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Indoor Environmental Conditions and Pulmonary Tuberculosis in Riverbank Settlements: A Cross-Sectional Study in Banjarmasin, Indonesia

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Pulmonary tuberculosis (TB) remains a major public health problem in Indonesia, particularly in densely populated riverbank settlements where housing conditions may influence airborne infection risk. However, empirical evidence linking household environmental measurements with TB occurrence in such settings remains limited. This study examined the relationship between indoor environmental conditions and pulmonary TB status among households living along the Martapura River in Banjarmasin. A cross-sectional study was conducted involving 60 households, consisting of 30 TB cases and 30 controls. Indoor temperature, humidity, ventilation area, occupant density, and airborne microbial count were measured using standardized environmental and microbiological procedures. Associations between environmental indicators and TB status were analyzed using chi-square tests and odds ratios (OR) with 95% confidence intervals. None of the measured indoor environmental variables showed a statistically significant association with pulmonary TB status (all $p > 0.05$). Although most households exhibited high humidity, inadequate ventilation, and elevated occupancy, these conditions were similarly distributed between case and control groups, resulting in non-significant effect estimates. The study did not find evidence of a significant association between indoor environmental quality and pulmonary TB status in riverbank settlements. The findings should be interpreted in light of the environmental homogeneity across households and the study's limited sample size. Further research incorporating larger samples and multivariable approaches is needed to better understand the environmental determinants of TB in similar high-density settings.

Keywords: Airborne Microbes, Indoor Environment, Ventilation, Occupant Density, Pulmonary Tuberculosis

INTRODUCTION

Tuberculosis (TB) remains a major global health problem, particularly in low-income and densely populated environments where environmental and social vulnerabilities converge (Andrade-Sales et al., 2025; Pandey et al., 2025a). Although Indonesia is among the world's eight highest-burden countries, the spatial distribution of TB is not uniform; specific ecological and housing contexts play an important role in shaping transmission risk (Shaluhiyah et al., 2025). One such context is the riverbank settlements commonly found in Banjarmasin, where houses are built in close proximity, ventilation is limited, and indoor microclimatic conditions tend to be humid and stagnant throughout the year (Chair et al., 2021; Febrita et al., 2024). These characteristics may influence the persistence of airborne pathogens, yet empirical data on these environmental mechanisms remain limited.

Riverbank settlements represent a unique microenvironment due to their structural density, limited building setbacks, reliance on natural ventilation, recurrent flooding, and high background humidity (Azuma & Bamba, 2018; Krishnan et al., 2022). These factors reduce airflow and natural lighting, creating indoor conditions that theoretically promote the survival of airborne microorganisms. In addition, riverbank housing differs substantially from typical urban residential environments. Proximity to river surfaces creates persistently higher ambient humidity, while limited sun exposure caused by dense building layouts reduces indoor evaporation and moisture dispersion (Febrita et al., 2024). Narrow pathways and tightly clustered wooden structures restrict natural air circulation, leading to indoor spaces that are consistently warmer, more humid, and less ventilated than standard urban housing with better airflow design. These meteorological and structural characteristics create a distinctive indoor microclimate that may influence airborne microbial persistence; however, empirical assessments of these mechanisms in riverbank contexts remain scarce.

Previous studies in Indonesia and other high-burden countries have reported inconsistent associations between household characteristics, such as ventilation, humidity, or crowding, and TB risk. Some found that poor ventilation and high occupant density increase infection probability (Amirus & Herleni, 2017; Budi et al., 2024; Jannah et al., 2023; Khairani et al., 2020; Mardianti et al., 2020; Muhammad et al., 2020; Sulidah et al., 2024; Wanyeki et al., 2006), whereas others reported no significant relationships, particularly in settings where environmental conditions were uniformly poor (Kusniawati et al., 2022; Muhammad et al., 2020; Pratama et al., 2013; Rahmawati et al., 2021). These inconsistencies highlight the need for studies that incorporate both objective physical measurements and microbiological assessments, which remain scarce in riverbank or similarly dense settlement environments.

Despite abundant literature on TB epidemiology, only a few studies have directly quantified indoor temperature, relative humidity, ventilation area, occupant density, and airborne microbial concentration within households at high risk of TB transmission. Most previous research has relied on self-reported housing characteristics or used proxies rather than empirical measurements. This gap is particularly relevant in Banjarmasin's riverbank communities, where environmental conditions are distinctive and may not reflect findings from urban, peri-urban, or rural regions studied previously. Moreover, little is known about whether environmental differences within such spatially homogeneous settlements are sufficient to distinguish TB-affected and non-TB households. To the best of our knowledge, no prior study in Indonesia has combined objective physical measurements with laboratory-based airborne microbial assessment specifically in riverbank settlements, making this research an important contribution to understanding TB risk in ecologically unique and understudied environments.

Given the limited evidence and the inconsistencies in prior findings, this study was designed to analyse the relationship between objectively measured housing quality, temperature, humidity, ventilation, occupant density, and airborne microbial count, and the occurrence of pulmonary TB among communities living along the Martapura River. By integrating environmental measurements with microbiological indoor air sampling, this study provides novel, context-specific evidence regarding the environmental determinants of TB in densely populated riverbank settlements, which may inform more targeted prevention strategies in similar high-risk settings.

METHOD

Study design and setting

This study employed a cross-sectional design to examine the relationship between indoor environmental quality and the presence of airborne microbes, as well as their association with pulmonary tuberculosis (PTB). All data, including environmental measurements and TB status, were collected at the same point in time. The study was conducted in households located within a 50-meter radius of the riverbank in the working area of Puskesmas Alalak Selatan, Banjarmasin, South Kalimantan.

Study population, case definition, and control selection

Cases were defined as individuals with pulmonary tuberculosis recorded in the Puskesmas registry and confirmed through medical records documenting microbiological evidence (sputum smear microscopy or Xpert MTB/RIF) or a physician's diagnosis in accordance with national TB program guidelines. Controls were individuals without a history of pulmonary TB who met the same residency and eligibility criteria as the case group.

Inclusion and exclusion criteria

Inclusion criteria for households included: (1) located within 50 meters of the riverbank, (2) occupied continuously for more than five years, (3) residents being permanent occupants, and (4) willingness to participate. Exclusion criteria included: (1) refusal to participate, (2) houses that were temporarily unoccupied or not feasible for environmental measurement, (3) recent major renovation within one month prior to sampling, and (4) any household where environmental conditions were affected by abnormal activities (e.g., indoor industrial or commercial operations). At the individual level, controls with any past diagnosis of PTB were excluded.

Sample size and sampling technique

A total of 60 households were selected through purposive (non-probability) sampling: 30 households from case residences and 30 from controls. The sample size was determined based on operational feasibility and the number of eligible documented TB cases during the study period. We acknowledge the absence of an a priori power calculation; this limitation is addressed in the Discussion.
Environmental measurements.

Temperature and relative humidity (RH)

Indoor air temperature (°C) and relative humidity (%) were measured using a calibrated TFA analog thermo-hygrometer from Germany. Measurements were taken in the main living area, 1.2–1.5 meters above floor level, away from direct sunlight and heat sources. Three readings were taken at 10-minute intervals, and the average value was recorded.

Ventilation assessment

Ventilation was quantified by measuring total open area of ventilators (height × width) using a measuring tape. Ventilation adequacy was calculated as the percentage of ventilator area relative to total floor area: *(ventilator area / floor area) × 100%*. Adequate ventilation was defined a priori as ≥10% of floor area, following building-health guidelines and previous literature. Cross-ventilation was evaluated qualitatively, based on the presence of openings on opposite walls.

Airborne microbial count (AMC)

Airborne microbial sampling and analysis were conducted by the *Banjarmasin Public Health Laboratory*, a certified regional reference laboratory responsible for environmental microbiology examinations. An active impaction air sampler was used at a calibrated flow rate of 100 L/min. Air sampling was conducted for 10 minutes (equivalent to 1 m³ of air) at 1.2–1.5 meters above the floor. Tryptic Soy Agar (TSA) plates were used for bacterial culture. Plates were incubated at 35 ± 2°C for 48 hours and colony-forming units were counted as CFU/m³. All procedures, including calibration, sampling, plate handling, and incubation, were performed according to institutional standard operating procedures (SOPs).

Quality assurance and calibration

The Banjarmasin Public Health Laboratory maintained calibration logs for all instruments and conducted routine internal quality controls. Field procedures adhered to established SOPs covering sampler placement, sample transport, aseptic handling, and data recording.

Variable categorization

Variable categorization was predefined in the research protocol.

1. Ventilation: adequate if ≥10% of floor area; inadequate if <10%.
2. Temperature & humidity: categorized based on literature-supported thresholds for microbial viability.
3. AMC**:** classified as *Meets Standard (MS)* or *Does Not Meet Standard (TMS)* using thresholds from local guidance; if unavailable, tertiles were used (low, medium, high).

Data analysis

Descriptive statistics were computed for all variables. Associations between environmental factors and PTB status were assessed using chi-square tests (or Fisher's exact test where appropriate). Statistical calculations, including chi-square statistics, p-values, odds ratios (OR), and 95% confidence intervals (CI), were performed using Statisty (https://statisty.app/), a validated online statistical calculator based on standard chi-square and logistic regression formulas. All values were cross-checked manually. Statistical significance was defined as $p < 0.05$.

RESULTS AND DISCUSSION

Indoor environmental characteristics measured in case and control households are summarized in Table 1.

Table 1.
Indor Air Quality in Riverbank Settlements

No	Environmental Factor	Unit	Lowest	Highest	Mean (±SD)
Case Group					
1	Air temperature	°C	27.4	34.7	32.1 (±1.8)
2	Humidity	%	61	94	73.6 (±8.9)
3	Ventilation	m²	0	0.72	0.17 (±0.1)
4	Occupant density	m²/person	1	18	3.2 (±3.2)
5	Airborne microbial count	CFU/m³	140	17,910	2,708 (±3,289)
Control Group					
1	Air temperature	°C	27.4	34.0	31.6 (±1.8)
2	Humidity	%	62	91	75.5 (±7.7)
3	Ventilation	m²	0	0.70	0.19 (±0.2)
4	Occupant density	m²/person	1	6	2.3 (±0.8)
5	Airborne microbial count	CFU/m³	420	10,110	3,411 (±1,993)

Both groups showed similar ranges of indoor temperature, relative humidity, ventilation area, floor area per occupant, and airborne microbial counts. The results of the bivariate analysis are presented in Table 2.

Table 2.

Association Between Indoor Environmental Factors and TB occurrence

Environmental Factor	Case MS	Case TMS	Control MS	Control TMS	OR	95% CI	p-value
Temperature	5	25	4	26	1.30	0.31–5.39	1.000
Humidity	0	30	0	30	–	–	Not analyzable
Ventilation	2	28	2	28	1.00	0.13–7.59	0.492
Occupant density	1	29	4	26	0.22	0.02–2.13	0.103
Airborne microbial count	4	26	5	25	0.77	0.19–3.19	1.000

None of the indoor environmental factors demonstrated a statistically significant association with pulmonary TB. Indoor temperature was not associated with TB status (OR = 1.30; 95% CI: 0.31–5.39; p = 1.000). Relative humidity could not be analyzed because all households exceeded the recommended 60% threshold, resulting in a zero-cell condition. Ventilation adequacy also showed no significant association with TB (OR = 1.00; 95% CI: 0.13–7.59; p = 0.492). Occupant density showed no significant relationship (OR = 0.22; 95% CI: 0.02–2.13; p = 0.103). Similarly, airborne microbial count showed no significant association with TB (OR = 0.77; 95% CI: 0.19–3.19; p = 1.000). Overall, none of the measured indoor environmental characteristics were significantly associated with pulmonary TB among households in Alalak Selatan District.

DISCUSSION

Overview of the Findings

This study examined the relationship between indoor environmental conditions and pulmonary tuberculosis (TB) among households in riverbank settlements of Alalak Selatan. None of the measured variables, temperature, humidity, ventilation, occupant density, or airborne microbial count, showed statistically significant associations with TB status. Although literature often highlights the contribution of poor indoor environments to airborne pathogen transmission, the findings of this study indicate that such associations were not detectable in this specific context. These results reflect the complex interplay between environmental, behavioral, and host-related factors that influence TB transmission, particularly in socio-environmentally homogeneous settings.

Comparison with Previous Studies

Studies in densely populated and low-income settlements have frequently demonstrated that inadequate ventilation, high humidity, and overcrowding increase the risk of TB transmission. Research conducted in riverbank communities in Bangladesh, informal settlements in India, and peri-urban African neighborhoods reported that environmental housing quality contributes meaningfully to TB burden (Razak et al., 2025). However, several studies conducted in settings with minimal environmental variability, such as densely built kampung settlements in Jakarta or riverside neighborhoods in Vietnam, found no significant differences in housing conditions between TB and non-TB households. (Adianto et al., 2022; Armenda et al., 2022; Pandey et al., 2025b; Shabrina et al., 2021; Singh et al., 2025; Sulidah et al., 2024; Timire et al., 2024). The findings of this study align with these latter observations, suggesting that environmental homogeneity may limit detectable contrasts between case and control households. When most homes share similar physical characteristics, poor ventilation, high humidity, and limited living space, the ability to statistically differentiate risk based on environmental metrics becomes substantially reduced (Nurfita & Rangkuti, 2022; Yulida et al., 2026).

Possible Explanations for Non-Significant Associations

Several contextual factors may help explain the absence of significant associations in this study. First, the indoor environments of case and control households were highly similar (Beckwith et al., 2022; Choi et al., 2023; Iqbal et al., 2024; Kirwa et al., 2021; Kloster et al., 2022; Olsiewski et al., 2022; Zhang et al., 2022). Nearly all homes exhibited suboptimal ventilation, elevated humidity, and high occupant density. This lack of variability reduces the discriminatory power of statistical tests, even if environmental factors contribute to overall transmission risk (Azizah, 2025; Liu et al., 2025; Wolkoff et al., 2021).

Second, all environmental measurements were conducted at a single time point during the dry season, which may not reflect seasonal variation or day-to-day fluctuations in ventilation or humidity. Cross-sectional sampling limits the ability to capture long-term exposure differences that may be relevant for TB transmission (Basil et al., 2024; Parsewar & Mehta, 2025; Sack et al., 2025).

Third, the sample size, although adequate for exploratory purposes, may be insufficient to detect modest associations. The wide confidence intervals observed for several variables demonstrate statistical imprecision.

Fourth, TB transmission depends on more than indoor physical conditions. Factors such as bacillary load of the index case, duration of exposure, cough frequency, and interpersonal proximity were not measured but may overshadow environmental influences.

Finally, the higher airborne microbial count observed in the control group likely reflects short-term differences in human activity, air movement, or household practices at the time of measurement. AMC is sensitive to transient conditions, and single-time-point sampling may not accurately represent cumulative microbial exposure relevant to TB transmission (Zhao et al., 2025).

Potential Confounding Factors

The absence of measured confounders represents an important limitation and provides further explanation for the null findings. Variations in host immunity, nutritional status, smoking history, and frequency of close contact with infectious individuals may have influenced TB risk independently of housing conditions. Immune suppression, poor nutritional intake, and smoking are well-established determinants of TB susceptibility (Aanandhi Muthukumar et al., 2023; Chen & Liang, 2022). In addition, behavioral factors, such as time spent indoors, sleeping arrangements, and household crowding patterns, may play a decisive role in transmission. Without adjusting for these variables, it is possible that the environmental effects detected in other studies were obscured in this analysis (Cui et al., 2024; LeGrand et al., 2025).

Strengths and Limitations

This study provides valuable insight into environmental conditions in riverbank settlements, a type of community for which published data remain limited. The use of direct environmental measurements and laboratory-based microbial assessment strengthens the reliability of the findings.

However, limitations must be acknowledged. The cross-sectional design prevents causal inference, as environmental exposures and disease status were measured simultaneously. Environmental homogeneity across households limited the variability required to detect differences between TB and non-TB groups. The sample size was modest, contributing to wide confidence intervals. Measurements were conducted at a single time point and may not represent typical environmental conditions. Finally, several potential confounders, including smoking, nutrition, immune status, and behavioral exposure patterns, were not assessed, which may have influenced the observed associations (Nurfita & Rangkuti, 2022).

Implications and Recommendations

The absence of significant associations in this study does not reduce the importance of indoor environmental quality in TB prevention. Rather, it suggests that in highly homogeneous and structurally similar riverbank settlements, environmental differences are insufficient to distinguish TB and non-TB households statistically. TB control interventions in such settings should therefore prioritize host-level and behavioral determinants, such as early detection, treatment adherence, smoking cessation, and nutritional support, while improvements to ventilation and housing quality remain important complementary measures (Daradkeh et al., 2025; Khan et al., 2024; Lukas et al., 2025; Sirohi et al., 2026). Future research should employ larger sample sizes, longitudinal designs, and multivariable approaches that integrate both environmental and individual determinants to better understand TB transmission dynamics in similar communities.

CONCLUSION

This study found no statistically significant association between indoor environmental conditions, namely temperature, humidity, ventilation, and household density, and the presence of airborne microbes or the incidence of pulmonary tuberculosis among riverbank households in Alalak Selatan. These findings should be interpreted cautiously, as the study was conducted in a setting where environmental characteristics were highly homogeneous across households, limiting the ability to detect meaningful differences between case and control groups. Moreover, the cross-sectional design, small sample size, and absence of adjustments for individual-level confounders such as immune status, smoking, nutritional condition, and interpersonal contact patterns further constrain the generalizability of the results.

Rather than indicating that indoor environmental factors are unimportant, the findings suggest that in uniformly dense and ventilationally constrained riverbank settlements, structural housing characteristics alone may not sufficiently explain variations in TB incidence. Practical implications therefore include prioritizing behavioral and clinical determinants, such as early case detection, treatment adherence, smoking cessation, and nutritional support, while broader housing improvements remain relevant for long-term respiratory health. Future studies should incorporate larger sample sizes, multivariate approaches, and longitudinal environmental assessments to better disentangle the combined effects of environmental and host-level factors on TB transmission in similar communities.

SUGGESTION

Based on the findings of this study, which did not identify significant associations between indoor environmental conditions and pulmonary tuberculosis status among riverbank households, several directions for future research are recommended. First, studies with larger sample sizes and multivariable analytical approaches are needed to more accurately assess the combined effects of environmental, behavioral, and host-related factors on TB transmission. Longitudinal designs may also help capture temporal variations in indoor environmental conditions, such as humidity and ventilation patterns, which single-point cross-sectional measurements cannot fully represent.

Future research should further explore the influence of individual-level determinants, such as nutritional status, smoking behavior, immune competence, and duration of contact with infectious individuals, which were not assessed in this study but may play a critical role in TB vulnerability. In addition, evaluating housing improvement interventions in riverbank settlements, including practical modifications to ventilation or building structure, may provide insight into feasible public health strategies even when environmental differences between households are minimal.

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