted in accordance with the ethical approval obtained from the Institutional Ethics Committee of Sri Manakula Vinayagar Medical College and Hospital (SMVMCH). Informed consent was obtained from each participant. Personal identifiers were not included in the analysis dataset.

3. RESULTS

3.1 Participant flow and baseline characteristics

All 180 enrolled TB-affected households had valid indoor CO and CO₂ measurements and were included in the primary analysis (Figure 1). The mean age of TB patients was 50.7 ± 17.4 years; 120 (66.7%) were male. Seventy-four (41.1%) had no formal education. Most respondents were married (89.4%), and 75.0% lived in nuclear families. Mean family size was 4.12 ± 1.45 , and median monthly household income was INR 7,000. Current smoking was reported by 40 (22.2%), alcohol use by 58 (32.2%), and secondhand smoke exposure by 40 (22.2%) respondents (Table 1).

Table 1. Baseline sociodemographic and lifestyle characteristics

Characteristic	Category/summary	n	Value
Age (years)	Mean $\pm$ SD; median; range	180	50.7 ± 17.4 ; 52; 11–94
Gender	Male	120	66.7%
	Female	60	33.3%
Education	No formal education	74	41.1%
Marital status	Married	161	89.4%
Residence	Rural	90	50.0%
	Urban	90	50.0%
Family type	Nuclear	135	75.0%
	Joint	45	25.0%
Family members	Mean $\pm$ SD; median; range	180	4.12 ± 1.45 ; 4; 1–10
Monthly household income (INR)	Mean $\pm$ SD; median; range	180	7197 ± 8335 ; 7000; 0–45000
Current smoking	Yes	40	22.2%
Alcohol use	Yes	58	32.2%
Secondhand-smoke exposure	Yes	40	22.2%
Betel-nut chewing	Yes	22	12.2%

Percentages are based on valid responses. SD, standard deviation; INR, Indian rupee.

3.2 Housing, ventilation and household air-quality characteristics

Most homes were pucca (73.9%) and of concrete construction (86.1%), with concrete/brick walls in 99.4%. Majority of the households 167 (92.8%) felt adequate ventilation in their home; however, only 30 (16.7%) had cross ventilation. A separate kitchen was present in 146 (81.1%), forced/mechanical ventilation in 67 (37.2%) and an air conditioner in 47 (26.1%). Biomass was used as a secondary cooking fuel in 42 (23.3%) households. The mean number of rooms was 3.68 ± 1.33 (n=176) (Table 2; Figure 3).

Table 2. Selected housing, ventilation and household air-quality characteristics

Characteristic	Category	n	%
Street/road type	Paved	156/179	87.2
House type	Pucca	133	73.9
Construction type	Concrete	155	86.1
Floor type	Tiles	103	57.2
Wall type	Concrete/brick	179	99.4
Overall ventilation	Adequate	167	92.8
Cross ventilation	Present	30	16.7
Separate kitchen	Present	146	81.1
Forced/mechanical ventilation	Present	67	37.2
Window insect mesh	Present	10	5.6
Primary cooking fuel	LPG	163/165	98.8
Secondary cooking fuel	Biomass	42	23.3
Mosquito coil use	Yes	124/165	75.2
Incense stick use	Yes	142	78.9
Air conditioner in home	Yes	47	26.1
Vehicle parked inside	Yes	12	6.7

Valid denominators differed for several variables because unclassifiable responses were excluded. LPG, liquefied petroleum gas.

3.3 Indoor CO and CO₂ concentrations and benchmark classification

Mean indoor CO₂ concentration was 588.8 ± 176.6 ppm, with a median of 537.3 ppm (IQR 477.2–631.8) and a range of 414.3–1307.1 ppm. Using 1000 ppm as the ventilation-related cut-off, 169 (93.9%) households had CO₂ concentrations <1000 ppm, whereas 11 (6.1%) had concentrations ≥1000 ppm.

Table 3. Indoor CO and CO₂ measurements and comparison with guideline benchmarks

Outcome/classification	n	Mean $\pm$ SD or n (%)	Median (IQR)	Range
CO (ppm)	180	1.080 ± 0.155	1.101 (0.955–1.197)	0.712–1.471
CO ₂ (ppm)	180	588.8 ± 176.6	537.3 (477.2–631.8)	414.3–1307.1
CO >6 ppm (WHO 24-h value)	180	0 (0.0%)	—	—
CO ₂ <1000 ppm	180	169 (93.9%)	—	—
CO ₂ ≥1000 ppm	180	11 (6.1%)	—	—

Footnote: CO, carbon monoxide; CO₂, carbon dioxide; ppm, parts per million; SD, standard deviation; IQR, interquartile range; WHO, World Health Organization.

3.4 Associations with categorical household and individual characteristics

Among categorical variables, occupation ($p=0.010$), residence ($p=0.046$), family type ($p=0.026$), secondary cooking fuel ($p=0.006$) and air-conditioner presence ($p=0.029$) were nominally associated with CO. Biomass secondary-fuel users had higher mean CO than LPG users (1.138 ± 0.153 vs 1.062 ± 0.151 ppm), and households with an air conditioner had higher mean CO than those without one (1.118 ± 0.126 vs 1.066 ± 0.162 ppm). No substantively interpretable categorical association with CO₂ was identified. The wall-type variable contained only one household in the non-concrete/brick category and was therefore not interpreted as a stable inferential comparison. Selected results are shown in Table 4.

Table 4. Selected categorical associations with indoor CO and CO₂

Characteristic	Comparison	CO result/p-value	CO ₂ p-value	Test
Occupation	6 categories	$p=0.010^*$	0.431	ANOVA
Residence	Urban vs rural	1.103 ± 0.134 vs 1.057 ± 0.171 ; $p=0.046^*$	0.123	t test
Family type	Joint vs nuclear	1.121 ± 0.135 vs 1.066 ± 0.159 ; $p=0.026^*$	0.512	t test
Secondary cooking fuel	Biomass vs LPG	1.138 ± 0.153 vs 1.062 ± 0.151 ; $p=0.006^*$	0.195	t test
Air conditioner in home	Yes vs no	1.118 ± 0.126 vs 1.066 ± 0.162 ; $p=0.029^*$	0.064	t test
Overall ventilation	Inadequate vs adequate	$p=0.730$	0.754	t test
Cross ventilation	Yes vs no	$p=0.745$	0.789	t test
Separate kitchen	No vs yes	$p=0.137$	0.436	t test
Current smoking	Yes vs no	$p=0.136$	0.753	t test
Primary cooking fuel	Biomass vs LPG	$p=0.831$	0.619	t test

*Nominal $p < 0.05$. No formal correction for multiple testing was applied. ANOVA, analysis of variance; LPG, liquefied petroleum gas.

3.5 Correlation with continuous variables and multiplicity

Monthly household income correlated weakly and positively with CO ($r=0.154$, $p=0.039$; $n=180$) and CO₂ ($r=0.226$, $p=0.002$; $n=180$). Number of rooms correlated weakly with CO₂ ($r=0.166$, $p=0.028$; $n=176$) but not with CO. Age, family size, years since painting and daily time spent at home were not significantly correlated with either outcome (Table 5; Figure 4). Given 96 exploratory inferential tests overall, isolated nominal p values were interpreted cautiously.

Table 5. Correlation of continuous variables with indoor CO and CO₂ concentrations

Variable	CO r	CO p	CO ₂ r	CO ₂ p	n
Age (years)	0.035	0.645	-0.091	0.224	180
Family members	0.110	0.141	-0.004	0.954	180
Number of rooms	0.020	0.794	0.166	0.028*	176
Years since house painted	-0.021	0.780	0.025	0.742	177
Daily home-stay duration	-0.058	0.455	0.031	0.691	168

Monthly household income	0.154	0.039*	0.226	0.002*	180
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*Nominal $p < 0.05$. r , Pearson correlation coefficient. n reflects the available-case denominator for each variable.

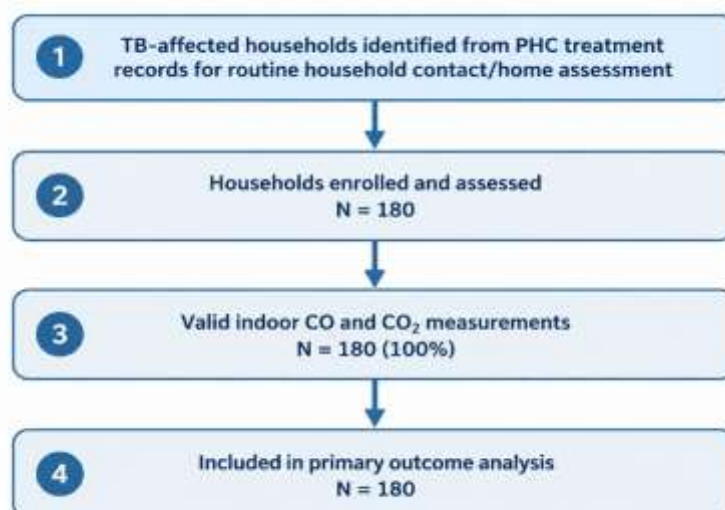


Figure 1. Participant flow through the household air-quality assessment.

All 180 enrolled TB-affected households had valid CO and CO₂ readings and were included in the primary analysis. *PHC*- Primary Health Centre; *CO*- carbon monoxide; *CO₂* - carbon dioxide.

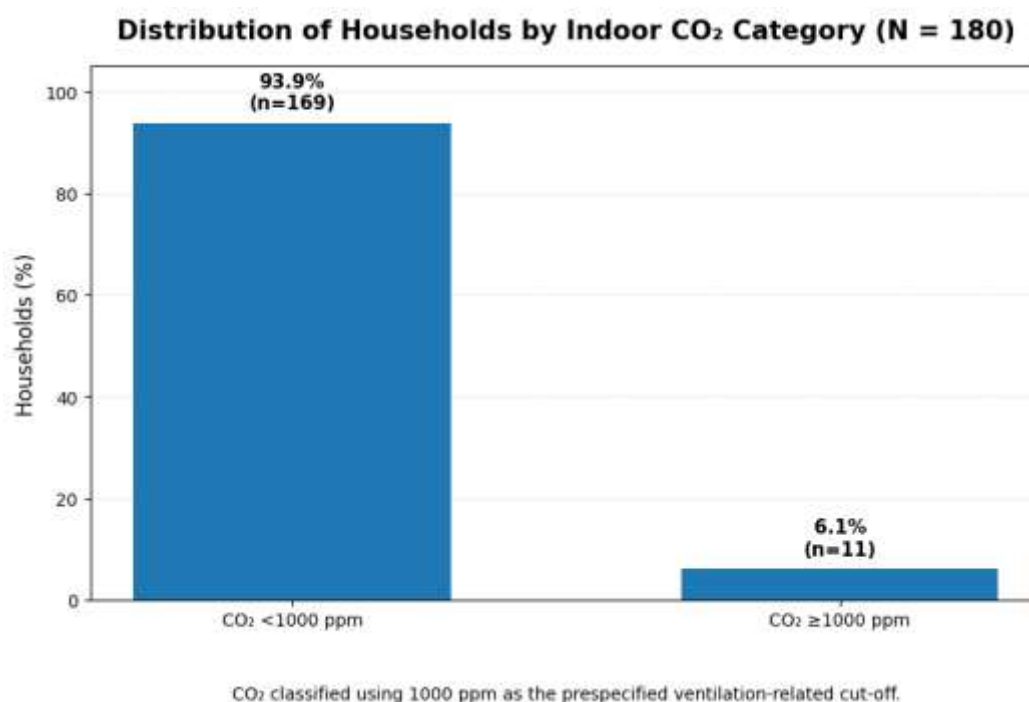


Figure 2. Distribution of households by indoor CO₂ ventilation category.

Bars show the percentage and count of 180 households in each prespecified CO₂ category. Five households (2.8%) exceeded 1120 ppm.

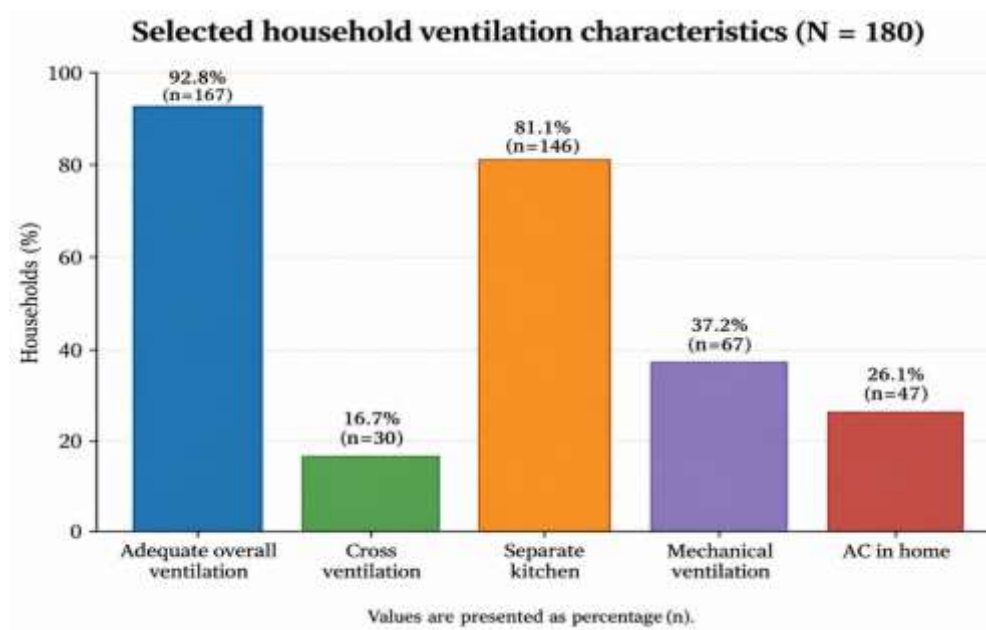


Figure 3. Selected household ventilation characteristics.

Percentages are based on 180 households. Overall ventilation was classified as adequate in 92.8%, while cross ventilation was present in 16.7%.

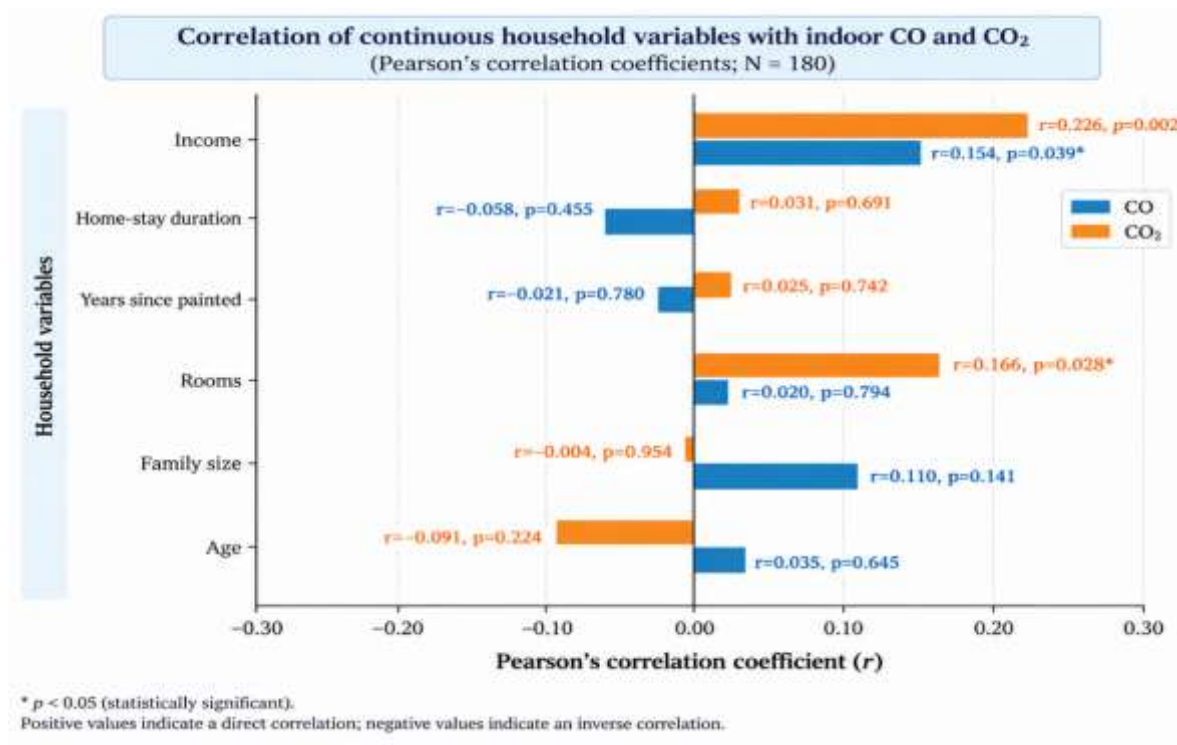


Figure 4. Correlation of continuous household variables with indoor CO and CO₂.

Horizontal bars show Pearson correlation coefficients. Asterisks denote nominal $p < 0.05$. The largest positive correlation was between household income and CO₂ ($r = 0.226$, $p = 0.002$).

4. DISCUSSION

This community-based assessment of 180 tuberculosis (TB)-affected households demonstrated generally low concentrations of indoor carbon monoxide (CO) and carbon dioxide (CO₂). Mean indoor CO was 1.08 ppm, with no observed value exceeding the WHO 8-hour or 24-hour guideline concentrations. Mean CO₂ was 588.8 ± 176.6 ppm. Using 1000 ppm as the ventilation-related benchmark, 169 (93.9%) households had CO₂ concentrations <1000 ppm, whereas 11 (6.1%) had concentrations ≥ 1000 ppm. Thus, most households had favourable CO₂ levels, although the subgroup exceeding 1000 ppm may represent households requiring closer assessment of fresh-air exchange.

Despite 92.8% of households felt they were having adequate ventilation; cross ventilation was present in only 16.7%. This discrepancy suggests that routine structural or observational assessment of ventilation may not fully reflect actual indoor air exchange. Direct CO₂ measurement therefore provides complementary information regarding the accumulation of occupant-generated, rebreathed air.

The use of 1000 ppm as the principal CO₂ benchmark is particularly relevant to TB transmission. Richardson et al.⁶ applied a CO₂-based transmission model in South African classrooms and estimated that a critical rebreathed-air fraction corresponding to approximately 1000 ppm CO₂ was associated with a ventilation rate considered relevant for reducing TB transmission.

Du et al.¹⁴ provided empirical evidence during a university TB outbreak involving 27 cases and 1,665 contacts. Ventilation engineering reduced maximum indoor CO₂ concentrations from approximately 3204 ppm to 591–603 ppm. Exposure to source cases under conditions with CO₂ >1000 ppm was significantly associated with subsequent infectious TB, while ventilation improvement to maintain CO₂ <1000 ppm was independently associated with a 97% reduction in incident infectious TB among contacts.¹⁴

The present finding that 93.9% of households had CO₂ <1000 ppm should be interpreted cautiously. CO₂ concentration varies with occupancy, room volume, outdoor-air exchange, window and door opening, cooking activities, and air-conditioner use. Households with apparently favourable daytime CO₂ levels may experience poorer ventilation during adverse weather, closed-window conditions, or prolonged air-conditioner use.

This limitation is illustrated by studies directly quantifying air exchange. Chamie et al.¹⁵ evaluated household ventilation in Kampala using a CO₂ tracer-decay technique. Median ventilation was 14 air changes per hour (ACH), and ventilation tended to be lower in sleeping rooms of index TB cases from households with co-prevalent TB than in households without co-prevalent disease.¹⁵ Thus, while spot CO₂ measurement offers a practical field indicator, tracer-decay methods provide a more direct estimate of air exchange.

Other ventilation studies further reinforce this interpretation. In traditional homes in rural KwaZulu-Natal, opening doors and windows substantially increased air exchange and reduced modelled TB transmission risk.⁴ Similarly, recent work from Puducherry demonstrated poorer air exchange under closed and air-conditioned conditions, with improvement during natural ventilation.⁵

The National Building Code of India 2016 provides additional contextual support. It recognises CO₂ as a surrogate indicator of ventilation efficiency in air-conditioned environments and recommends ventilation rates that generally prevent CO₂ from exceeding approximately 1000 ppm.¹⁶ However, because outdoor CO₂ was not measured simultaneously, the present study could not assess indoor–outdoor CO₂ differentials.

1000 ppm should not be interpreted as a toxicological or absolute safety threshold. Rather, it represents a practical indicator of ventilation and accumulation of rebreathed air. TB transmission risk is influenced additionally by infectiousness of the source case, duration and proximity of exposure, room occupancy and volume, susceptibility of contacts, and cumulative time spent sharing indoor air.^{6,14}

The categorical association analysis was largely null for CO₂ but more heterogeneous for CO. No categorical household characteristic consistently predicted CO₂ concentration, but Household income and number of rooms showed weak positive correlations with CO₂; however, the small effect sizes and exploratory nature of the analysis limit causal interpretation.

Five categorical variables were nominally associated with CO: occupation, residence, family type, secondary cooking fuel and air-conditioner presence. Among these, secondary biomass-fuel use had the clearest biologically plausible pathway, with biomass users having higher mean CO than LPG users. Associations with residence, occupation and family structure are more difficult to interpret and could represent confounding or chance.

Multiplicity is particularly important because 96 exploratory inferential tests were performed. At a nominal α of 0.05, some statistically significant associations could arise by chance. The observed relationships should therefore be considered hypothesis-generating rather than confirmatory, with emphasis placed on biological plausibility, effect size and replication.

The uniformly low CO concentrations suggest little evidence of substantial combustion-related CO accumulation during household assessment. Nevertheless, the higher mean CO among secondary biomass users is consistent with known combustion pathways. WHO guidance recognises household fuel combustion as an important indoor-air hazard,^{8,9} while previous evidence has linked tobacco smoke, biomass exposure and inadequate ventilation with TB.^{10–12}

4.1 Public-health and clinical implications

Natural and cross ventilation should remain central components of household TB infection-control counselling. Direct CO₂ measurement may help identify households requiring more detailed ventilation assessment. However, interventions should focus on improving fresh-air exchange rather than simply achieving a numerical CO₂ target. Opening windows and doors where feasible, encouraging cross-ventilation, avoiding prolonged recirculation of indoor air during air-conditioner use, and reducing biomass-fuel exposure represent practical household-level measures.

4.2 Strengths

The study evaluated 180 TB-affected households using paired objective CO and CO₂ measurements. Complete CO and CO₂ measurements were available for all households. The use of a clearly defined 1000-ppm CO₂ benchmark improves comparability with TB-related ventilation literature.^{6,14} The analysis also explicitly recognised the exploratory nature of multiple statistical comparisons.

4.3 Limitations

The principal limitation was the use of single 24-hour CO and CO₂ measurements in each household, which could not capture day-to-day or seasonal variation. This cannot substitute for repeated monitoring or CO₂ tracer-decay estimation of ACH.¹⁵ Outdoor CO₂, room volume, and occupancy-adjusted ventilation rates were not measured.

Several ventilation variables were based on observation or self-report, and some variables required complete-case analysis.

4.4 Recommendations for future research

Future studies should incorporate repeated 24-hour or continuous CO₂ and CO monitoring during different days and seasons, together with outdoor CO₂, room volume, occupancy, window/door status and air-conditioner use. CO₂ tracer-decay techniques should be considered for direct ACH estimation.¹⁵ Longitudinal studies linking ventilation measurements with latent TB infection or incident TB among household contacts would help determine whether time spent above 1000 ppm predicts transmission.

5. CONCLUSION

In this assessment of 180 TB-affected households in Puducherry, indoor CO concentrations were uniformly low. Mean CO₂ was 588.8 ± 176.6 ppm; 169 (93.9%) households had CO₂ <1000 ppm and 11 (6.1%) had CO₂ $\geq$ 1000 ppm. The 1000-ppm benchmark is supported by TB-related modelling, empirical outbreak evidence and ventilation guidance, but should be regarded as a pragmatic indicator of ventilation and rebreathed air rather than an absolute safety threshold.^{6,14,16} Promotion of natural and cross ventilation, objective CO₂ assessment where feasible, minimisation of biomass-fuel exposure and adequate fresh-air exchange during air-conditioner use remain practical household TB-control measures.

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