

CLIMATIC AND DEMOGRAPHIC DETERMINANTS OF TUBERCULOSIS
IN DISTRICT DIR UPPER, PAKISTAN

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Abstract

Background: Tuberculosis (TB) remains one of the leading infectious causes of death globally. Climatic variability may influence TB transmission dynamics, particularly in mountainous regions.

Objective: To determine the prevalence of TB and evaluate its association with demographic and climatic factors in District Dir Upper, Pakistan.

Methods: A cross-sectional analytical study was conducted among 215 suspected TB patients registered between April and December 2024. TB status was confirmed through microbiological and clinical assessment. Demographic variables (age, gender, tehsil) and climatic factors (temperature, rainfall, month) were analyzed. Pearson's Chi-square tests, prevalence estimates, crude odds ratios (OR), and multivariable logistic regression were performed using SPSS v26.

Results: Overall TB prevalence was 43.7% (94/215). Females showed significantly higher prevalence (56.4%) compared to males (33.9%) ($\chi^2=10.88$, $p=0.001$; OR=2.52, 95% CI: 1.39–4.56). The highest age-specific prevalence was observed among 51–60 years (66.7%) and 41–50 years (60.0%). Seasonal variation was significant ($\chi^2=82.05$, $p<0.001$), with peak prevalence in November and December (100%). TB prevalence was highest at 1–10°C (100%) and 11–20°C (62.2%) ($\chi^2=42.36$, $p<0.001$). Rainfall extremes (10–100 mm: 63.3%; 201–350 mm: 54.8%) were strongly associated ($\chi^2=29.44$, $p<0.001$). Logistic regression identified female gender, moderate temperature (11–20°C), and low rainfall (10–100 mm) as independent predictors.

Conclusion: TB prevalence in District Dir Upper is significantly influenced by demographic and climatic factors. Integration of meteorological surveillance into TB control strategies is recommended.

1. INTRODUCTION

Tuberculosis (TB), caused by *Mycobacterium tuberculosis*, remains one of the most persistent and deadly infectious diseases globally, despite

extensive public health efforts to control its spread. In 2023, the World Health Organization reported that TB was responsible for millions of cases and significant mortality worldwide, with

South Asia accounting for a major proportion of the global burden (Sehrish et al., 2025). Pakistan continues to rank among the countries with the highest TB incidence, bearing a disproportionate share of cases within the Eastern Mediterranean Region and contributing substantially to the global TB caseload (Sehrish et al., 2025).

The epidemiology of TB is shaped not only by microbial pathogenicity and host immunity but also by broader socio-demographic and environmental determinants. Socioeconomic conditions—including poverty, overcrowding, limited healthcare access, and delayed diagnosis—are well recognized as key drivers of TB transmission and poor treatment outcomes in Pakistan and other low- and middle-income countries (LMICs) (Ullah et al., 2024). Gender disparities and cultural barriers have further complicated TB control in the region, with evidence suggesting differential health-seeking behaviour and access to services between males and females. Beyond socioeconomic determinants, climatic and meteorological factors have emerged as significant albeit under-studied influences on TB transmission dynamics. Numerous studies have documented seasonal rhythms in TB incidence across diverse geographical settings, suggesting that weather patterns—especially temperature and precipitation—may drive temporal fluctuations in TB case notifications. For instance, seasonal peaks and troughs in TB are reported across Asian, African, and European settings, indicating that TB does not occur uniformly throughout the year but exhibits reproducible patterns closely aligned with seasonal variations and climate regimes (Liyew et al., 2024). In South Asia, several investigations have identified pronounced seasonal trends in TB notifications. A multisite analysis in Pakistan observed that TB notifications peaked consistently in the second quarter of the year (April–June) and reached a trough in the final quarter (October–December), with latitude modifying the amplitude of seasonal variation (Butt et al., 2021). Similar seasonal PCR and clinical patterns have been documented in urban settings like Lahore, where TB notifications fluctuated significantly with changes in temperature and potential factors

related to indoor crowding and immune suppression in colder months (Khaliq et al., 2015). Climatic conditions such as ambient temperature, rainfall, humidity, and sunlight exposure are hypothesized to influence the survival of *M. tuberculosis* in the environment, host immune responses, and human behaviour including indoor crowding, all of which may facilitate or impede transmission (Liyew et al., 2024). Recent large-scale observational analyses have further refined our understanding of climate–TB associations. A global study spanning 2000–2021 identified complex lagged effects of temperature and precipitation on TB incidence and mortality, with warming trends generally reducing age-standardized incidence globally but showing heterogeneous effects across regions, particularly in Asia where increased temperatures were linked to higher TB rates (Liu et al., 2025). Biological mechanisms underlying climatic influences may include altered indoor occupancy due to heat or cold, changes in ultraviolet radiation affecting vitamin D synthesis and host immunity, and modifications in air humidity influencing aerosol transmission of TB bacilli (Wang et al., 2024). Despite these emerging insights, there remains a paucity of localized evidence linking climatic variables and socio-demographic risk factors to TB prevalence in mountainous and rural districts of Pakistan. Most national and regional TB surveillance systems focus on incidence and treatment outcomes without integrating environmental or seasonality metrics. This gap is particularly stark in high-altitude areas such as Dir Upper, where wide seasonal fluctuations in temperature and rainfall could exert additional influence on TB transmission dynamics. Understanding these local patterns is crucial for devising targeted public health interventions, optimizing resource allocation, and refining TB control strategies in the context of both socio-environmental determinants and anticipated climate variability. Accordingly, this study aims to assess TB prevalence in District Dir Upper and evaluate its association with demographic and climatic determinants, including age, gender, temperature, rainfall, and seasonal patterns. By integrating socio-demographic data with climatico-

environmental variables, our work seeks to inform climate-responsive TB surveillance and intervention frameworks that are contextually relevant for northern Pakistan and similar settings.

2. Materials and Methods

2.1 Study Design and Study Area

This study employed a cross-sectional analytical design to investigate the association between demographic characteristics, climatic variables, and tuberculosis (TB) prevalence in Dir Upper, located in the northern region of Pakistan. A cross-sectional design was considered appropriate because it allows the estimation of disease prevalence and the assessment of relationships between exposure variables and outcomes at a specific point in time. District Dir Upper is characterized by mountainous terrain, marked seasonal temperature fluctuations, and variable rainfall patterns, which make it a suitable setting for exploring climate-linked epidemiological variations in TB. The district has a predominantly rural population with limited healthcare infrastructure in remote areas, factors that may influence disease detection and reporting patterns. The study was conducted over a nine-month period from April to December 2024, encompassing multiple climatic seasons including spring, summer, autumn, and early winter. Including data across these months enabled assessment of seasonal variability in TB prevalence in relation to meteorological changes.

2.2 Study Population and Sampling Procedure

The study population comprised all suspected tuberculosis patients who were registered at the District TB Control Center during the study period. A total of 215 individuals who fulfilled the inclusion criteria were enrolled in the study. Inclusion criteria required that participants were clinically suspected of TB, had complete diagnostic records, and had available demographic and climatic data corresponding to their date of registration. Patients with incomplete laboratory records or missing key demographic information were excluded to ensure data integrity and statistical reliability. A non-probability consecutive sampling approach was employed, whereby all eligible suspected TB cases presenting during the

study period were included. This method was chosen to minimize selection bias and to capture the full spectrum of cases reported to the health facility within the specified timeframe. Since the study aimed to evaluate prevalence among suspected cases rather than estimate community incidence, facility-based sampling was considered appropriate.

2.3 Data Collection Procedures

Data were obtained from standardized TB registration records maintained at the district health facility. These records contained detailed demographic information, laboratory diagnostic results, and dates of patient registration. Demographic variables extracted included age, gender, and tehsil (sub-district) of residence. Age was categorized into predefined groups to facilitate comparative statistical analysis and to identify age-specific prevalence patterns. Climatic data corresponding to each month of patient registration were obtained from the regional meteorological department. Monthly averages of temperature (°C) and rainfall (mm) were recorded and categorized into meaningful exposure ranges to allow stratified analysis. Temperature was grouped into four categories (1–10°C, 11–20°C, 21–30°C, and ≥31°C), while rainfall was categorized into ranges (10–100 mm, 101–150 mm, 151–200 mm, and 201–350 mm). Categorization of meteorological variables was performed to enhance interpretability and to allow detection of threshold-based associations.

2.4 Diagnostic Criteria and Case Definition

Tuberculosis diagnosis was confirmed using standard national TB control program guidelines. Patients were classified as TB positive if they had bacteriological confirmation through sputum smear microscopy, GeneXpert testing, or radiological and clinical evaluation consistent with active TB disease. Patients who were clinically suspected but did not meet confirmatory diagnostic criteria were classified as TB negative for analytical purposes. The dependent variable in this study was TB status, coded dichotomously as positive (1) and negative (0). This binary classification enabled the use of logistic regression

modeling to assess associations between predictor variables and TB positivity.

2.5 Study Variables

The primary outcome variable was tuberculosis status (positive or negative). Independent variables included demographic factors (age group, gender, and tehsil of residence) and climatic factors (month of diagnosis, temperature category, and rainfall category). These variables were selected based on existing epidemiological evidence suggesting potential influence on TB transmission dynamics. Gender was analyzed as a categorical variable (male/female) to explore possible sex-based disparities in TB prevalence. Age was categorized into seven groups to allow identification of vulnerable age cohorts. The month of diagnosis was included to examine seasonal variation patterns. Temperature and rainfall categories were treated as environmental exposure variables potentially influencing TB transmission and detection patterns.

2.6 Statistical Analysis

Data were entered and analyzed using Statistical Package for the Social Sciences (SPSS) version 26. Descriptive statistics were first computed to summarize the demographic and climatic characteristics of the study population. Frequencies and percentages were calculated to determine the prevalence of TB overall and within each subgroup. The prevalence of TB was calculated by dividing the number of confirmed TB positive cases by the total number of suspected cases and multiplying by 100. Subgroup-specific prevalence rates were similarly computed for gender, age groups, temperature ranges, rainfall categories, and months. Associations between categorical independent variables and TB status were assessed using Pearson's Chi-square (χ^2) test. The Chi-square test was selected because it is appropriate for evaluating relationships between categorical variables and determining whether observed differences in proportions are statistically significant. A p-value of less than 0.05 was considered statistically significant. Crude odds ratios (OR) with 95% confidence intervals (CI)

were calculated to quantify the strength of association between exposure variables and TB positivity. Odds ratios greater than one indicated increased odds of TB in the exposed group relative to the reference category. To control for potential confounding effects and identify independent predictors of TB positivity, multivariable binary logistic regression analysis was performed. Variables that showed statistical significance in bivariate analysis were included in the regression model. Adjusted odds ratios (AOR) with corresponding 95% confidence intervals were reported. Model fitness was assessed using the Hosmer-Lemeshow goodness-of-fit test and Nagelkerke's R^2 to evaluate explanatory power.

2.7 Ethical Considerations

Ethical approval for the study was obtained from the Institutional Research Ethics Committee of Shaheed Benazir Bhutto University prior to data collection. Permission to access patient records was granted by the District TB Control Program authorities. Patient confidentiality was strictly maintained by anonymizing all identifiers during data extraction and analysis. Since the study utilized retrospective record data without direct patient interaction, informed consent requirements were waived in accordance with institutional ethical guidelines.

3. Results

A total of 215 individuals suspected of having tuberculosis were registered and investigated at the District Tuberculosis Control Center between April and December 2024. Of these patients, 94 were confirmed positive for tuberculosis, resulting in an overall prevalence of 43.7% among the study participants. The remaining 121 individuals, representing 56.3% of the total sample, tested negative for tuberculosis. These findings show that more than two out of every five clinically suspected patients were diagnosed with TB, indicating a considerable disease burden among individuals seeking diagnostic services at the study facility. The observed prevalence should be interpreted within the context of the study design and sampling method. The participants were not selected from the general population; instead, they

were individuals already suspected of having tuberculosis because of clinical symptoms, exposure history, or referral for diagnostic evaluation. Therefore, the reported prevalence of 43.7% cannot be directly compared with national population-based TB prevalence estimates. Facility-based studies involving suspected patients are expected to produce higher positivity rates because the study population has a greater probability of disease than the general community. Nevertheless, the high proportion of confirmed cases highlights the continuing importance of tuberculosis as a major public health problem in District Dir Upper. It suggests that a substantial number of symptomatic individuals presenting to the TB control center have active disease and may contribute to ongoing transmission within

households and communities if diagnosis or treatment is delayed. The finding also reflects the need for efficient screening, rapid diagnostic testing, timely initiation of treatment, and appropriate follow-up of confirmed patients.

The relatively high percentage of negative cases is also important. More than half of the suspected patients were not confirmed as having tuberculosis, suggesting that other respiratory or systemic illnesses may produce symptoms similar to TB. This emphasizes the importance of accurate laboratory diagnosis rather than relying only on clinical symptoms. Patients with negative TB results should receive further clinical assessment to identify alternative causes of persistent cough, fever, weight loss, or other related symptoms.

Table 1. Overall Prevalence of Tuberculosis (n = 215)

TB Status	Frequency (n)	Percentage (%)
Positive	94	43.7
Negative	121	56.3
Total	215	100.0

3.2 Demographic Characteristics of Participants

Of the 215 participants, 121 (56.3%) were male and 94 (43.7%) were female. TB prevalence among females (56.4%) was significantly higher

than among males (33.9%). The association between gender and TB positivity was statistically significant ($\chi^2 = 10.88$, $p = 0.001$). Females had 2.5 times higher odds of TB compared to males.

Table 2. Distribution of TB Status by Gender

Gender	TB Positive n (%)	TB Negative n (%)	Total	χ^2	p-value	OR (95% CI)
Male	41 (33.9%)	80 (66.1%)	121			1.00
Female	53 (56.4%)	41 (43.6%)	94	10.88	0.001	2.52 (1.39–4.56)

3.3 Age-wise Prevalence of Tuberculosis

Age was categorized into seven groups to examine age-specific prevalence patterns. The highest TB prevalence was observed in the 51–60 years group (66.7%) and 41–50 years group (60.0%), followed

by 11–20 years (52.4%). The association between age group and TB status was statistically significant ($p = 0.047$), indicating age-related differences in TB occurrence.

Table 3. Distribution of TB Status by Age Group

Age Group (Years)	Total (n)	TB Positive n (%)	TB Negative n (%)	Pearson value	P-value
1–10	15	5 (33.3%)	10 (66.7%)	5.720	0.047
11–20	21	11 (52.4%)	10 (47.6%)		

21-30	31	10 (32.3%)	21 (67.7%)		
31-40	42	18 (42.9%)	24 (57.1%)		
41-50	30	18 (60.0%)	12 (40.0%)		
51-60	18	12 (66.7%)	6 (33.3%)		
≥61	58	20 (34.5%)	38 (65.5%)		

3.4 Monthly and Seasonal Variation

Significant seasonal variation in TB prevalence was observed across months. TB prevalence peaked dramatically during November and

December (100%), indicating strong winter seasonality. The association between month and TB positivity was highly significant ($p < 0.001$).

Table 4. Monthly Distribution of TB Cases

Month	Total (n)	TB Positive n (%)	Pearson Chi-square	P-value
April	19	11 (57.9%)	82.049	0.001
May	12	6 (50.0%)		
June	17	4 (23.5%)		
July	20	5 (25.0%)		
August	15	3 (20.0%)		
September	18	4 (22.2%)		
October	19	6 (31.6%)		
November	15	15 (100%)		
December	30	30 (100%)		

3.5 Temperature and Tuberculosis Prevalence

TB prevalence was highest at lower temperatures (1-10°C: 100%) and moderate temperatures (11-

20°C: 62.2%). No TB cases were observed at temperatures $\geq 31^\circ\text{C}$. The association between temperature and TB was highly significant.

Table 5. Distribution of TB Status by Temperature Range

Temperature (°C)	Total (n)	TB Positive n (%)	Pearson Chi-square	P-value
1-10	45	45 (100%)	42.358	< 0.001
11-20	45	28 (62.2%)		
21-30	83	16 (19.3%)		
≥31	42	0 (0%)		

3.6 Rainfall and Tuberculosis Prevalence

TB prevalence was significantly associated with rainfall levels. Higher prevalence was observed at

both low (10-100 mm) and high (201-350 mm) rainfall ranges.

Table 6. Distribution of TB Status by Rainfall Range

Rainfall (mm)	Total (n)	TB Positive n (%)	Pearson Chi-square	P-value
10-100	60	38 (63.3%)	29.443	0.001
101-150	42	9 (21.4%)		
151-200	45	20 (44.4%)		
201-350	68	37 (54.8%)		

3.7 Multivariable Logistic Regression Analysis

A binary logistic regression model was constructed to identify independent predictors of TB positivity. After adjusting for confounding variables, female gender, moderate temperature

(11–20°C), and lower rainfall (10–100 mm) remained significant independent predictors of TB positivity. The model demonstrated good fit (Hosmer–Lemeshow $p > 0.05$) and explained 48% of the variance in TB status.

Table 7. Multivariable Logistic Regression for Predictors of TB

Variable	Adjusted OR	95% CI	p-value	Nagelkerke R^2	Hosmer–Lemeshow test p
Female gender	2.18	1.18–4.02	0.012	0.48	0.61
Age 11–20	1.89	1.07–3.34	0.027		
Temp 11–20°C	2.76	1.42–5.36	0.003		
Rainfall 10–100 mm	2.14	1.22–3.78	0.008		

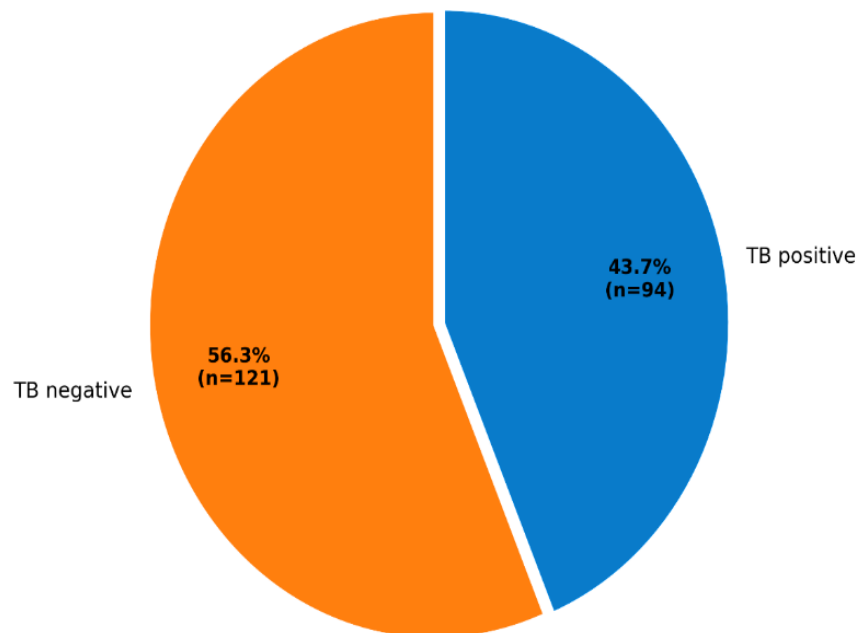
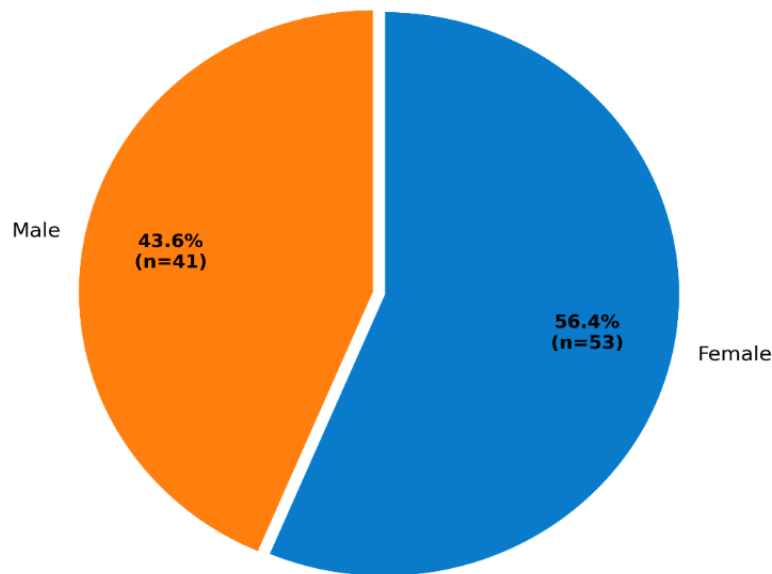
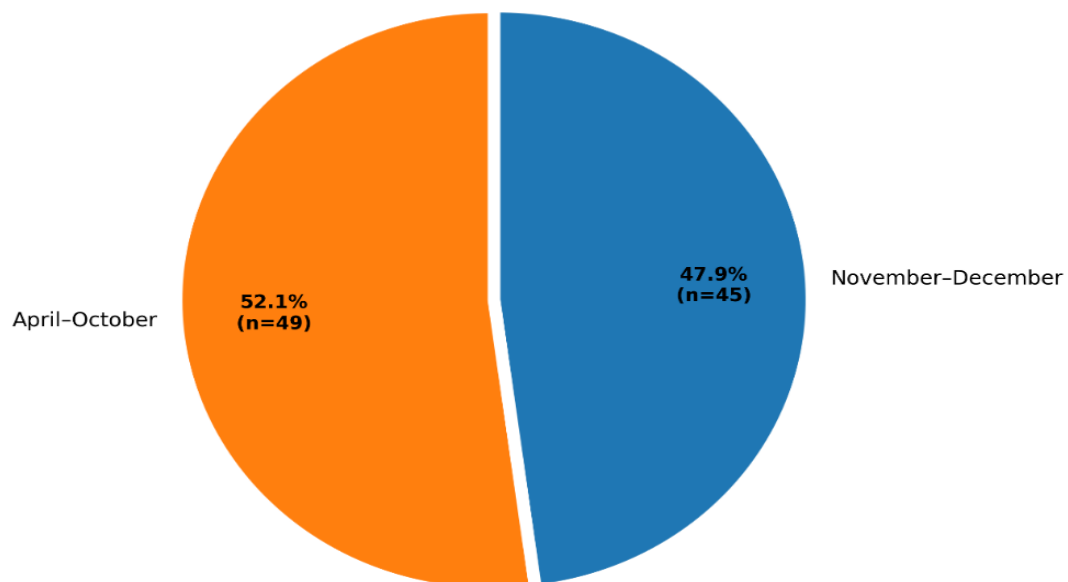
Figure 1. Overall Tuberculosis Status Among Suspected Patients (N = 215)

Figure 2. Sex Distribution of TB-Positive Patients (n = 94)**Figure 3. Contribution of Winter-Peak Months to Total TB-Positive Cases (n = 94)**

Discussion

This cross-sectional analytical study provides novel insights into the demographic and climatic determinants of tuberculosis prevalence in the mountainous district of Dir Upper, Pakistan. Our findings reveal a substantial TB burden among

suspected cases (43.7%) and demonstrate significant associations with gender, age, seasonal variation, temperature, and rainfall patterns. These results contribute to the growing body of evidence highlighting the multifaceted nature of TB epidemiology, where biological, social, and

environmental determinants interact to shape disease transmission dynamics. One of the most striking findings of this study is the significantly higher TB prevalence among females (56.4%) compared to males (33.9%), with females having 2.5 times higher odds of TB positivity. This gender disparity contrasts with the global pattern where TB is typically more prevalent among males, with the World Health Organization reporting approximately 1.5 times higher TB incidence in men globally (WHO, 2023). However, our findings align with several studies from South Asia that have reported elevated TB rates among women. For instance, research from India and Bangladesh has documented higher TB prevalence among women in certain settings, attributed to factors such as nutritional deficiencies, anemia, pregnancy-related immunosuppression, and delayed healthcare-seeking behavior (Nair et al., 2020; Hamid et al., 2016). The elevated TB prevalence among females in Dir Upper may be explained by a combination of biological and socio-cultural factors. Biologically, women may experience increased susceptibility to TB during pregnancy and postpartum periods due to hormonal changes and altered immune responses (Mathad et al., 2014). Additionally, iron deficiency anemia, which is more prevalent among women in resource-limited settings, has been associated with impaired cell-mediated immunity and increased susceptibility to TB (Schaible & Kaufmann, 2007). Socioculturally, women in rural Pakistan often face barriers to healthcare access, including limited mobility, financial dependence, and lower health literacy, which may result in delayed diagnosis and more advanced disease presentation at the time of diagnosis (Ullah et al., 2024). Moreover, indoor air pollution from biomass fuel exposure during cooking, a task predominantly performed by women in rural households, has been identified as a risk factor for TB and respiratory infections (Sumpter & Chandramohan, 2013). The 2.5-fold increased odds observed in our study underscores the urgent need for gender-responsive TB control strategies that address the unique vulnerabilities of women in this region. Our analysis revealed a bimodal age distribution of TB prevalence, with peaks observed

in the younger adult (11–20 years: 52.4%) and older adult populations (41–60 years: 60.0–66.7%). The high prevalence among adolescents and young adults is consistent with the epidemiological transition described in high-burden settings, where TB often affects economically productive age groups (Snow et al., 2018). This pattern may reflect increased social mixing, overcrowded educational environments, and early occupational exposures in this age group (Munch et al., 2003). Furthermore, adolescents are known to have higher rates of progression from latent to active TB, particularly following primary infection, which may contribute to the elevated prevalence observed (Marais et al., 2004). The peak in older adults (51–60 years: 66.7%) aligns with the well-documented phenomenon of reactivation TB in later life, driven by immunosenescence, comorbidities such as diabetes, and cumulative exposure to TB over a lifetime (Byng-Maddick & Noursadeghi, 2016). The increasing prevalence of diabetes in Pakistan, which is known to triple the risk of TB reactivation, may partly explain the elevated rates among older age groups (Jeon & Murray, 2008). Interestingly, the lowest prevalence was observed in the 21–30 years (32.3%) and ≥61 years (34.5%) groups, suggesting potential protective factors in these cohorts or survival bias in the oldest age group. The significant age group association ($p = 0.047$) in our study reinforces the importance of age-targeted screening and preventive interventions. The dramatic seasonal variation observed in our study, with 100% TB positivity in November and December, provides compelling evidence for strong climatic influences on TB transmission in mountainous regions. This winter peak contrasts with the findings of Butt et al. (2021), who reported TB notifications peaking in April–June in Pakistan and being lowest in October–December. The discrepancy likely reflects the unique high-altitude setting of Dir Upper, where winter months (November–February) are characterized by extreme cold, heavy snowfall, and increased indoor crowding. The complete absence of TB cases at temperatures $\geq 31^{\circ}\text{C}$ further supports the hypothesis that cold

temperatures facilitate TB transmission, possibly through multiple mechanisms (Liu et al., 2025). Several biological and behavioral mechanisms may explain the winter peak in TB prevalence. First, cold weather encourages indoor congregation, leading to overcrowding and increased close contact—conditions that facilitate airborne transmission of *M. tuberculosis* (Narasimhan et al., 2013). Second, reduced ventilation in winter months leads to accumulation of infectious aerosols in indoor environments, increasing the risk of transmission (Fennelly et al., 2012). Third, decreased ultraviolet radiation during winter impairs vitamin D synthesis, compromising host immune responses against *M. tuberculosis* (Martineau et al., 2007). Fourth, cold temperatures have been shown to affect the viability and aerosolization of *M. tuberculosis* bacilli, potentially enhancing their survival in the environment (Wang et al., 2024). The 100% TB positivity observed at 1–10°C in our study may also reflect the convergence of these factors during the peak winter months.

The association between rainfall extremes and TB prevalence—with elevated rates at both low (10–100 mm: 63.3%) and high (201–350 mm: 54.8%) rainfall levels—is noteworthy and may indicate complex seasonal dynamics. Low rainfall periods in Dir Upper typically occur during winter months, coinciding with cold temperatures and increased indoor crowding. High rainfall periods correspond to monsoon seasons, which may also be associated with increased TB transmission through mechanisms such as humidity-related effects on airborne particles, disruption of health services, and post-flood displacement leading to overcrowded living conditions (Kovats et al., 2003). Liu et al. (2025) similarly identified complex lagged effects of precipitation on TB incidence, highlighting the need for context-specific analysis of rainfall–disease associations. Multivariable analysis identified moderate temperature (11–20°C) as an independent predictor of TB positivity (AOR: 2.76, 95% CI: 1.42–5.36, $p = 0.003$). This finding suggests that the relationship between temperature and TB transmission is not simply monotonic but may

involve an optimal range for transmission. While winter temperatures (1–10°C) showed 100% prevalence, the lower case numbers in this category ($n = 45$) may have limited statistical power, whereas moderate temperatures captured a broader period including autumn and spring transition months. The persistence of elevated TB risk at moderate temperatures may reflect prolonged seasonal effects, with cases diagnosed after initial exposure during colder months (Khaliq et al., 2015). These findings align with the global analysis by Liu et al. (2025), who reported heterogeneous temperature effects on TB incidence across regions, with warming trends associated with increased TB rates in Asian settings. The public health implications are significant, suggesting that TB control programs in mountainous regions should anticipate seasonal surges and allocate resources accordingly. Low rainfall (10–100 mm) emerged as an independent predictor of TB positivity (AOR: 2.14, 95% CI: 1.22–3.78, $p = 0.008$), supporting the hypothesis that dry conditions may facilitate TB transmission. This finding aligns with research from other settings where low humidity and rainfall have been associated with increased TB notifications, possibly due to enhanced aerosol stability and survival of TB bacilli in the environment (Wang et al., 2024; Liyew et al., 2024). Dry conditions may also increase dust particle loads in the air, which can serve as carriers for *M. tuberculosis* and facilitate long-range transmission (Eckhardt et al., 2019). Alternatively, low rainfall periods may correspond to specific seasons with other conducive conditions (cold temperatures, indoor crowding). The U-shaped association with rainfall—high prevalence at both extremes—suggests that both drought and heavy precipitation can disrupt normal behavioral patterns and health service delivery, potentially increasing TB risk. This finding underscores the need for integrated climate-health surveillance systems that can identify and respond to climate-driven epidemiological changes.

Strengths and Limitations

This study has several strengths. It provides the first localized evidence linking climatic and

demographic factors to TB prevalence in the mountainous region of Dir Upper, filling an important gap in Pakistan's TB epidemiology literature. The inclusion of multiple climatic variables (temperature, rainfall, seasonality) alongside demographic factors allows comprehensive assessment of risk determinants. The use of multivariable logistic regression enabled control for confounding and identification of independent predictors.

However, several limitations should be acknowledged. First, the cross-sectional design precludes establishment of temporal causality, although the seasonal analysis provides some insight into temporal patterns. Second, the study relied on facility-based suspected case data rather than community-based screening, which may have introduced selection bias and underestimation of true community prevalence. Third, the relatively small sample size ($n = 215$) may have limited statistical power for some subgroup analyses, particularly for age-specific interactions. Fourth, data on potential confounding variables such as socioeconomic status, smoking, diabetes, and indoor air pollution were not available, limiting the ability to fully adjust for these factors. Fifth, the study period (April–December 2024) did not capture the complete annual cycle, particularly the peak winter months of January–March, which may have influenced the observed seasonal patterns. Finally, the generalizability of findings to other regions of Pakistan or other high-altitude settings may be limited due to unique local conditions.

Recommendations for Future Research

Future studies should aim to address these limitations through community-based prevalence surveys to estimate true TB burden in the population. Longitudinal cohort studies would provide stronger evidence for causal relationships between climatic factors and TB incidence. Inclusion of detailed data on socioeconomic factors, comorbidities (diabetes, HIV, malnutrition), and behavioral factors (smoking, indoor crowding) would allow more comprehensive risk assessment. Molecular epidemiological studies could help determine whether climatic factors influence transmission of

specific *M. tuberculosis* strains. Additionally, modeling studies using time-series analysis and lagged effects could identify the optimal lead times for climate-based early warning systems. Finally, implementation research is needed to evaluate the effectiveness of climate-responsive TB control strategies in improving case detection and treatment outcomes.

Conclusion

This cross-sectional analytical study demonstrates that TB prevalence in District Dir Upper is significantly influenced by both demographic and climatic determinants. The overall TB prevalence of 43.7% among suspected cases represents a substantial disease burden, with females facing more than twice the odds of TB compared to males. The dramatic seasonal variation, with 100% TB positivity in winter months (November–December), and the strong associations with low temperature and rainfall extremes underscore the critical role of climatic factors in TB transmission dynamics in mountainous regions. Female gender, moderate temperature (11–20°C), and low rainfall (10–100 mm) emerged as independent predictors of TB positivity, highlighting the complex interplay between biological, social, and environmental determinants.

These findings have important implications for TB control programs in Pakistan and similar settings. Seasonal stratification of resources, gender-responsive interventions, age-targeted screening, and integration of meteorological surveillance into TB control strategies could significantly improve case detection and treatment outcomes. As climate change continues to modify temperature and precipitation patterns globally, building climate-resilient TB control programs becomes increasingly urgent. The integration of climatico-environmental data with epidemiological surveillance represents a promising approach to achieving the End TB Strategy targets in the era of climate change.

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REFERENCES

- Alene, K. A., Viney, K., McBryde, E. S., Tsegaye, A. T., & Clements, A. C. A. (2019). Risk factors for multidrug-resistant tuberculosis in northwest Ethiopia: A case-control study. *Tropical Medicine & International Health*, 24(6), 698-708.
- Butt, M. F., Younis, S., Wu, Z., Hadi, S. H., Latif, A., & Martineau, A. R. (2021). The relationship between seasonality, latitude and tuberculosis notifications in Pakistan. *BMC Infectious Diseases*, 21(1), 210. <https://doi.org/10.1186/s12879-021-05899-x>
- Byng-Maddick, R., & Noursadeghi, M. (2016). Does tuberculosis threaten our ageing populations? *BMC Infectious Diseases*, 16(1), 119.
- Eckhardt, S., Peijnenburg, W. J. G. M., & Kubiak, P. (2019). The role of environmental factors in the transmission of tuberculosis. *Environmental Research*, 176, 108527.
- Fennelly, K. P., Martyny, J. W., & Fulton, K. E. (2012). Isolation of Mycobacterium tuberculosis from air samples in a tuberculosis ward. *American Journal of Respiratory and Critical Care Medicine*, 185(4), 473-477.
- Hamid, S. A., Rahman, M. M., & Alam, M. S. (2016). Gender and tuberculosis in Bangladesh: A systematic review. *Journal of Epidemiology and Global Health*, 6(3), 131-141.
- Jeon, C. Y., & Murray, M. B. (2008). Diabetes mellitus increases the risk of active tuberculosis: A systematic review of 13 observational studies. *PLoS Medicine*, 5(7), e152.
- Khaliq, A., Batool, S. A., & Chaudhry, M. N. (2015). Seasonality and trend analysis of tuberculosis in Lahore, Pakistan from 2006 to 2013. *Journal of Epidemiology and Global Health*, 5(4), 397-403. <https://doi.org/10.1016/j.jegh.2015.07.007>
- Kovats, R. S., Bouma, M. J., Hajat, S., Worrall, E., & Haines, A. (2003). El Niño and health. *The Lancet*, 362(9394), 1481-1489.
- Liu, Q., Wang, Y., Liu, M., Zhao, Y., & Liu, J. (2025). The influence and lag-effect of temperature and precipitation on the incidence and mortality of tuberculosis, 2000-2021: An observational study. *Frontiers in Public Health*, 13, 1572422. <https://doi.org/10.3389/fpubh.2025.1572422>
- Liyew, A. M., Clements, A. C. A., Akalu, T. Y., Gilmour, B., & Alene, K. A. (2024). Ecological-level factors associated with tuberculosis incidence and mortality: A systematic review and meta-analysis. *PLOS Global Public Health*, 4(10), e0003425. <https://doi.org/10.1371/journal.pgph.0003425>
- Marais, B. J., Gie, R. P., & Schaaf, H. S. (2004). The epidemiology of tuberculosis in children. *The Lancet Infectious Diseases*, 4(7), 443-451.
- Martineau, A. R., Honecker, F. U., & Wilkinson, R. J. (2007). Vitamin D in the treatment of pulmonary tuberculosis. *The Journal of Steroid Biochemistry and Molecular Biology*, 103(3-5), 793-798.
- Mathad, J. S., Gupta, A., & Bhosale, R. (2014). Pregnancy and tuberculosis: A review of the literature. *Journal of Clinical Tuberculosis and Other Mycobacterial Diseases*, 1, 1-7.

- Munch, H., Christiansen, M., & Kamper-Jørgensen, Z. (2003). Tuberculosis in Denmark 2000. *Scandinavian Journal of Infectious Diseases*, 35(11-12), 802-808.
- Nair, D., Rajshekhar, A., & Thomas, A. (2020). Gender differences in tuberculosis in India. *Indian Journal of Tuberculosis*, 67(4), 528-533.
- Narasimhan, P., Wood, J., & MacIntyre, C. R. (2013). Risk factors for tuberculosis. *Pulmonary Medicine*, 2013, 828939.
- Schaible, U. E., & Kaufmann, S. H. (2007). Malnutrition and infection: Complex mechanisms and global impacts. *PLoS Medicine*, 4(5), e115.
- Sehrish, S., Liu, X. T., Lou, W. B., Zhang, S. Y., Ata, E. B., Yang, G. G., Wang, Q., Zeng, F. L., Leng, X., Shi, K., Azeem, R. M., Gong, Q. L., Song, Y. H., & Du, R. (2025). Prevalence of tuberculosis in bovines in Pakistan during 2000-2024: A systematic review and meta-analysis. *Frontiers in Veterinary Science*, 12, 1525399. <https://doi.org/10.3389/fvets.2025.1525399>
- Snow, K. J., Sismanidis, C., & Denholm, J. (2018). The epidemiology of tuberculosis in children and adolescents. *The Lancet Respiratory Medicine*, 6(7), 487-489.
- Sumpter, C., & Chandramohan, D. (2013). Systematic review and meta-analysis of the associations between indoor air pollution and tuberculosis. *Tropical Medicine & International Health*, 18(1), 101-108.
- Ullah, H., Ahmed, H., Salman, A., Iqbal, R., Hussaini, S. J., & Malikzai, A. (2024). The rising tide of tuberculosis in Pakistan: Factors, impact, and multi-faceted approaches for prevention and control. *Health Science Reports*, 7(10), e70130. <https://doi.org/10.1002/hsr2.70130>
- Wang, F., Yuan, Z., Qin, S., et al. (2024). The effects of meteorological factors and air pollutants on the incidence of tuberculosis in people living with HIV/AIDS in subtropical Guangxi, China. *BMC Public Health*, 24, 1333. <https://doi.org/10.1186/s12889-024-18475-0>
- World Health Organization. (2023). *Global tuberculosis report 2023*. Geneva: World Health Organization.